Semi-holography and heavy ion collisions

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Θεσσαλονίκη

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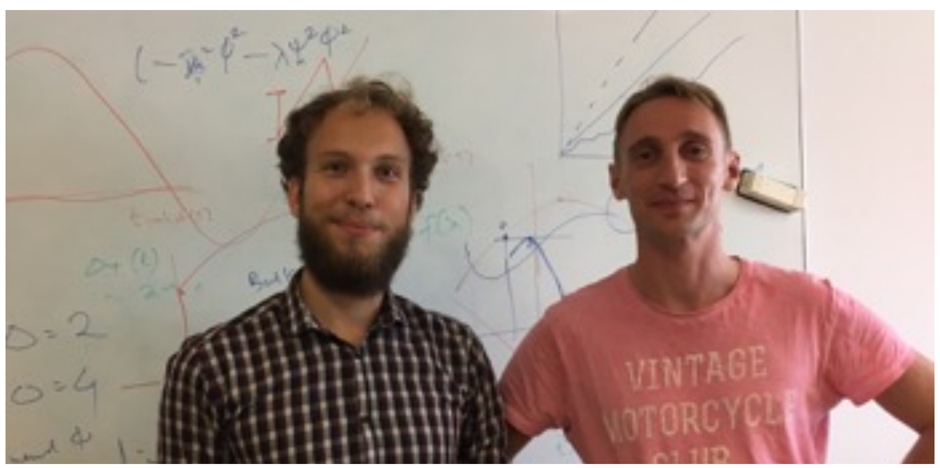


DY

YH

(i) E. Iancu and AM, JHEP 1506 (2015) 003 [arXiv:1410.6448] (<u>First proposal</u>)

(ii) AM, F. Preis, A. Rebhan and S. Stricker, JHEP 1605 (2016) 141 [arXiv:1512.06445] (<u>Refinement + Consistency test + numerical feasibility test</u>)

(iii) C. Ecker, AM, F. Preis, A. Rebhan and S. Stricker, [arXiv:16**.*****] (<u>First study of thermalization</u>)

(iv) Y. Hidaka AM, F. Preis, A. Soloviev, A. Rebhan and D. L. Yang [arXIv:1610.*****] (<u>predictions for collective flow observables</u>)

Introduction

An outstanding theoretical challenge: Develop a consistent framework that can combine weakly and strongly coupled dofs, i.e. construct a generalized EFT such that it can include nonperturbative effects

The holographic duality may model the IR of QCD via (usual) 5-dimensional classical gravity but the latter does not capture the weakly coupled UV, while pQCD fails in the IR.

To understand bound states of QCD, their interactions and also QGP formed by heavy-ion collisions we need to include both weakly and strongly coupled dofs at various energy scales (and not just extrapolate to intermediate coupling)

Semi-holography: A proposal in this direction

The case for HIC

At initial stage, the dynamics is perturbative and experimental evidence suggests that it should be described by the color glass condensate (CGC) framework following from McLerran-Venugopalan model of nuclear structure functions

At later stage, fast "hydrolyzation" and small η/s suggest that a strongly coupled bath of IR gluons is formed which may be successfully described by a holographic model

SEMIHOLOGRAPHY: Combine CGC and Holography to construct a model with a small number of effective parameters [see J. Cassalderrey Solana et. al. (also talks by W. van der Schee and A. Sadofyev) for a different hybrid approach for jet quenching]

Recap of saturation physics

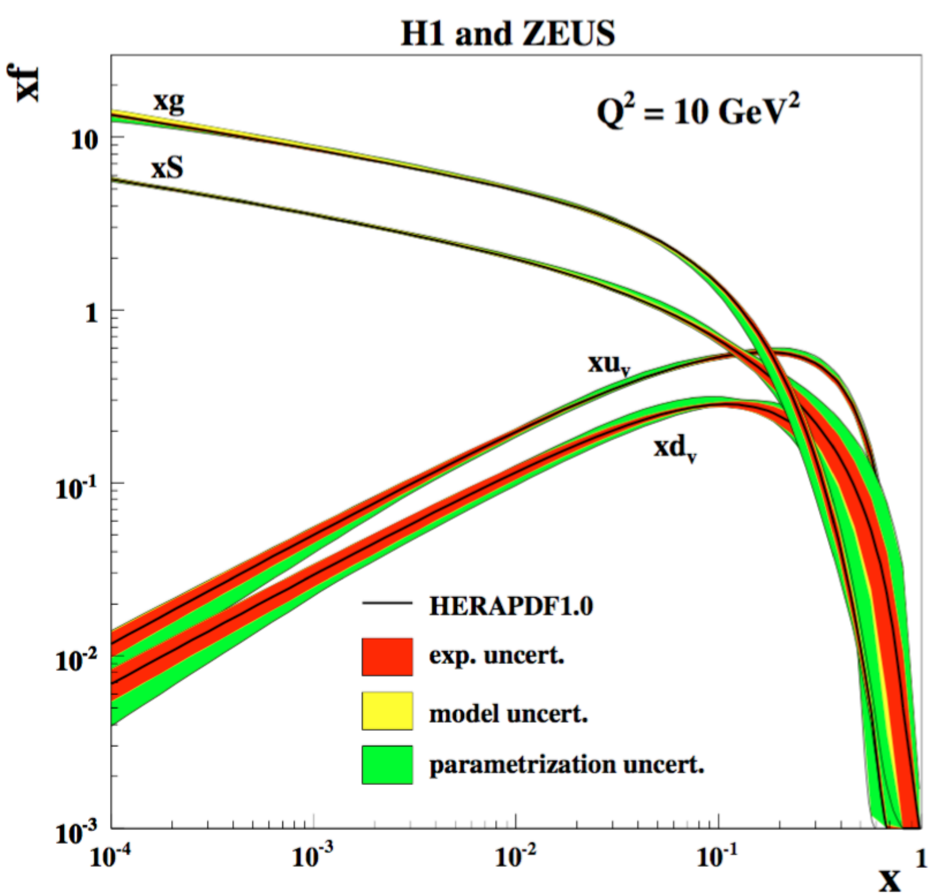
(Iancu, Leonidov & McLerran 2000; see F. Gelis & E. Iancu, [arXiv: 1002.0333] for review)

