What Can Gubser Flow Tell Us?— Analytic Solutions, Attractors in Spin Hydrodynamics, Nonlinear Response, and Polarization

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极端条件下的QCD，烟台大学

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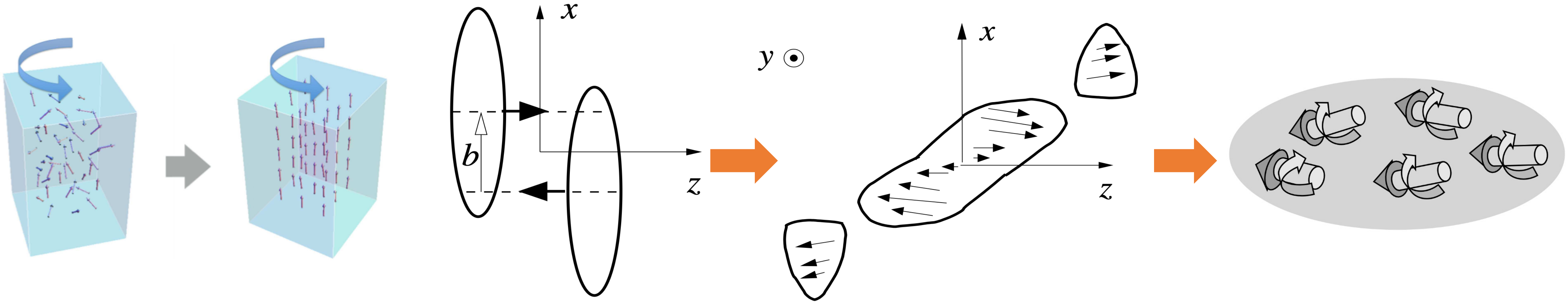
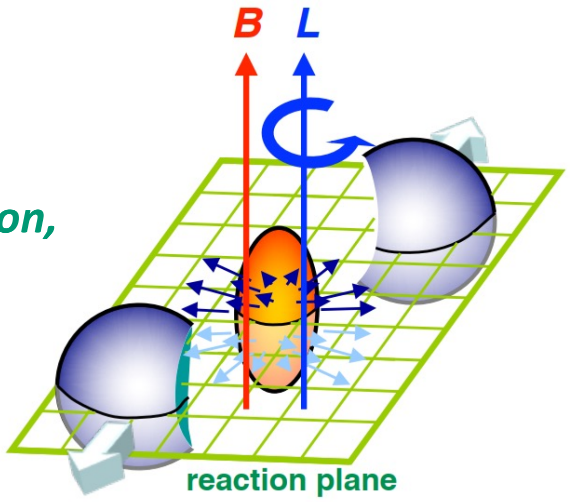
Spin polarization in heavy-ion collisions





Barnett effect:

Rotation $\Longrightarrow$ Magnetization

Barnett, Magnetization by rotation, Phys. Rev. 6, 239 (1915).

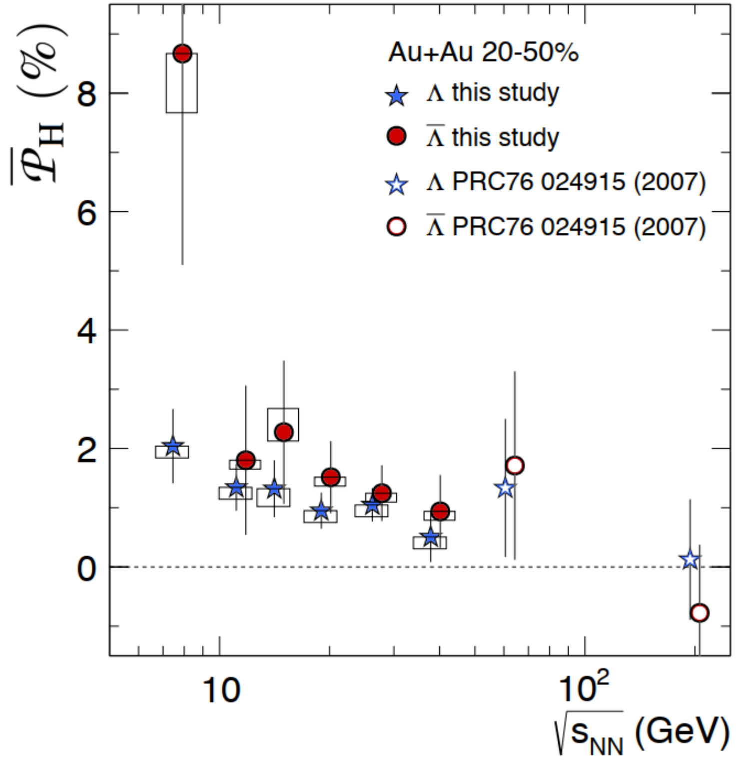
- **Huge global orbital angular momentum ($L\sim10^5\hbar$) is generated in HIC.**

- **Global orbital angular momentum can induce the polarization of Λ hyperons and spin alignment of vector mesons through spin-orbit coupling.**

Liang, Wang, PRL (2005); PLB (2005);
Gao, Chen, Deng, Liang, Wang, Wang, PRC (2008)

Global polarization for Λ and $\overline{\Lambda}$ hyperons

STAR, Nature 548, 62 (2017)



