Jet-medium interaction and Gubser flow

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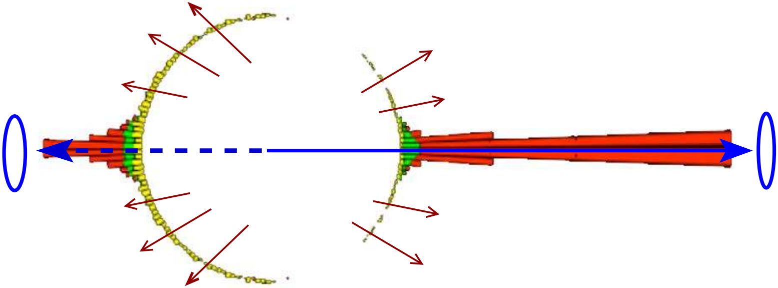
arXiv:1707.09519, with Charles Gale and Sangyong Jeon



Motivation

- Experiments: jet substructures ⇔ soft yields at large cone radii.
  CMS(11,16),...
- Theory: jet-medium interaction ⇔ fluid dynamics description.
  Tachibana and Hirano(17), Chesler and Yaffe(08), Chen et al(17), Qin et al(09)
  Betz et. al (09), Chaudhuri and Heinz(06), Casalderrey-Solana et al(05), ...

Challenge

- Understand jet-medium interaction in an expanding and viscous QGP.

Dynamical properties of the QGP medium: $\hat{q}$, $\hat{e}$, η/s, etc.

Outline

- Our (semi-analytical) approach of jet-medium interaction in hydro:

  Gubser flow + mode-by-mode solution of linearized hydro

- Properties of jet parton going through QGP – Mach cone structure.
- Associated particle spectrum from jet-medium interaction

  * *Dynamical* viscous suppression.

  * *Hydrodynamical* viscous suppression.

- Summary and outlook.

Describe jet-medium interaction in fluid dynamics

Energy-momentum conservation : a jet parton + background fluid

$$\partial_\mu T^{\mu\nu} = \partial_\mu \left(\underbrace{T^{\mu\nu}_{\rm hydro}}_{\text{background fluid}} + \underbrace{T^{\mu\nu}_{\rm jet}}_{\text{jet parton}} + \underbrace{\delta T^{\mu\nu}}_{\text{jet-medium}} \right) = 0$$

- Determine $\delta T^{\mu\nu}$ mode-by-mode for a viscous medium

$$\delta\tilde{T}^{\mu\nu}(k) \longrightarrow \delta\tilde{T}^{\mu\nu}_{\rm hydro}(k) \; : \qquad k\lambda_{\rm mfp} \ll 1$$

* Long wave-length modes captured in viscous hydrodynamics.

* Applicability of viscous hydrodynamics.

* Separation between hard and soft (thermalized) scales.

Iancu and Wu(15)

Describe jet-medium interaction in fluid dynamics

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- Jet-medium interaction as perturbations on top of background medium

$$\begin{cases} \partial_\mu T^{\mu\nu}_{\texttt{hydro}} = 0 \\ \partial_\mu \delta T^{\mu\nu} = -\partial_\mu T^{\mu\nu}_{\texttt{jet}} = J^\nu : \quad \text{EoM of jet-medium interaction} \end{cases}$$

J^ν determind via the evolution of the jet parton distribution

Tachibana, Chang and Qin(17)

$$\rightarrow J^\nu = -\partial_\mu T^{\mu\nu}_{\texttt{jet}} = \hat{e} v^\nu_{\texttt{jet}} n_{\texttt{jet}}(\mathbf{x}, t), \quad \hat{e} = -\langle \Delta E \rangle / \langle \Delta x \rangle$$

*Contribution from broadening can be negligible for $E_{\text{jet}} \gg T$.

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- Jet energy loss: $\hat{e} = \kappa T^2$. Betz et al.(11), Casalderry-Solana et al.(14), Fincar et al.(14)
- From $\hat{e} = \hat{q}/4T$ and $T^3/\hat{q} \sim 1.25\, \eta/s$ Majumder, Muller and Wang(07)

$$\begin{cases} \text{weakly coupled :} & \kappa \approx 3/(\eta/s) \\ \text{strongly coupled :} & \kappa \gg 3/(\eta/s) \end{cases}$$

* *Dynamical* viscous suppression $\Leftrightarrow$ reduced $\hat{e}$ in more viscous medium.