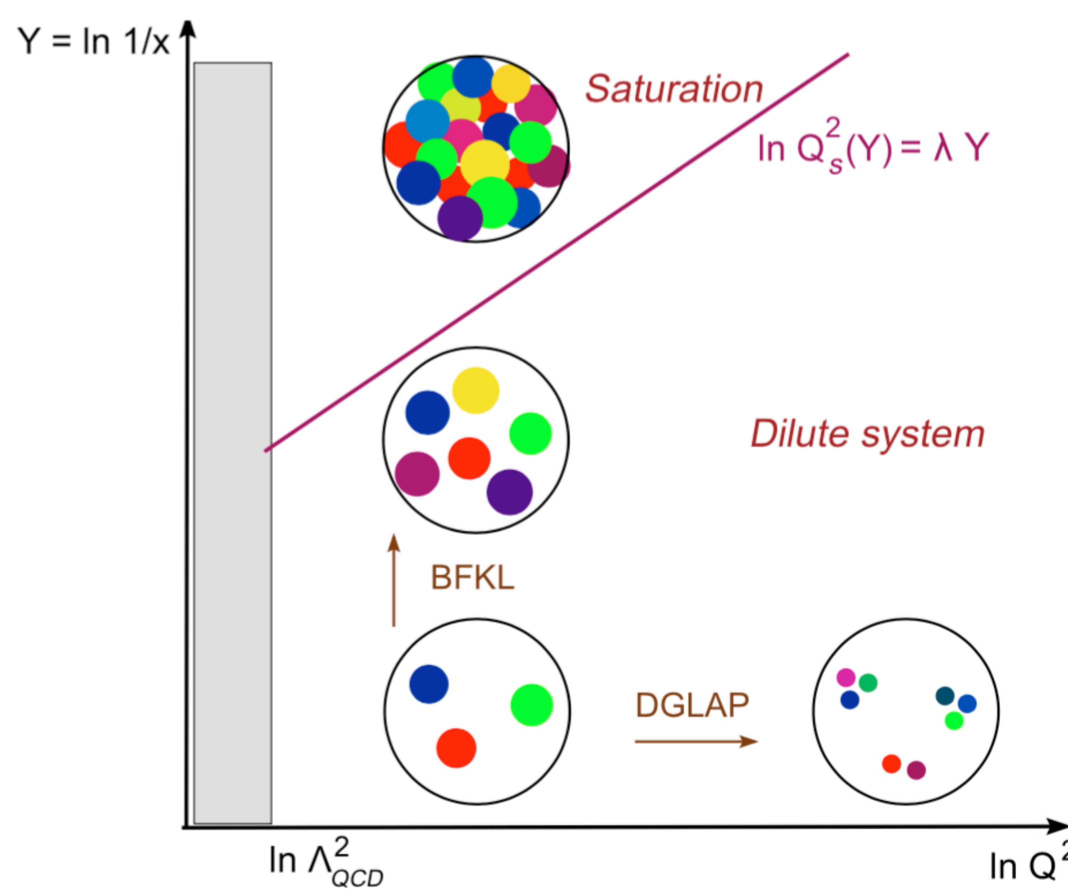
$xG(x,Q^2) =$ number of gluons with transverse area $\geq 1/Q^2$ and $k^+/P^+ = x$ of longitudinal momentum

$xG(x,Q^2) \propto x^{-0.3}$ at fixed $Q^2 > 1\text{Gev}^2$ and small x

Maximal $xG(x,Q^2) \approx O(1/\alpha_s)$ is achieved at $Q^2 = Q_s^2(x) = Q_0^2(x/0.0003)^{0.3}$ with $Q_0 \approx 1\text{Gev}$.

Over-occupied weakly coupled ($\alpha_s(Q_s) \ll 1$) gluonic system at semi-hard scale Q_s





