Jet quenching parameter $\hat{q}$ during initial stages

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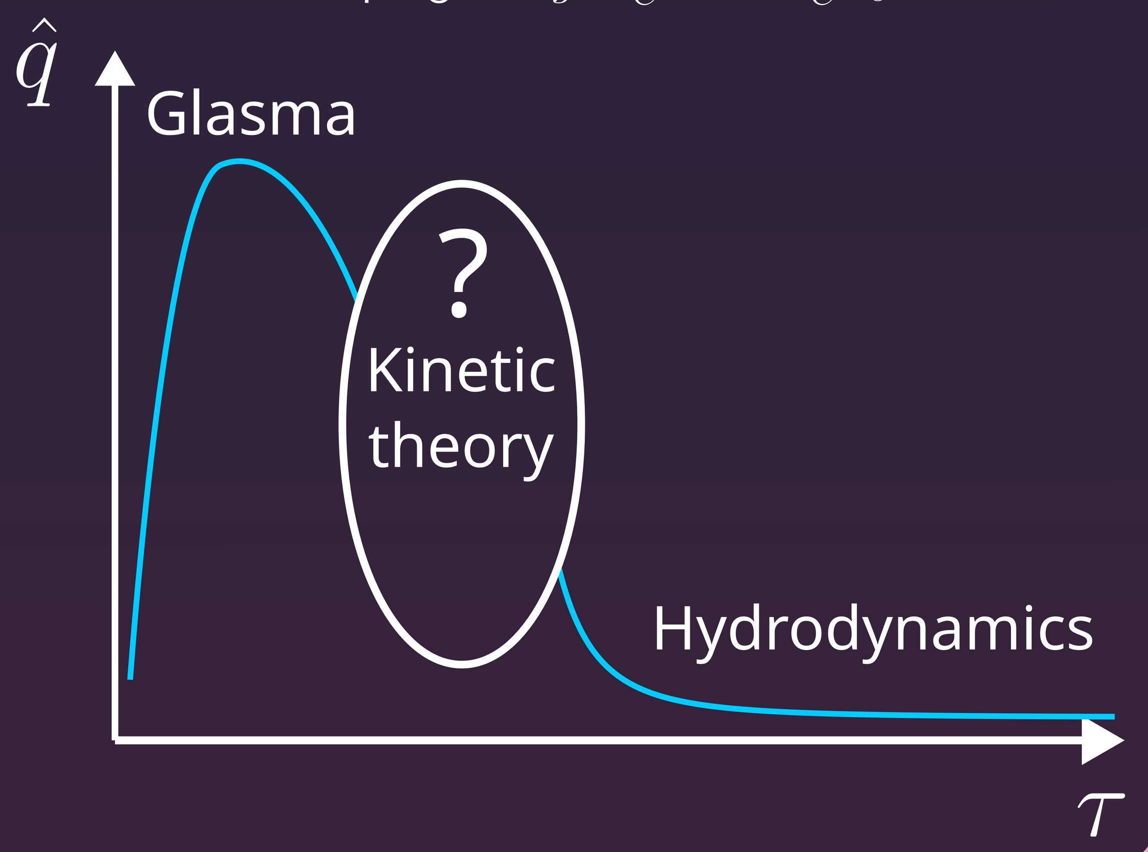
based on arXiv:2303.12595 [hep-ph]

