Hard probes during the initial stages in heavy-ion collisions

Based on 2303.12520, 2303.12595, 2312.00447 and 2312.11252
(in collaboration with K. Boguslavski, A. Kurkela, T. Lappi, J. Peuron)

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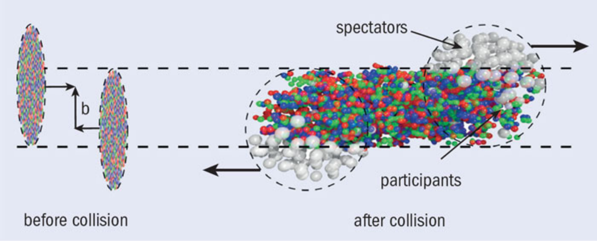
TU Wien

26.06.2024, QCD Master Class, Saint-Jacut-de-la-Mer

Outline

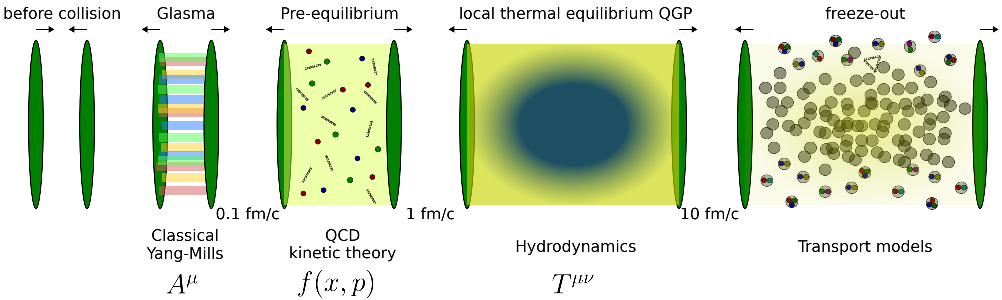
Heavy-ion collisions and the quark-gluon plasma

- Study high-temperature properties of the strong interaction
- Collision of atomic nuclei at LHC or RHIC
- Creates high-temperature QCD matter = Quark-Gluon plasma (QGP)



[Alberica Toia 2013, CERN COURIER]

Time-evolution of the QGP in heavy-ion collisions



Interested in pre-equilibrium stages ("Initial stages")

$\rightarrow$ **QCD out of equilibrium**

[Rev.Mod.Phys. 93 (2021) [Berges, Heller, Mazeliauskas, Venugopalan]]

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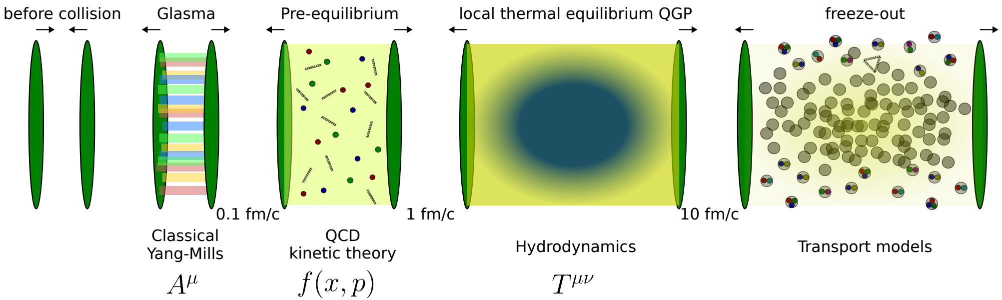
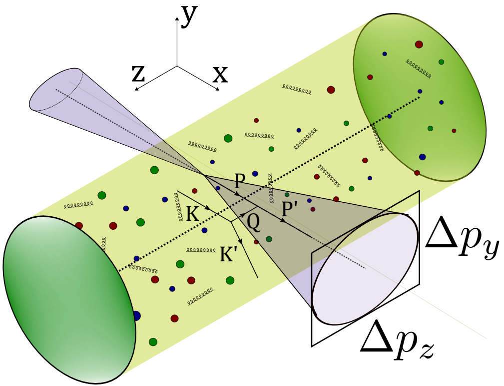


Interested in pre-equilibrium stages ("Initial stages")
$\rightarrow$ **QCD out of equilibrium** (sign problem in lattice QCD)

[Rev.Mod.Phys. 93 (2021) [Berges, Heller, Mazeliauskas, Venugopalan]]

How can we study the initial stages?

- To study initial stages
  $\rightarrow$ very **energetic** or **heavy** probes
  (must be created early)
- Here depicted: **jets**



How can we study the initial stages?

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  $\rightarrow$ very **energetic** or **heavy** probes
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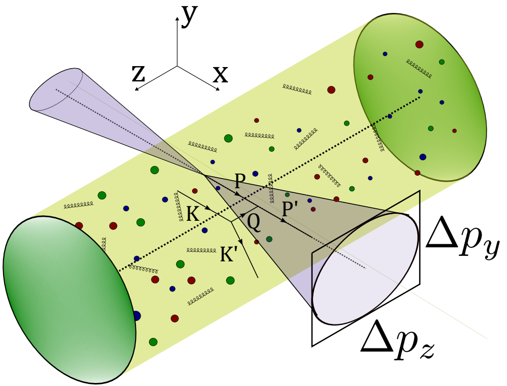
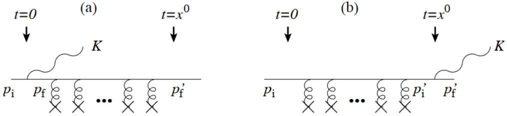
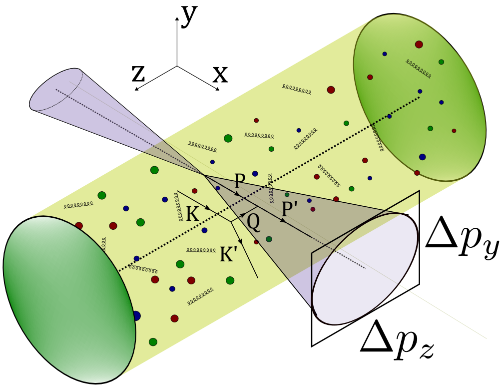
- Here depicted: **jets**
  - **Highly energetic partons** created in initial collision
  - Splits into many particles
    $\rightarrow$ then measured in the detectors
  - Imprints of **medium interactions**



Jet energy loss through medium-induced radiation

- Very many works on energy loss of energetic parton
- **Difficulties**:
  Including the LPM effect





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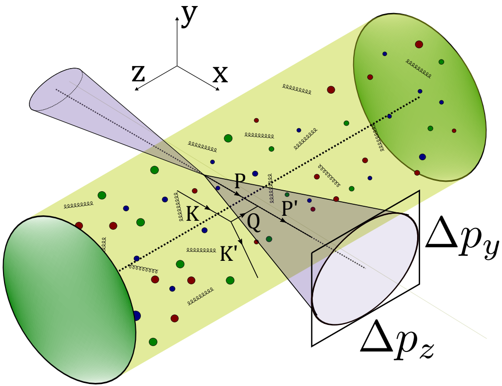
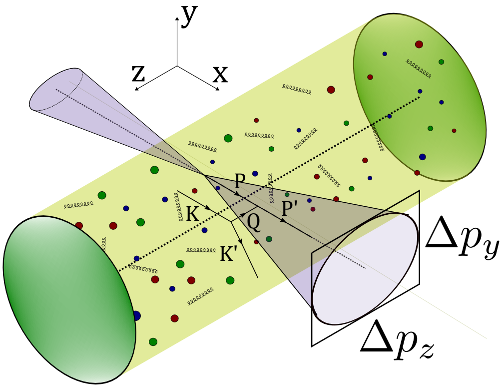
- **Harmonic approximation**:
  Depend on single medium parameter $\hat{q}$
  "Jet quenching parameter"