$Q_{s,A}(x) \approx Q_{s,p}(x) A^{1/3}$

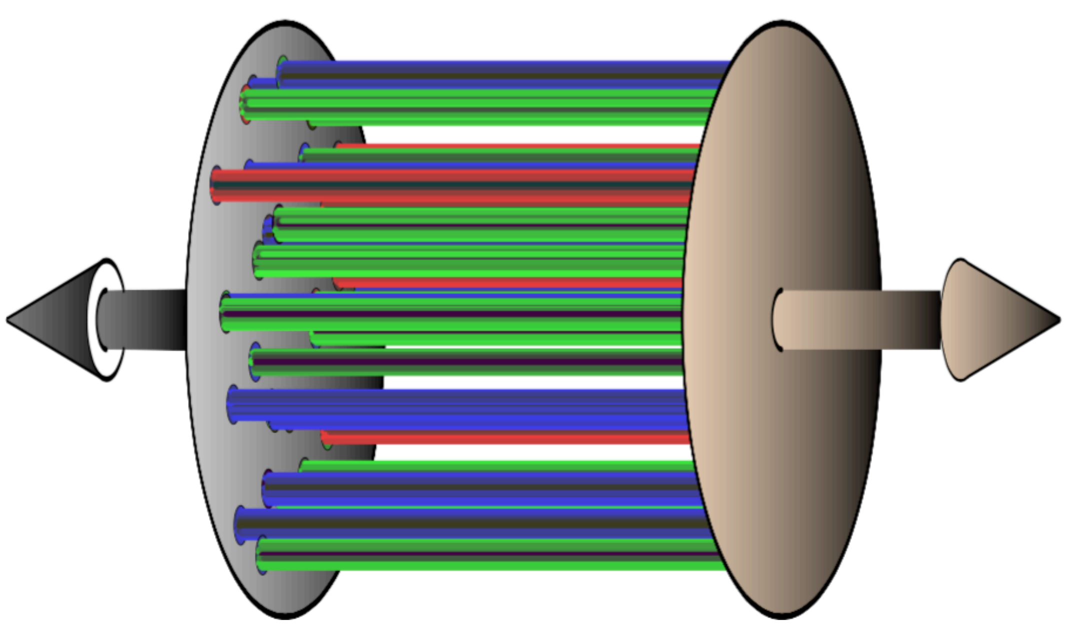
Color glass condensate/Glasma

(Kovner, McLerran, Weigert 1995; McLerran,& Lappi, 2005)

Saturation physics: At initial stage of collisions most gluons have transverse and longitudinal momenta of $\mathcal{O}(Q_s)$

Can be described by classical YM equations due to over-occupation at leading order

At initial time, these are sourced by frozen large x color sources of colliding nuclei which follow a Gaussian distribution with width $\mathcal{O}(Q_s)$



GLASMA initial stage: Longitudinal chromoelectric and chromomagnetic flux tubes of transverse width $\approx 1/Q_s$

The semi-holographic framework for large N pure QCD

The perturbative fields design the sources of the holographic theory

$$S[A_\mu^a, \Lambda] = S^{\mathrm{pQCD}}[A_\mu^a, \Lambda] + \ln Z^{\mathrm{NP-Hol}}\left[\tilde{g}_{\mathrm{YM}}[A_\mu^a, \Lambda], \tilde{\theta}[A_\mu^a, \Lambda], g_{\mu\nu}^{(\mathrm{b})}[A_\mu^a, \Lambda]\right]$$

The holographic IR is an emergent strongly coupled pure YM theory — so it has only three marginal couplings/sources

$$\ln Z^{\mathrm{NP-Hol}} = S^{\mathrm{grav}}_{\mathrm{on-shell}}$$

Gravitation can model confinement [E. Witten 1998] (see U. Gursoy, E. Kiritsis and F. Nitti 2008 for a bottom-up approach — also talk by Matti Jarvinen)

Which principles determine $\tilde{g}_{\mathrm{YM}}[A^a_\mu, \Lambda], \tilde{\theta}[A^a_\mu, \Lambda], g^{(\mathrm{b})}_{\mu\nu}[A^a_\mu, \Lambda]$?

Which principles determine the classical gravity theory for the holographic IR?

(i) Existence of a local em-tensor for the full system that is conserved in flat space and which can be constructed without knowing the UV/IR Lagrangians explicitly

(ii) Renormalizability of UV and IR

(iii) Cancellation of Borel poles of pQCD (or similar divergences in perturbation series for glasma)

(iv) Reconstruction of holography as RG flow — specially if $\alpha_s \approx \Lambda_{\mathrm{QCD}}$

Progress: The general solution of (i) is known and lot of progress on others

A toy model addressing all points to appear [S. Banerjee, N. Gaddam, AM]

Here we do not present a fundamental derivation but construct a phenomenological model for HIC incorporating points (i) and (ii) in a minimalistic way.

The gravitational theory in HIC: Einstein's gravity minimally coupled to a dilaton-axion pair (assume confinement plays no role until hadronization)

Self-consistent solution of classical gravity gives:

$$\overline{\mathcal{T}}^{\mu\nu} = 2\frac{\delta \ln Z^{\mathrm{NP-Hol}}}{\delta g^{(\mathrm{b})}_{\mu\nu}} = \sqrt{-g^{(\mathrm{b})}}\mathcal{T}^{\mu\nu}$$

holographic em-tensor
— GRAVITON

$$\overline{\mathcal{H}} = \frac{\delta \ln Z^{\mathrm{NP-Hol}}}{\delta \tilde{g}_{\mathrm{YM}}} = \sqrt{-g^{(\mathrm{b})}}\mathcal{H}$$

holographic glueball density
— DILATON

$$\overline{\mathcal{A}} = \frac{\delta \ln Z^{\mathrm{NP-Hol}}}{\delta \tilde{\theta}} = \sqrt{-g^{(\mathrm{b})}}\mathcal{A}$$

holographic Pontryagin density
— AXION

It is consistent with the variational principle to rewrite:

$$S[A^a_\mu,\Lambda] = S^{\mathrm{pQCD}}[A^a_\mu,\Lambda] + \int \mathrm{d}^4x\, \tilde{g}_{\mathrm{YM}}[A^a_\mu,\Lambda]\overline{\mathcal{H}} + \int \mathrm{d}^4x\, \tilde{\theta}[A^a_\mu,\Lambda]\overline{\mathcal{A}} + \frac{1}{2}\int \mathrm{d}^4x\, g^{(\mathrm{b})}_{\mu\nu}[A^a_\mu,\Lambda]\overline{\mathcal{T}}^{\mu\nu}$$

on-shell gravitational action

Furthermore if we assume that:

$$g^{(b)}_{\mu\nu} = \eta_{\mu\nu} + \gamma\, t^{\mathrm{pQCD}}_{\mu\nu}[A_\mu, \Lambda]$$

