Addressing the Initial Stages in heavy-ion collisions using jet quenching

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

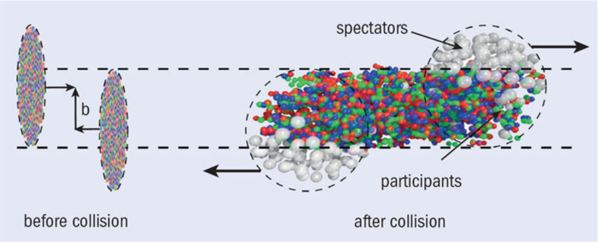
Florian Lindenbauer

TU Wien

22.02.2024 FAKT Workshop 2024, Bruck an der Mur

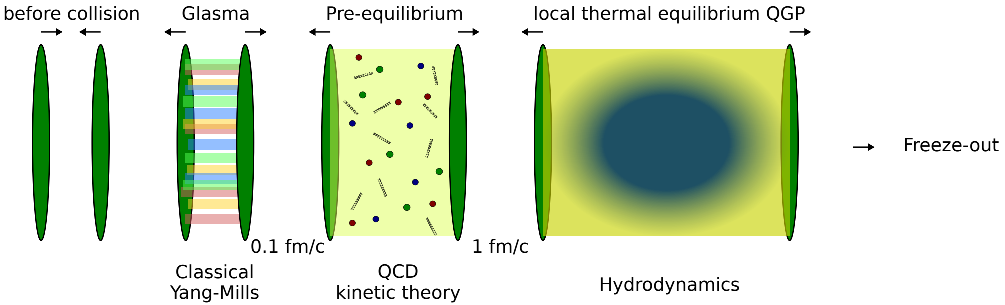
Heavy-ion collisions and the quark-gluon plasma

- Study 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

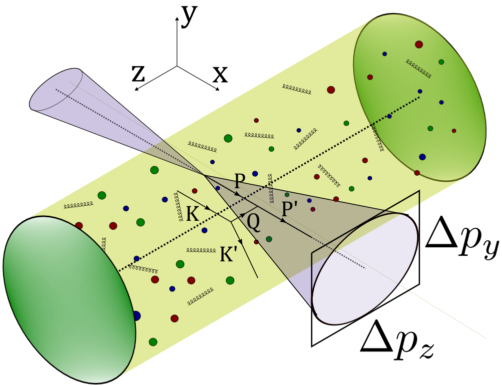


Interested in pre-equilibrium stages ("Initial stages")

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

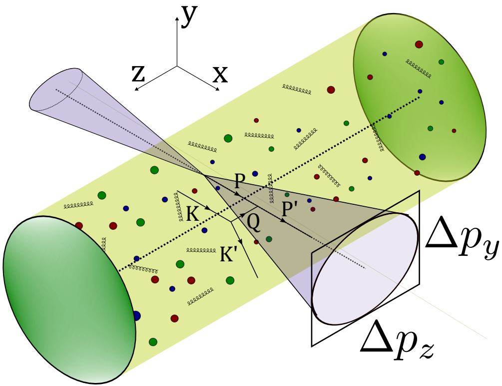
How can we study the QGP?

- Several experimental observables: Heavy quarks, Lepton production, Photon emission, ...
- Here: Focus on **jets**



How can we study the QGP?

- Several experimental observables: Heavy quarks, Lepton production, Photon emission, ...
- Here: Focus on **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

MEDIUM-INDUCED RADIATIVE ENERGY LOSS; EQUIVALENCE BETWEEN THE BDMPS AND ZAKHAROV FORMALISMS*

R. Baier [1], Yu. L. Dokshitzer [2], A. H. Mueller [3] and D. Schiff [4]

[1] *Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany*
[2] *INFN sezione di Milano, via G. Celoria 16, 20133 Milan, Italy*†
[3] *Physics Department, Columbia University, New York, NY 10027, USA*
[4] *LPTHE*‡ , *Université Paris-Sud, Bâtiment 211, F-91405 Orsay, France*

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Radiative Energy Loss of High Energy Partons Traversing an Expanding QCD Plasma

R. Baier

Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany

Yu.L. Dokshitzer*

INFN, Sezione di Milano, Milan, Italy

A.H. Mueller†

Physics Department, Columbia University, New York, NY 10027, USA

D. Schiff‡

LPTHE, Université Paris-Sud, Bâtiment 211, F-91405 Orsay, France

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ON THE ENERGY LOSS OF HIGH ENERGY QUARKS IN A FINITE-SIZE QUARK-GLUON PLASMA