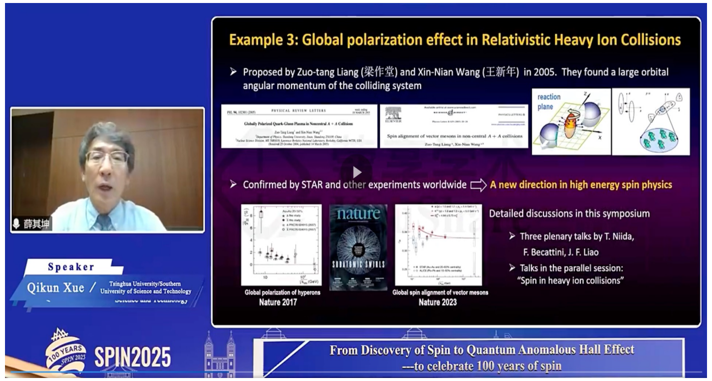
- Estimate by Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)

$$P_\Lambda \simeq \frac{\omega}{2T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\overline{\Lambda}} \simeq \frac{\omega}{2T} - \frac{\mu_\Lambda B}{T}$$

- $\omega = (9 \pm 1) \times 10^{21}$/s, larger than that previously observed in any other system.

- QGP is the most vortical fluid observed to date.



One of the most important discoveries in spin physics in China.

相对论重离子碰撞中的整体极化现象是中国高能自旋物理中最重要的发现之一。

parity-violating decay of hyperons

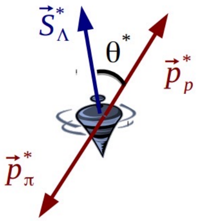
In case of Λ's decay, daughter proton preferentially decays in the direction of Λ's spin (opposite for anti-Λ)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha \mathbf{P_\Lambda} \cdot \mathbf{p_p^*})$$

α: Λ decay parameter (=0.642±0.013)

P_Λ: Λ polarization

p_p^*: proton momentum in Λ rest frame



$\Lambda \rightarrow p + \pi^+$

(BR: 63.9%, c τ ~7.9 cm)

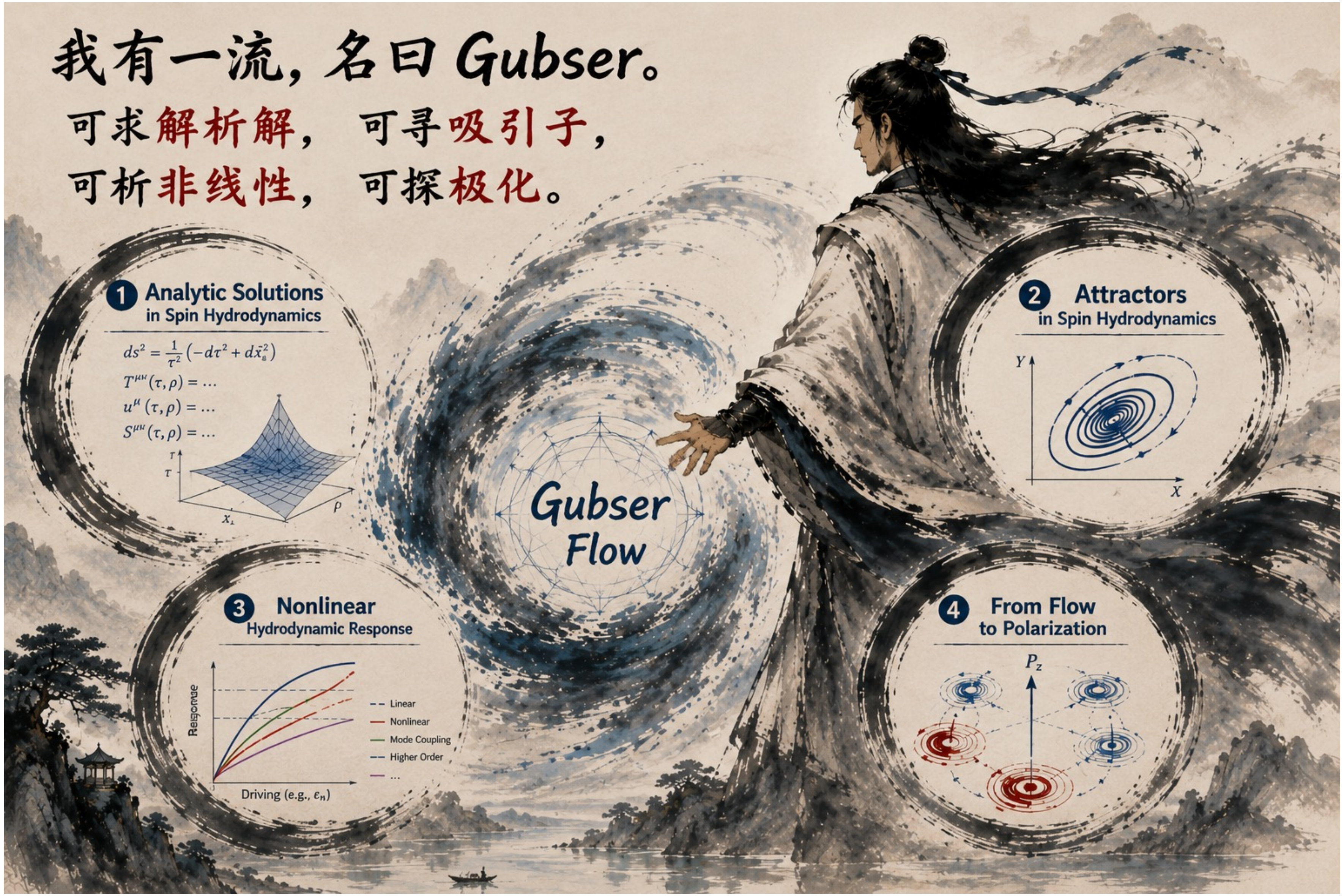
Liang, Wang, PRL (2005)
Betz, Gyulassy, Torrieri, PRC (2007)
Becattini, Piccinini, Rizzo, PRC (2008)
Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)
Fang, Pang, Q. Wang, X. Wang, PRC (2016)
...