$$\tilde{g}_{\mathrm{YM}} = \beta\, \mathrm{tr}\,(F_{\mu\nu}F^{\mu\nu})$$

$$\tilde{\theta} = \alpha\, \mathrm{tr}\,(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

not independent parameters

$$\alpha = \frac{1}{\Lambda^4} f_1\left(\frac{\Lambda^{\mathrm{QCD}}}{\Lambda}\right), \quad \beta = \frac{1}{\Lambda^4} f_2\left(\frac{\Lambda^{\mathrm{QCD}}}{\Lambda}\right), \quad \gamma = \frac{1}{\Lambda^4} f_3\left(\frac{\Lambda^{\mathrm{QCD}}}{\Lambda}\right)$$

then both UV and IR are renormalizable (both UV and IR are marginally deformed)

$$\boxed{\begin{aligned} S[A^a_\mu, \Lambda] = S^{\mathrm{pQCD}}[A^a_\mu, \Lambda] + \beta \int \mathrm{d}^4x\, \mathrm{tr}(F_{\mu\nu}F^{\mu\nu})\overline{\mathcal{H}} + \alpha \int \mathrm{d}^4x\, \mathrm{tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})\overline{\mathcal{A}} \\ + \frac{1}{2}\gamma \int \mathrm{d}^4x\, t^{\mathrm{pQCD}}_{\mu\nu}[A^a_\mu, \Lambda]\overline{\mathcal{T}}^{\mu\nu} \end{aligned}}$$

So we can solve the full system iteratively

What about HIC?

(E. Iancu and AM 2014; AM, F. Preis, A. Rebhan and S. Stricker 2015)

$$\boxed{S = S_{\mathrm{YM}}^{\mathrm{glasma}}[A_\mu^a] + W_{\mathrm{CFT}}[g_{\mu\nu}^{(\mathrm{b})}, \phi^{(\mathrm{b})} \chi^{(\mathrm{b})}]}$$

glasma at LO is classical YM

$W_{\mathrm{CFT}} =$ self-consistent on-shell gravitational action with following sources

$$g_{\mu\nu}^{(\mathrm{b})} = \eta_{\mu\nu} + \frac{\gamma}{Q_s^4} t_{\mu\nu}^{\mathrm{YM}}[A_\mu], \;\; \phi^{(\mathrm{b})} = \frac{\beta}{4N_c Q_s^4} \mathrm{tr}(F_{\mu\nu}F^{\mu\nu}), \;\; \chi^{(\mathrm{b})} = \frac{\alpha}{4N_c Q_s^4} \mathrm{tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

$$t_{\mu\nu}^{YM}[A_\mu] = \frac{1}{N_c}\left(\mathrm{tr}(F_{\mu\alpha}F_\nu{}^\alpha) - \frac{1}{4}\eta_{\mu\nu}\mathrm{tr}\left(F_{\alpha\beta}F^{\alpha\beta}\right)\right)$$

Unique solution of gravity in method of characteristics from a given initial condition and given boundary sources [P.Chesler and L.Yaffe; W. van der Schee and B.Schenke]

Our initial conditions [E.Iancu and AM 2014]:

(i) Glasma initial conditions for classical YM fields

(ii) Pure AdS with vanishing dilaton and axion in gravity (in practice a small seed black hole is needed)

In FG coordinates where $G_{\mu r}=0, G_{rr}=l^2/r^2$ we have asymptotic $r \approx 0$ behaviors:

$$\Phi(r,x^\mu)=\phi^{(\mathrm{b})}(x^\mu)+\cdots+r^4(\mathcal{H}+\text{local functional of sources})+\cdots$$

$$\mathcal{X}(r,x^\mu)=\chi^{(\mathrm{b})}(x^\mu)+\cdots+r^4(\mathcal{A}(x^\mu)+\text{local functional of sources})+\cdots$$

$$G_{\mu\nu}(r,x^\mu)=g^{(\mathrm{b})}_{\mu\nu}(x^\mu)+\cdots+r^4(\mathcal{T}_{\mu\nu}+\text{local functional of sources})+\mathcal{O}(r^4\ln r)$$

$$g^{(\mathrm{b})}_{\mu\nu}=\eta_{\mu\nu}+\tfrac{\gamma}{Q_s^4}t^{\mathrm{YM}}_{\mu\nu}[A_\mu],\ \ \phi^{(\mathrm{b})}=\tfrac{\beta}{4N_cQ_s^4}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}),\ \ \chi^{(\mathrm{b})}=\tfrac{\alpha}{4N_cQ_s^4}\mathrm{tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

$$t^{YM}_{\mu\nu}[A_\mu]=\frac{1}{N_c}\left(\mathrm{tr}(F_{\mu\alpha}F_\nu{}^\alpha)-\frac{1}{4}\eta_{\mu\nu}\mathrm{tr}\left(F_{\alpha\beta}F^{\alpha\beta}\right)\right)$$

Inputs

$$\overline{\mathcal{H}}\equiv\sqrt{-g^{(\mathrm{b})}}\mathcal{H},\quad \overline{\mathcal{A}}\equiv\sqrt{-g^{(\mathrm{b})}}\mathcal{A},\quad \overline{\mathcal{T}}^{\mu\nu}\equiv\sqrt{-g^{(\mathrm{b})}}g^{(\mathrm{b})\mu\alpha}\mathcal{T}_{\alpha\beta}g^{(\mathrm{b})\beta\nu}$$

