Jet quenching parameter during the initial stages

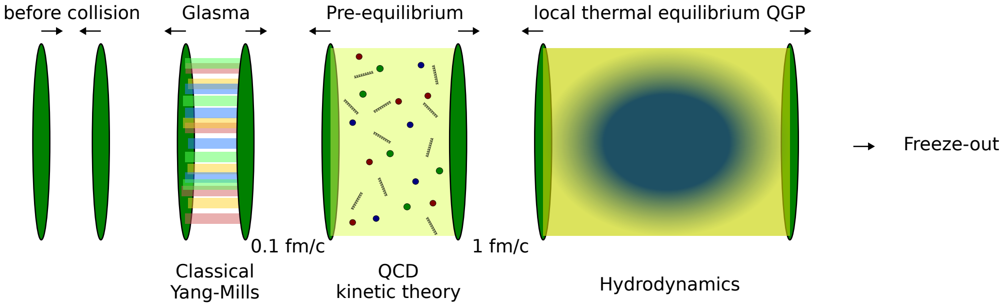
Based on arXiv:2303.12595 and arXiv:2312.00447
(in collaboration with K. Boguslavski, A. Kurkela, T. Lappi, J. Peuron)

Florian Lindenbauer

TU Wien

14.02.2024 ECT*, Trento

Time-evolution of the QGP in heavy-ion collisions

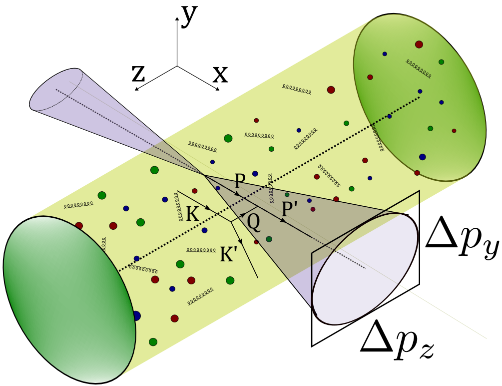


Here: Consider thermalization stage (kinetic theory)

Jet quenching parameter $\hat{q}$

- Quantifies **momentum broadening**

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}L} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}t}$$



- $\hat{z}$: Beam direction, $\hat{x}$: jet direction

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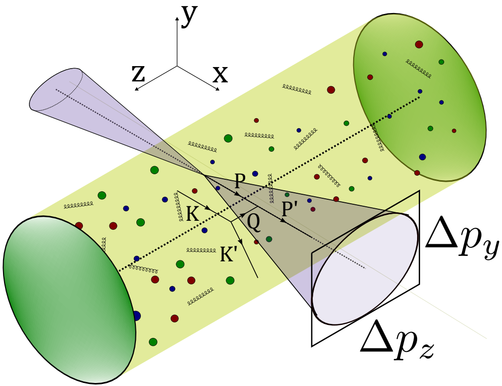

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- Measures **jet-medium** interactions

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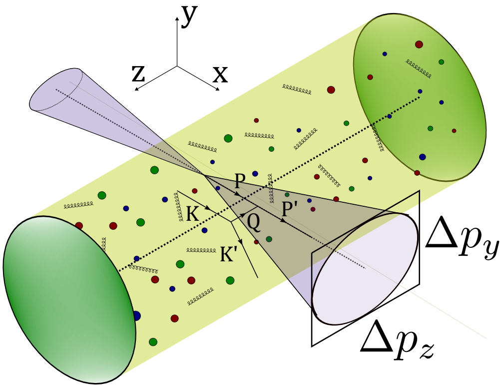

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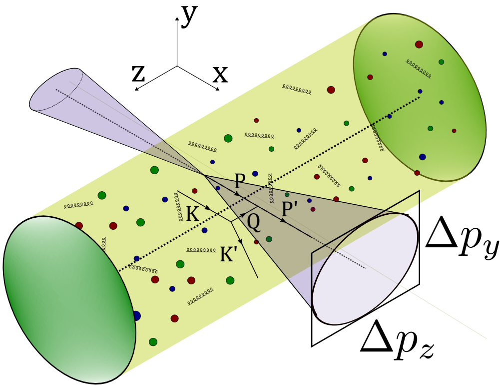
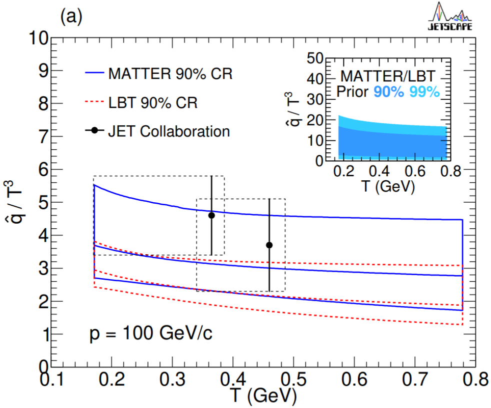
- Measures **jet-medium** interactions
- Input to **energy loss**
  - BDMPS-Z-like calculations
  - Harmonic approximation
  - Interaction potential $v(b) \approx \frac{1}{4}\hat{q}b^2$
- $\hat{z}$: Beam direction, $\hat{x}$: jet direction