We shall consider mostly the $\kappa \approx 3/(\eta/s)$ scenario.

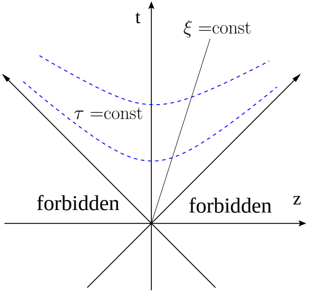
$\partial_\mu T^{\mu\nu}_{\text{hydro}} = 0$: Gubser's analytical solution

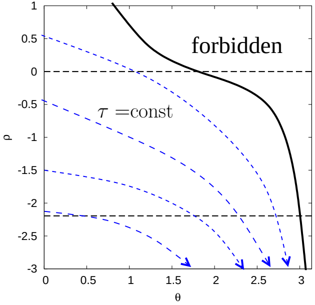
- Conformal medium + rotational symmetry and Bjorkn boost invariance

  Gubser (10), Gubser and Yarom(10)

  Radial and longitudinal expansion of a viscous medium ≈ QGP expansion

- A new coordinate system: $(\tau, r, \phi, \xi) \leftrightarrow (\rho, \theta, \phi, \xi)$





$$ds^2 = d\rho^2 + d\xi^2 + \cosh^2\rho(\underbrace{d\theta^2 + \sin^2\theta d\phi^2}_{SO(3)\ \text{symmetry}})$$

$\partial_\mu \delta T^{\mu\nu} = J^\nu$: mode-by-mode solution in expanding system

- $SO(3)$ symmetry in $(\theta, \phi) \Rightarrow$ mode expansion in spherical harmonics.
  Gubser and Yarom(11), Staig and Shuryak(11), LY and Grönqvist(16)
- Reduce to EoM of hydro perturbations: δT, δu^μ

$$\text{e.g.} \quad \delta\tilde{T} = \tilde{T} \sum_{lm} \int \frac{dk_\xi}{2\pi} t^{lm}(\rho) Y_{lm}(\theta,\phi) e^{ik_\xi \xi}$$

$$\text{so that} \quad (\delta\tilde{T}, \delta\tilde{u}^\mu) \longrightarrow \tilde{\mathcal{V}}^{lm}(\rho, k_\xi) = (\underbrace{t^{lm}, v_s^{lm}, v_\xi^{lm}}_{\text{scalar}}, \underbrace{v_v^{lm}}_{\text{vector}})$$

and expand source J^ν into modes $\rightarrow \tilde{\mathcal{S}}^{lm}(\rho, k_\xi)$

$$\tilde{\mathcal{S}}^{lm}(\rho, k_\xi) = \begin{pmatrix} -\frac{1}{3\,w} c^\rho_{lm}(\rho, k_\xi) \\ -\frac{2\,T\tanh\rho}{3\,w\,T'} c^s_{lm}(\rho, k_\xi) \\ \frac{T}{w(\,T + H_0\tanh\rho)} c^{lm}_\xi(\rho, k_\xi) \\ -\frac{2\,T\tanh\rho}{3\,w\,T'} c^{lm}_v(\rho, k_\xi) \end{pmatrix}$$

We shall ignore k_ξ-dependence and v_ξ, so the whole system is boost invariant!

Dynamical properties of mode evolution (not very sensitive to source)

- Equation of motion of $(t^{lm}, v_s^{lm}, v_v^{lm})$

$$\partial_\rho \tilde{\mathcal{V}}^{lm}(\rho) = \underbrace{-\Gamma(\rho, l)}_{\text{medium response}} \tilde{\mathcal{V}}^{lm}(\rho) + \underbrace{\tilde{\mathcal{S}}^{lm}(\rho)}_{\text{source from jet parton}},$$

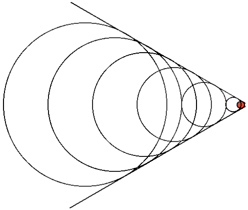
* Viscosity damps mode evolution: $\sim \exp(-\Delta\rho l^2 \eta/s)$

