Hard probes of **pre-equilibrium** dynamics in *heavy-ion collisions*

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Research Council of Finland

SEWM, University of Helsinki, August 2026

This talk

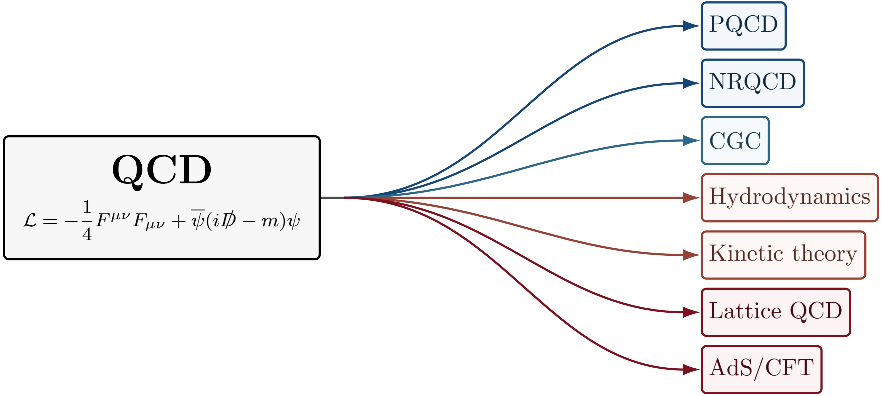
I. Theory of heavy-ion collisions
II. Pre-equilibrium physics
III. QCD at high energies
IV. Hard probes in pre-equilibrium
V. Latest developments
VI. This SEWM

I. Theory of heavy-ion collisions

- Effective theories of QCD
- Multistage approach
- No phenomenology, only theory

The S in SEWM

[EFTs in QCD]

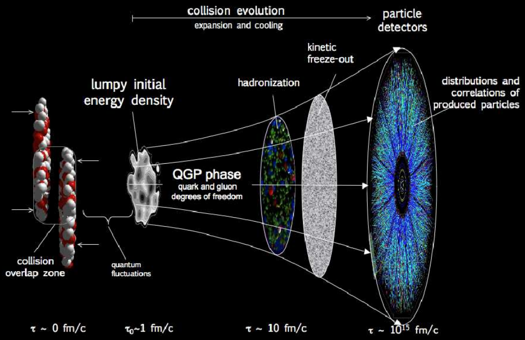


● perturbative ● weak coupling ● transport ● non-perturbative

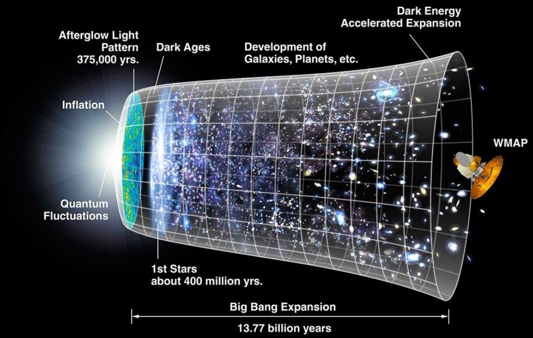
Heavy-ion collisions

[little bang & big bang]

- Timescale: $\mathrm{fm}/c \approx 10^{-23}\,\mathrm{s}$

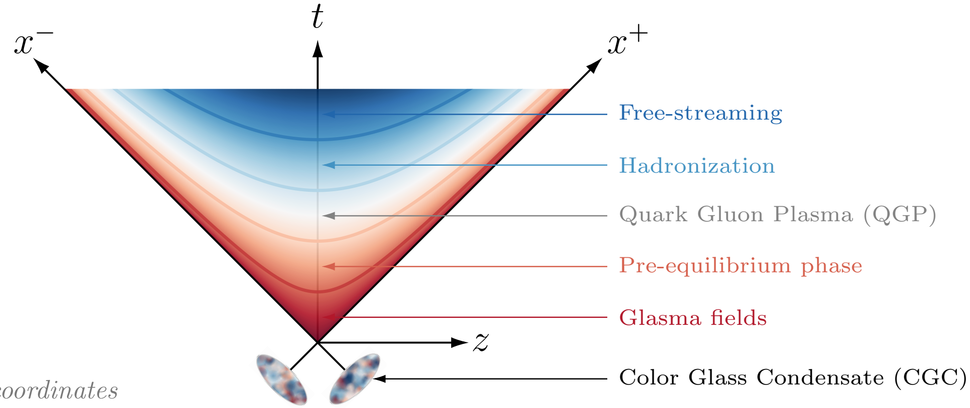


- Timescale: billion years $\approx 10^{17}\,\mathrm{s}$



Multistage process

[stages at weak coupling]



Light-cone coordinates
$x^{\pm} = t \pm z$

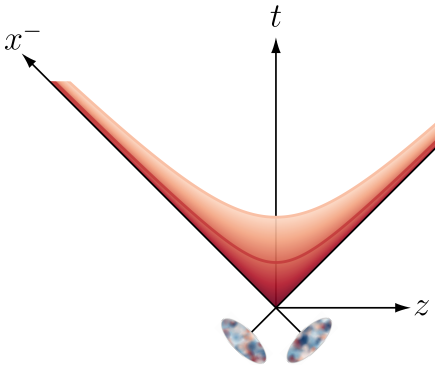
Gelis ***[2102.07604]*** *Heinz, Schenke* ***[2412.19393]***

II. Pre-equilibrium dynamics

- Thermalization of QCD matter
- Probes of pre-equilibrium

Pre-equilibrium stages

[CGC, Glasma, EKT]



Color glass condensate

- EFT for QCD at small-x

⇒ Color fields $f_g \gg 1$, saturation Q_s

Glasma

- Collision of two CGC fields

⇒ Out-of-equilibrium gluon field

Yang-Mills $[D_\mu, F^{\mu\nu}] = 0$

Effective kinetic theory

- Quarks & gluons as quasiparticles

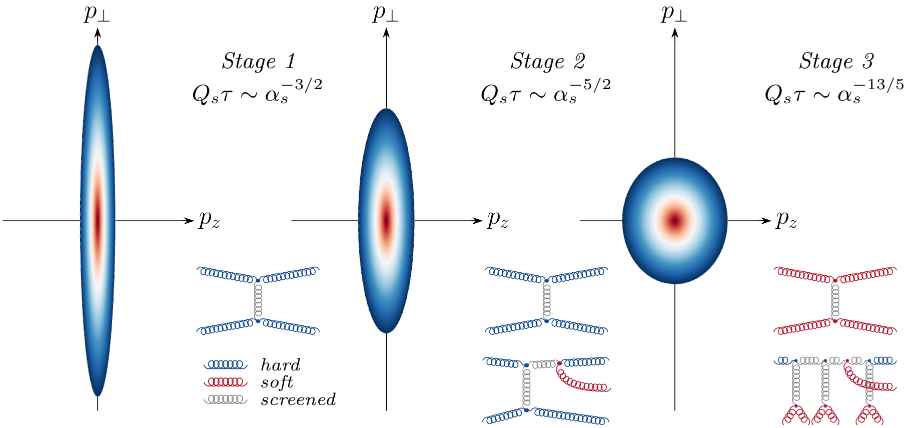
⇒ Thermalization from glasma

Boltzmann $p^\mu \partial_\mu f_{q,g} = \mathcal{C}[f_{q,g}]$

Gelis, Iancu, Jalilian-Marian, Venugopalan ***[1002.0333]*** *Lappi, McLerran* ***[hep-ph/0602189]***
Arnold, Moore, Yaffe ***[hep-ph/0209353]*** *Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney* ***[1805.01604]***