Estimates of the jet quenching parameter

- **Mostly** considered in **equilibrium** or hydrodynamics
- Extractions from experiment: (only) hydrodynamic medium

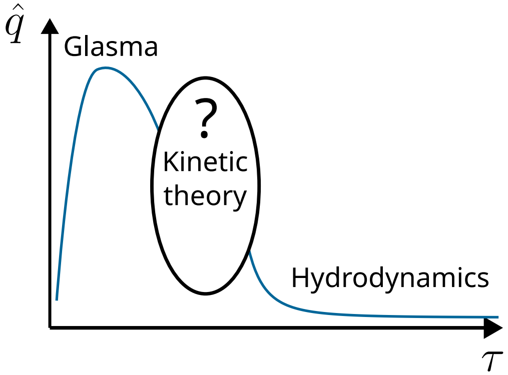


[Phys.Rev.C 104 (2021) [JETSCAPE]]

Estimates of the jet quenching parameter

- **Mostly** considered in **equilibrium** or hydrodynamics
- Extractions from experiment: (only) hydrodynamic medium
- Recently also considered in Glasma[1] (see also Dana's talk (Wed 12:00))
- **Goal: $\hat{q}$ during thermalization** $\rightarrow$ between Glasma and hydro

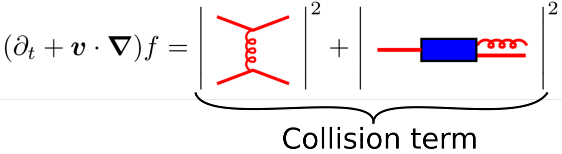
Schematic overview of $\hat{q}$ evolution



[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]]

Effective kinetic theory description of the QGP

- Gluons with **distribution function** $f(t, \mathbf{p})$
- Time evolution described by **Boltzmann equation** at leading-order[2]



$$-\frac{\partial f(\mathbf{p}, \tau)}{\partial \tau} + \frac{p_z}{\tau} \frac{\partial f(\mathbf{p}, \tau)}{\partial p_z} = \mathcal{C}^{2\leftrightarrow 2}[f] + \mathcal{C}^{`1\leftrightarrow 2'}[f]$$

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Effective kinetic theory description of the QGP

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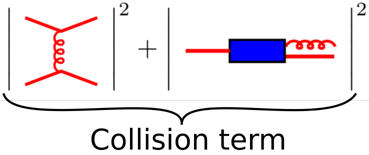
$$(\partial_t + \boldsymbol{v} \cdot \boldsymbol{\nabla})f =$$



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

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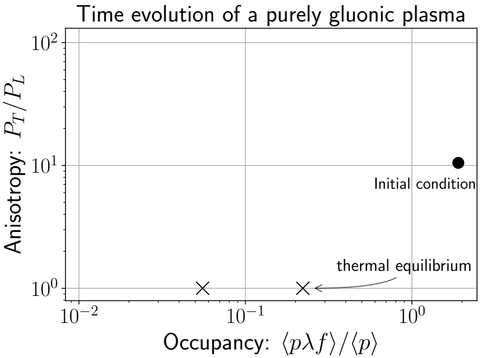
Bottom-up thermalization in heavy-ion collisions

- 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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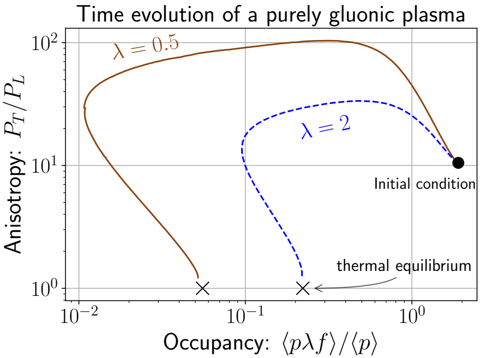

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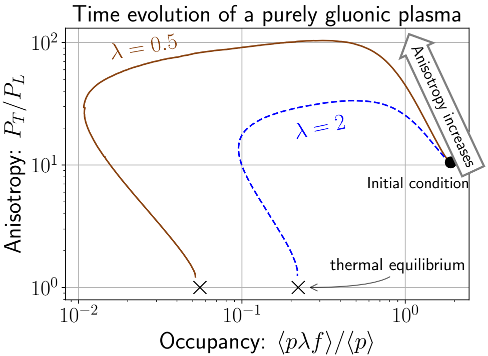