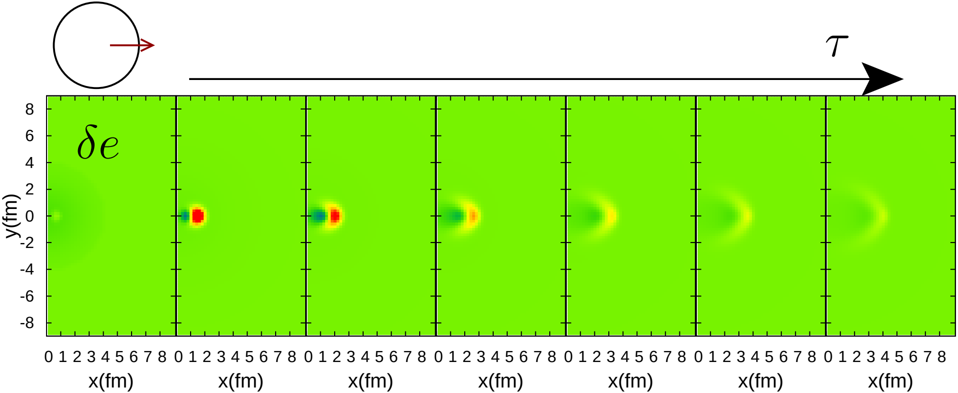
$\Rightarrow$ *Hydrodynamical* viscous suppression

* Eigen-modes of medium response:

$$v_v^{lm}: \quad \text{diffusive}$$
$$(t^{lm}, v_s^{lm}): \quad \text{sound propagation}$$

Sound propagation $\Rightarrow$ **Mach cone**

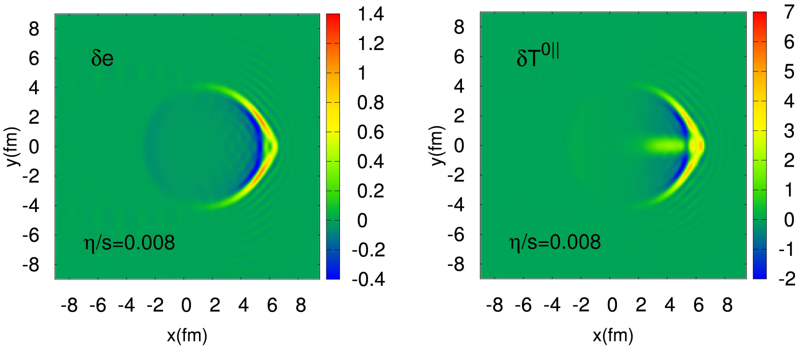




$$\eta/s = 1/4\pi$$

Mach cone structure and jet-medium interaction

"ideal" fluid ($\tau = 6.0$ fm/c):



- Common features of mach cone structure: shock, depletion, etc.
  - * Distorted by medium expansion: $\theta^M > 2\sin^{-1}(c_s/c)$
- δe has *only* scalar modes, $\delta T^{0\|}$ has of scalar and vector modes.
  - * A diffusive wake in $\delta T^{0\|}$ along the path of jet parton. Chesler and Yaffe(08)

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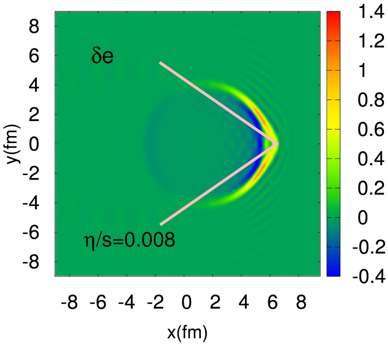

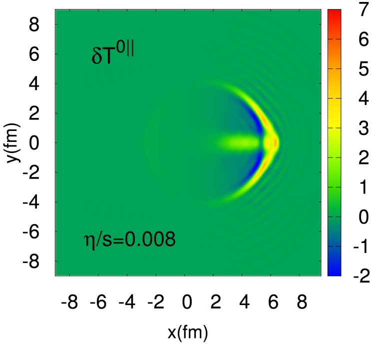

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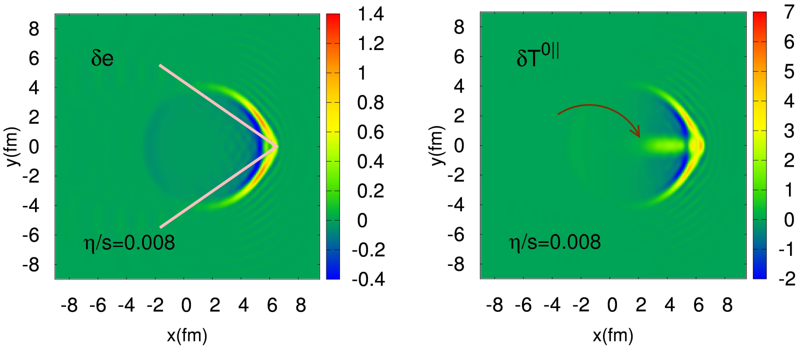