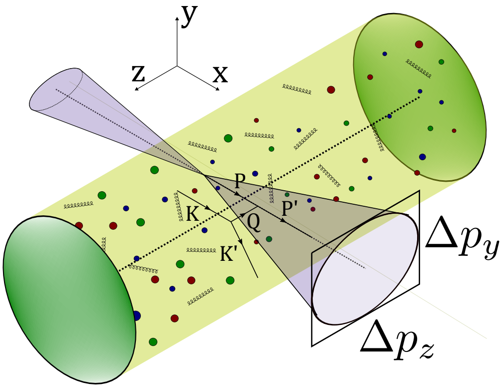
B.G. Zakharov

Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

L.D. Landau Institute for Theoretical Physics, GSP-1, 117940, Kosygina Str. 2, 117334 Moscow, Russia

Jet energy loss through medium-induced radiation

- Very many works on energy loss of energetic parton
- **Difficulties**: Correctly including the LPM suppression



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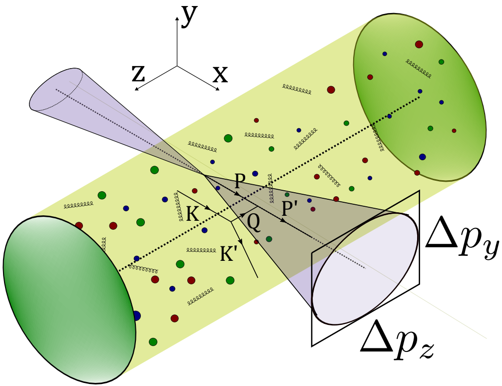
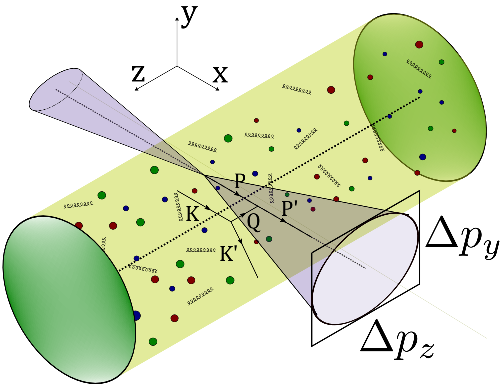
- **Harmonic approximation**: Depend on single medium parameter $\hat{q}$ **"Jet quenching parameter"**



Jet energy loss through medium-induced radiation

- Very many works on energy loss of energetic parton
- **Difficulties**: Correctly including the LPM suppression
- **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]

A B S T R A C T

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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Estimates of $\hat{q}$

Physics Letters B

Volume 834, 10 November 2022, 137464

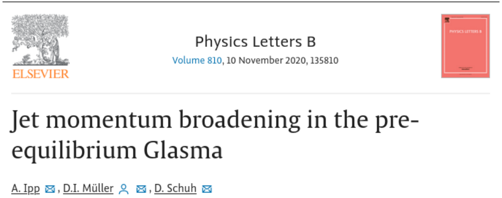
Jet quenching in glasma

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

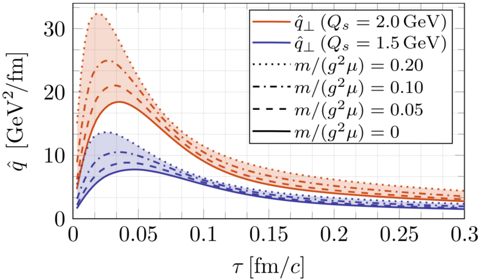
Estimates of $\hat{q}$


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 $\hat{q}$


PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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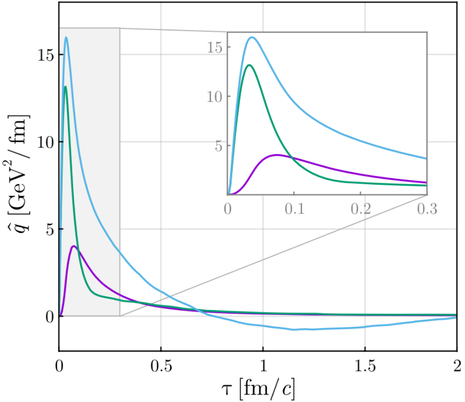
Simulating jets and heavy quarks in the glasma using the colored particle-in-cell method