Bottom-up thermalization

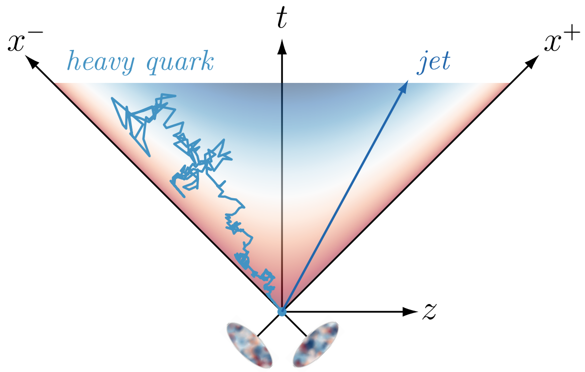
[parametric picture]



Baier, Mueller, Son, Schaefer **[hep-ph/0009237]** Kurkela, Zhu **[1506.06778]** Schlichting, Teaney **[1908.02113]** Berges, Heller, Mazeliauskas, Venugopalan **[2005.12299]**

Hard probes in QGP

[jets, heavy quarks]



Hard probes

- Produced in initial hard scattering
  → *pQCD + nuclear PDFs*
- Evolution in QGP medium
  → *medium + probe-medium interaction*

Heavy quarks

- QGP medium ∼ thermal stochastic

⇒ Diffusive motion
  → *Langevin, Fokker-Planck, Boltzmann*

Jets

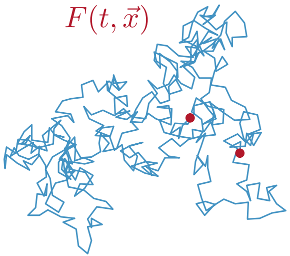
- QGP medium ∼ independent scatterings

⇒ Medium-induced radiation
  → *BDMPS-Z, GLV, AMY*

Hard probes in QGP

[standard picture, oversimplified]

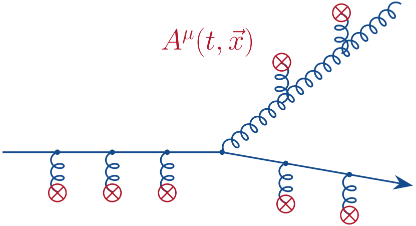
Heavy quark diffusion



- Stochastic force $F(t,\vec{x})$

⇒ $\kappa = 2T^2/D_s \sim$ diffusion coefficient

Jet quenching



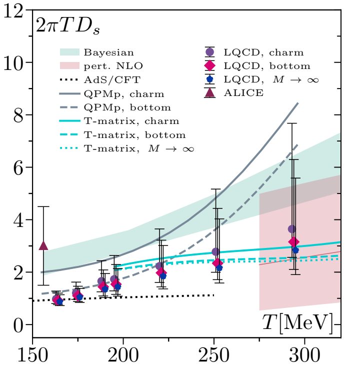
- Uncorrelated potential $A^\mu(t,\vec{x})$

⇒ $\hat{q} = \langle k_\perp^2 \rangle / L \sim$ broadening rate

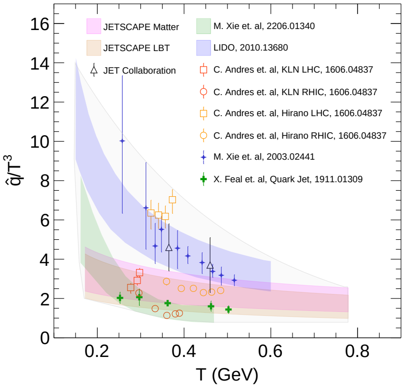
Hard probes in QGP

[temperature dependence, many models]

Heavy quark diffusion



Jet quenching



Bollweg, Dasilva Golán, Kaczmarek, Larsen, Moore, Mukherjee, Petreczky, Shu, Stendebach, Weber ***[2506.11958]***
Apolinário, Lee, Winn ***[2203.16352]***

Hard probes in pre-equilibrium?

[big question]

~~2017~~ 2026 Big Questions

- **1. How does QGP form and hydrodynamize within 1 fm/c?** . . . What can we learn about the timescales and dynamics of hydrodynamization, and hence QGP formation, by analyzing the wakes that jets leave behind as they traverse a droplet of QGP?
- **There has been enormous progress.**
- **New elements of big question: how does the pre-hydrodynamic medium influence the evolution of jets and heavy quarks?** Via this, or via small systems, or via jet wakes, how can we see imprints of hydrodynamization processes in experimental data?

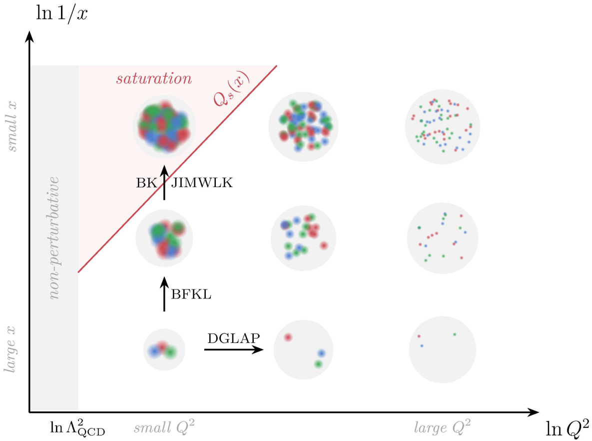
Busza, Rajagopal, van der Schee [1802.04801] Rajagopal@KITP26 [Outlook for the field of heavy ion physics]

III. QCD at high energies

- Probing nuclear structure
- Initial-state models & CGC
- The glasma fields

Probing nuclear structure

[kinematic landscape]



DIS kinematics

- $Q^2 \to$ photon virtuality $\sim$ resolution
- $x \to$ parton momentum fraction

RGE evolution

- Resums $\log Q^2$ (DGLAP) or $\log 1/x$ (BFKL)

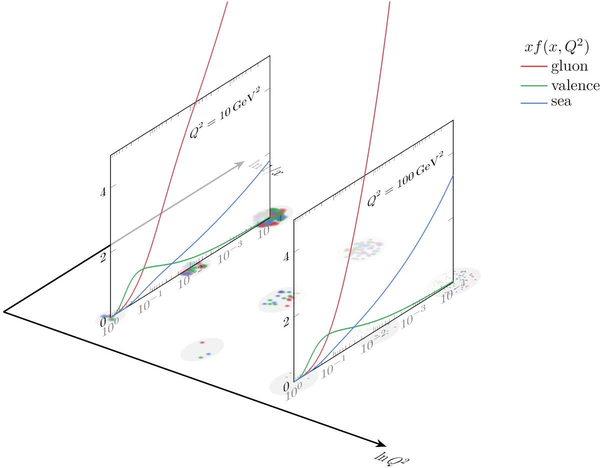
⇒ Nonlinear $\sim$ BK/JIMWLK

Saturation

- Rise in gluon number at small x

Probing nuclear structure

[gluon saturation]