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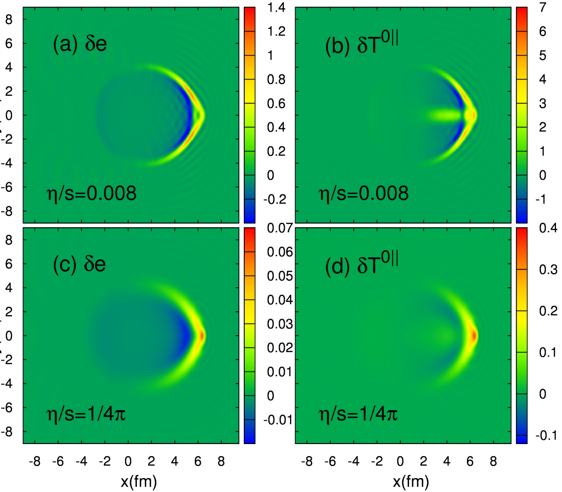
Viscous effects on the cone structure



* *Dynamical* viscous suppression: an overall suppression of the cone structure proportional to $1/(\eta/s)$ *i.e.*, a factor 1/10.

* *Hydro* viscous suppression: suppresses and smears the cone structure, *e.g.*, the diffusive wave gets damped and broadened.

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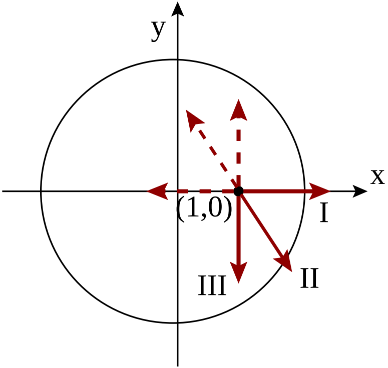
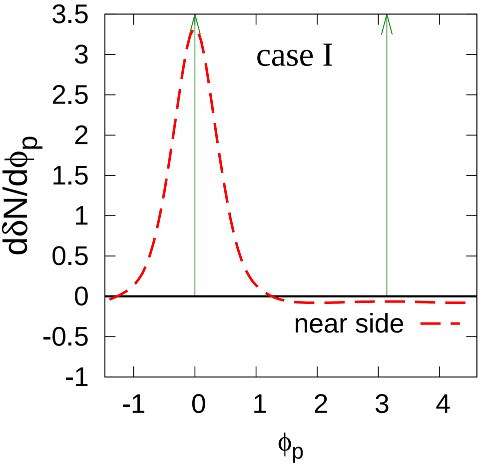
Particle spectrum and di-jet in heavy-ion collisions



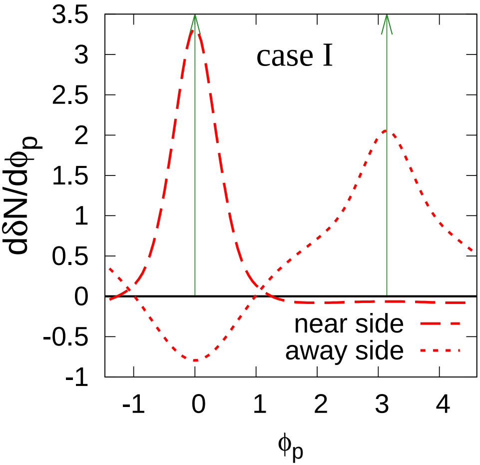
- Ultra-central Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV, di-jet (photon-jet).
- 'Knife-shaped' dijet partons (boost invariant) with sufficiently high energy.

$$J^\mu(t, \mathbf{x}) = \hat{e} v^\mu_{\text{jet}} n_{\text{jet}}(t, \mathbf{x}) = \hat{e} v^\mu_{\text{jet}} \delta^{(2)}(\mathbf{x}_\perp - \mathbf{v}_{\text{jet}} \Delta\tau)/\tau$$