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

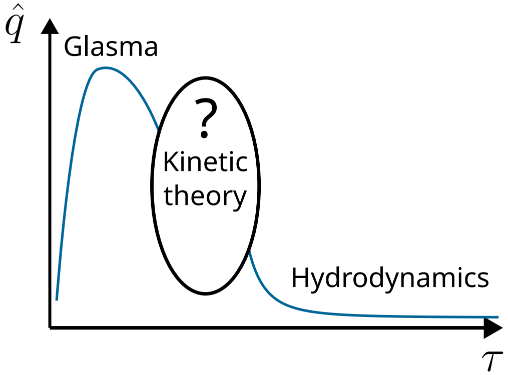


$\hat{q}$ in the glasma using classical statistical simulations

Goal of our work

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

Schematic overview of $\hat{q}$ evolution

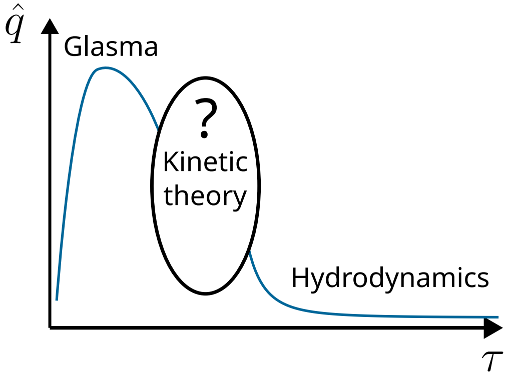


[1] [Phys.Lett.B 810 (2020) [Ipp, Müller, Schuh], Phys.Rev.C 105 (2022) [Carrington, Czajka, Mrowczynski], Phys.Rev.D 107 (2023) [Avramescu, Baran, Greco, Ipp, Müller, Ruggieri]]

Goal of our work

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

Schematic overview of $\hat{q}$ evolution



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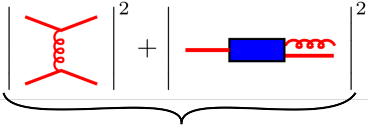
Effective kinetic theory description of the QGP

- Gluons with **distribution function** $f(t, \mathbf{p})$

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

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



Collision term

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

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

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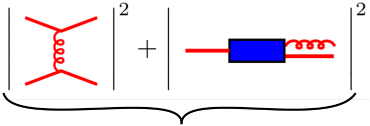


Collision term

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

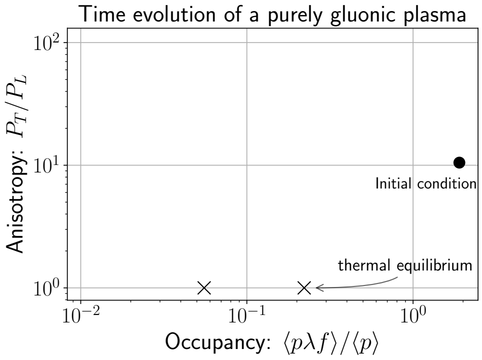
[2] [JHEP 01 (2003) [Arnold, Moore, Yaffe], Int.J.Mod.Phys.E 16 (2007) [Arnold]]

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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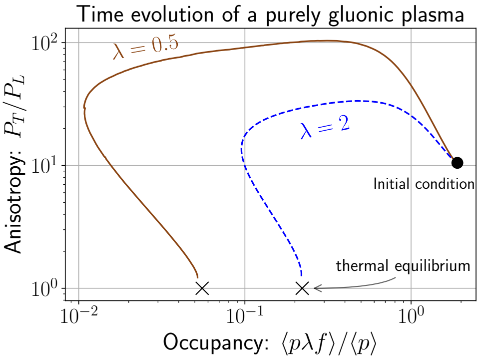

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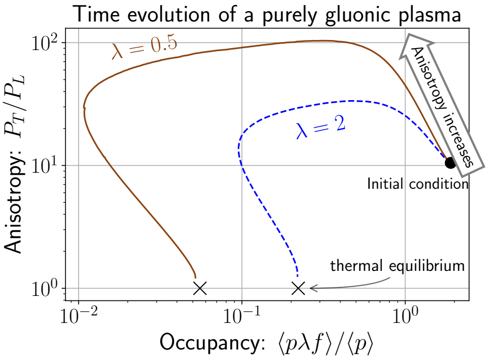

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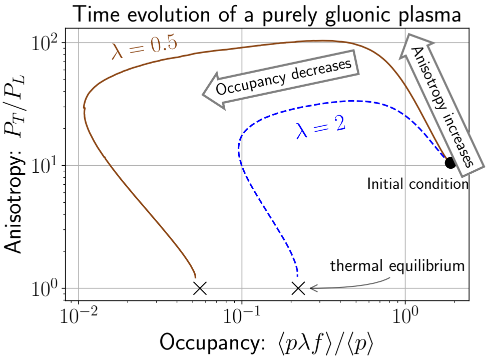

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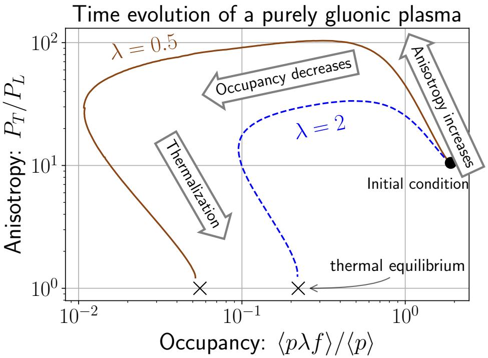