Small x growth

- Gluon PDF $xg(x, Q^2)$ rises at small x

⇒ Large occupation number $f \sim 1/\alpha_s$ → classical fields

Saturation mechanism

- Balance between gluon recombination $gg \to g$ and emission $g \to gg$

⇒ Recombination tames gluon growth

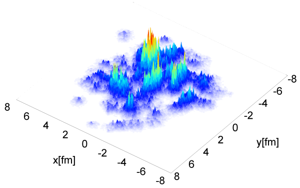
Saturation

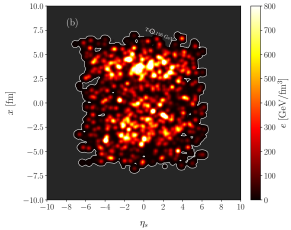
- Saturation scale $Q_s^2 \sim A^{1/3} x^{-\lambda}$

Initial state models

[a few examples]

- **CGC/saturated** *[small x, Q_s]*
  → IP-Glasma, McDipper, KLN
- **pQCD/collinear** *[moderate/large Q^2]*
  → EKRT





- **Geometrical/parametrizations** *(Trento)* & **Event generators** *(Pythia, EPOS)*

This talk

- Hard probes in **CGC**-based initial state model → boost-invariant glasma

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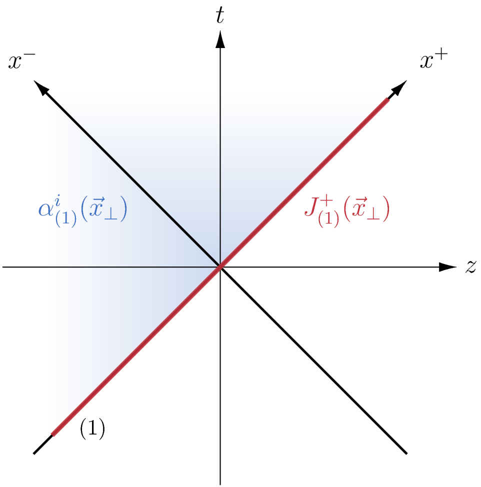
Schenke, Tribedy, Venugopalan ***[1202.6646]*** *Eskola, Kajantie, Ruuskanen, Tuominen* ***[hep-ph/9909456]***

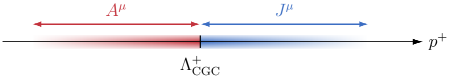
Color glass condensate

[separation of scales]



CGC fields *[before collision]*

- Separation of scales
  $\rightarrow$ small-x $\sim$ classical fields A^μ
  $\rightarrow$ large-x $\sim$ color sources J^μ
- Classical Yang-Mills $[D_\mu, F^{\mu\nu}] = J^\nu$

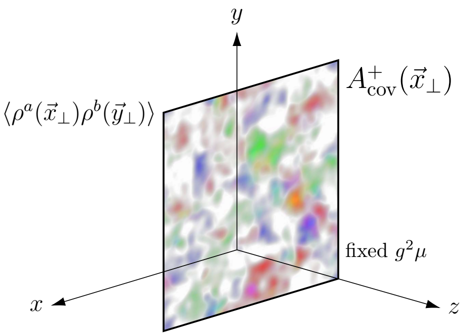


Gluon field

- Pure gauge $\alpha^i_{(1)}(\vec{x}_\perp) = \frac{i}{g} V_{(1)}\, \partial^i V^\dagger_{(1)}$
- Wilson line
  $$V_{(1)} = P \exp\left[-ig \int_{-\infty}^{+\infty} \mathrm{d}x^- \, \frac{\rho_{(1)}}{\nabla^2_\perp}\right]$$

Single color sheet

[model for color charge]



MV model

- **Color current** of nucleus $\rightarrow$ generated by **color charge ρ** $\leftrightarrow$ stochastic variable
- **MV model** for color charges ρ

  $\langle\rho(\vec{x}_\perp)\rho(\vec{y}_\perp)\rangle \propto g^2\mu^2\,\delta^{(2)}(\vec{x}_\perp - \vec{y}_\perp)$
- Saturation momentum $g^2\mu \propto Q_s$

  $Q_s \approx 2\,\text{GeV}$ at LHC central collisions

Beyond MV

- Model $\rho(\vec{x}_\perp)$, consider $\vec{b}_\perp$ dependence

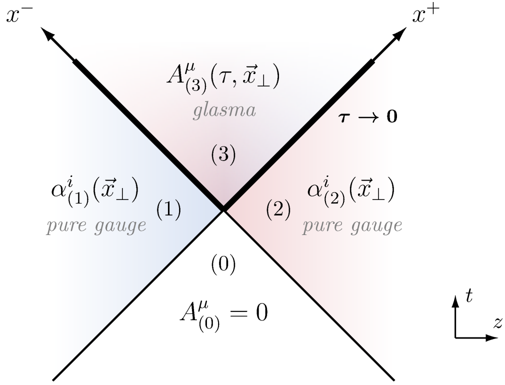
$\Rightarrow$ Proton shape + fluctuations

$\Rightarrow$ Nuclear structure + subnuclear fluctuations

McLerran, Venugopalan ***[hep-ph/9309289]***

Collision of CGC fields

[glasma fields]



CGC fields *[regions 1, 2]*

- Analytical **pure gauge** fields

Initial condition *[light-cone]*

- Match CGC fields on the light cone
- Impose **boost-invariance** $\Rightarrow$ 2+1D fields
  $\rightarrow$ Milne coordinates $\tau = \sqrt{x^+ x^-}$, $\eta = \ln(x^+/x^-)$

Glasma fields *[region 3]*

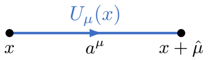
- Numerically solve **CYM equations** on lattice
- Real-time lattice gauge theory techniques
  $\rightarrow$ Gauge link and plaquette variables

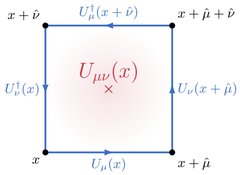
Lappi ***[hep-ph/0602189]***

Numerical simulation

[lattice & fields]

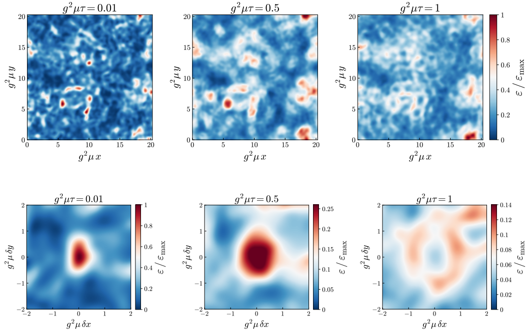
Real-time lattice gauge theory





- $U(x,y) = P\exp\left[ig\int_y^x \mathrm{d}z^\mu A_\mu(z)\right]$
  $\rightarrow$ gauge link
- $U_{\mu\nu}(x) = U_\mu(x)U_\nu(x+\hat{\mu})U^\dagger_\mu(x+\hat{\nu})U^\dagger_\nu(x)$
  $\rightarrow$ plaquette

Energy density profiles

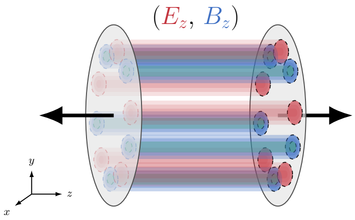


The glasma fields

[physical picture]