To understand the macroscopic evolution and spin polarization of the system, we need a powerful analytic tool.

Outline

Spin hydrodynamics →

Azimuthal Perturbations →



Introduction to Gubser flow

Conservation equations in hydrodynamics

- **Energy-momentum conservation equation**

$$\partial_\mu T^{\mu\nu} = 0$$

- **Constitution equation**

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \pi^{\mu\nu}$$
$$\pi^{\mu\nu} = -\Pi g^{\mu\nu} + 2\eta_s \sigma^{\mu\nu}$$

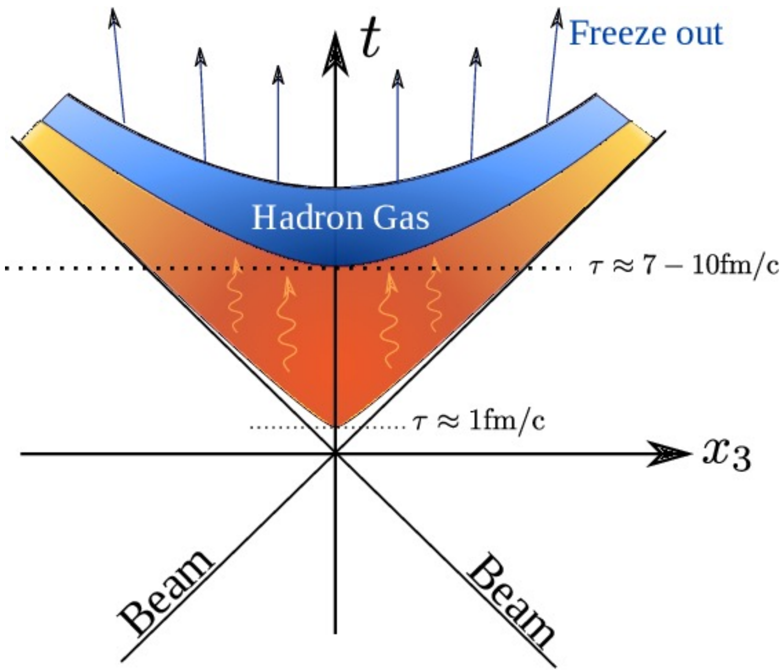
- **Equation of state**

$$P = P(\epsilon)$$

Pressure as a function of energy density

Introduction to Bjorken flow

- **Bjorken flow:** a well-known 0+1D analytic solution of relativistic hydrodynamics with longitudinal boost invariance.



Physical picture:

- Fluid elements at different rapidities evolve with the same proper time.
- The system is **longitudinally boost invariant**; all thermodynamic variables depend only on proper time.

Formalism:

In Milne coordinates (τ,x,y,η), the Bjorken flow is **comoving**.

$$\boxed{u^\mu = (1,0,0,0)}$$

Scaling law for energy density

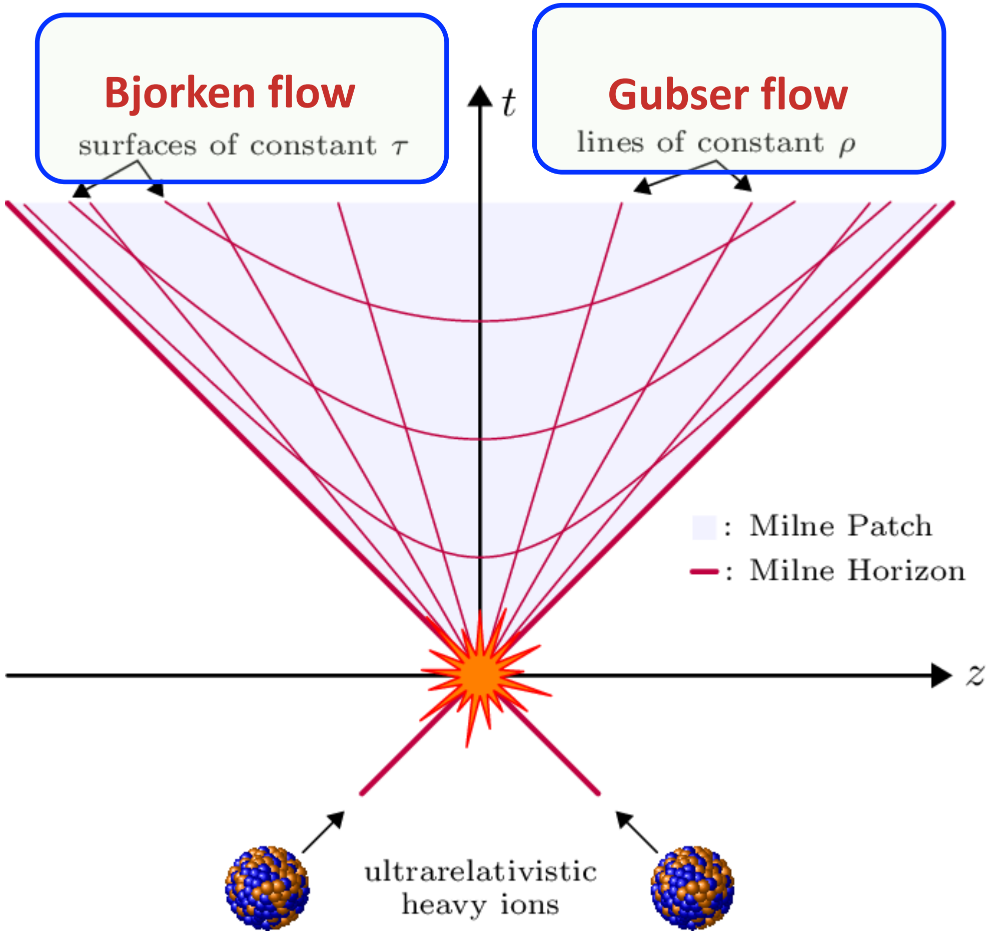
$$e(\tau) = e(\tau_0)\left(\frac{\tau_0}{\tau}\right)^{4/3}$$