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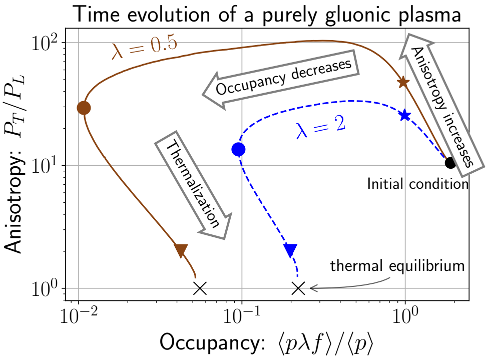
Markers represent **different stages**



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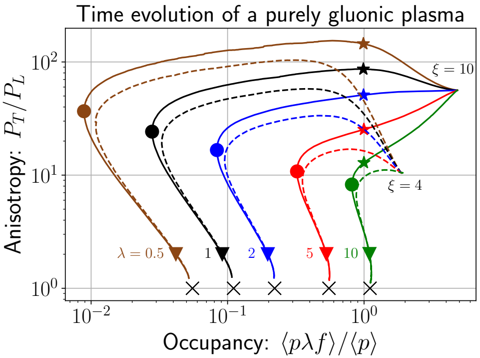

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Generalization of $\hat{q} \to \hat{q}^{ij}$ for anisotropic systems

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

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

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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

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

Outgoing plasma particle

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

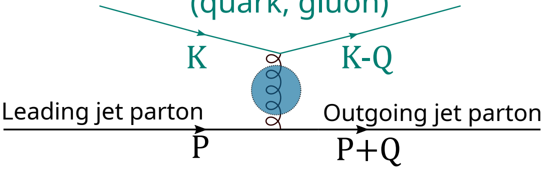
Incoming plasma particles with momentum k

Matrix element
with medium corrections (self-energy))

appropriate phase-space measure

Matrix element

Plasma particle (quark, gluon)



Medium modifications (screening)

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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- Cutoff $\Lambda_\perp$ restricts transverse momentum transfer $q_\perp < \Lambda_\perp$ (needed in eikonal limit $p \to \infty$)
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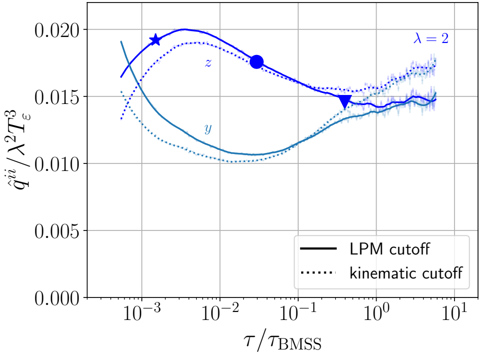
- **kinematic cutoff** $\Lambda_\perp^{\mathrm{kin}}(E,T) = \zeta^{\mathrm{kin}} g(ET)^{1/2}$
  obtained from comparing leading log behavior for large p and $\Lambda_\perp$
- **LPM cutoff** $\Lambda_\perp^{\mathrm{LPM}}(E,T) = \zeta^{\mathrm{LPM}} g(ET^3)^{1/4}$
  Estimate for momentum broadening during 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
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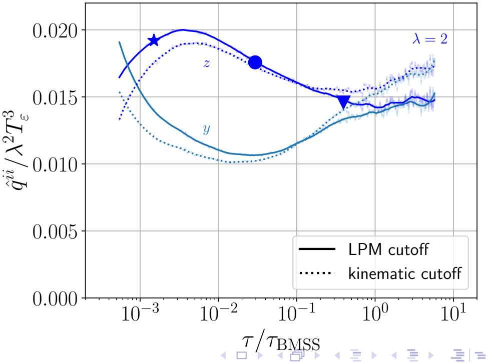

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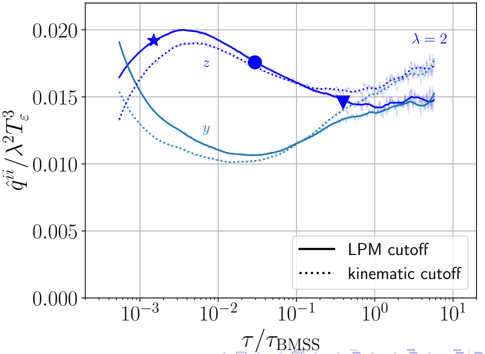
- Obtain $\hat{q}$ for multiple fixed $\Lambda_\perp$.
- Interpolate, using[6]