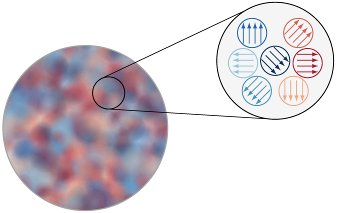
Flux tubes

- Initially only **longitudinal** **electric** and **magnetic** fields



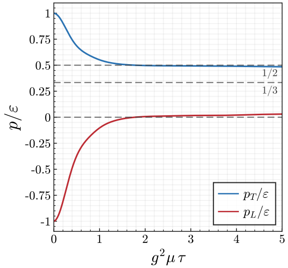
Correlation domains

- Fields correlated inside flux tubes of **size** $\sim 1/Q_s$



Anisotropy

- Pressure **transverse** T $\neq$ **longitudinal** L



Kovner, McLerran, Weigert ***[hep-ph/9505320]*** *Lappi, McLerran* ***[hep-ph/0602189]*** *Fukushima* ***[1603.02340]*** *Dumitru, Gelis, McLerran, Venugopalan* ***[0805.3012]*** *Fukushima, Gelis* ***[1106.1396]***

IV. Hard probes in pre-equilibrium

- Particles, field correlators & Wilson loops
- Transport in glasma & kinetic theory
- Jets & heavy quarks

Classical transport

[Wong's equations]

[coordinates]

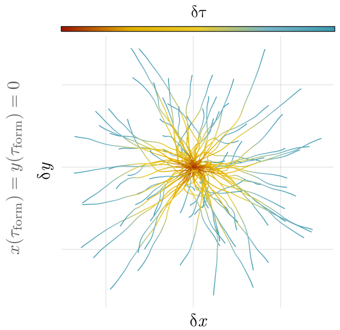
$$\frac{\mathrm{d}x^\mu}{\mathrm{d}\lambda} = \frac{p^\mu}{m}$$

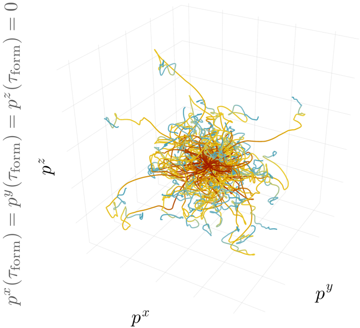
[momenta]

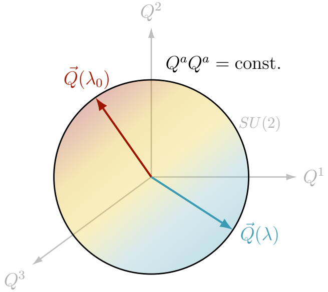
$$\frac{\mathrm{d}p^\mu}{\mathrm{d}\lambda} = \frac{g}{m} Q^a F^{\mu\nu,a} p_\nu$$

[color charge]

$$\frac{\mathrm{d}Q^a}{\mathrm{d}\lambda} = -\frac{g}{m} f^{abc} Q^c A^b_\mu p^\mu$$







Wong **[Nuovo Cim A65]** **DA**, Băran, Greco, Ipp, Müller, Ruggieri **[2303.05599]**

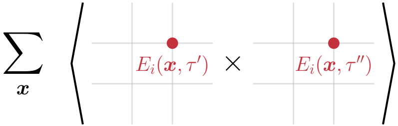
Field correlators

[Lorentz force correlator]

- Momentum broadening

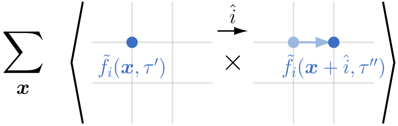
$$\langle \delta p_i^2(\tau) \rangle = g^2 \int_{\tau_{\mathrm{form}}}^{\tau} \mathrm{d}\tau' \int_{\tau_{\mathrm{form}}}^{\tau} \mathrm{d}\tau'' \, \langle \mathrm{Tr} [\tilde{\mathcal{F}}_i(\tau') \tilde{\mathcal{F}}_i(\tau'')] \rangle$$

$\rightarrow$ Lorentz force $\mathcal{F}_i = F_{i\mu} p^\mu / E_p$ parallel transported $\tilde{\mathcal{F}}_i$



- **Static heavy quarks** with $m \rightarrow \infty$

$\langle \delta p_i^2 \rangle |_{m \rightarrow \infty} \propto \int \mathrm{d}\tau' \int \mathrm{d}\tau'' \, \langle \mathrm{Tr} [E_i(\tau') E_i(\tau'')] \rangle$



- **Eikonal jets** with $p^x \rightarrow \infty$

$\langle \delta p_i^2 \rangle |_{p^x \rightarrow \infty} \propto \int \mathrm{d}\tau' \int \mathrm{d}\tau'' \, \langle \mathrm{Tr} [\tilde{f}_i(\tau') \tilde{f}_i(\tau'')] \rangle$

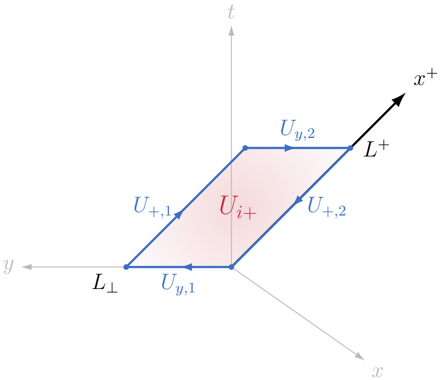
$\tilde{f}_i$ transported along x

$f_y = E_y - B_z$, $f_z = E_z + B_y$

Wilson loops

[Abelian case for simplicity]

- Wilson loop formulation $\leftrightarrow$ force correlator method



Momentum broadening

- Dipole approximation $L \ll L^+$

$$\langle \mathrm{Re}\, U_{i+} \rangle = \exp\left[-\frac{L^2}{2}\langle p_i^2 \rangle\right] \approx 1 - \frac{L^2}{2}\langle p_i^2 \rangle$$

- Stokes theorem

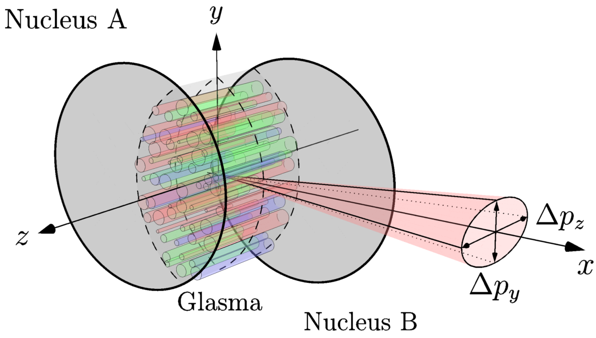
$$\Rightarrow U_{i+} = \exp\left[-iq \int_0^{L^+} \mathrm{d}x^+ \int_0^L \mathrm{d}x_i\, F_{i+}\right]$$

- Momentum broadening $\rightarrow$ Lorentz force

$$\langle p_i^2 \rangle = q^2 \int_0^{x^+} \mathrm{d}\xi \int_0^{x^+} \mathrm{d}\xi' \, \langle F_{i+}(\xi) F_{i+}(\xi') \rangle$$

Ipp, Müller, Schuh **[2009.14206]** **[2001.10001]** *Liu, Rajagopal, Wiedemann* **[hep-ph/0605178]**
Casalderrey-Solana, Teaney **[hep-th/0701123]** *Panero, Rummukainen, Schäfer* **[1307.5850]**