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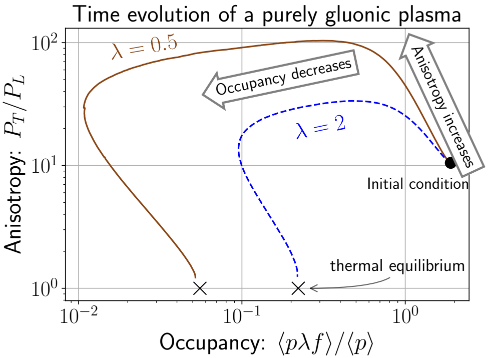
  - **Phase 2**: Occupancy decreases



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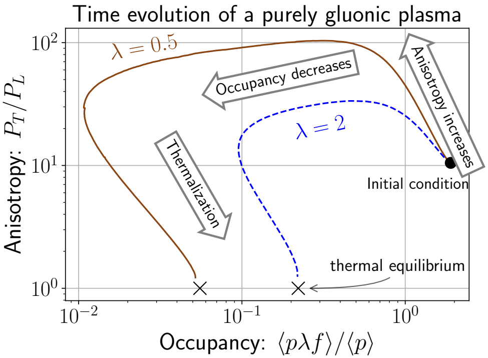

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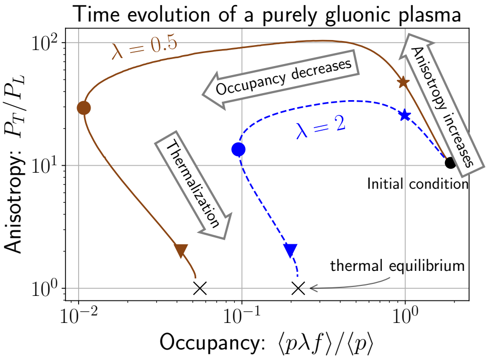
Markers represent **different stages**



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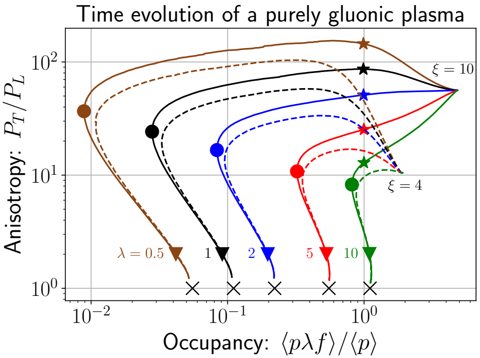

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Generalization of $\hat{q} \to \hat{q}^{ij}$ for anisotropic systems

- **Previously** (isotropic definition):

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

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

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- Note that we only take into account **elastic** $2 \leftrightarrow 2$ **processes!**

Jet quenching parameter in kinetic theory

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

Jet quenching parameter in kinetic theory

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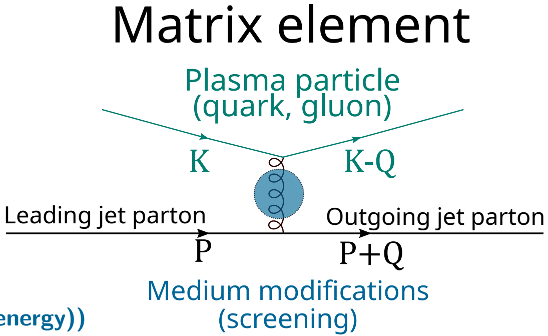
Outgoing plasma particle

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

Incoming plasma particles with momentum k

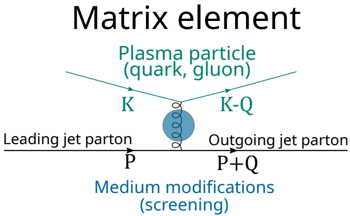
Matrix element
with medium corrections (self-energy))

appropriate phase-space measure



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

- Scattering matrix element includes **in-medium propagator**
- Receives **self-energy corrections**



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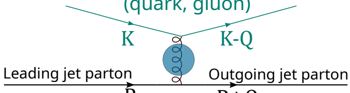
Screening in the matrix element of $\hat{q}$

- Scattering matrix element includes **in-medium propagator**
- Receives **self-energy corrections**
- Anisotropic hard thermal loop (HTL) self-energy $\rightarrow$ unstable modes[5]
- **Approximation: Use isotropic HTL matrix element**
  Similar approximation also in EKT implementations[6]

Matrix element



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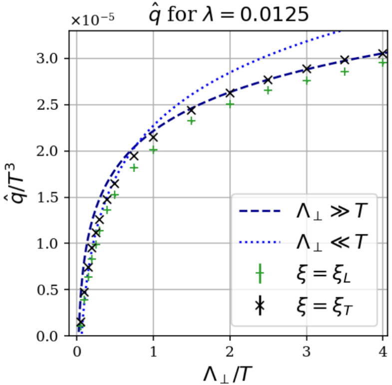
Screening approximation to the matrix element