τ: proper time; η: rapidity

Bjorken flow has no transverse expansion!
How can one incorporate transverse expansion while retaining analytic control?

Introduction to Gubser flow (I)

- **Gubser flow:** a 1+1D analytic solution of relativistic hydrodynamics with longitudinal and transverse expansion



Motivation:
Extend Bjorken flow to include radial expansion

Basic idea:
Can we find special coordinates in which the flow becomes static, $u^{\mu} = (1,0,0,0)$?

Answer:
Use a conformal (Weyl) transformation

Gubser, PRD (2010);
Gubser, Yarom, NPB (2011)

Introduction to Gubser flow (II)

(1) Set up the hydrodynamic equations in flat $R^{3,1}$ spacetime.

$\mathbb{R}^{3,1}$

Minkowski spacetime

(2) Weyl transformation

$dS_3 \times \mathbb{R}$

de Sitter spacetime

(4) Inverse Weyl transformation

(3) Solving hydrodynamic equations in $dS_3 \times R$ spacetime.

$$u^\mu = (1,0,0,0)$$

$$\begin{aligned} ds^2 &= -dt^2 + dx^2 + dy^2 + dz^2 \\ &= -d\tau^2 + dx_\perp^2 + x_\perp^2 d\varphi^2 + \tau^2 d\eta^2, \end{aligned}$$

τ: proper time
$x_\perp$: transverse radius

ϕ: azimuthal angle in transverse plane
η: space rapidity

$$\begin{aligned} d\hat{s}^2 &\equiv \boxed{\frac{1}{\tau^2}} ds^2 \\ &= -d\rho^2 + \cosh^2\rho \left(d\theta^2 + \sin^2\theta d\varphi^2\right) + d\eta^2 \end{aligned}$$

Weyl rescaling

$$\begin{aligned} \sinh\rho &= -\frac{L^2 - \tau^2 + x_\perp^2}{2L\tau}, \\ \tan\theta &= \frac{2Lx_\perp}{L^2 + \tau^2 - x_\perp^2}, \end{aligned}$$

Introduction to Gubser flow (II)

- **Gubser flow:** a 1+1D analytic solution of relativistic hydrodynamics with transverse expansion

$$(\tau, x_\perp, \phi, \eta)$$

τ: proper time
$x_\perp$: transverse radius
ϕ: azimuthal angle in the transverse plane
η: space rapidity

Scaling law for energy density in $R^{3,1}$ spacetime

$$\varepsilon = \frac{CL^{8/3}}{\tau^{4/3}} \frac{1}{\boxed{\left[L^4 + (x_\perp^2 - \tau^2)^2 + 2L^2(x_\perp^2 + \tau^2)\right]^{4/3}}}$$

C: integration constant
L: system size

Fluid velocity in $R^{3,1}$ spacetime

$$u_\mu = \left(-\frac{1}{\cosh\rho}\frac{L^2 + x^2 + \tau^2}{2L\tau}, \boxed{-\frac{1}{\cosh\rho}\frac{x_\perp}{L}, 0, 0}\right)$$

$$\cosh\rho = \frac{1}{2L\tau}\left[L^4 + (x_\perp^2 - \tau^2)^2 + 2L^2(x_\perp^2 + \tau^2)\right]^{1/2}$$

Radial flow emerges, but azimuthal symmetry remains!

Analytic solution for canonical spin hydrodynamics

D.-L. Wang, X.-Q. Xie, S. Fang, S. Pu, Phys. Rev. D 105 (2022) 114050

Canonical spin hydrodynamics (I)

- **Energy-momentum conservation equation**

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (e+p)u^\mu u^\nu + pg^{\mu\nu} + \pi^{\mu\nu} + \boxed{2q^{[\mu}u^{\nu]} + \phi^{\mu\nu}}$$

New terms in spin hydrodynamics

$$\begin{aligned} q^\mu &= -\lambda\left(\frac{1}{T}\nabla_\perp^\mu T - u^\alpha\nabla_\alpha u^\mu - 4\omega^{\mu\nu}u_\nu\right), \\ \phi^{\mu\nu} &= -\gamma\left(\nabla_\perp^{[\mu}u^{\nu]} - 2\Delta^{\mu\alpha}\Delta^{\nu\beta}\omega_{\alpha\beta}\right). \end{aligned}$$