Transport coefficients in glasma



Probes in glasma

- **Momentum broadening**
  $\boldsymbol{\delta p_i^2}(\tau) = p_i^2(\tau) - p_i^2(\tau_{\text{form}})$

  → Directional for each $i = (L, T)$

  → Fixed formation time τ_{form}

- **Transport coefficients**
  $$\frac{\mathrm{d}}{\mathrm{d}\tau}\langle \boldsymbol{\delta p_i^2}(\tau)\rangle = \begin{cases} \boldsymbol{\kappa^i_{\text{glasma}}} & \textit{[heavy quarks]} \\ \boldsymbol{\hat{q}^i_{\text{glasma}}} & \textit{[jets]} \end{cases}$$

  → Averaged over glasma & particles

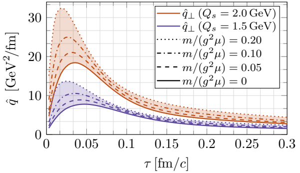
- $\hat{q}_{\text{glasma}} \neq \hat{q}_{\text{QGP}}$ → independent kicks & $\kappa_{\text{glasma}} \neq \kappa_{\text{QGP}}$ → diffusive motion
- Many methods: classical transport, force correlator, Wilson loop, quantum evolution

*Ipp, Müller, Schuh [**2009.14206**]*

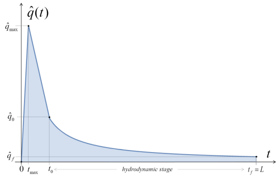
$\hat{q}$ in glasma

[selected results]

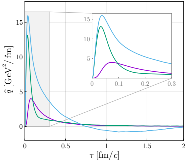
2021



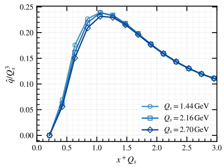
2022



2023

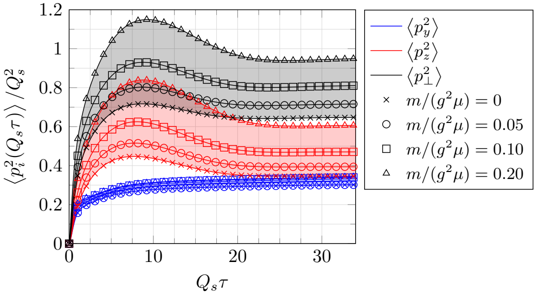


2026



Ipp, Müller, Schuh ***[2009.14206]*** *Carrington, Czajka, Mrowczynski* ***[2112.06812]***
DA*, Băran, Greco, Ipp, Müller, Ruggieri* ***[2303.05599]*** ***DA****, Lamas, Lappi, Li, Salgado* ***[2605.10413]***

Jets in glasma



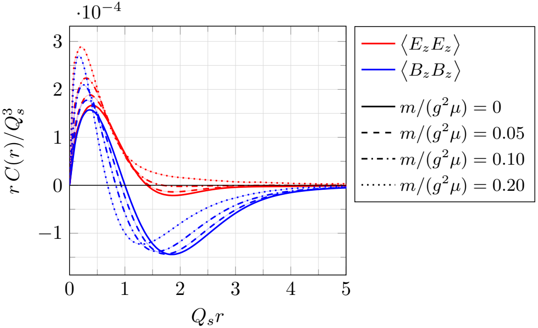
Momentum broadening $\langle p^2\rangle$

- Glasma $\rightarrow$ numerical fields
- Jets $\rightarrow$ eikonal trajectories
- Method $\rightarrow$ force correlators

$\Rightarrow$ **Anisotropic broadening $\langle p_z^2\rangle > \langle p_y^2\rangle$**

Ipp, Müller, Schuh [2009.14206] [2001.10001]

Jets in glasma



Field correlators $\langle F_z F_z \rangle$

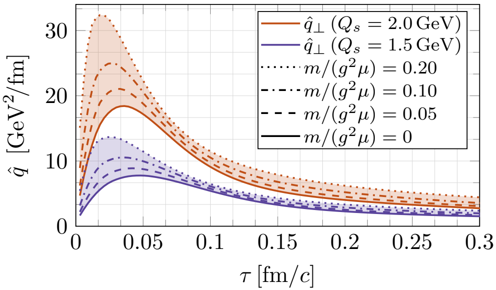
- Glasma $\rightarrow$ numerical fields
- Jets $\rightarrow$ eikonal trajectories
- Method $\rightarrow$ lattice correlators

$\Rightarrow$ Anisotropic broadening $\langle p_z^2 \rangle > \langle p_y^2 \rangle$

$\Rightarrow$ **Electric fields E_z** are more efficient at deflecting jets than magnetic fields B_z

Ipp, Müller, Schuh [2009.14206] [2001.10001]

Jets in glasma



Jet quenching parameter $\hat{q}$

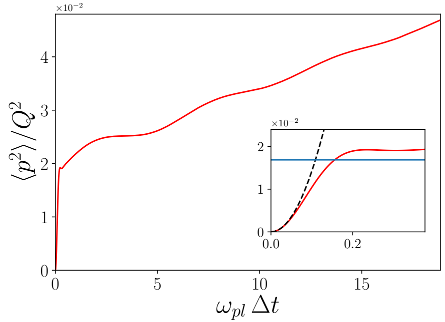
- Glasma → numerical fields
- Jets → eikonal trajectories
- Method → force correlators

⇒ **Very large $\hat{q}$** in glasma at early τ
Jet $\hat{q}$ increases with glasma Q_s

Ipp, Müller, Schuh [2009.14206]

Jets in glasma

2020 2021 2024 2025



Momentum broadening $\langle p^2 \rangle$

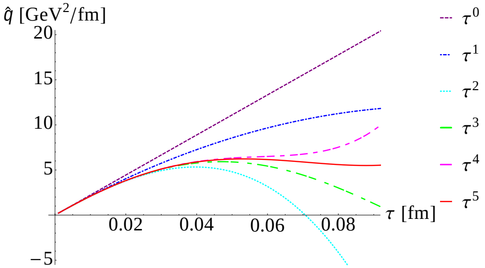
- Fields → numerical overoccupied gluons
- Heavy quarks → static, only E fields
- Method → force correlator

⇒ **Early rapid growth + late time oscillations with plasmon frequency**

*Boguslavski, Kurkela, Lappi, Peuron [**2005.02418**]*

Jets in glasma

2020 **2021** 2024 2025



Momentum broadening Δp_T^2

- Glasma $\rightarrow$ analytical fields, τ expansion
- Jets $\rightarrow$ Fokker-Planck equation
- Method $\rightarrow$ classical transport

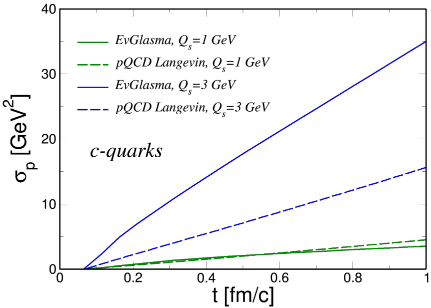
$\Rightarrow$ Results compatible with lattice $\hat{q}$

$\Rightarrow$ **Estimate** $\Delta p_T^2|^{\text{glasma}} / \Delta p_T^2|^{\text{QGP}} \approx 0.93$

*Carrington, Czajka, Mrowczynski [**2112.06812**]*

Heavy quarks in glasma

2020 **2021** 2024 2025



Momentum variance σ_p

- Glasma $\rightarrow$ numerical fields
- Heavy quarks $\rightarrow$ Wong's equations
- Method $\rightarrow$ classical transport