Jet energy loss through medium-induced radiation

- Very many works on energy loss of energetic parton
- **Difficulties**:
  Including the LPM effect
- **Harmonic approximation**:
  Depend on single medium parameter $\hat{q}$
  "Jet quenching parameter"
- Quantifies **momentum broadening**

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}L} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}t} = \int \mathrm{d}^2 q_\perp \, q_\perp^2 \frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}$$



Estimates of $\hat{q}$

Physics Letters B
Volume 803, 10 April 2020, 135318

Jet quenching as a probe of the initial stages in heavy-ion collisions ☆

Carlota Andres [a], Néstor Armesto [b], Harri Niemi [c d], Risto Paatelainen [e d], Carlos A. Salgado [b]

ABSTRACT

Jet quenching provides a very flexible variety of observables which are sensitive to different energy- and time-scales of the strongly interacting matter created in heavy-ion collisions. Exploiting this versatility would make jet quenching an excellent chronometer of the yoctosecond structure of the evolution process. Here we show, for the first time, that a combination of jet quenching observables is sensitive to the initial stages of heavy-ion collisions, when the approach to local thermal equilibrium is expected to happen. Specifically, we find that in order to reproduce at the same time the inclusive particle production suppression, R_{AA}, and the high-p_T azimuthal asymmetries, v_2, energy loss must be strongly suppressed for the first ~ 0.6 fm. This exploratory analysis shows the potential of jet observables, possibly more sophisticated than the ones studied here, to constrain the dynamics of the initial stages of the evolution.

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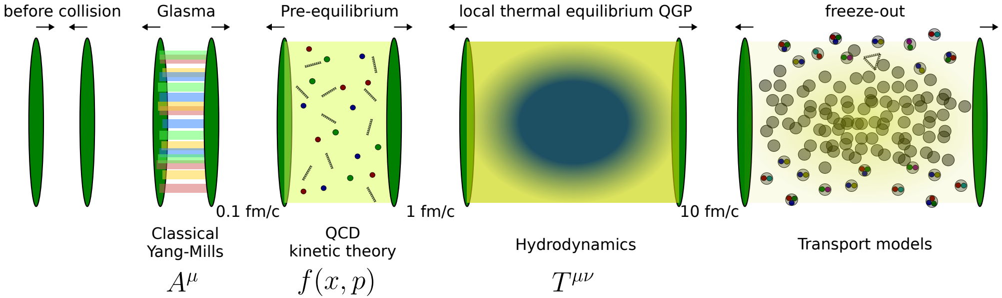
Jet quenching provides a very flexible variety of observables which are sensitive to different energy- and time-scales of the strongly interacting matter created in heavy-ion collisions. Exploiting this versatility would make jet quenching an excellent chronometer of the yoctosecond structure of the evolution process. Here we show, for the first time, that a combination of jet quenching observables is sensitive to the initial stages of heavy-ion collisions, when the approach to local thermal equilibrium is expected to happen. Specifically, we find that in order to reproduce at the same time the inclusive particle production suppression, R_{AA}, and the high-p_T azimuthal asymmetries, v_2, energy loss must be strongly suppressed for the first ~ 0.6 fm. This exploratory analysis shows the potential of jet observables, possibly more sophisticated than the ones studied here, to constrain the dynamics of the initial stages of the evolution.

Estimates of $\hat{q}$



Estimates of $\hat{q}$

ELSEVIER

Physics Letters B
Volume 834, 10 November 2022, 137464

Jet quenching in glasma

Margaret E. Carrington [a b], Alina Czajka [c], Stanisław Mrówczyński [c d]

In conclusion, our approach, which is presented in detail in [22], provides a reliable estimate of momentum broadening in glasma. Our calculation gives a value of $\hat{q}$ that is several $\mathrm{GeV}^2/\mathrm{fm}$, which is much larger than equilibrium values, and produces accumulated transverse momentum broadening of the same order as the contribution from the equilibrium phase. Our results therefore indicate that the transient glasma phase plays an important role in the jet quenching. This conclusion is significant because it contradicts previous beliefs that the contribution to momentum broadening from the glasma phase can be safely neglected.

$\hat{q}$ in the glasma using τ expansion

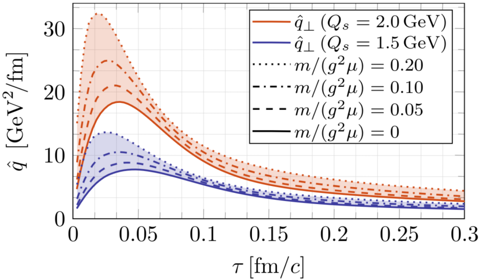
Estimates of $\hat{q}$

Physics Letters B
Volume 810, 10 November 2020, 135810

ELSEVIER

Jet momentum broadening in the pre-equilibrium Glasma

A. Ipp, D.I. Müller, D. Schuh



$\hat{q}$ in the glasma using classical statistical simulations

Estimates of $\hat{q}$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Simulating jets and heavy quarks in the glasma using the colored particle-in-cell method
Dana Avramescu, Virgil Băran, Vincenzo Greco, Andreas Ipp, David Müller, and Marco Ruggieri
Phys. Rev. D **107**, 114021 – Published 15 June 2023
Article References Citing Articles (2) PDF HTML Export Citation

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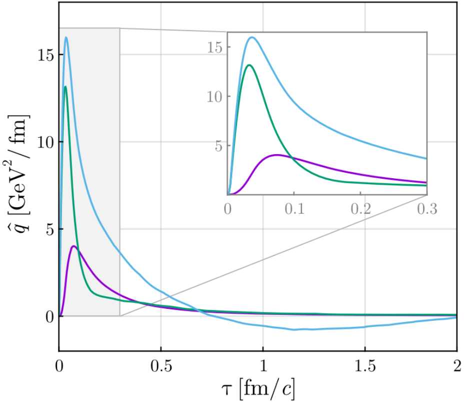
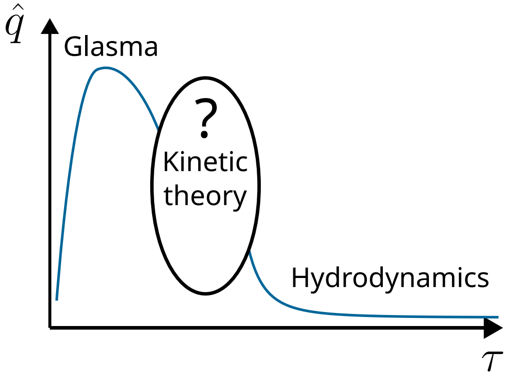


Goal of our work

- **Mostly** considered in **equilibrium** or hydrodynamics

Schematic overview of $\hat{q}$ evolution

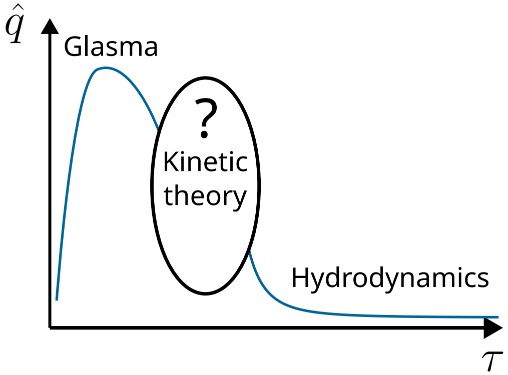


[1] [Phys.Lett.B 810 (2020) [Ipp, Müller, Schuh], Phys.Rev.C 105 (2022) [Carrington, Czajka, Mrowczynski], Phys.Rev.D 107 (2023) [Avramescu, Baran, Greco, Ipp, Müller, Ruggieri]]

Goal of our work

Schematic overview of $\hat{q}$ evolution

- **Mostly** considered in **equilibrium** or hydrodynamics
- Recently also considered in Glasma[1]
- **Goal: $\hat{q}$ during thermalization** $\rightarrow$ between Glasma and hydro
- **Question:** Supports large Glasma values?