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



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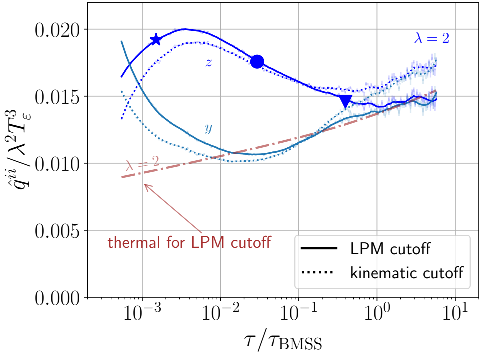
- Similar results for both cutoffs



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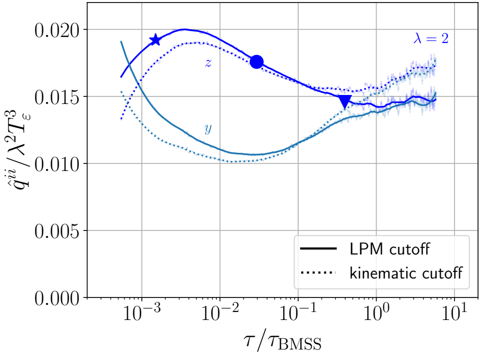

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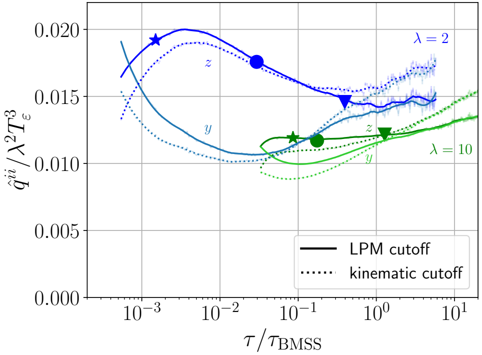

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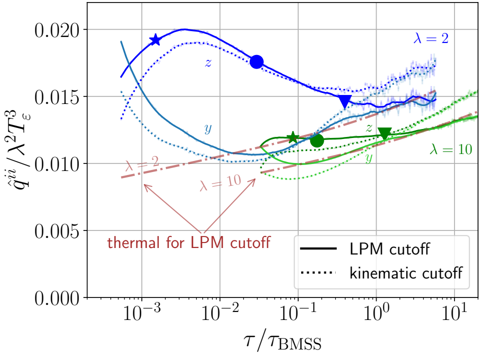
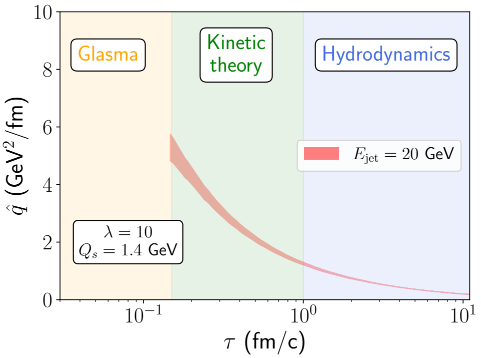


[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Time evolution of jet quenching parameter

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



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

[5] [Phys.Lett.B 810 (2020) [Ipp, Müller, Schuh]]

Time evolution of jet quenching parameter

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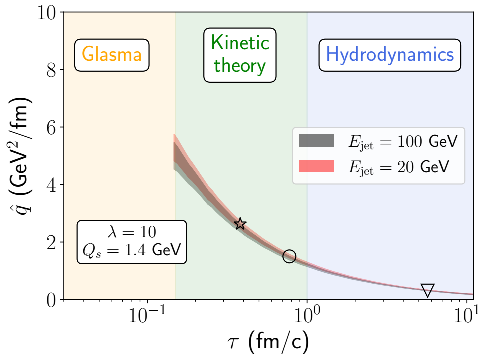

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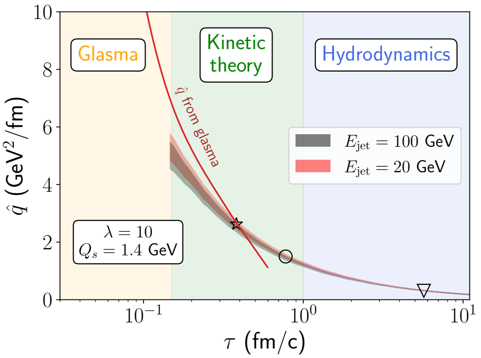
- Connects **large values** from **Glasma**[5] and lower values in hydrodynamic stage



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5 [Phys.Lett.B 810 (2020) [Ipp, Müller, Schuh]]