Hattori, Hongo, Huang, Matsuo, Taya PLB(2019) ; JHEP (2022); Cao, Hattori, Hongo, Huang, Taya, PTEP (2022)
Fukushima, SP, Lecture Note (2020); PLB(2021); Wang, Fang, SP, PRD(2021); Wang, Xie, Fang, SP, PRD (2022)
S.Y. Li, M.A Stephanov, H.U Yee, PRL (2021); D. She, A. Huang, D.F. Hou, J.F Liao, Sci. Bull. (2022)

Recent review:

SP, X.G. Huang, "Relativistic spin hydrodynamics", Acta Phys.Sin. 72 (2023) 7, 071202

Canonical spin hydrodynamics (II)

- **Angular momentum conservation equation**

$$\nabla_\mu J^{\mu\nu\alpha} = 0 \qquad J^{\mu\nu\alpha} = \boxed{x^\nu T^{\mu\alpha} - x^\alpha T^{\mu\nu}} + \boxed{\Sigma^{\mu\nu\alpha}}$$

Total angular momentum

Orbital angular momentum

Rank-3 spin tensor

- **Decomposition of the rank-3 spin tensor**

$$\Sigma^{\alpha\boxed{\mu\nu}} = u^\alpha \boxed{S^{\mu\nu}} + \Sigma^{\alpha\mu\nu}_{(1)},$$

Anti-symmetic in μ,ν

Spin density

has 6 independent components

S^{ij} 3 rotations; S^{0i} 3 boosts

- **Thermodynamic relations**

Spin (chemical) potential

$$\begin{aligned} e+p &= Ts + \boxed{\omega_{\mu\nu}} S^{\mu\nu}, \\ dp &= sdT + S^{\mu\nu} d\omega_{\mu\nu}, \end{aligned}$$

Challenges in applying Gubser flow (I)

10 differential equations

Energy-momentum conservation equation

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \mathbf{4}$$

Angular momentum conservation equation

$$\nabla_\alpha \Sigma^{\alpha\mu\nu} = -2T^{[\mu\nu]}, \qquad \mathbf{6}$$

Equations of state

$$p = p(e) \qquad S^{\mu\nu} = S^{\mu\nu}(e, \omega^{\mu\nu})$$

10 independent variables

$$e, u^\mu, \omega^{\mu\nu},$$

1 3 6

Challenges in applying Gubser flow (II)

$\mathbb{R}^{3,1}$

Minkowski spacetime

(2) Weyl transformation

(4) Inverse Weyl transformation

$dS_3 \times \mathbb{R}$

de Sitter spacetime

$$d\hat{s}^2 \equiv \boxed{\frac{1}{\tau^2}} ds^2$$

Weyl rescaling

$$J^{\mu\nu\alpha} = \boxed{x^\nu T^{\mu\alpha} - x^\alpha T^{\mu\nu}} + \boxed{\Sigma^{\mu\nu\alpha}}$$

Total angular momentum

Orbital angular momentum

Rank-3 spin tensor

The total angular-momentum current is not Weyl covariant !!!

$$\hat{\nabla}_\alpha \hat{\Sigma}^{\alpha\mu\nu} = \hat{T}^{[\mu\nu]} \boxed{- \left(\hat{u}_\alpha \hat{S}^{\alpha\nu} \hat{g}^{\mu\beta} + \hat{u}_\alpha \hat{S}^{\mu\alpha} \hat{g}^{\nu\beta} + \hat{u}^\mu \hat{S}^{\nu\beta} - \hat{u}^\nu \hat{S}^{\mu\beta} \right) \tau^{-1} \hat{\nabla}_\beta \tau}$$

Our approach

- **Impose special initial conditions**

$$\hat{S}^{\theta\varphi}(\rho,\theta)=\hat{S}^{\theta\eta}(\rho,\theta)=0 \qquad \hat{S}^{\rho\varphi}(\rho,\theta)=\hat{S}^{\rho\eta}(\rho,\theta)=0$$

With these initial conditions, these components remain zero throughout the evolution.

- **Equations of state**

$$\hat{e} = c_s^{-2}\hat{p}=3\hat{p}, \qquad \hat{S}^{\mu\nu} = a\hat{T}^2\hat{\omega}^{\mu\nu},$$

- **Solutions in $dS_3 \times R$ spacetime**

$$\begin{aligned}\hat{S}^{\rho\theta} &= c_1\cosh^{-3}\rho,\\ \hat{S}^{\varphi\eta} &= c_2\cosh^{-3}\rho\sin^{-1}\theta A(\rho)+\mathcal{O}\left(\overline{\omega}^2\right).\end{aligned}$$

$$\begin{aligned}A(\rho) &= 1+\left(\frac{\hat{\gamma}}{\hat{s}}\right)\frac{6}{a}\frac{\hat{s}_0}{\hat{T}_0^2}\cosh^{\frac{2}{3}}\rho_0\left[\mathrm{Sech}^{\frac{2}{3}}\rho_0 F\left(\frac{1}{3},\frac{1}{2};\frac{4}{3};\mathrm{Sech}^2\rho_0\right)\right.\\ &\left.-\mathrm{Sech}^{\frac{2}{3}}\rho F\left(\frac{1}{3},\frac{1}{2};\frac{4}{3};\mathrm{Sech}^2\rho\right)\right]\\ &+\mathcal{O}\left(\frac{\hat{\omega}^{\alpha\beta}\hat{\omega}_{\alpha\beta}}{\hat{T}^2},\left(\frac{\hat{\eta}_s}{\hat{s}}\right)^2,\left(\frac{\hat{\gamma}}{\hat{s}}\right)^2,\frac{\hat{\gamma}\hat{\eta}_s}{\hat{s}^2}\right),\end{aligned}$$