- Cooper-Frye freeze-out at constant $\tau = 6.0$ fm/c.



$$\frac{\eta}{s} = \frac{1}{4\pi}$$



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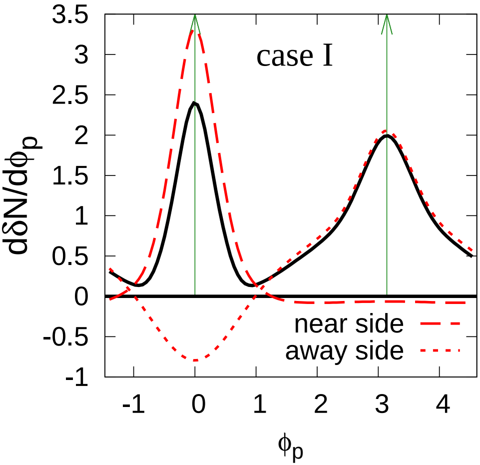

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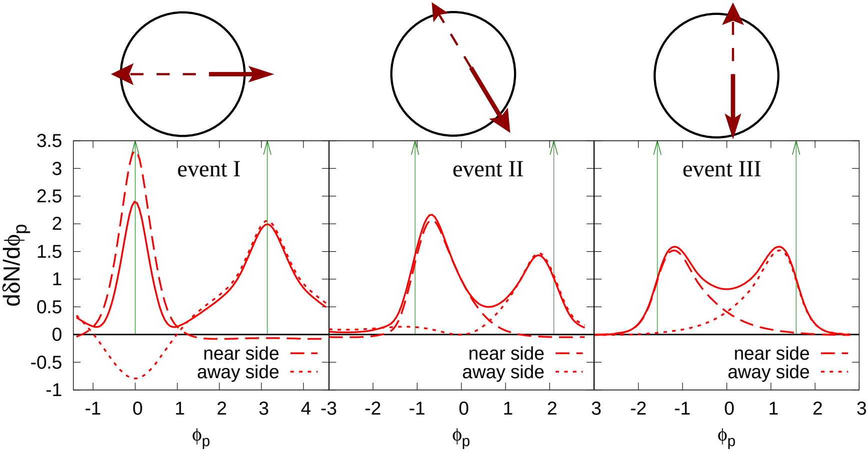

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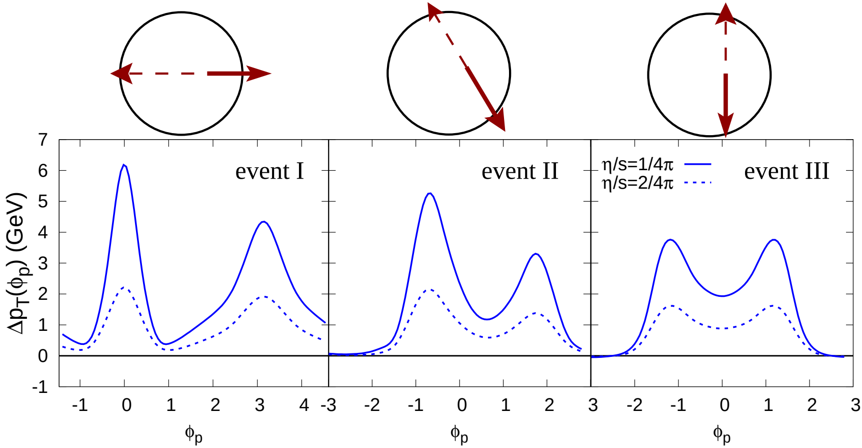
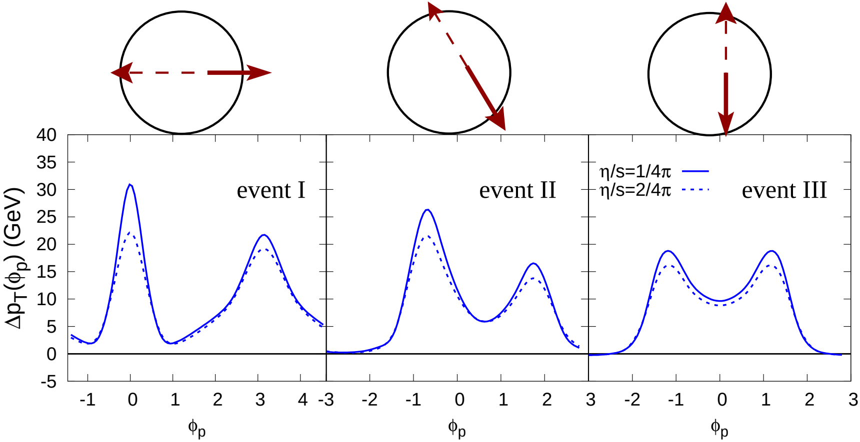