Outputs

Consistently with the variational principle we can rewrite the classical action for glasma with IR-CFT operators appearing as self-consistent mean fields

$$S=-\tfrac{1}{4N_c}\int \mathrm{d}^4x\,\mathrm{tr}(F_{\mu\nu}F^{\mu\nu})+\int \mathrm{d}^4x\overline{\mathcal{H}}\phi^{(\mathrm{b})}+\int \mathrm{d}^4x\overline{\mathcal{A}}\chi^{(\mathrm{b})}+\tfrac{1}{2}\int \mathrm{d}^4x\overline{\mathcal{T}}^{\mu\nu}g^{(\mathrm{b})}_{\mu\nu}$$

The modified glasma classical YM equations (in flat space):

$$D_\mu F^{\mu\nu} = \frac{\beta}{Q_s^4} D_\mu(\overline{\mathcal{H}} F^{\mu\nu}) + \frac{\alpha}{Q_s^4}(\partial_\mu \overline{\mathcal{A}})\tilde{F}^{\mu\nu} + \frac{\gamma}{Q_s^4} D_\mu \left(\overline{\mathcal{T}}^{\mu\alpha} F_\alpha{}^\nu - \overline{\mathcal{T}}^{\nu\alpha} F_\alpha{}^\mu - \frac{1}{2}\overline{\mathcal{T}}^{\alpha\beta}\eta_{\alpha\beta} F^{\mu\nu} \right)$$

ITERATIVE SCHEME: [E. Iancu and AM 2014]

(i) Solve glasma equations with $\alpha = \beta = \gamma = 0$

(ii) Substitute this solution in the gravitational sources $\phi^{(\mathrm{b})}, \chi^{(\mathrm{b})}, g^{(\mathrm{b})}_{\mu\nu}$ and obtain the self-consistent mean fields $\overline{\mathcal{H}}, \overline{\mathcal{A}}, \overline{\mathcal{T}}^{\mu\nu}$ by solving gravity equations

(iii) Solve the glasma equations again with these new self-consistent mean fields

(iv) Re do step 2 and continue until solutions in both sectors converge

At each step of iteration the glasma and gravity initial conditions are held fixed

The em-tensor

(AM, F. Preis, A. Rebhan and S. Stricker 2015)

One can readily construct the local em-tensor of the full system from the action that is conserved in flat space where the full system lives.

$$T^{\mu\nu} = t^{\mu\nu}_{\rm YM} + \overline{\mathcal{T}}^{\mu\nu} - \frac{\gamma}{Q_s^4 N_c}\overline{\mathcal{T}}^{\alpha\beta}\left(\mathrm{tr}(F_\alpha{}^\mu F_\beta{}^\nu) - \frac{1}{2}\eta_{\alpha\beta}\mathrm{tr}(F^{\mu\rho}F^\nu{}_\rho) + \frac{1}{4}\delta^\mu_{(\alpha}\delta^\nu_{\beta)}\mathrm{tr}(F_{\rho\sigma}F^{\rho\sigma})\right)$$

$$-\frac{\beta}{Q_s^4 N_c}\overline{\mathcal{H}}\,\mathrm{tr}(F^{\mu\rho}F^\nu{}_\rho) - \frac{\alpha}{4Q_s^4 N_c}\eta^{\mu\nu}\overline{\mathcal{A}}\,\mathrm{tr}(F^{\rho\sigma}\tilde{F}_{\rho\sigma})$$

THEOREM: When <u>both</u> the modified glasma equations and the equations of gravity are satisfied, i.e. when iteration converges the above em-tensor is conserved i.e.

$$\boxed{\partial_\mu T^{\mu\nu} = 0.}$$

To prove the theorem one does not need to know how we solve for the IR-CFT operators explicitly

One just needs to impose the IR-CFT Ward identity

$$\boxed{\nabla_{(\mathrm{b})\mu}\mathcal{T}^{\mu\nu} = \frac{\beta}{4N_cQ_s^4}\mathcal{H}\nabla^{\nu}_{(\mathrm{b})}\mathrm{Tr}(F_{\alpha\beta}F^{\alpha\beta}) + \frac{\alpha}{4N_cQ_s^4}\mathcal{A}\nabla^{\nu}_{(\mathrm{b})}\mathrm{Tr}(F_{\alpha\beta}\tilde{F}^{\alpha\beta})}$$

The above should be reinterpreted as the modified Ward identity of a marginally deformed IR-CFT living in flat space

$$\begin{aligned}\partial_\mu\mathcal{T}^{\mu\nu} = \frac{\beta}{4N_cQ_s^4}\mathcal{H}g^{(\mathrm{b})\nu\rho}[t_{\mathrm{YM}}]\partial_\rho\mathrm{Tr}(F_{\alpha\beta}F^{\alpha\beta}) + \frac{\alpha}{4N_cQ_s^4}\mathcal{A}g^{(\mathrm{b})\nu\rho}[t_{\mathrm{YM}}]\partial_\rho\mathrm{Tr}(F_{\alpha\beta}\tilde{F}^{\alpha\beta})\\ -\mathcal{T}^{\alpha\nu}\Gamma^{\gamma}_{\alpha\gamma}[t_{\mathrm{YM}}] - \mathcal{T}^{\alpha\beta}\Gamma^{\nu}_{\alpha\beta}[t_{\mathrm{YM}}]\end{aligned}$$

$$g^{(\mathrm{b})\mu\nu} = \eta^{\mu\nu} - \frac{\gamma}{Q_s^4}t^{\mu\nu}_{\mathrm{YM}} + \mathcal{O}(\gamma^2) \qquad \Gamma^{\rho}_{\mu\nu} = \frac{\gamma}{2Q_s^4}\left(\partial_\mu t^{\rho}_{\mathrm{YM}\nu} + \partial_\nu t^{\rho}_{\mathrm{YM}\mu} - \partial^\rho t_{\mathrm{YM}\mu\nu}\right) + \mathcal{O}(\gamma^2)$$