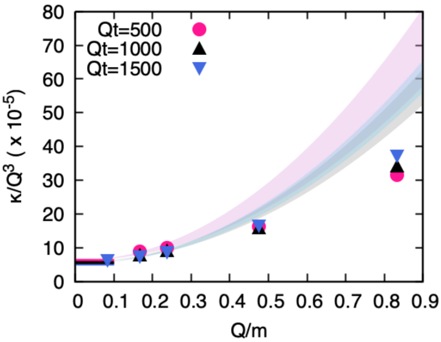
$\Rightarrow$ Comparison with **Langevin** diffusion $\sigma_p \propto t$

$\Rightarrow$ **Broadening in glasma $\neq$ diffusive motion**

*Pooja, Das, Oliva, Ruggieri [**2110.14610**]*

Heavy quarks in glasma

2020 2021 **2024** 2025



Diffusion coefficient κ

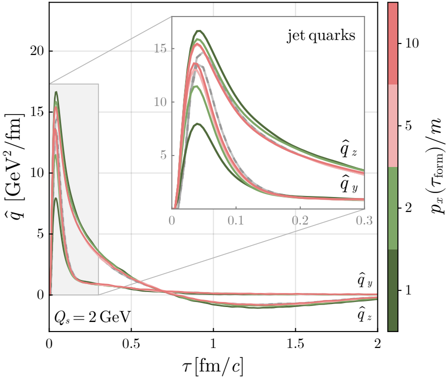
- Fields $\to$ real-time lattice simulation
- Heavy quarks $\to$ relativistic Dirac equation
- Method $\to$ spectral functions

$\Rightarrow$ Extract $\kappa(m)$ from charm to bottom mass

$\Rightarrow$ **Deviations of κ from static quark limit**

Pandey, Schlichting, Sharma [2312.12280]

Hard probes in glasma



Jet quenching parameter $\hat{q}$

- Glasma → numerical fields
- Jets → Wong's equations
- Method → classical transport

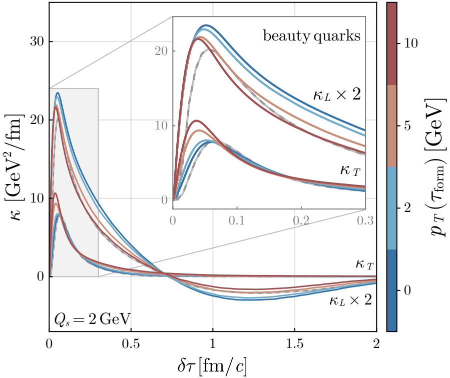
⇒ **Anisotropic broadening $\hat{q}_z > \hat{q}_y$**

⇒ **Large peak $\hat{q}_{\mathrm{glasma}} \approx 25\,\mathrm{GeV}^2/\mathrm{fm}$**

Compare with $\hat{q}_{\mathrm{QGP}} \approx 2 - 3\,\mathrm{GeV}^2/\mathrm{fm}$

DA, Băran, Greco, Ipp, Müller, Ruggieri [2307.07999] [2303.05599] JETSCAPE [2102.11337]

Hard probes in glasma



Transport coefficient κ

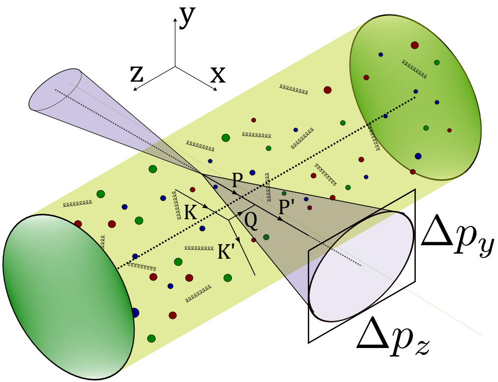
- Glasma → numerical fields
- Heavy quarks → Wong's equations
- Method → classical transport

⇒ **Anisotropic broadening $\kappa_L > \kappa_T$**

⇒ **Large peak $\kappa_{\mathrm{glasma}} \approx 30\,\mathrm{GeV}^2/\mathrm{fm}$**

DA, Băran, Greco, Ipp, Müller, Ruggieri [2307.07999] [2303.05599]

Transport coefficients in EKT



Probes in kinetic theory

- Boltzmann equation

$$\frac{\mathrm{d}}{\mathrm{d}\tau} f_{\boldsymbol{q},\boldsymbol{g}} = (\mathcal{C}_{1\leftrightarrow 2} + \mathcal{C}_{2\leftrightarrow 2} + \mathcal{C}_{\tau})[f_{\boldsymbol{q},\boldsymbol{g}}]$$

  → Overoccupied $f \sim 1/\alpha_s$ at $Q_s\tau \sim 1$
  → Debye mass $m_D \sim$ soft scale
  → Saturation momentum $Q_s \sim$ hard scale

- **Transport coefficients**

$$\hat{\boldsymbol{q}}, \boldsymbol{\kappa} \propto \int \mathrm{d}\Gamma_{\mathrm{PS}}\, \boldsymbol{q}^2 |\mathcal{M}|^2 f_{\boldsymbol{q},\boldsymbol{g}}(1 + f_{\boldsymbol{q},\boldsymbol{g}})$$

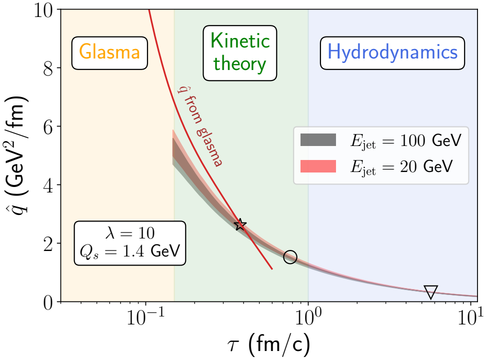
  → Scattering matrix $\mathcal{M}$ from HTL
  [Hard Thermal Loop]

- EKT ∼ scattering with plasma gluon/quark ≠ glasma ∼ deflection by gluon field

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [2303.12520] [2303.12595] [2312.00447]

Jets in EKT

2024



Jet quenching parameter $\hat{q}$

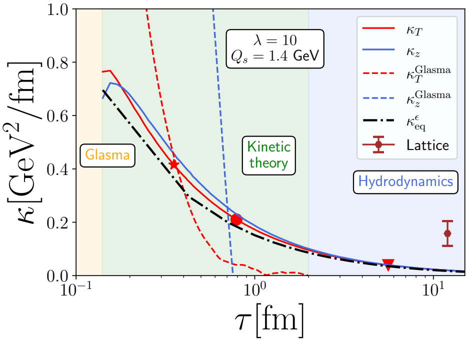
- Energy density matched to glasma at $Q_s\tau \sim 1$
- Depends on choice of $\Lambda_\perp$ momentum cutoff
- Matched to JETSCAPE values at E_{jet}

$\Rightarrow$ **Large glasma $\hat{q}$ compatible with EKT**

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [2303.12595] [2312.00447]

Heavy quarks in EKT

2024



Transport coefficient κ

- Energy density matched to glasma at $Q_s\tau \sim 1$
- Compared with equilibrium κ_{eq} & lattice
- Matched for same m_D, $T_\star$ and ε