Motivation

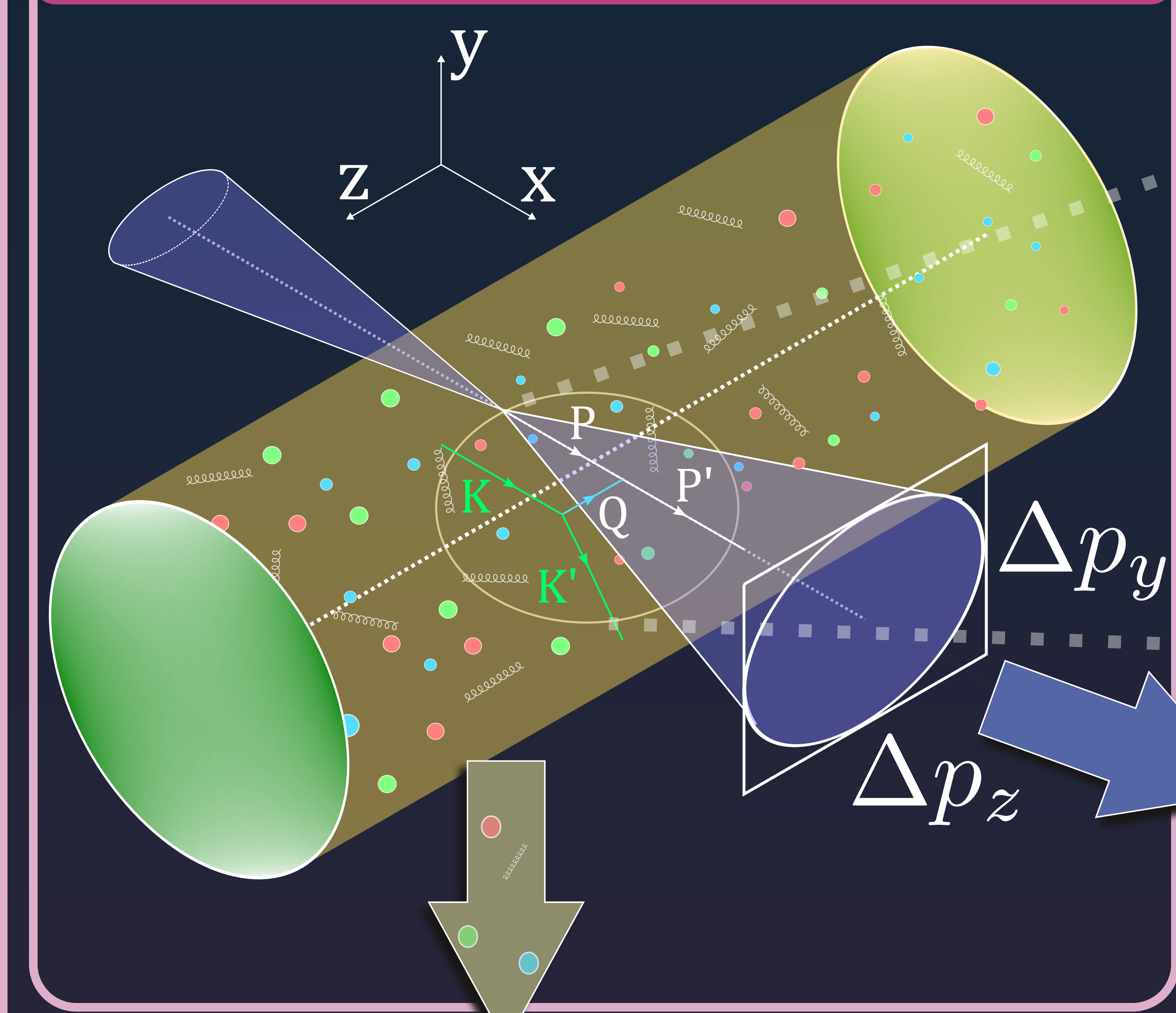
- Study properties of the strong interaction = Quantum Chromodynamics (QCD)
- **Quark-Gluon Plasma** (QGP) generated in **heavy-ion collisions** at LHC or RHIC
- Several stages in time evolution of QGP (see figure below)
- Study early stages using jets. They originate from initial hard scattering and probe all stages of the plasma evolution
- Jet-medium interaction characterized by the **jet quenching parameter**

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2\rangle}{\mathrm{d}L} = \int \mathrm{d}^2 q_\perp\, q_\perp^2 \frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}. \tag{1}$$