Spin density in 3+1 dim spacetime

Solutions in $R^{3,1}$ spacetime

$$S^{0x} = \frac{4L^2}{\tau} C_+ G(L,\tau,x_\perp)^{-1},$$
$$S^{0y} = \frac{4L^2}{\tau} C_- G(L,\tau,x_\perp)^{-1},$$
$$S^{xz} = \frac{4L^2}{\tau} D_+ G(L,\tau,x_\perp)^{-1},$$
$$S^{yz} = \frac{4L^2}{\tau} D_- G(L,\tau,x_\perp)^{-1}.$$

In large L (QGP size) or early proper time limit

- **Decay behavior of spin density**

$$S^{0x}, S^{0y}, S^{xz}, S^{yz} \propto \tau^{-1}$$

- **Decay behavior of spin potential**

$$\omega^{0x}, \omega^{0y}, \omega^{xz}, \omega^{yz} \propto \boxed{\tau^{-1/3}}$$

- **Decay behavior of thermal vorticity**

$$\varpi^{\mu\nu} \sim \boxed{\tau^{-2/3}}$$

- **Decay behavior of thermal shear**

$$\xi^{\mu\nu} \sim \boxed{\tau^{-2/3}}$$

Spin (chemical) potential may not be negligible in modified Cooper-Frye formula!

Attractors in spin hydrodynamics

G.-H. Li, X. Ren, D.-L. Wang, S. Pu, arXiv:2603.27182 (2026).

Two issues in spin hydrodynamics (I)

(1) Spin (density) is not a conserved quantity.

$$\Sigma^{\alpha\mu\nu} = u^{\alpha}\boxed{S^{\mu\nu}} + \Sigma_{(1)}^{\alpha\mu\nu}, \qquad e+p = Ts + \boxed{\omega_{\mu\nu}}S^{\mu\nu},$$

Spin density

Spin (chemical) potential

Bjorken-type spin hydrodynamics:

$$S^{z} \propto \tau^{-1}\exp\left[-\tilde{\alpha}(\tau^{2}/\tau_{0}^{2}-1)\right]$$

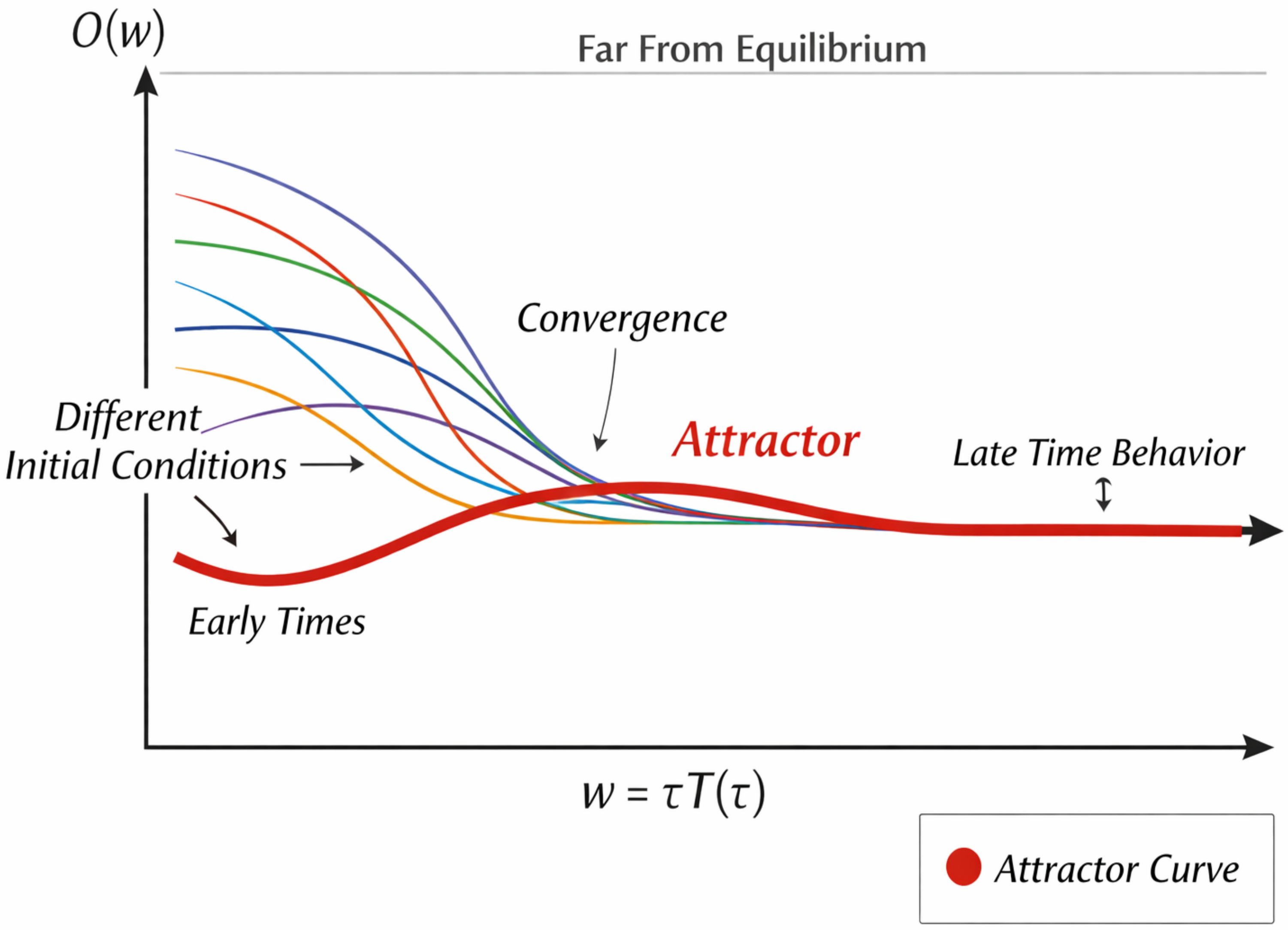
D.L. Wang, Shuo Fang, SP, PRD (2021)