⇒ **Large glasma κ incompatible with EKT**

Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [2303.12520]

V. Latest developments

- Quantum jet evolution in glasma
- Jet quenching in correlation domains

Light-front QCD

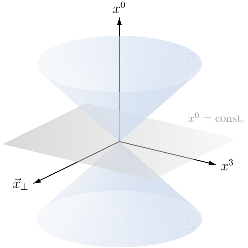
[machinery of LF quantization]

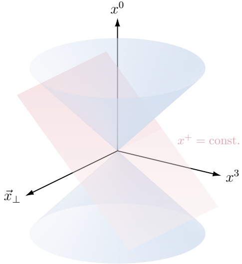
Light-front Hamiltonian approach

- Quantize on light-front $x^+ = \text{const.}$ & light-cone gauge $A^+ = 0$
- Evolution simplifies to a Schrödinger equation
  $$i\frac{\partial}{\partial x^+}|\psi; x^+\rangle = P^-(x^+)|\psi; x^+\rangle$$
- In a background field, split $P^-(x^+) = P^- + V(x^+)$
  → *For jet along x^+, background field A^- drives the dynamics*

⇒ **Solve for quantum quark in a classical gluon field**

⇒ **Consider only $|q\rangle$ sector in glasma fields**

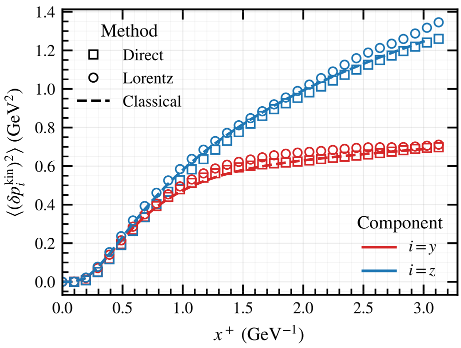




Brodsky, Pauli, Pinsky ***[hep-ph/9705477]*** *Li, Lappi, Zhao, Salgado* ***[2305.12490]***
Vary, Mondal, Xu, Zhao, Li ***[2512.08283]***

Quantum vs. classical

[momentum broadening]



Two ways to compute quantum

- Direct quantum calculation $\langle(\delta p_i^{\rm kin})^2\rangle_\psi$
  $\rightarrow \langle O\rangle_\psi = \langle\psi; x^+|O|\psi; x^+\rangle$
- Lorentz force calculation
  $\langle(\delta p_i^{\rm kin})^2\rangle_\psi = g^2\int_0^{x^+}\mathrm{d}\lambda\int_0^{x^+}\mathrm{d}\lambda'\langle f_{i,H}(\lambda)f_{i,H}(\lambda')\rangle_\psi$
  $\rightarrow f_{i,H}(x^+) = U^\dagger(x^+;0)f_i(x^+)U(x^+;0)$

$\Rightarrow$ Both agree with the classical result

$\Rightarrow$ No way to distinguish classical from quantum

$\Rightarrow$ Go beyond $|q\rangle$, include $|qg\rangle$ for gluon radiation

DA, Lamas, Lappi, Li, Salgado [2604.08520] [2605.10413]

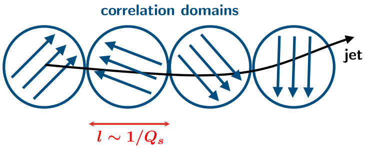
BDMPS-Z in correlation domains

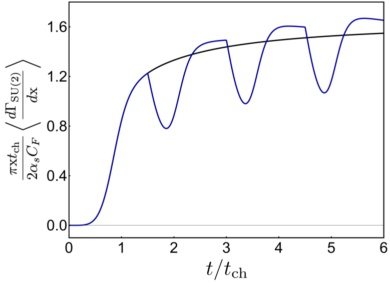
[along eikonal jet trajectory]

Toy model for glasma

- Correlation length $l \sim 1/Q_s$
  $\rightarrow \langle A(t,\vec{x})A(s,\vec{y})\rangle \neq \delta(t-s)\delta^{(2)}(\vec{x}-\vec{y})$
- Piece-wise longitudinal electric field
  $A^\mu = \delta^{\mu t}\vec{x}\cdot\vec{E}_n(z)$ for $z \in [\ell_n, \ell_{n+1})$
  $\rightarrow$ *Gaussian integral over E_n in each tube n*
- Emission kernel $\Rightarrow$ soft radiation rate $\mathrm{d}\Gamma/\mathrm{d}x$
  $K(\mathbf{x},t;\mathbf{y},s) \propto$
  $\int Dr\, \exp\left[\frac{i\omega}{2}\int_s^t \mathrm{d}\tau\,\dot{r}^2\right] \mathrm{Tr}\, P\exp\left[iT^c\int_s^t \mathrm{d}\tau\,\vec{E}^c(\tau)\cdot\vec{x}(\tau)\right]$

⇒ Jet quenching à la BDMPS-Z





Barata, Hauksson, Mayo López, Sadofyev [2406.07615] Aurenche, Zakharov [1205.6462]

Adam Takacs
Parton shower for jet thermalization

Jie Zhu
3+1D pre-equilibrium dynamics

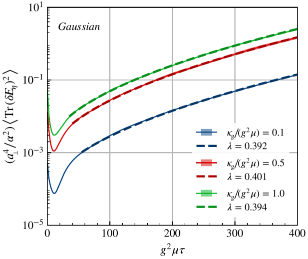
VI. This SEWM

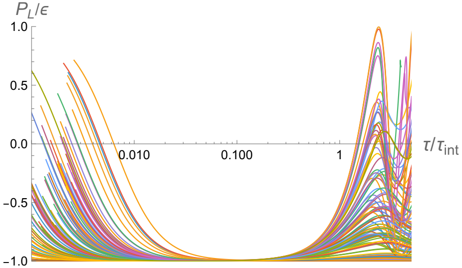
- Lots of related works
- Here is a short selection
- Many things to learn from your talks!

Pooja
Chaos in glasma
Clemens Werthmann
Hydro attractor in CYM

Thermalization in CYM

[chaotic behaviour, hydro attractors]





Leading Lyapunov exponent

- Perturb glasma longitudinal E fields, fit growth $\propto e^{\lambda\sqrt{g^2\mu\tau}}$, $\lambda \approx 0.39$ for SU(2)

⇒ **Universal Lyapunov exponent, same λ regardless of perturbation type**

CYM attractor

- Classical Yang-Mills, P_L/ϵ evolution in τ, random initial conditions

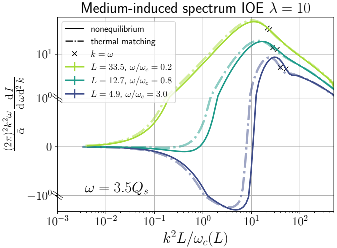
⇒ **Curves align only at early times, no attractor at late times**

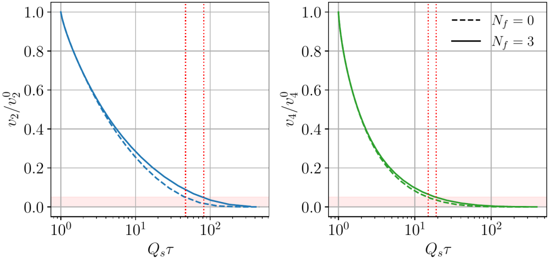
Pooja, DA, Lappi [2601.19679]