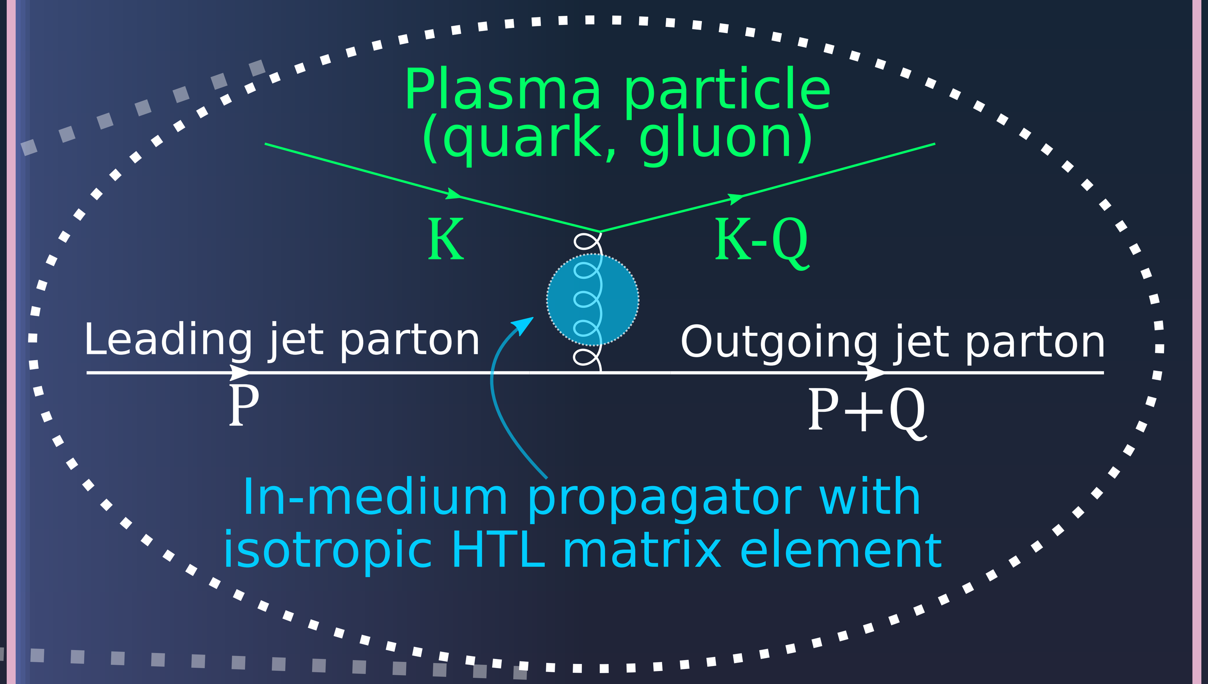
- Quantifies **momentum broadening**
- Mostly discussed in thermal (or hydrodynamic) medium → look at $\hat{q}$ at early stages within kinetic theory
- Glasma simulations and calculations point to large value of $\hat{q}$ during the Glasma stage [2,3]
- No calculation/simulation between Glasma and hydrodynamic stage exists
- Here: **Medium described by kinetic theory, $\hat{q}$ from elastic scattering rate** (as calculated from Eq. (1,2))
- Use 't Hooft coupling $\lambda = g^2 N_C = 4\pi N_C \alpha_s$