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Effective kinetic theory description of the QGP

- Plasma without quarks

$$\mathcal{L} = -\frac{1}{4} F^i_{\mu\nu} F_i^{\mu\nu} + \bar{\psi}(i \not{D} - m)\psi$$

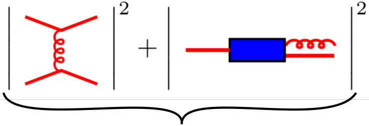
[2][JHEP 01 (2003) [Arnold, Moore, Yaffe], Int.J.Mod.Phys.E 16 (2007) [Arnold]]

Effective kinetic theory description of the QGP

- Plasma without quarks
- Gluons with **distribution function** $f(t, \mathbf{p})$

- Time evolution described by **Boltzmann equation** at leading-order[2]

$$(\partial_t + \boldsymbol{v} \cdot \boldsymbol{\nabla}) f =$$



Collision term

- Azimuthal symmetry around beam axis $\hat{z}$,
  Bjorken expansion, homogeneous in transverse plane

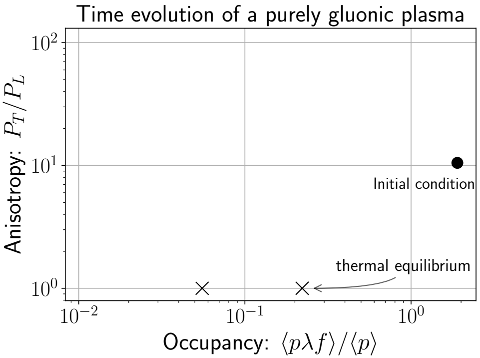
[2] [JHEP 01 (2003) [Arnold, Moore, Yaffe], Int.J.Mod.Phys.E 16 (2007) [Arnold]]

Bottom-up thermalization in heavy-ion collisions

- Initial condition[3], with $\lambda = g^2 N_C$

$$f(p_\perp, p_z) = \frac{2A}{\lambda} \frac{\langle p_T \rangle}{\sqrt{p_\perp^2 + \xi^2 p_z^2}} \times \exp\left(\frac{-2}{3\langle p_T \rangle^2} \left(p_\perp^2 + \xi^2 p_z^2 \right) \right)$$

$\xi \sim$ anisotropy, $\langle p_T \rangle = 1.8 Q_s$,
$Q_s \sim$ saturation scale



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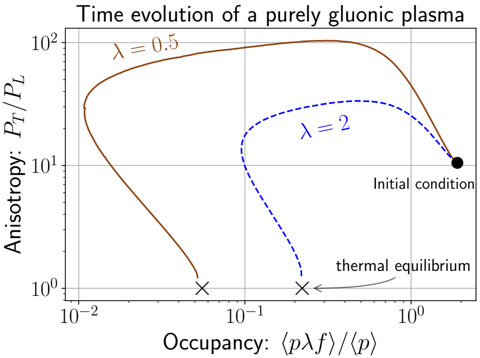

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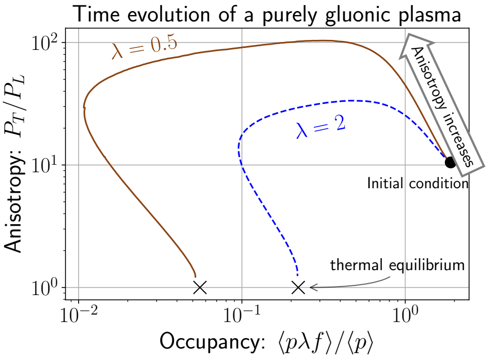

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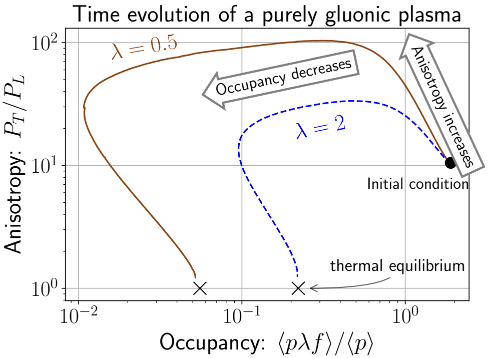

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  - **Phase 1**: Anisotropy increases
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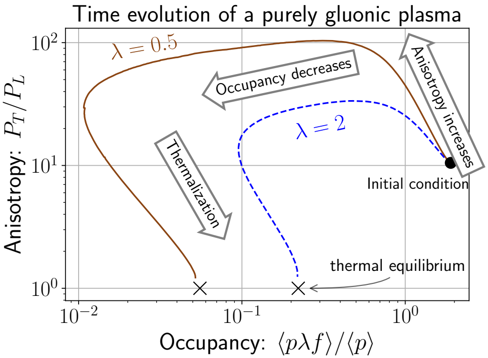
  - **Phase 3**: System thermalizes at time[4] $\tau_{\mathrm{BMSS}} = \left(\frac{\lambda}{12\pi}\right)^{-13/5} / Q_s$



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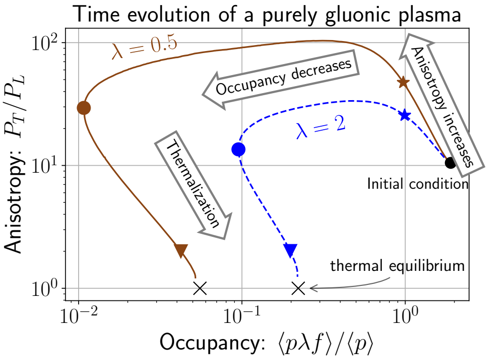
Markers represent **different stages**



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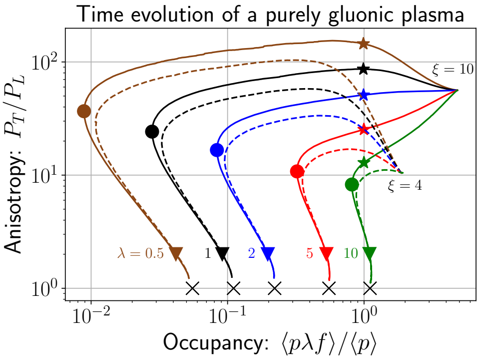

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Generalization of $\hat{q} \to \hat{q}^{ij}$ for anisotropic systems

- **Previously** (isotropic definition):

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}L} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}t} = \int \mathrm{d}^2 q_\perp \, q_\perp^2 \frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}$$

with elastic scattering rate Γ^{el}

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  with elastic scattering rate Γ^{el}

- **To take into account anisotropies:**
  Define matrix

$$\hat{q}^{ij} = \int \mathrm{d}^2 q_\perp \, q_\perp^i q_\perp^j \frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}$$

  Thus $\hat{q} = \hat{q}^{yy} + \hat{q}^{zz}$ (and $\hat{q}^{yz} = 0$)

Jet quenching parameter in kinetic theory

- Provided we know $f(\mathbf{k})$:

Jet quenching parameter in kinetic theory

- Provided we know $f(\mathbf{k})$:

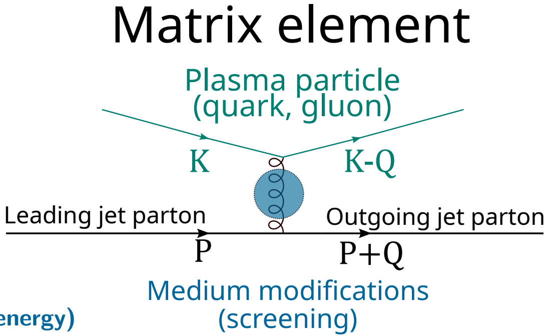
Outgoing plasma particle

$$\hat{q}^{ij} = \int_{\substack{q_\perp < \Lambda_\perp \\ p\to\infty}} \mathrm{d}\Gamma_{\rm PS}\, q^i q^j \, |\mathcal{M}|^2 f(k)\,(1 + f(k'))$$