Typical decaying behavior as a function of proper time	
Spin density	exponential X power-law decay
number density	power-law decay

(2) The initial conditions for spin density are poorly constrained.

What if attractors exist in spin hydrodynamics?

Attractors in relativistic hydrodynamics



- **Hydrodynamic attractors show that the system can be effectively described by a few macroscopic variables well before local equilibrium is reached.**

Heller, Spalinski, PRL (2015) PRL (2020); Romatschke PRL (2018); Romatschke, Yan, PLB (2018); Denicol, Noronha, PRD (2018); Strickland, JHEP (2018); Almaalol, Kurkela, Strickland PRL (2020), ...

Setup for Gubser-type spin hydrodynamics

- **Spin hydrodynamics at second order**

$$\boxed{\tau_q \Delta^{\mu\nu} u^\alpha \nabla_\alpha q_\nu} + q^\mu = \lambda (T^{-1} \Delta^{\mu\alpha} \nabla_\alpha T + u^\alpha \nabla_\alpha u^\mu - 4\omega^{\mu\nu} u_\nu)$$

$$\boxed{\tau_\phi \Delta^\mu_\alpha \Delta^\nu_\beta u^\rho \nabla_\rho \phi^{\alpha\beta} + \lambda_\theta \phi^{\mu\nu} \nabla_\alpha u^\alpha} + \phi^{\mu\nu} = 2\gamma_s \Delta^{\mu\alpha} \Delta^{\nu\beta} (\nabla_{[\alpha} u_{\beta]} + 2\omega_{\alpha\beta}),$$

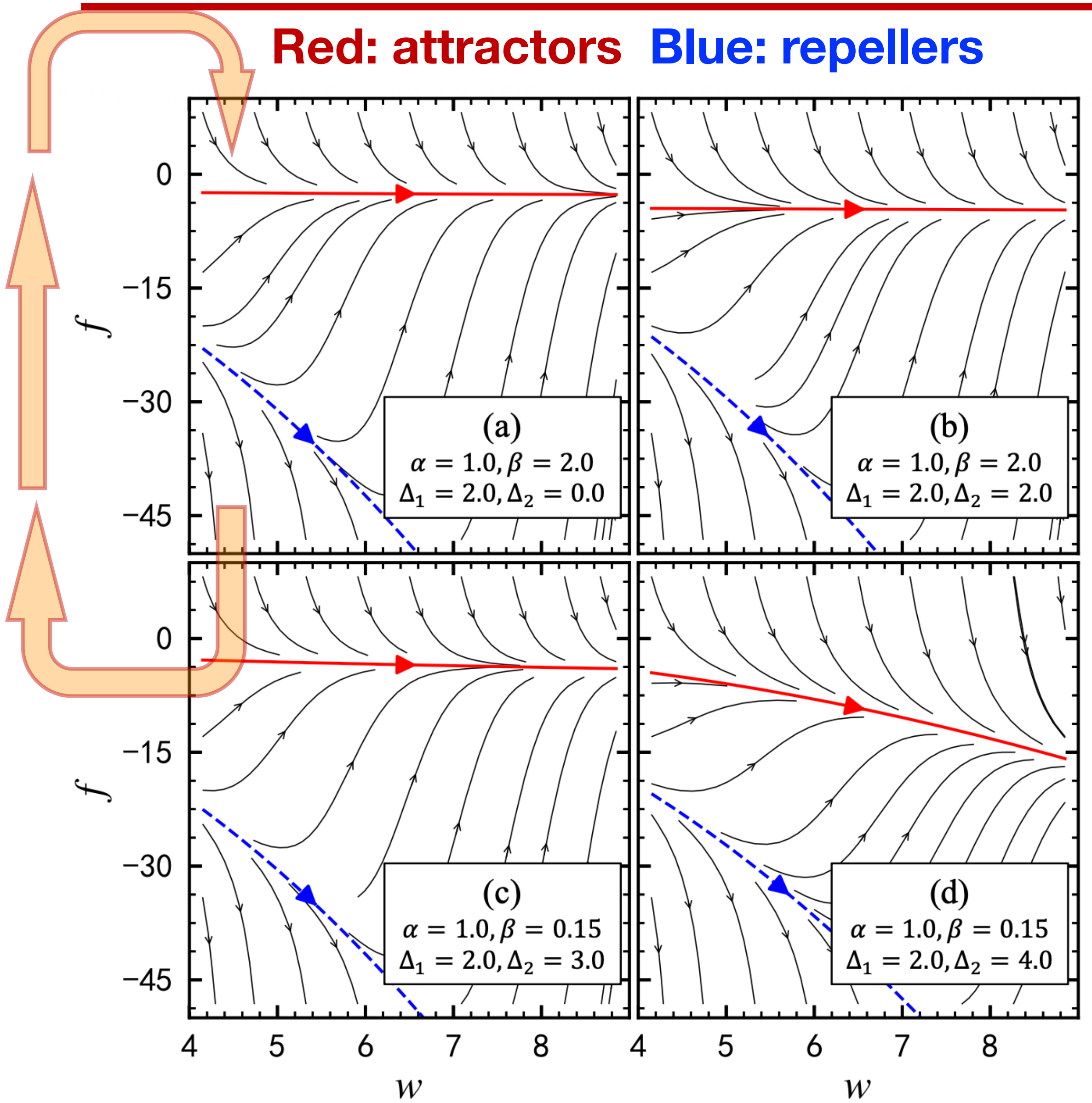
Second order corrections related to spin effects