- Even simpler 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[7] $\xi_L = e^{5/6}/\sqrt{8}$
- Transverse broadening[8]: $\xi_T = e^{1/3}/2$
- Agrees with analytic limits[9] (small, large cutoffs)



s, u, t: Mandelstam variables

[7] [Phys.Rev.D 89 (2014) [York, Kurkela, Lu, Moore]]
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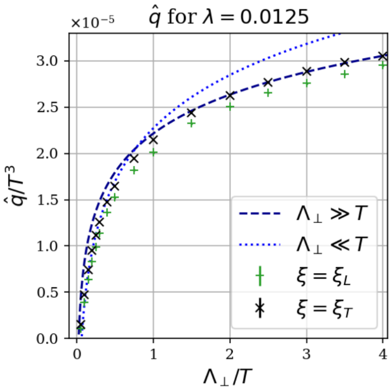
- **Use isotropic HTL from now on**



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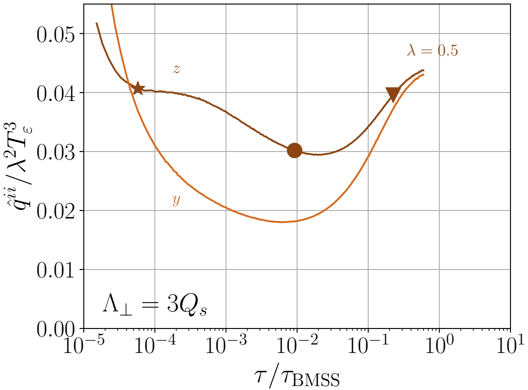
Time evolution of $\hat{q}$

- 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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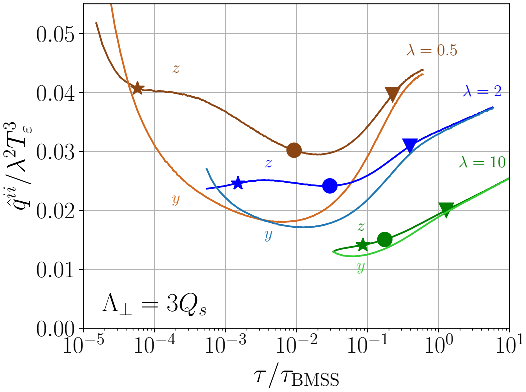

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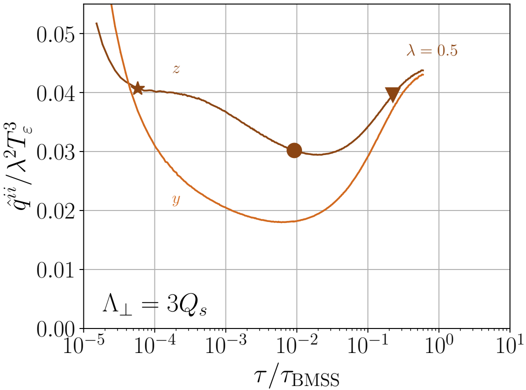

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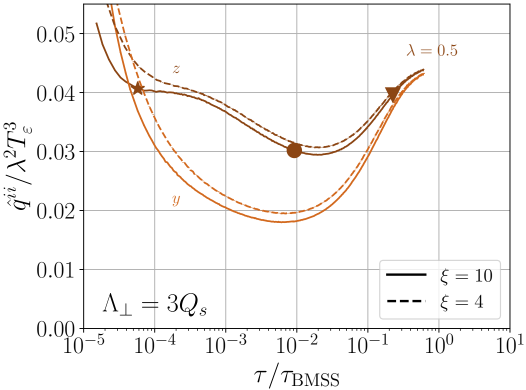
- Weak dependence on initial anisotropy ξ



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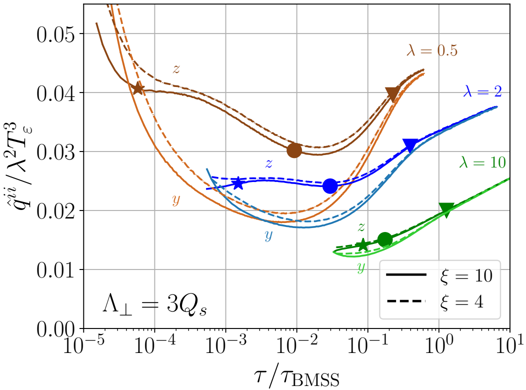
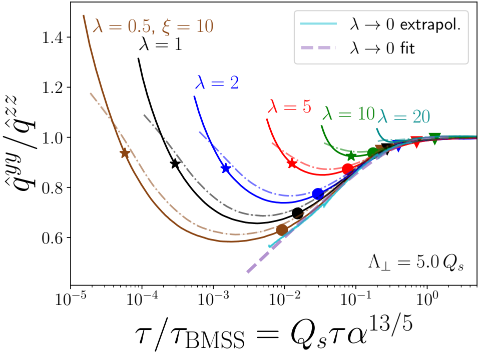