Incoming plasma particles with momentum k

Matrix element
with medium corrections (self-energy)

appropriate phase-space measure



Making sense of the cutoff

- Cutoff $\Lambda_\perp$ restricts transverse momentum transfer $q_\perp < \Lambda_\perp$ (needed in eikonal limit $p \to \infty$)

$$\hat{q} \sim \int \mathrm{d}^2 q_\perp \, q_\perp^2 \underbrace{\frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}}_{1/q_\perp^4 \text{ for large } q_\perp} \sim \int \frac{\mathrm{d} q_\perp}{q_\perp}$$

Making sense of the cutoff

- Cutoff $\Lambda_\perp$ restricts transverse momentum transfer $q_\perp < \Lambda_\perp$ (needed in eikonal limit $p \to \infty$)
- Cutoff somehow grow with jet energy

[arXiv:2312.00447 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

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- **kinematic cutoff** $\Lambda_\perp^{\mathrm{kin}}(E, T) = \zeta^{\mathrm{kin}} g(ET)^{1/2}$ obtained from comparing leading log behavior for large p and $\Lambda_\perp$

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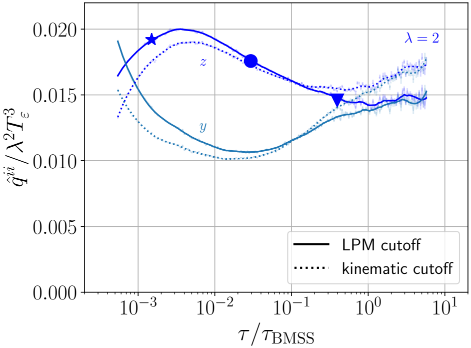
- **kinematic cutoff** $\Lambda_\perp^{\mathrm{kin}}(E,T) = \zeta^{\mathrm{kin}} g(ET)^{1/2}$
  obtained from comparing leading log behavior for large p and $\Lambda_\perp$
- **LPM cutoff** $\Lambda_\perp^{\mathrm{LPM}}(E,T) = \zeta^{\mathrm{LPM}} g(ET^3)^{1/4}$
  Estimate for momentum broadening during LPM 'formation time':
  $Q_\perp^2 \sim \hat{q}t^{\mathrm{form}}$, $t^{\mathrm{form}} \sim \sqrt{E/\hat{q}}$, approximately $\hat{q} \sim g^4 T^3$

[arXiv:2312.00447 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Results for $\hat{q}$

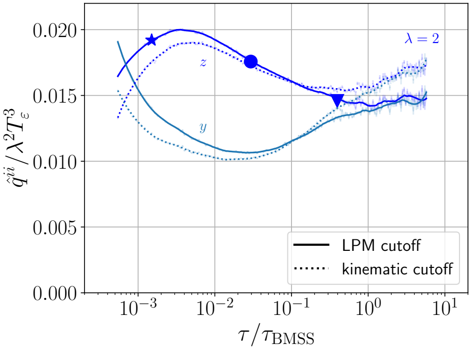
- Use cutoffs
  - $\Lambda_\perp^{\mathrm{LPM}}(E, T_\varepsilon) = \zeta^{\mathrm{LPM}} g(ET_\varepsilon^3)^{1/4}$
  - $\Lambda_\perp^{\mathrm{kin}}(E, T_\varepsilon) = \zeta^{\mathrm{kin}} g(ET_\varepsilon)^{1/2}$



[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Results for $\hat{q}$

- Use cutoffs
  - $\Lambda_\perp^{\mathrm{LPM}}(E, T_\varepsilon) = \zeta^{\mathrm{LPM}} g (E T_\varepsilon^3)^{1/4}$
  - $\Lambda_\perp^{\mathrm{kin}}(E, T_\varepsilon) = \zeta^{\mathrm{kin}} g (E T_\varepsilon)^{1/2}$
- Fix ζ^i at triangle marker to match with JETSCAPE[5] for $\lambda = 10$, use jet energy $E = 100\,\mathrm{GeV}$ and $Q_s = 1.4\,\mathrm{GeV}$.



[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

[5] [Phys.Rev.C 104 (2021) [JETSCAPE]]

[6] [Values available at https://zenodo.org/records/10419537]

Results for $\hat{q}$

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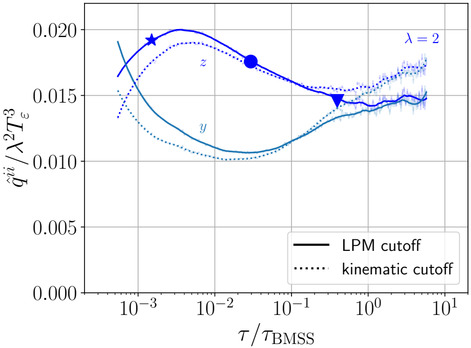
  - $\Lambda_\perp^{\mathrm{LPM}}(E, T_\varepsilon) = \zeta^{\mathrm{LPM}} g(E T_\varepsilon^3)^{1/4}$
  - $\Lambda_\perp^{\mathrm{kin}}(E, T_\varepsilon) = \zeta^{\mathrm{kin}} g(E T_\varepsilon)^{1/2}$
- Fix ζ^i at triangle marker to match with JETSCAPE[5] for $\lambda = 10$, use jet energy $E = 100\,\mathrm{GeV}$ and $Q_s = 1.4\,\mathrm{GeV}$.
- Obtain $\hat{q}$ for multiple fixed $\Lambda_\perp$.
- Interpolate, using[6]

$$\hat{q}^{xx}(\Lambda_\perp \gg T_\varepsilon) \simeq a_x \ln \frac{\Lambda_\perp}{Q_s} + b_x$$



[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

[5] [Phys.Rev.C 104 (2021) [JETSCAPE]]

[6] [Values available at https://zenodo.org/records/10419537]

Results for $\hat{q}$

- Use cutoffs
  - $\Lambda_\perp^{\mathrm{LPM}}(E, T_\varepsilon) = \zeta^{\mathrm{LPM}} g(ET_\varepsilon^3)^{1/4}$
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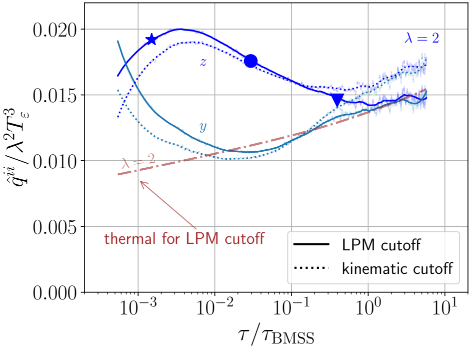
- Similar results for both cutoffs



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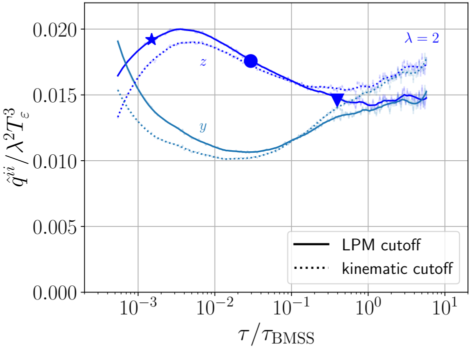

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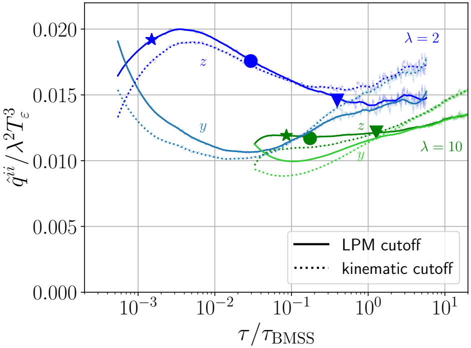