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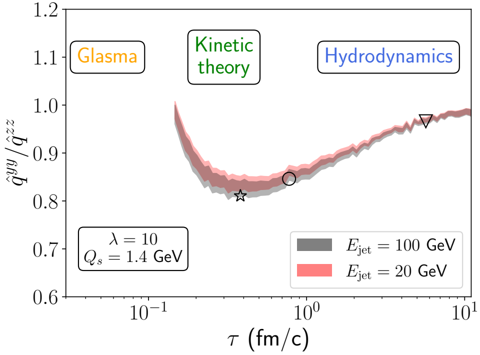


[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

[5] [Phys.Lett.B 810 (2020) [Ipp, Müller, Schuh]]

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
  - **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]

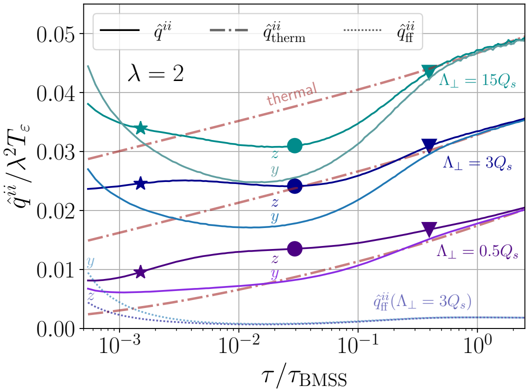
Bose-enhanced terms

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

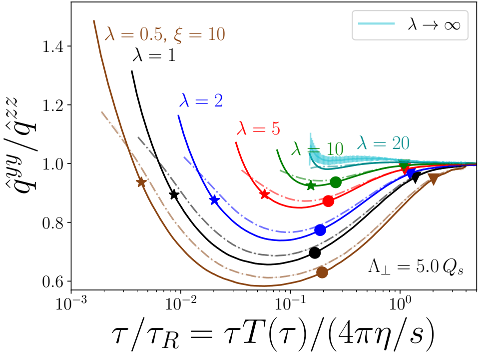
$$f(\mathbf{k}) \sim \delta(k_z)$$

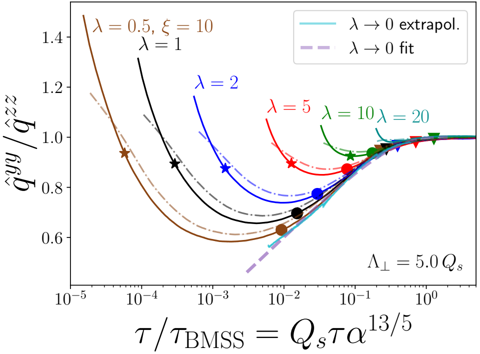
Leads to $\hat{q}^{zz}_{\text{ff}} = 0$

- Reason for different ordering: Bose-enhanced part $\hat{q}_{\text{ff}}$ = term quadratic in $f(\mathbf{k})$



$\hat{q}$ and the limiting attractors



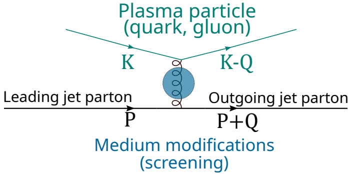


- Approach to weak coupling attractor even at moderate couplings
- Fit for bottom-up attractor:
  $\frac{\hat{q}^{yy}}{\hat{q}^{zz}}(\tau) \approx 1 + c_1 \ln\left(1 - e^{-c_2 \tau/tau_{\mathrm{BMSS}}}\right)$ with $c_1 = 0.12$, $c_2 = 3.45$.

Screening 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]

Matrix element



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[6] [Phys.Rev.D 68 (2003) [Romatschke, Strickland]]

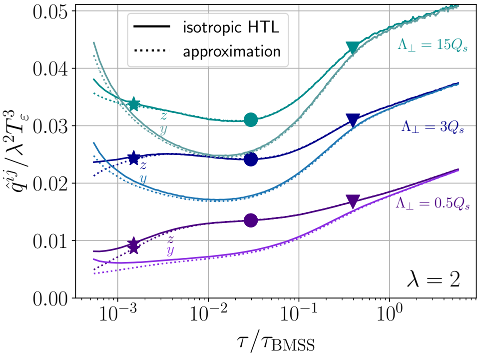
[7] [Phys.Rev.Lett. 115 (2015) [Kurkela, Zhu]; Phys.Rev.Lett. 122 (2019) [Kurkela, Mazeliauskas]; Phys.Rev.D 104 (2021) [Du, Schlichting]]

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**

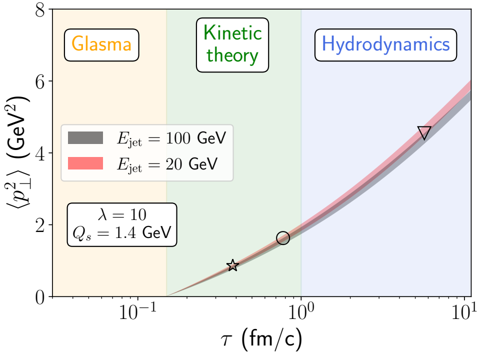


s, u, t: Mandelstam variables

[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.