Ratio of $\hat{q}^{yy}/\hat{q}^{zz}$

- Ratio $\hat{q}^{yy}/\hat{q}^{zz}$ follows attractor in thermalization time $\tau_{\rm BMSS}$
  $\rightarrow$ "bottom-up limiting attractor"[10]

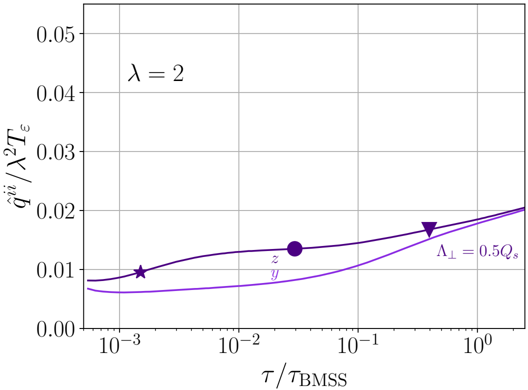
- See Tuomas' talk (Thu 09:00)



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

Cutoff dependence and comparison with equilibrium

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



Cutoff dependence and comparison with equilibrium

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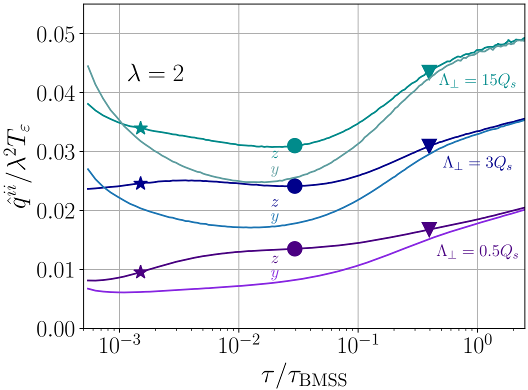
- **Ordering $\hat{q}^{yy} \lessgtr \hat{q}^{zz}$ depends on cutoff**



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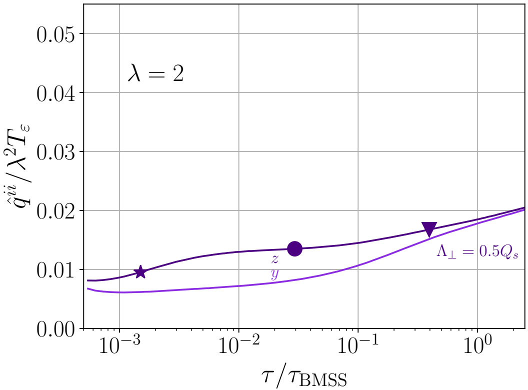

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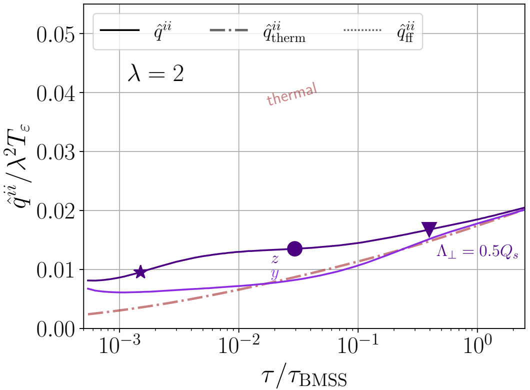
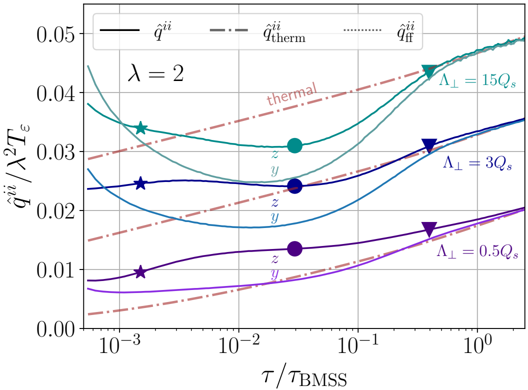
- Compare with **energy-density matched thermal equilibrium**