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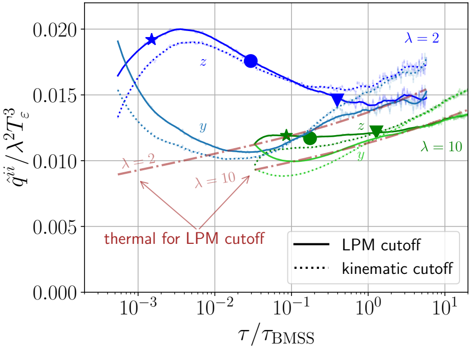

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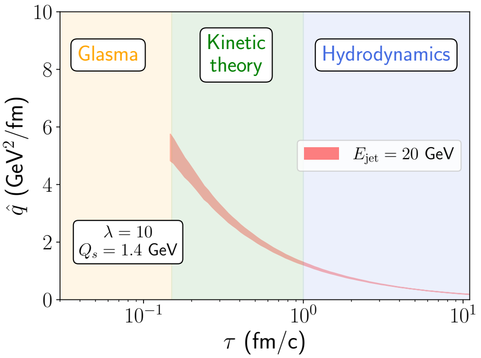
Time evolution of jet quenching parameter

- Model cutoff variation for fixed jet energy
- Dependence on initial conditions and cutoff (bands)



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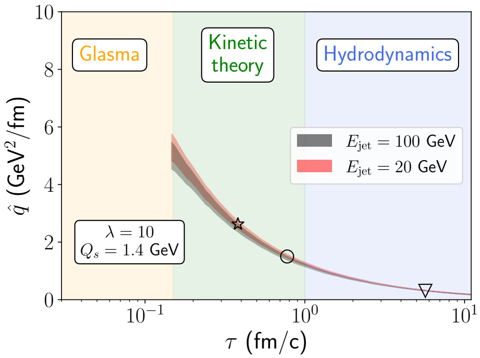

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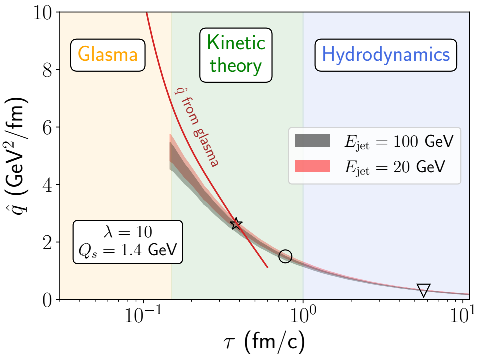

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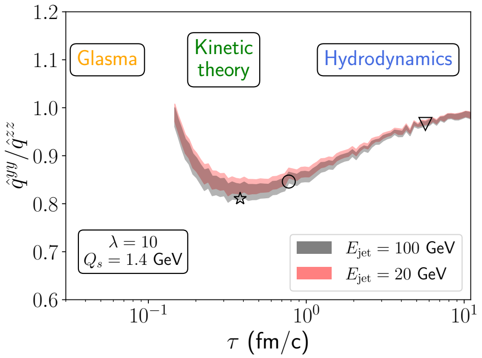

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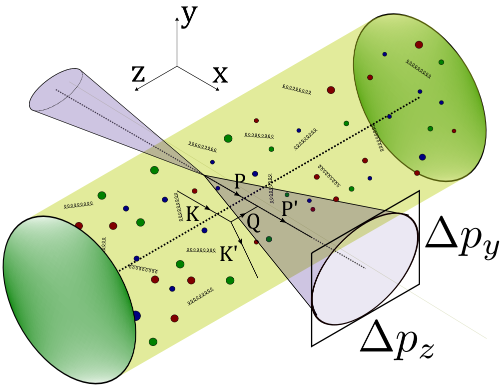
Similar in spirit: Heavy quark diffusion κ

- To study initial stages
  $\rightarrow$ very **energetic** or **heavy** probes
  (must be created early)
- Here depicted: **jets**



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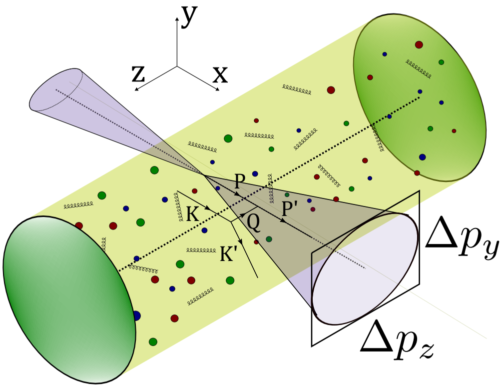

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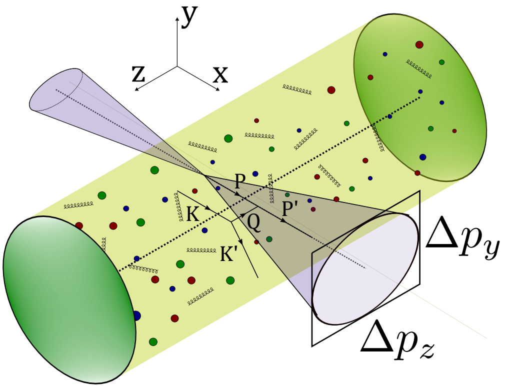
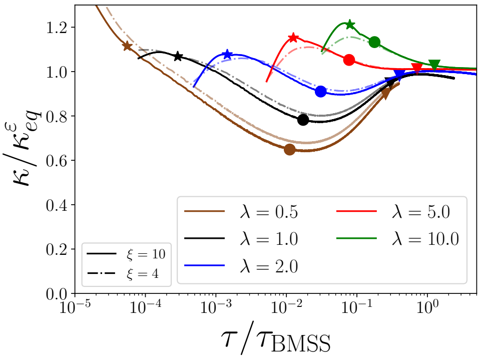
- From jets to heavy quarks:
  - **Jets:** $v \to c$, $m \to 0$
  - **Heavy quarks:** $v \to 0$, $m \to \infty$



Heavy quark diffusion coefficient κ

- Similar idea as $\hat{q}$: Study κ during bottom-up thermalization
- κ measures average momentum transfer to heavy quark

$$\kappa = \int \mathrm{d}\Gamma_{\tilde{\mathrm{PS}}}\, q^2 \left|\mathcal{M}_\kappa\right|^2 f(k) \left(1 + f(k')\right)$$



[Phys.Rev.D 109 (2024) [Boguslavski, Kurkela, Lappi, FL, Peuron]]

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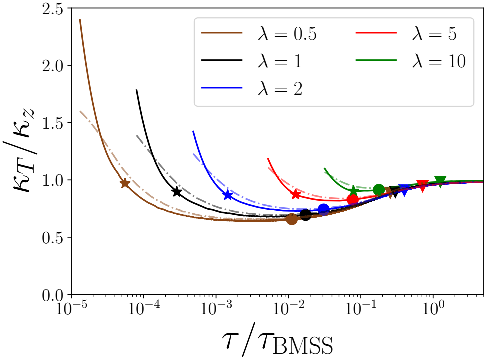

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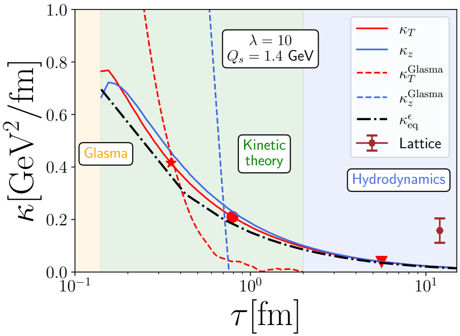


[PoS HardProbes2023 (2024) [Avramescu, Băran, Greco, Ipp, Müller, Ruggieri]]