$$\frac{\eta}{s} = \frac{1}{4\pi} \text{ and } \frac{2}{4\pi}$$

* *Dynamical* viscous suppression (overall reduction) $\Rightarrow$ dominant!
* *Hydrodynamical* viscous suppression $\Rightarrow$ not very important
* Viscous correction in δf $\Rightarrow$ negligible.



fixed $\kappa = \frac{20\pi}{3} \gg 3/(\eta/s)$, for a strongly coupled system

* $\hat{e}$ is independent of η/s, no *dynamical* viscous suppression.
* Totally induced by *hydro* viscous suppression.

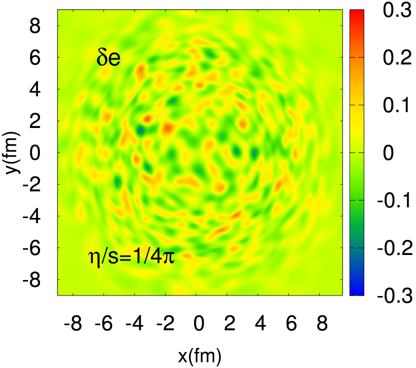
Summary:

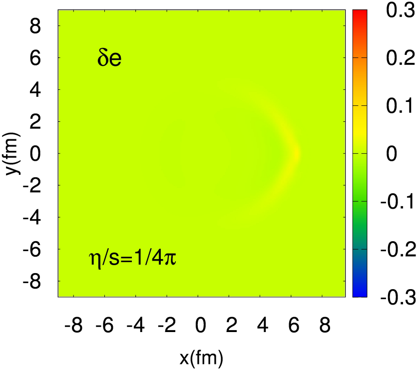
- A formalism to study jet-medium interaction mode-by-mode.
- Expansion and dissipation change Mach cone, and particle spectrum.
  - * *Dynamical* viscous suppression: $\hat{e} \propto 1/(\eta/s)$
  - * *Hydrodynamical* viscous suppression: $\sim \exp(-k^2 \Delta t \eta/sT)$
  - * How parton loses energy to the medium is important.

Outlook:

- To compare and check viscous hydrodynamic simulations.
- Interplay with thermal noise:

$$\partial_\mu \delta T^{\mu\nu} = J^\nu - \partial_\mu S^{\mu\nu}\,, \qquad \langle S^{\mu\nu} S^{\alpha\beta} \rangle \sim 2\eta T$$

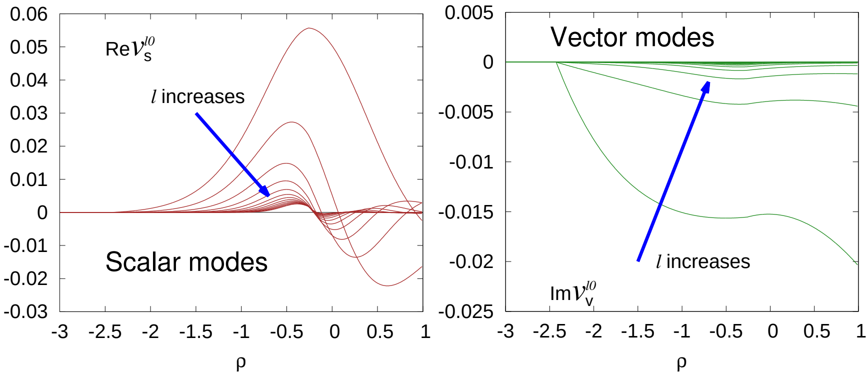




$\tau = 6$ fm/c $\quad \eta/s = 1/4\pi$

Back-up

$$\eta/s = 1/4\pi$$



- Scalar modes exhibit sound wave propagation, especially at late time.
- Vector modes are diffusive.

Mode summation converges up to $l < 35$.