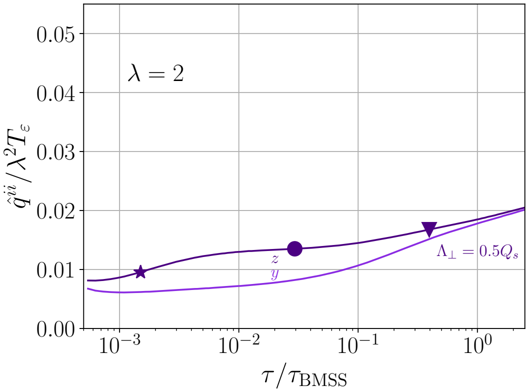
Where does $\hat{q}$ enter?

- **BDMPS-Z calculations** (in-medium splittings, energy-loss) e.g. in harmonic approximation
  - Recently generalized to include flowing/inhomogeneous systems[9]
  - anisotropic systems with $\hat{q}^{yy} \neq \hat{q}^{zz}$: Jet polarisation[10] $\rightarrow$ daughter gluons of gluon-splitting can carry net polarisation (see Siggi's talk (Wed 9:30))
- In **JETSCAPE**[11]: MATTER and LBT energy loss models can be parametrized in terms of $\hat{q}$
- $\hat{q}$ encodes **interaction strength** (moment of scattering potential)

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

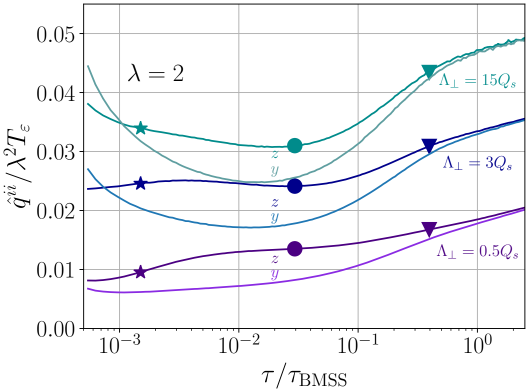
Cutoff dependence and comparison with equilibrium

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



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**



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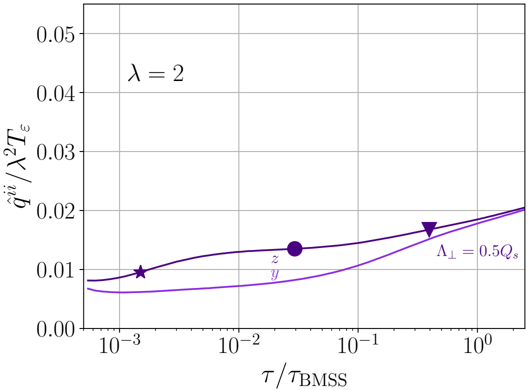

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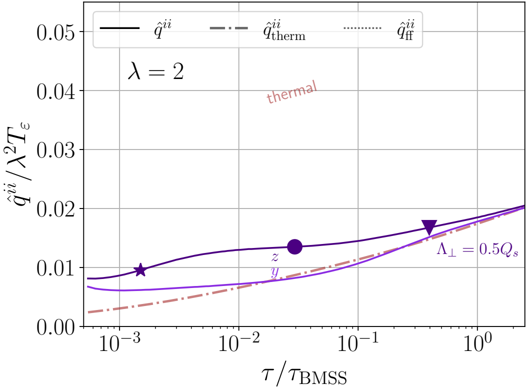
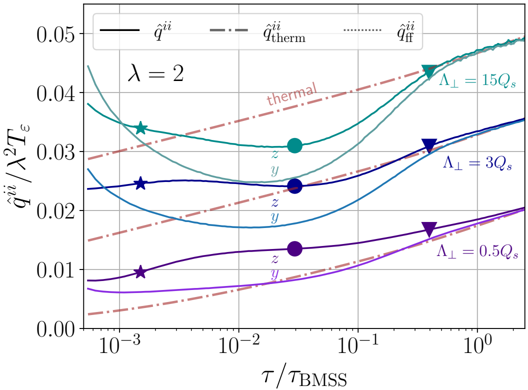
- Compare with **energy-density matched thermal equilibrium**