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**



Toy model for underoccupation

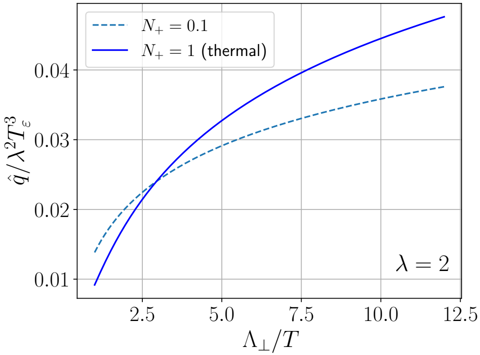
- Scaled thermal distribution

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

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

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

Scaled thermal distribution



Making sense of the cutoff

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

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

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- **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 varying cutoff

- Use cutoffs
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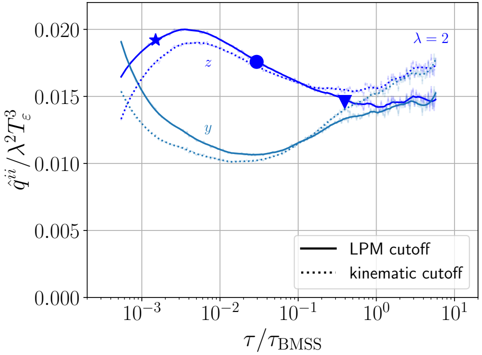

[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

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

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

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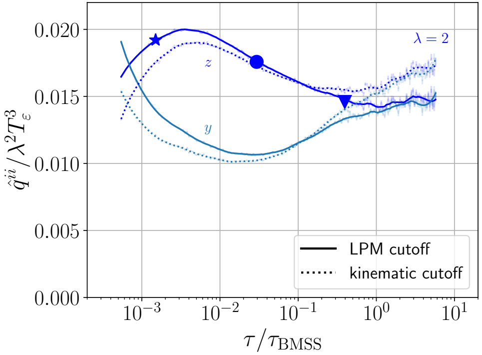

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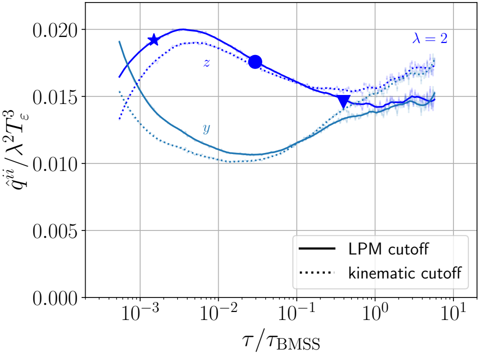

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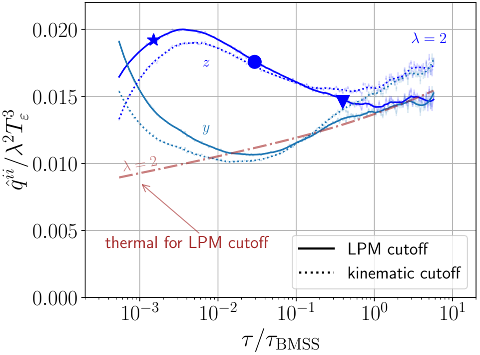

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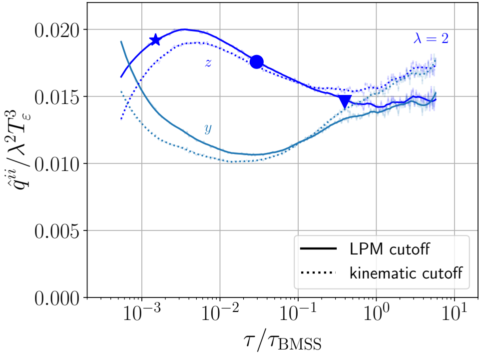

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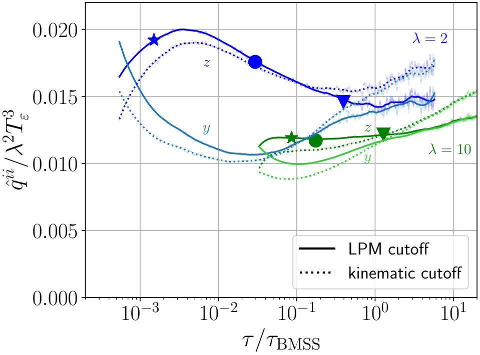

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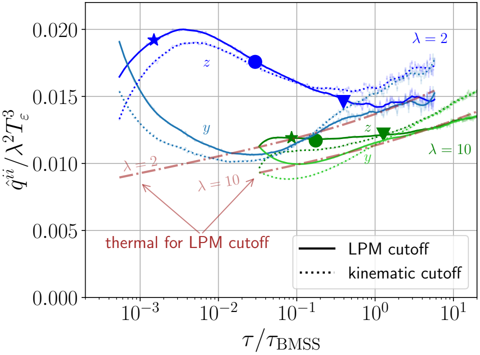