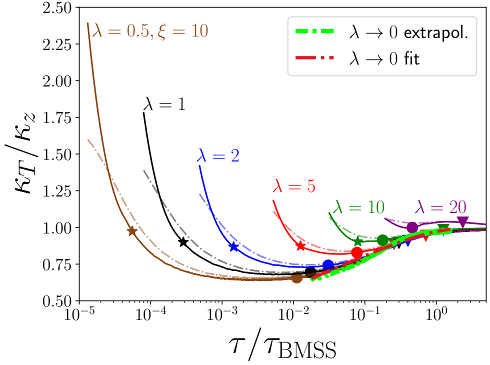
[Phys.Rev.D 107 (2023) [Brambilla, Leino, Mayer-Steudte, Petreczky]]

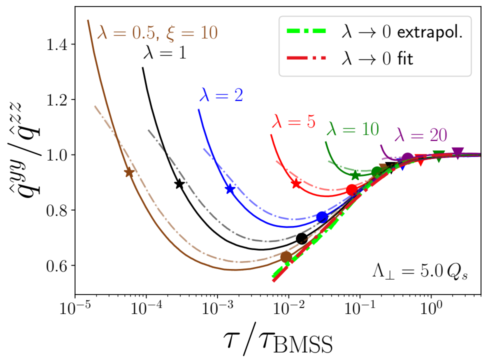
[Phys.Rev.D 109 (2024) [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Anisotropies fall on universal curve . . .

[Phys.Lett.B 852 (2024)]

[Boguslavski, Kurkela, Lappi, FL, Peuron]





- Approach to universal curve when scaled with $\tau_{\mathrm{BMSS}} = \alpha^{-13/5} / Q_s$
- Many quantities plotted as function of different time . . .

Conclusions and outlook

- Studied momentum broadening of jets and heavy-quarks during initial stages in heavy-ion collisions
- Values of $\hat{q}$ and κ within 30% of thermal estimate
- $\hat{q}$ connects to Glasma, κ shows larger deviations
- More momentum broadening along the beam axis ($\hat{q}^{zz} > \hat{q}^{yy}$)

Outlook

- Accelerating EKT simulations using machine learning
- Revisit approximations in EKT simulations (HTL-screening)
- Obtain gluon emission spectrum from pre-equilibrium $\hat{q}$

[Code and data: https://zenodo.org/records/10419537, https://zenodo.org/records/10409474]

Bottom-up vs. hydrodynamic attractor

- Often universal behavior in τ/τ_R,

$$\tau_R = \frac{4\pi\eta/s}{T}.$$

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- Conformal (first order) relativistic hydrodynamics [6]:

$$\frac{P_L}{P_T} = 1 - 8 \underbrace{\frac{\eta/s}{\tau T}}_{\sim\tau_R/\tau}$$

[6] [[Romatschke, Romatschke] (2019)]

Bottom-up vs. hydrodynamic attractor

- Often universal behavior in τ/τ_R,

$$\tau_R = \frac{4\pi\eta/s}{T}.$$

Two different pictures emerge:

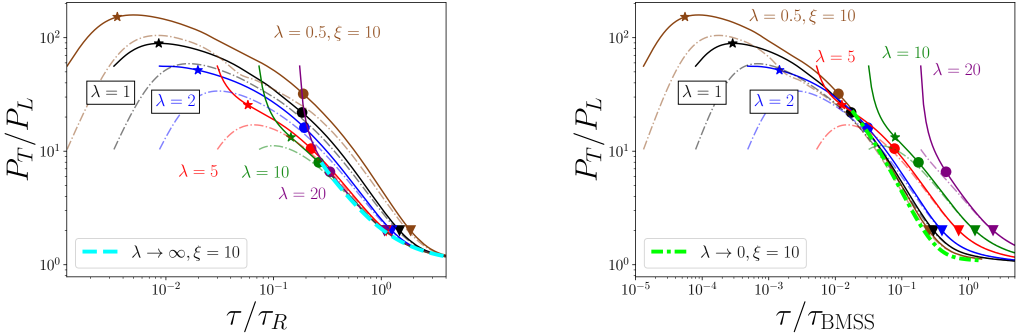
- **Bottom-up** expects thermalization around $\tau_{\mathrm{BMSS}} = \alpha_s^{-13/5}/Q_s$
- **Hydrodynamics** expects thermalization around $\tau_R = \frac{4\pi\eta/s}{T}$

How to reconcile these different time scales?

Pressure ratio

$$\tau_R = \frac{4\pi\eta/s}{T},\ \tau_{\mathrm{BMSS}} = \alpha_s^{-13/5}/Q_s$$

- **Kinetic theory simulations** for **different couplings** $0.5 \leq \lambda \leq 20$ and **initial conditions**.

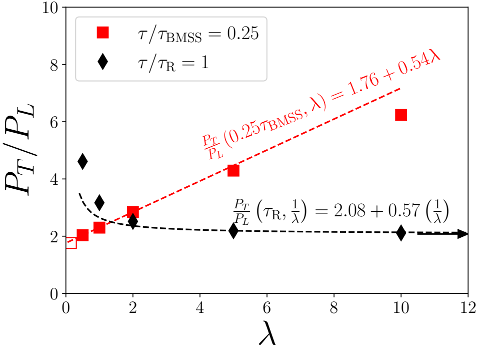


- Attractor for each λ (insensitive to IC)
- Curves **approach limiting attractors** after •

Extrapolation to limiting attractors

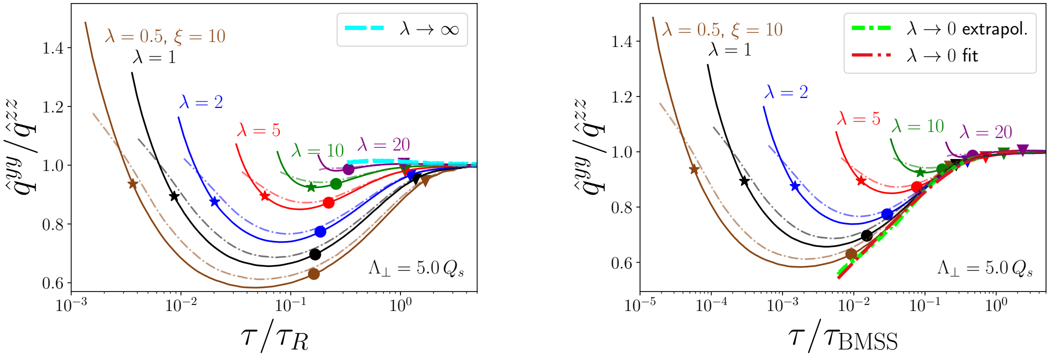
$$\tau_R = \frac{4\pi\eta/s}{T}$$
$$\tau_{\mathrm{BMSS}} = \alpha_s^{-13/5}/Q_s$$

- Obtain limiting attractors by extrapolating at fixed τ/τ_R or $\tau/\tau_{\mathrm{BMSS}}$
- **Bottom-up attractor**: Linear extrapolation to $\lambda \to 0$
- **Hydro attractor**: Linear extrapolation to $1/\lambda \to 0$



$\hat{q}$ and the limiting attractors

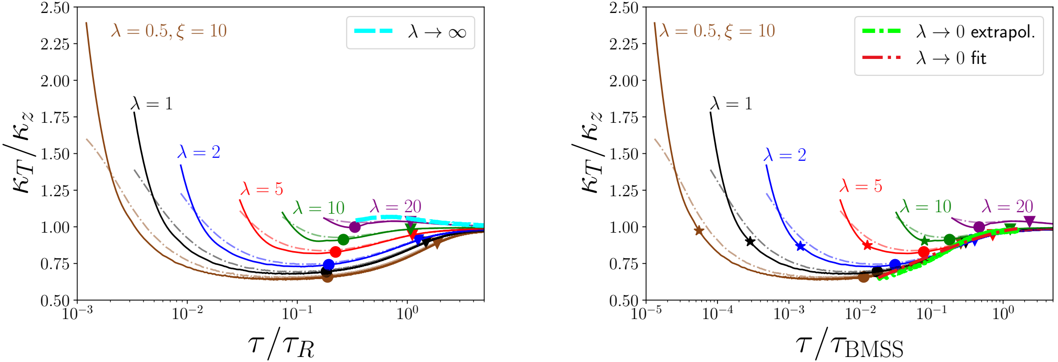
[Phys.Lett.B 852 (2024) [Boguslavski, Kurkela, Lappi, FL, Peuron]]