Numerical Feasibility Test

(AM, F. Preis, A. Rebhan and S. Stricker 2015)

Simplest non-trivial example (but alas without an instance of thermalization) comes by assuming:

Homogeneity, Isotropy and $\alpha = \beta = 0$

Let gauge group be $SU(2)$

Choose temporal gauge $A_t^a = 0$

Color-spin locking $A_i^a(t) = f(t)\delta_i^a$

Then $$E_i^a(t) = f'(t)\delta_i^a, \quad B_i^a(t) = \delta_i^a f^2(t)$$

In this configuration $$g_{\mu\nu}^{(\mathrm{b})}(t) = \Omega^2[f(t)]\eta_{\mu\nu}$$

Since the bulk is pure gravity, we can invoke Birkhoff's theorem: Homogeneity and isotropy imply that the solution in gravity is a "large" time-dependent diffeomorphism of an AdS-Sch BH

So we can obtain IR-CFT em-tensor without solving gravity explicitly

IR-CFT em-tensor = conformal + diffeomorphism transformations of thermal em-tensor + anomalous terms with precise central charges ($c\,\&\,a$)

$$\mathcal{T}^{\mu\nu} = -\frac{N_c^2}{64\pi^2}\left(g^{\mu\nu}\left(\frac{R^2}{2} - R_{\alpha\beta}R^{\alpha\beta}\right) + 2R^{\mu\lambda}R^{\nu}{}_{\lambda} - \frac{4}{3}RR^{\mu\nu}\right)$$

$$+\text{conformal rescaling and diffeomorphism of } \mathrm{diag}(3P, P, P, P)$$

Glasma equations

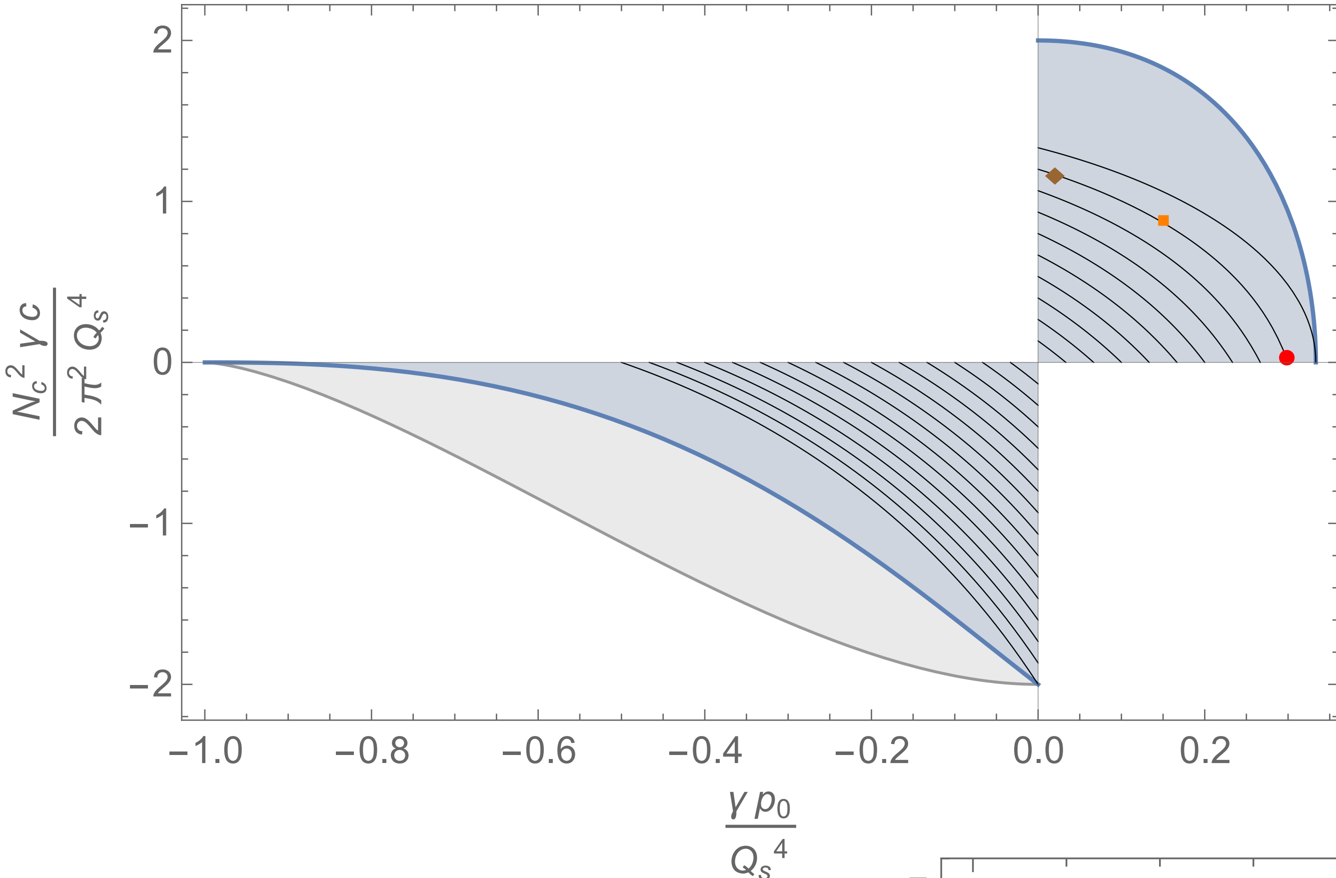
$$\ddot{f} + 2\frac{1-\frac{1}{2}\frac{\gamma}{Q_s^4}(\mathcal{E}+\mathcal{P})}{1+\frac{1}{2}\frac{\gamma}{Q_s^4}(\mathcal{E}+\mathcal{P})}f^3 + \frac{1}{2}\frac{\gamma}{Q_s^4}\frac{(\dot{\mathcal{E}}+\dot{\mathcal{P}})}{1+\frac{1}{2}\frac{\gamma}{Q_s^4}(\mathcal{E}+\mathcal{P})}\dot{f} = 0$$

$$\mathcal{T}^{\mu\nu} \equiv \mathrm{diag}(\mathcal{E},\mathcal{P},\mathcal{P},\mathcal{P})$$