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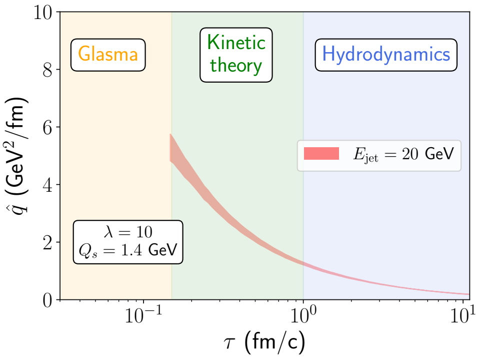
Time evolution of jet quenching parameter

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



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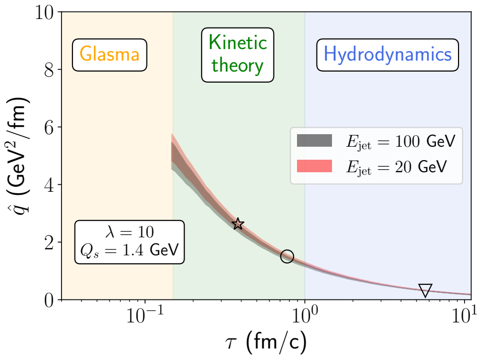

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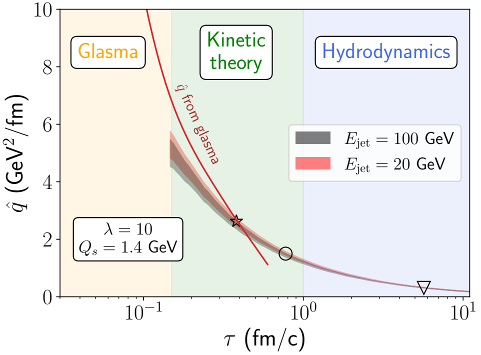

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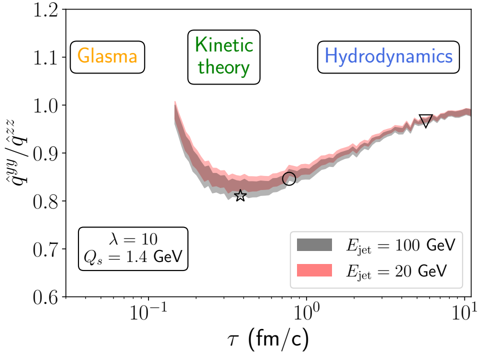

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What about momentum broadening?

- Per definition, $\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}\tau}$
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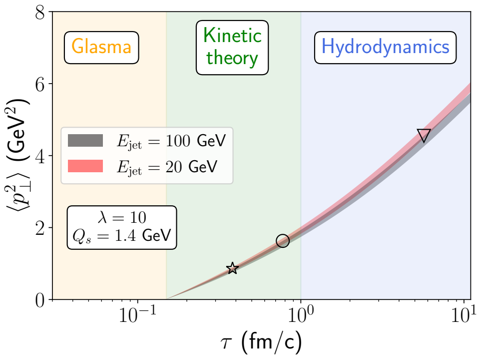

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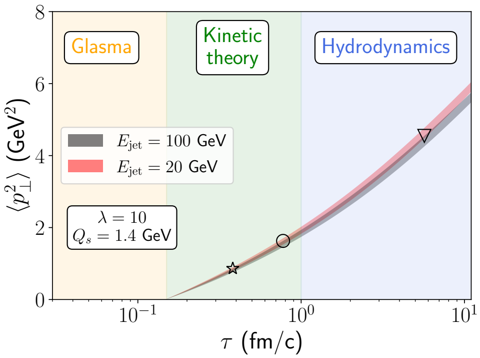

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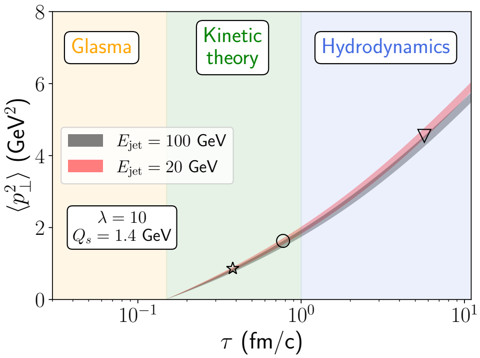

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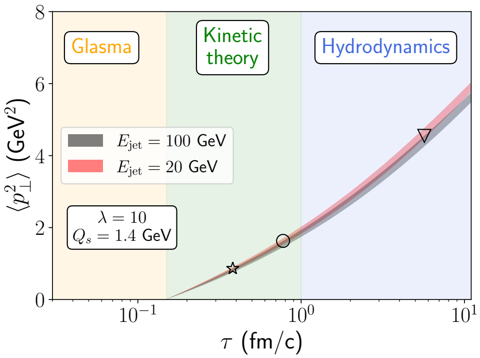
- Think of $\hat{q}$ as medium parameter.
- What else can we do with $\hat{q}$ during initial stages?