Jet quenching



Scattering process and formula



Anisotropic definition

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

leads to usual $\hat{q} = \hat{q}^{yy} + \hat{q}^{zz}$

$f(\vec{k})$

Medium: Kinetic theory

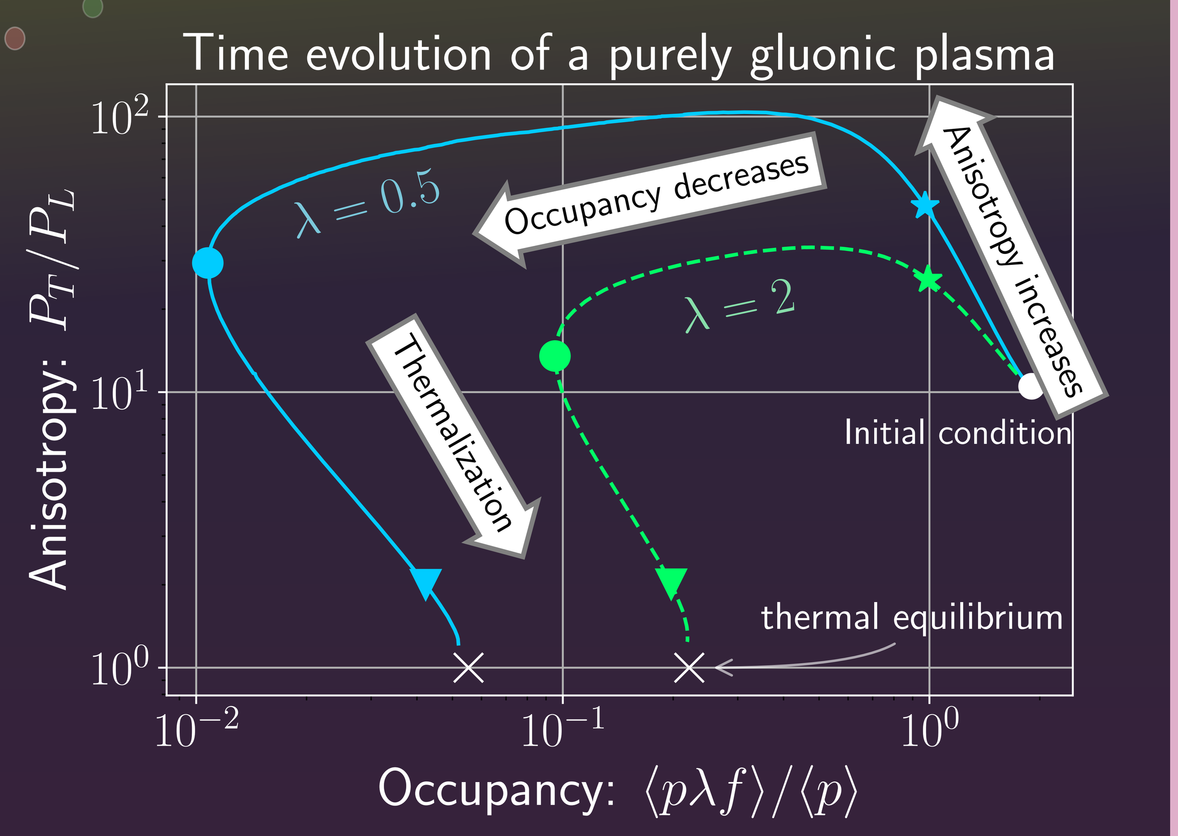
- **Quasi-particles** with **distribution function** $f(t,\vec{p})$
- Time evolution described by **Boltzmann equation** [4]

$$(\partial_t + \vec{v}\cdot\vec{\nabla})f = \underbrace{\left|\;\;\right|^2 + \left|\;\;\right|^2}_{\text{Collision term}}$$

- Assume: Expanding system, mid-rapidity, homogeneous in $x-y$ with cylindrical symmetry (around beam axis $\hat{z}$)
- We solve the Boltzmann equation numerically for a purely gluonic system (dominant degrees of freedom for thermalization)
- Initial condition [5]