Iterations converge in about 4 repetitions — the full em-tensor is then conserved

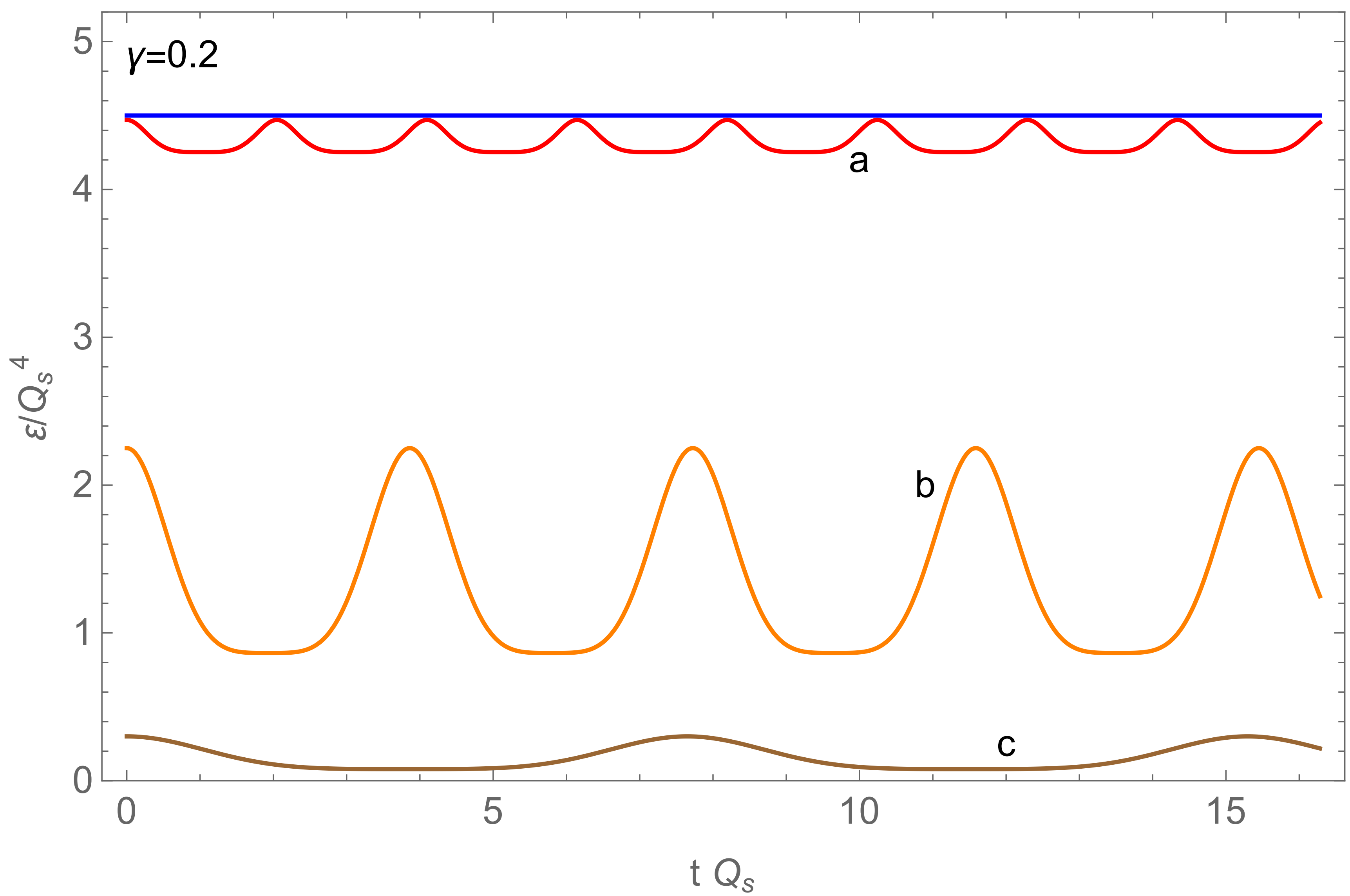
The total BH entropy remains constant but energy-density of both YM and IR-CFT keeps oscillating forever

<u>No irreversible transfer of energy to IR as QN modes of BH are not excited!</u>



Various initial conditions with same total energy but different ratios of YM to IR-CFT energy

c = mass of BH



<u>Blue line</u>: Total energy
<u>Red, orange and brown lines</u>: Oscillating YM energy

Non-linearities imply amplitude and period are related

Homogeneous Thermalization

(C. Ecker, AM, F. Preis, A. Rebhan and S. Stricker : in progress)

What if we manage to simulate with (stochastic) glasma initial conditions for YM fields?

IR must thermalize due to BH formation. Will the UV glasma fields thermalize too?