Florian Lindenbauer
Medium-induced radiation
Sergio Cabodevila
Azimuthal anisotropy

Thermalization in EKT

[radiation, azimuthal dependence]





Radiation in EKT

- Gluon spectrum from Improved Opacity Expansion (IOE), background from EKT

⇒ **Early-stage evolution leaves a sizable imprint on jet radiation**

Azimuthal isotropization

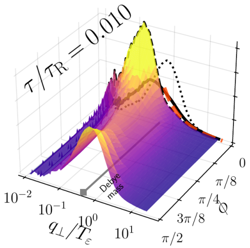
- BEDA → simplified EKT + follow how $v_n(\tau)$ relax to isotropy

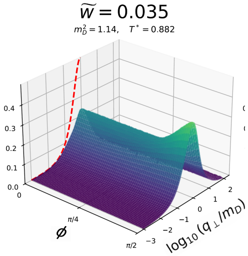
⇒ **Clear hierarchy in the relaxation time of each harmonic v_n**

*Barata, Boguslavski, Lindenbauer, Sadofyev [**2511.07519**] Barrera Cabodevila, Du, Salgado, Wu [**2607.07796**]*

Collision kernel in EKT

[jet-medium momentum exchange]





Collision kernel $C(q_\perp)$

- Bottom-up thermalizing plasma → QCD kinetic theory, isoHTL-screened $2 \leftrightarrow 2$ matrix elements

⇒ **Full non-equilibrium kernel deviates from the thermal one at early times**

Collision kernel $C(q_\perp)$

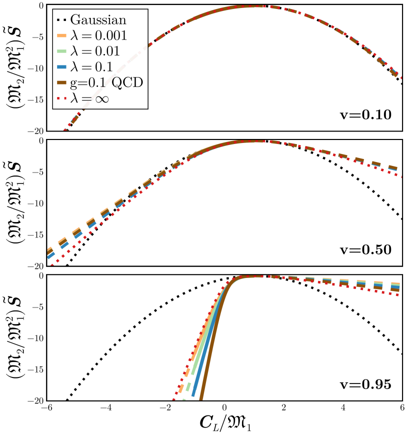
- Medium parton kicks the jet parton by $\vec{q}_\perp$, sampled from EKT distributions

⇒ **Initial anisotropy peaks C at $\phi = \pi/2$, the peak washes out quickly**

*Altenburger, Boguslavski, Lindenbauer [**2509.03868**]*

Non-Gaussian broadening

[heavy quarks]



HQ transport beyond LL

- Momentum kernel from a Wilson loop

$$P(\mathbf{k};v) = \int \frac{d^3\mathbf{L}}{(2\pi)^3} e^{-i\mathbf{k}\cdot\mathbf{L}} \langle W_v \rangle(\mathbf{L};\Delta t)$$

- Gaussian core from the central limit theorem
- Plot normalized log-probability $\frac{\mathfrak{M}_2}{\mathfrak{M}_1^2}\tilde{S}(C_L;v)$ as a function of $\frac{C_L}{\mathfrak{M}_1}$

  → *Black dotted curve = Gaussian benchmark*

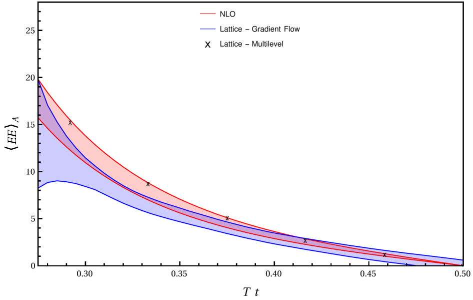
⇒ Asymmetric exponential tails same at weak + strong coupling

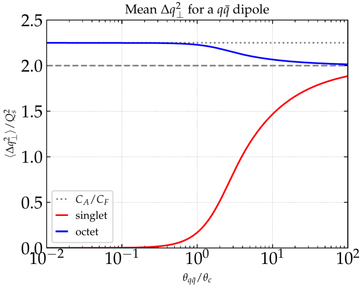
Du Plessis, Scheihing-Hitschfeld [2604.21895] Rajagopal, Scheihing-Hitschfeld, Wiedemann [2501.06289]

Panayiotis Panayiotou
Transport of quarkonia
Pietro Benzoni
Momentum broadening of dipole

Transport in OQS

[quarkonia transport, dipole broadening]





Quarkonium in the medium

- Asymmetric correlator $\langle EE\rangle_A$ at NLO

⇒ **Agrees well with recent lattice calculations at high temperature**

Dipoles in the medium

- Lindblad evolution for $q\bar{q}$ dipole, $\theta_c \sim (\hat{q}L^3)^{-1/2}$

⇒ **Color decoherence sets in before the pair goes classical**

*Brambilla, Panayiotou, Säppi, Vairo [**2505.16604**] Arleo, Benzoni, Caucal, Gossiaux [**2606.07744**]*

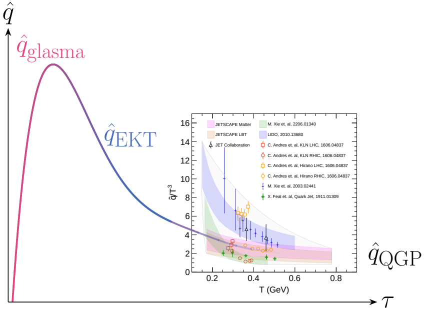
This talk in a nutshell

- Hard probes are affected by pre-equilibrium
- Their transport is non-trivial

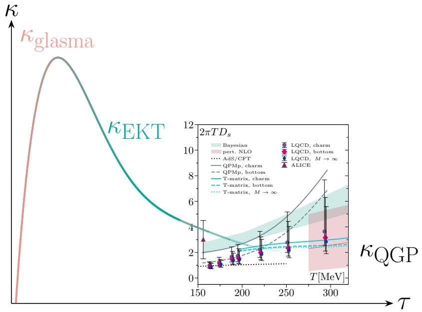
Queue of $\hat{q}$s and κs

[all wearing different hats]

Jet quenching*



Heavy quark diffusion*



** Not to scale, just a sketch + heavy quark plot shows $2\pi T D_s$ not κ*

Apolinário, Lee, Winn ***[2203.16352]***

Altenkort, Kaczmarek, Larsen, Mukherjee, Petreczky, Shu, Stendebach ***[2302.08501]***

Summary

[main questions]

What we know

- Transport coefficients for hard probes in glasma are large & anisotropic
  $\hat{q}_{\text{glasma}}, \kappa_{\text{glasma}} \sim 10\times$thermal QGP values
- Classical & quantum + kinetic theory methods give good agreement for jet $\hat{q}$
- Transport (only broadening) in very early stages is very different than in QGP

What we don't know

- If the large transport coefficients in pre-equilibrium leave a measurable imprint on experimental data
- Classical + kinetic theory methods do not agree for heavy quark κ, but why?
- How to compute energy loss for jets in glasma, there is ongoing progress

- **More theoretical work is needed**
  →How to match glasma + EKT & describe with both particles + fields?
  →Is the effect of the early stage on hard probes washed out by the QGP?

Upcoming workshops & conferences

[just a few relevant ones]

A decade of jet substructure in heavy ion collisions

CERN

Dec 2026

Initial Stages in high-energy nuclear collisions

Jyväskylä

Jun 2027

Constraining the first instants of the Quark Gluon Plasma

ECT, Trento*

Sep 2027

Kiitos!