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

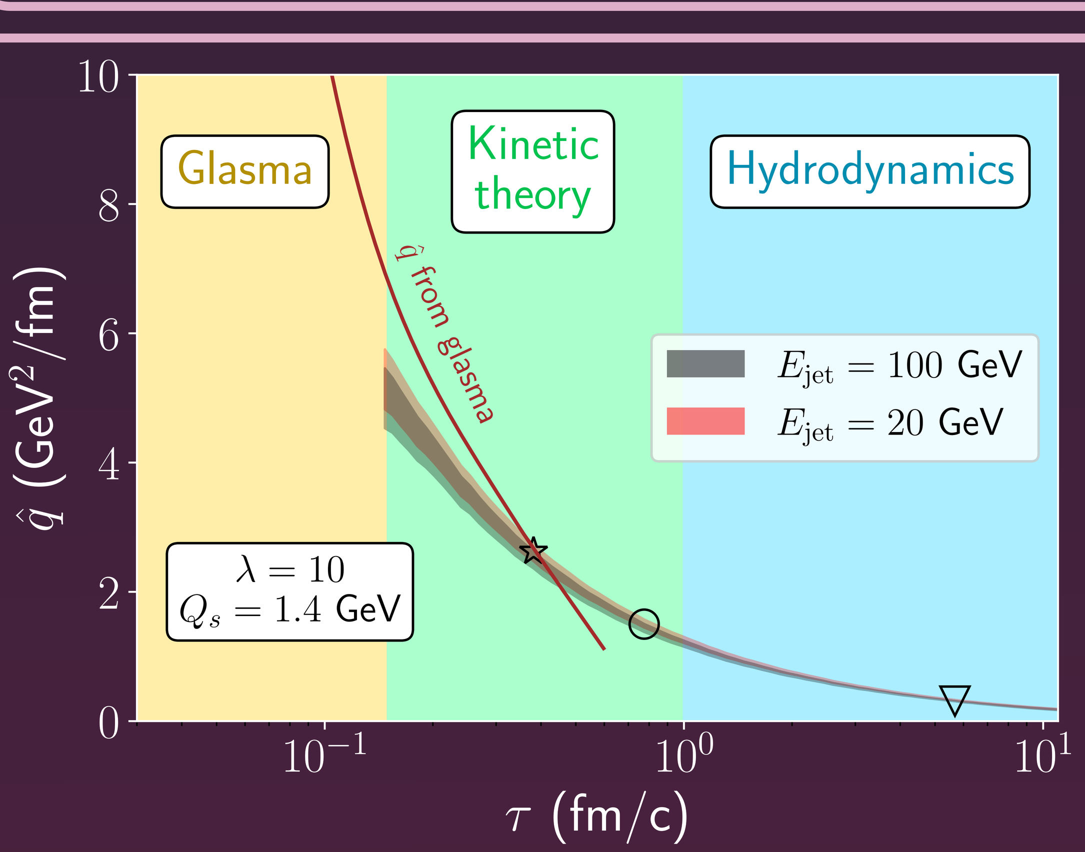
$\xi \sim$ anisotropy, $\langle p_T\rangle = 1.8\,Q_s$, $Q_s \sim$ saturation scale



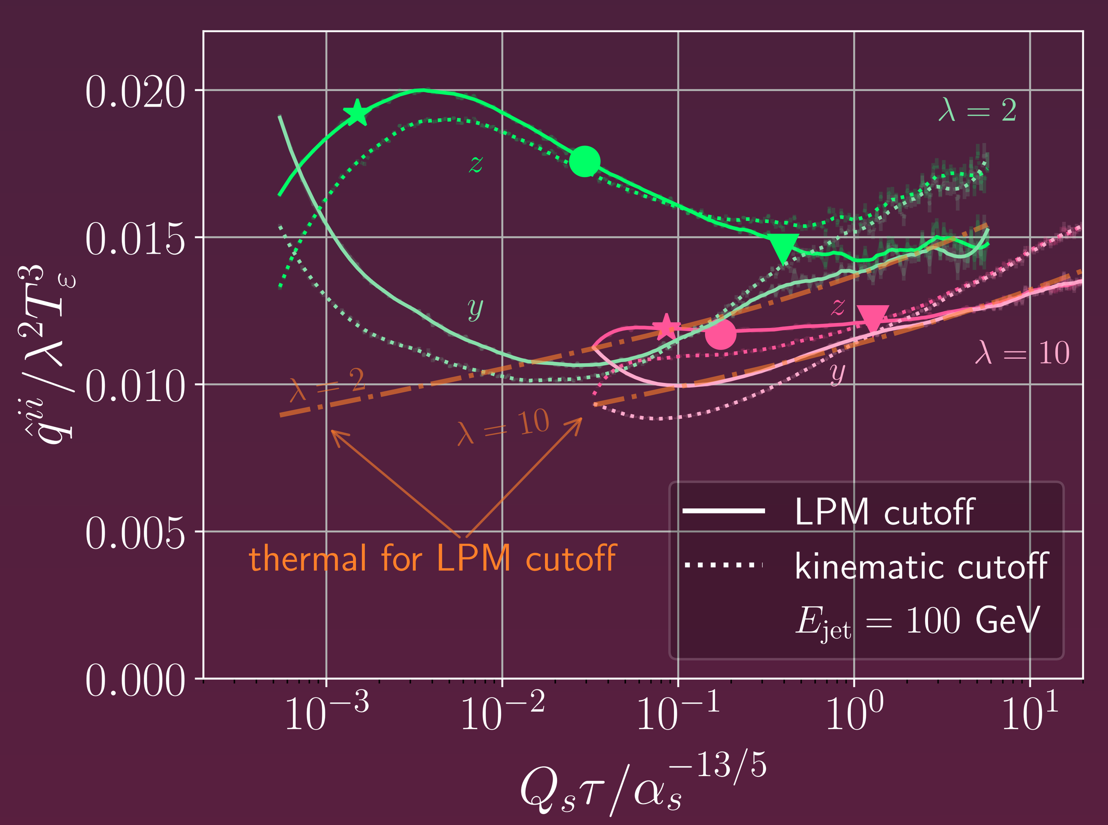
- **Markers** ★ ● ▼ represent **different stages** of bottom-up (arrows in figure)
- Characteristic thermalization time scale $\tau_{\mathrm{BMSS}} = \alpha_s^{-13/5}/Q_s$