- Approach to weak coupling attractor even at moderate couplings

κ and the limiting attractors

[Phys.Lett.B 852 (2024) [Boguslavski, Kurkela, Lappi, FL, Peuron]]



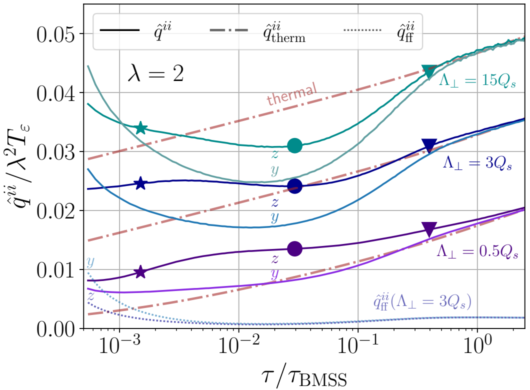
- Similar to $\hat{q}$: Approach to weak coupling attractor even at moderate λ

Bose-enhanced terms

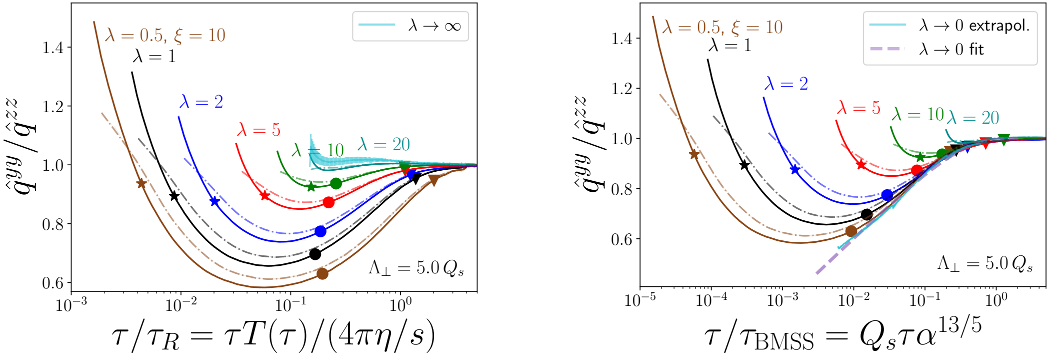
- $\hat{q}$ for fixed coupling $\lambda = 2$ and varying cutoffs $\Lambda_\perp$
- 2D distribution

  $$f(\mathbf{k}) \sim \delta(k_z)$$

  Leads to $\hat{q}^{zz}_{\rm ff} = 0$
- Reason for different ordering: Bose-enhanced part $\hat{q}_{\rm ff}$ = term quadratic in $f(\mathbf{k})$



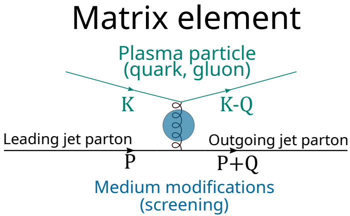
$\hat{q}$ and the limiting attractors



- Approach to weak coupling attractor even at moderate couplings
- Fit for bottom-up attractor:
  $\frac{\hat{q}^{yy}}{\hat{q}^{zz}}(\tau) \approx 1 + c_1 \ln\left(1 - e^{-c_2\tau/tau_{\rm BMSS}}\right)$ with $c_1 = 0.12$, $c_2 = 3.45$.

Screening in the matrix element of $\hat{q}$

- Scattering matrix element includes **in-medium propagator**
- Receives **self-energy corrections**
- Anisotropic hard thermal loop (HTL) self-energy $\rightarrow$ unstable modes[6]
- **Approximation: Use isotropic HTL matrix element**
  Similar approximation also in EKT implementations[7]



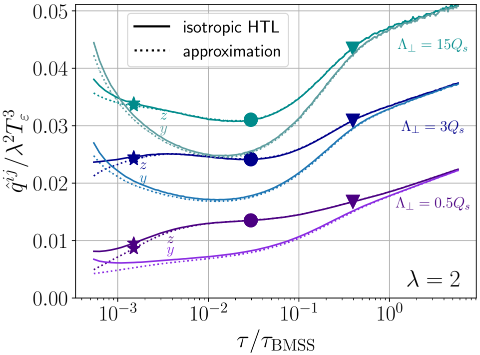
[6] [Phys.Rev.D 68 (2003) [Romatschke, Strickland]]
[7] [Phys.Rev.Lett. 115 (2015) [Kurkela, Zhu]; Phys.Rev.Lett. 122 (2019) [Kurkela, Mazeliauskas]; Phys.Rev.D 104 (2021) [Du, Schlichting]]

Screening approximation to the matrix element

- Compare with simple screening approximation

$$\frac{(s-u)^2}{t^2} \to \frac{(s-u)^2}{t^2} \frac{q^4}{(q^2+\xi_T^2 m_D^2)^2}$$

- Longitudinal[8] $\xi_L = e^{5/6}/\sqrt{8}$
- Transverse broadening: $\xi_T = e^{1/3}/2$
- **Good agreement**

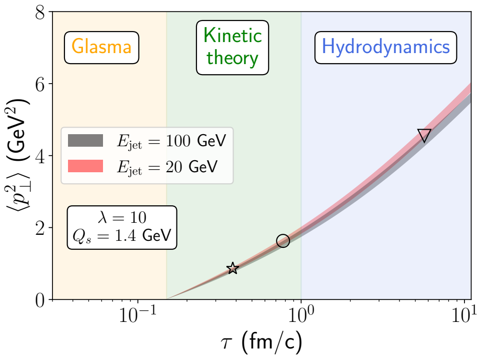


s, u, t: Mandelstam variables

[8] [Phys.Rev.D 89 (2014) [York, Kurkela, Lu, Moore]]

What about momentum broadening?

- Per definition, $\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}\tau}$
- Naïvely $\Delta p_\perp^2 = \int \mathrm{d}\tau\, \hat{q}(\tau)$ over lifetime of jet
- But: only true if no splittings occur.
- Think of $\hat{q}$ as medium parameter.



Toy model for underoccupation

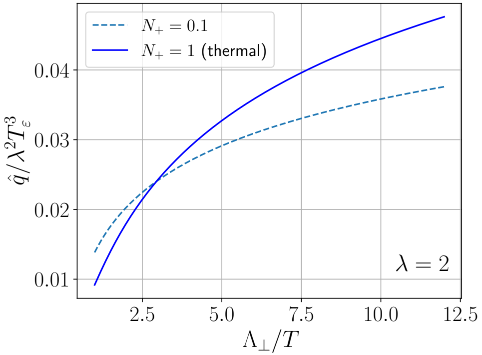
- Scaled thermal distribution

$$f(k;T) = \frac{N_+}{\exp(k/T) - 1}$$

Explains ordering $\hat{q}_{\text{therm}} \lessgtr \hat{q}$ for underoccupancy

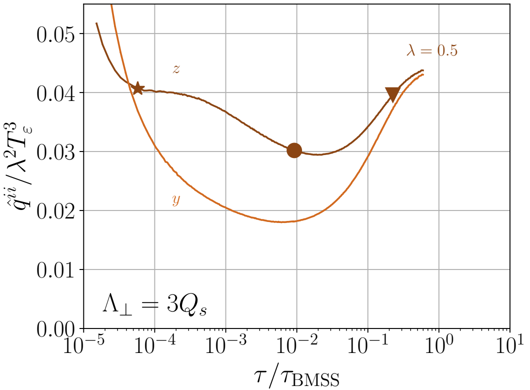
[arXiv:2312.00447 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Scaled thermal distribution