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

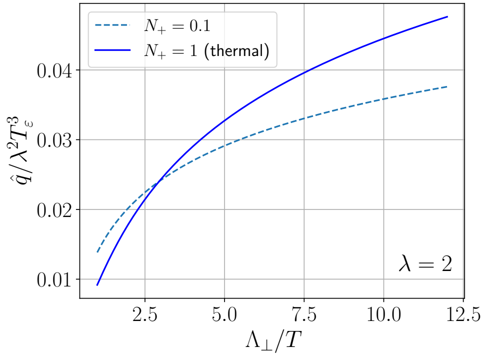
Scaled thermal distribution

- Scaled thermal distribution

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

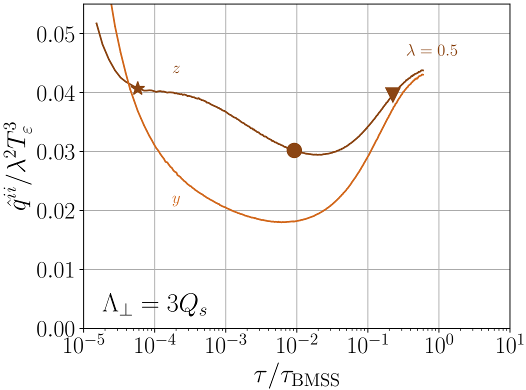
Explains ordering $\hat{q}_{\text{therm}} \lessgtr \hat{q}$ for underoccupancy

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



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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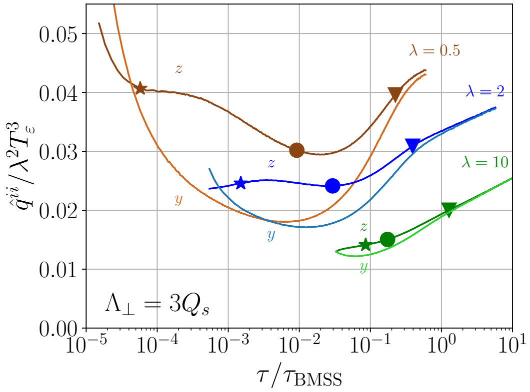

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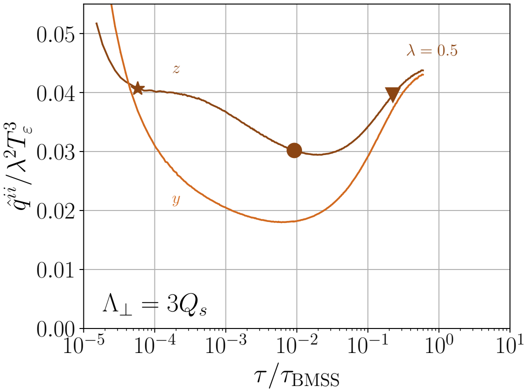

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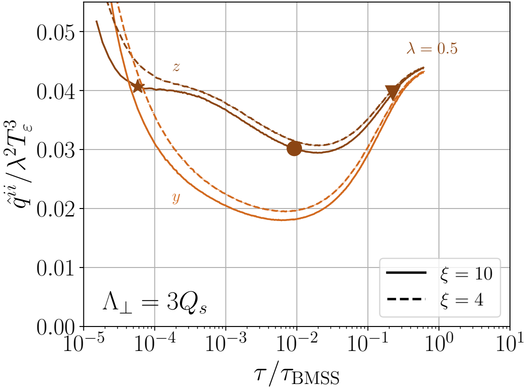

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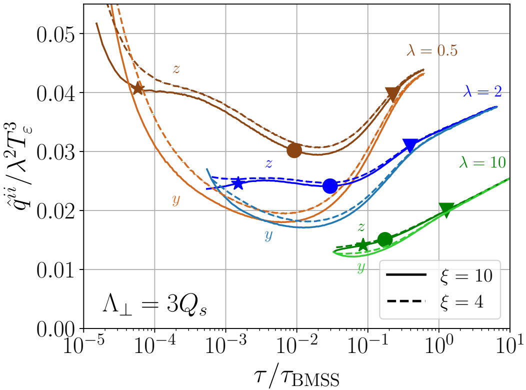
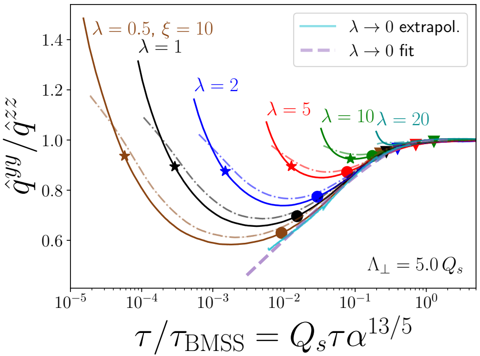


Ratio of $\hat{q}^{yy}/\hat{q}^{zz}$

- Ratio $\hat{q}^{yy}/\hat{q}^{zz}$ follows attractor in thermalization time τ_{BMSS}
  $\rightarrow$ "bottom-up limiting attractor"[12]



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