Comparison with Glasma

- **Weak dependence on** initial **anisotropy** ξ and **cutoff models**
- **Bands:** Different initial conditions (anisotropy ξ) and cutoff models (see below)
- Little jet energy dependence
- **Connects large values from Glasma** (curve from Ref. [2]) and lower **values in hydrodynamic stage**
- We extract $\hat{q}$ as **medium parameter** relevant for a jet with a specific energy



Cutoff models



- Temperature via **Landau matching**, $\varepsilon^{\mathrm{eq}}(T_\varepsilon) = \varepsilon^{\mathrm{simulation}}$

$$T_\varepsilon(\tau) = \left(\frac{30\,\varepsilon(\tau)}{\pi^2 \times \#\text{d.o.f.}}\right)^{1/4}$$

Temperature of equilibrium system with same energy density

- Parameter $\hat{q}$ depends on cutoff $q_\perp < \Lambda_\perp$, use **different cutoff models**:
  - LPM cutoff $\Lambda_\perp^{\mathrm{LPM}}(E,T) = \zeta^{\mathrm{LPM}} g \times (ET^3)^{1/4}$
  - kinematic cutoff $\Lambda_\perp^{\mathrm{kin}}(E,T) = \zeta^{\mathrm{kin}} g \times (ET)^{1/2}$

Typical momentum transfer $Q_\perp^2 \sim \hat{q}t^{\mathrm{form}}$, formation time $t^{\mathrm{form}} \sim \sqrt{\omega/\hat{q}}$, estimate $\hat{q} \sim g^4 T^3$ (assume dominated by $\omega \sim E_{\mathrm{jet}}$)

- Fix ζ^i at triangle marker to match with JETSCAPE [6] (LBT parametrization) for $\lambda = 10$ and $Q_s = 1.4$ GeV
- Numerically: Interpolate in large cutoff region $\hat{q}^{yy}(\Lambda_\perp \gg T_\varepsilon) \simeq a_y \ln \Lambda_\perp/Q_s + b_y$ (similar with z)

Conclusions

- We obtain **consistent evolution** of $\hat{q}$ **between Glasma** and **hydrodynamic phases**
- Little dependence on jet energy and initial conditions
- **Momentum broadening along beam axis enhanced** → mostly $\hat{q}^{zz} > \hat{q}^{yy}$ → anisotropic broadening
- Anisotropic $\hat{q}^{yy} \neq \hat{q}^{zz}$ → Jet polarisation [7]
- Similar results for heavy-quark diffusion coefficient κ (see talk by J. Peuron [8])

Outlook

- Different jet momenta, angles and screening prescriptions
- Parameter $\hat{q}$ enters energy loss calculations in BDMPS-Z formalism with harmonic approximation → include our value of $\hat{q}$ in jet quenching models
- Study **impact of pre-equilibrium medium** via $\hat{q}$

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[1] arXiv:2303.12595 [Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron]
[2] Phys.Lett.B 810 (2020) [Ipp, Müller, Schuh]
[3] Phys.Rev.C 105 (2022) [Carrington et al.], Phys.Rev. D 107 (2023) [Avramescu et al.]
[4] JHEP 01 (2003) [Arnold, Moore, Yaffe], Int.J.Mod.Phys.E 16 (2007) [Arnold]
[5] Phys.Rev.Lett. 115 (2015) [Kurkela, Zhu]
[6] Phys.Rev.C 104 (2021) [JETSCAPE]
[7] arXiv:2303.03914 [Hauksson, Iancu]
[8] arXiv:2303.12520 [Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron]

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