Time evolution of $\hat{q}$

- Landau matching
  $\varepsilon^{\mathrm{eq}}(T_\varepsilon) = \varepsilon^{\mathrm{sim}}$
- Obtain $\hat{q}^{ii}$ for a fixed cutoff $\Lambda_\perp$
- For coupling $\lambda = 0.5$
- Mostly $\hat{q}^{zz} > \hat{q}^{yy} \rightarrow$
  Momentum broadening along beam axis enhanced



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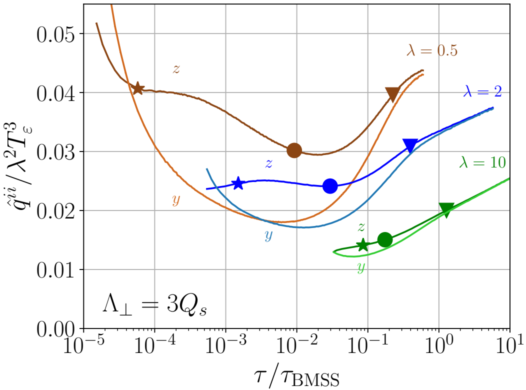

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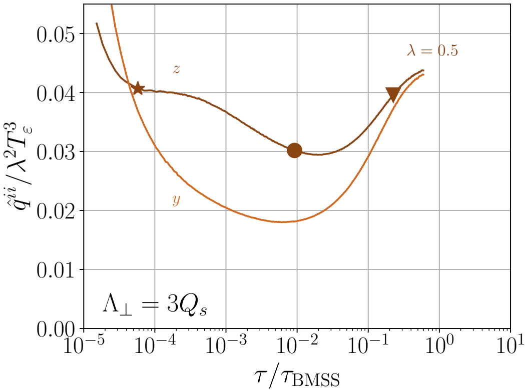

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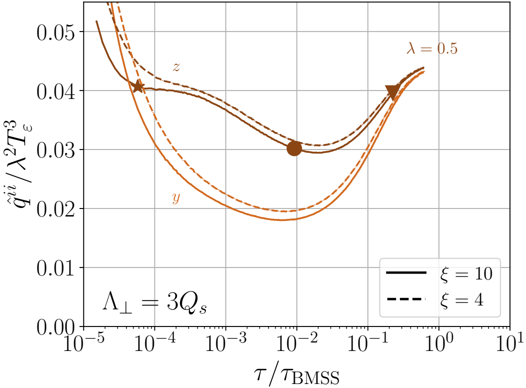
- Weak dependence on initial anisotropy ξ



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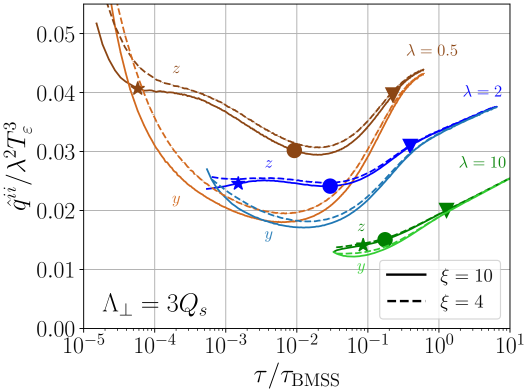
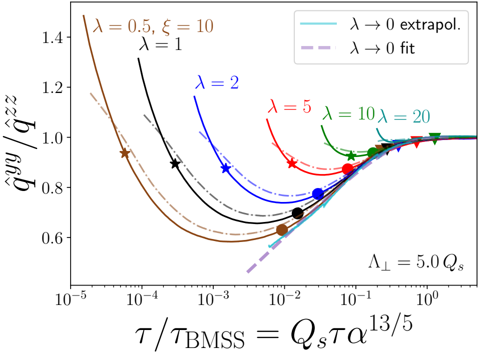


Ratio of $\hat{q}^{yy}/\hat{q}^{zz}$

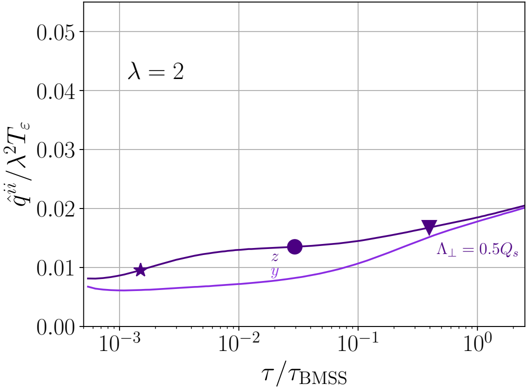
- Ratio $\hat{q}^{yy}/\hat{q}^{zz}$ follows attractor in thermalization time $\tau_{\rm BMSS}$ $\rightarrow$ "bottom-up limiting attractor"[9]



[9] [arXiv:2312.11252 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Cutoff dependence and comparison with equilibrium

- $\hat{q}$ for fixed coupling $\lambda = 2$



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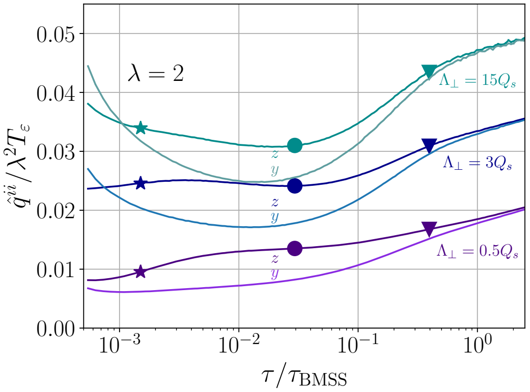

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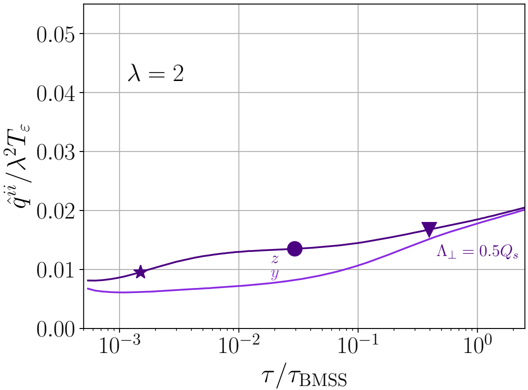
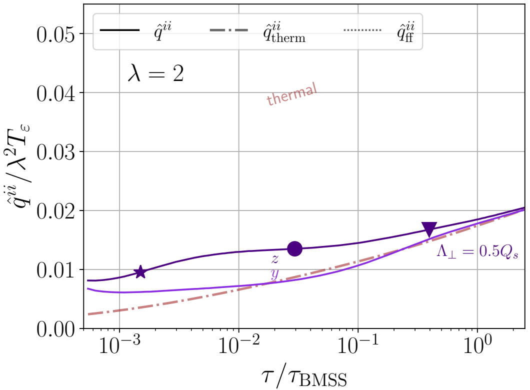


Cutoff dependence and comparison with equilibrium

- $\hat{q}$ for fixed coupling $\lambda = 2$ and varying cutoffs $\Lambda_\perp$
- **Ordering $\hat{q}^{yy} \lessgtr \hat{q}^{zz}$ depends on cutoff**
- Compare with **energy-density matched thermal equilibrium**



Cutoff dependence and comparison with equilibrium

- $\hat{q}$ for fixed coupling $\lambda = 2$ and varying cutoffs $\Lambda_\perp$
- **Ordering $\hat{q}^{yy} \lessgtr \hat{q}^{zz}$ depends on cutoff**
- Energy-matched **equilibrium over- or underestimates $\hat{q}$, depending on cutoff**