Where does $\hat{q}$ enter?

- **BDMPS-Z calculations** (in-medium splittings, energy-loss) e.g. in harmonic approximation
  - Recently generalized to include flowing/inhomogeneous systems[14]
  - anisotropic systems with $\hat{q}^{yy} \neq \hat{q}^{zz}$: Jet polarisation[15] $\rightarrow$ daughter gluons of gluon-splitting can carry net polarisation (see Siggi's talk (Wed 9:30))
- In **JETSCAPE**[16]: MATTER and LBT energy loss models can be parametrized in terms of $\hat{q}$
- $\hat{q}$ encodes **interaction strength** (moment of scattering potential)

[14] [Phys.Rev.D 106 (2022) [Andres, Dominguez, Sadofyev, Salgado], Phys.Rev.D 108 (2023) [Barata, Mayo López, Sadofyev, Salgado]]
[15] [JHEP 08 (2023) [Hauksson, Iancu]]
[16] [Phys.Rev.C 104 (2021) [JETSCAPE]]

Conclusions and outlook

- Extract $\hat{q}$ using QCD kinetic theory for anisotropic bottom-up evolution
- Model cutoff dependence
- **Results:**
  - $\hat{q}$ within 20% of Landau-matched thermal estimate (similar[17] to κ)
  - **connects Glasma** to **hydro** values
  - $\hat{q}^{zz} > \hat{q}^{yy}$ during most of the evolution $\rightarrow$ anisotropic broadening

Outlook

- Impact of pre-equilibrium value of $\hat{q}$ in jet energy loss and polarization?
- Signatures of initial stages?

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

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

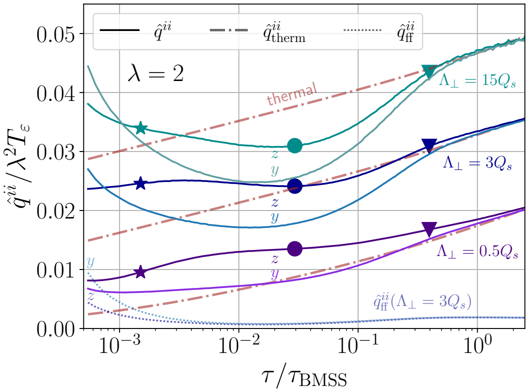
Bose-enhanced terms

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

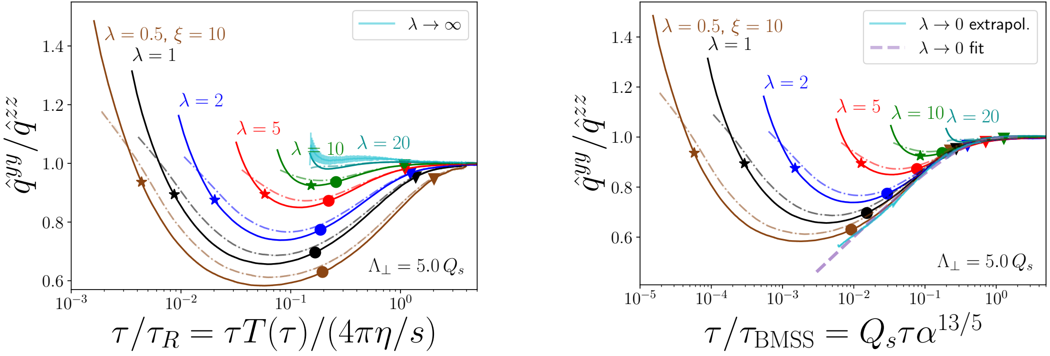
$$f(\mathbf{k}) \sim \delta(k_z)$$

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



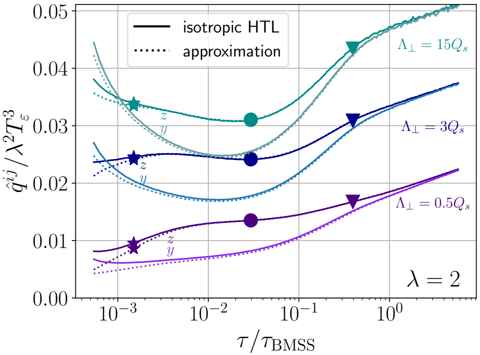
- Approach to weak coupling attractor even at moderate couplings
- Fit for bottom-up attractor:
  $\frac{\hat{q}^{yy}}{\hat{q}^{zz}}(\tau) \approx 1 + c_1 \ln\left(1 - e^{-c_2 \tau / tau_{\mathrm{BMSS}}}\right)$ with $c_1 = 0.12$, $c_2 = 3.45$.

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



s, u, t: Mandelstam variables

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