Yes — at late time gravity can be described by a dual field [Fluid/Gravity Correspondence BHMR 2007] living in a self-consistent weakly curved space

Furthermore there exists an entropy current in hydro limit

$$\nabla_{(b)\mu} S^{\mu} > 0 \Rightarrow \partial_{\mu} \tilde{S}^{\mu} > 0 \text{ with } \tilde{S}^{\mu} = \sqrt{-g^{(\mathrm{b})}} S^{\mu}$$

Therefore, there exists an entropy current for the full system and so UV must thermalize with IR (argument does not work in homogeneous case)

Even without coupling to BH, homogeneous (but anistropic) dynamics of glasma is chaotic — so there is inherent ergodicity

Furthermore, if we switch on the dilaton and axion couplings, there will be irreversible energy transfer to IR through QN modes of gravity.

The YM fields will have mean energy density depleted.

However, there will be still oscillations in YM energy and for short periods of time the YM sector can also gain energy from IR (exploiting non-trivial dynamical boundary metric).

In the long run, we expect Boltzmann weighting in glasma phase space — but will it be Fokker-Planck or strongly non-Markovian evolution?

QUESTION: Is the thermalization bottom-up or top-down?

Holography prefers TOP-DOWN but perturbative physics prefers BOTTOM-UP [Baier, Mueller and Son 2007].

In semi-holography? Quantum complexity and initial condition dependence?

Semi-holography with kinetic theory

(Y: Hidaka , AM, F. Preis, A. Rebhan, A. Soloviev, S. Stricker and D. L. Yang : in progress)

At late time the classical YM description of glasma is strictly not valid as the system is not overoccupied.

We must switch to kinetic theory [see A. Kurkela and E. Lu 2014 (also talks by A. Kurkela and Y Zhu)] for the YM sector

The sources for gravity will be given by perturbative gluonic correlation functions in semiholography

A successful semiholographic formulation has been done.

Simplification: The gravity equations can be substituted by a fluid living in a self-consistent curved background metric that is determined by gluonic correlation functions. The latter can be recast as quantum kinetic theory.

QUESTION: How are the collective flow observables modified?

For simplicity we put only $\gamma \neq 0$ and consider only NLO corrections to glasma

$$S[A_\mu^a(x), D(y,z)] = S^{\rm LO} + S^{\rm NLO}$$

$\boxed{\text{Action for YM fields and propagator}}$

$$S^{\rm LO} = -\frac{1}{4N_c}\int {\rm d}^4x\,{\rm tr}(F_{\mu\nu}F^{\mu\nu}) + W^{\rm CFT}\left[g^{({\rm b})}_{\mu\nu} = \eta_{\mu\nu} + \frac{\gamma}{Q_s^4}t^{\rm cl}_{\mu\nu}\right]$$

$$S^{\rm NLO} = \frac{i}{2}{\rm Tr}\ln D^{-1} + \frac{i}{2}D^{-1}_{(0)}[A^a_\mu]D + W^{\rm CFT}\left[g^{({\rm b})}_{\mu\nu} = \eta_{\mu\nu} + \frac{\gamma}{Q_s^4}\left(t^{\rm cl}_{\mu\nu} + t^{\rm q}_{\mu\nu}\right)\right] - W^{\rm CFT}\left[g^{({\rm b})}_{\mu\nu} = \eta_{\mu\nu} + \frac{\gamma}{Q_s^4}t^{\rm cl}_{\mu\nu}\right]$$

$$t^{\rm cl}_{\mu\nu} = \frac{1}{N_c}\left({\rm tr}(F_{\mu\alpha}F_\nu{}^\alpha) - \frac{1}{4}\eta_{\mu\nu}{\rm tr}\left(F_{\alpha\beta}F^{\alpha\beta}\right)\right)$$

$\boxed{\text{Both YM fields and propagators source the bulk graviton}}$

$$\begin{aligned} t^{\rm q}_{\mu\nu} = \frac{1}{4}\lim_{x\to y}\Big\{\Big[&\partial^x_\gamma\partial^{y\gamma}\left(\delta^\alpha_\mu\delta^\beta_\nu + \delta^\alpha_\nu\delta^\beta_\mu\right) + \left(\partial^x_\mu\partial^y_\nu + \partial^x_\nu\partial^y_\mu\right)\eta^{\alpha\beta} \\ &- \partial^x_\mu\partial^{y\alpha}\delta^\beta_\nu - \partial^{x\alpha}\partial^y_\mu\delta^\beta_\nu - \partial^{x\alpha}\partial^y_\nu\delta^\beta_\mu - \partial^x_\nu\partial^{y\beta}\delta^\alpha_\mu \\ &- \eta_{\mu\nu}\left[\eta^{\alpha\beta}\partial^x_\gamma\partial^{y\gamma} - \partial^{x\beta}\partial^{y\alpha}\right]\Big\}{\rm tr}\Big(D_{\alpha\beta}(x,y) + D_{\alpha\beta}(y,x)\Big) \end{aligned}$$

$\boxed{\text{Gives self-energy in Schwinger-Dyson eom for D}}$

$D^{-1}_{(0)}[A_\mu] \equiv$ inverse propagator obtained from quadratic term in $F_{\mu\nu}F^{\mu\nu}$

$\boxed{\text{Can be readily solved at late time by assuming that YM fields vanish. Furthermore, we can replace the bulk gravitational dynamics with a fluid.}}$

Outlook

Semiholography brings in rich dynamics of isotropization and thermalization which cannot be obtained simply by interpolating between weak and strong coupling, but rather by <u>bringing all degrees of freedom together</u>.

Even the homogeneous and isotropic case has non-trivial dynamics when the bulk dilaton and axion are switched on. The quest is on — <u>bottom-up vs top-down, quantum complexity, initial condition dependence, Fokker-Planck or non-Markovian</u>?

Numerics are extremely challenging — iteration requires extreme precision as generically convergence is slow.

<u>HIC could be a great opportunity to learn how to construct a nonperturbative effective framework for quantum many-body systems.</u>

Please join our adventure

Thank you for your attention