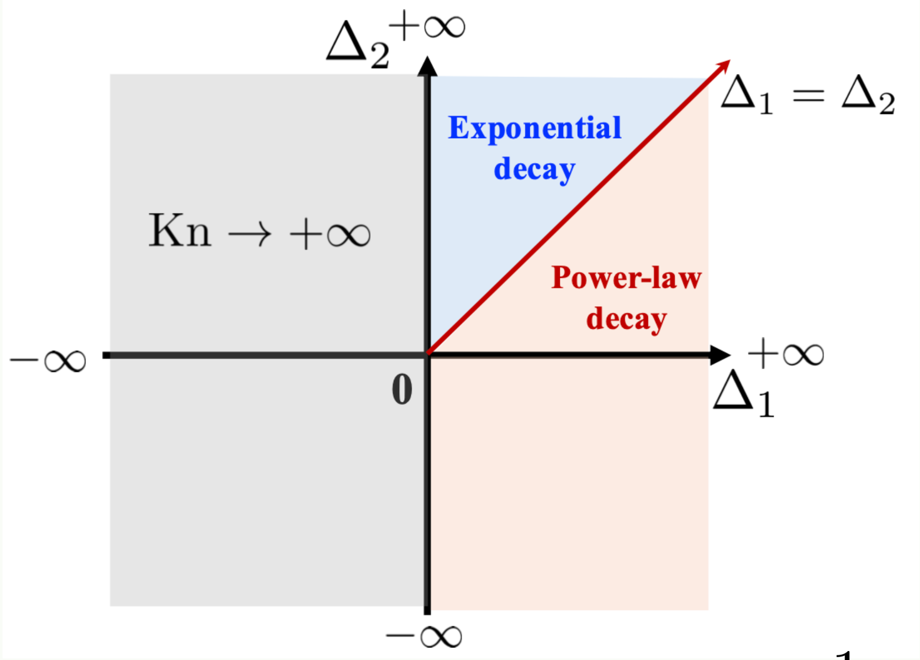
The equation for $\hat{S} \equiv \hat{S}^{\varphi\eta}$, all other components remain zero if they are initially zero.

$$0 = \frac{d^2}{d\rho^2}\hat{S} + \left(\frac{20}{3}\tanh\rho + \hat{\tau}_\phi^{-1}\right)\frac{d}{d\rho}\hat{S} + \left(3 + 8\tanh^2\rho + 3\hat{\tau}_\phi^{-1}\tanh\rho + 8\hat{\gamma}_s\hat{\tau}_\phi^{-1}\hat{\chi}^{-1}\right)\hat{S}$$

Attractors in spin hydrodynamics in Gubser flow

Red: attractors Blue: repellers





$$L \gg \tau,\ S^{tx}, S^{ty}, S^{zx}, S^{zy} \sim \frac{1}{\tau L^2}$$

$$\tau \gg L,\ S^{tx}, S^{ty}, S^{zx}, S^{zy} \sim \frac{L^4}{\tau^7}.$$

L: size of the system

Gui-Hui Li, Xiang Ren, D. L. Wang, SP, arXiv: 2603.27182

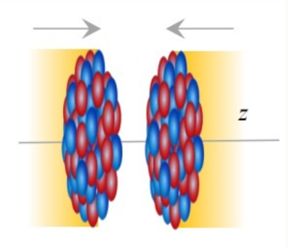
Nonlinear Hydrodynamic Response

X. Ren, J.-Y. Hu, H.-j. Xu, S. Pu, Phys. Rev. D 114 (2026) 034001.

Nonlinear response of the flow Harmonics

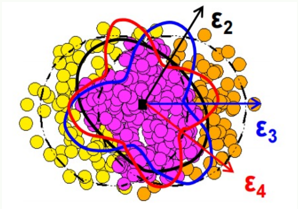
- **Linear response** $v_n \propto \epsilon_n$ $\quad v_2 \propto \epsilon_2$

Collision



Nuclear structure and fluctuations

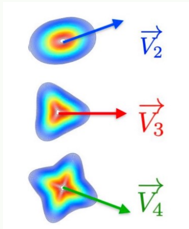
Initial state



Initial-state spatial anisotropy (ϵ_n)

Anisotropic pressure gradients

Final state

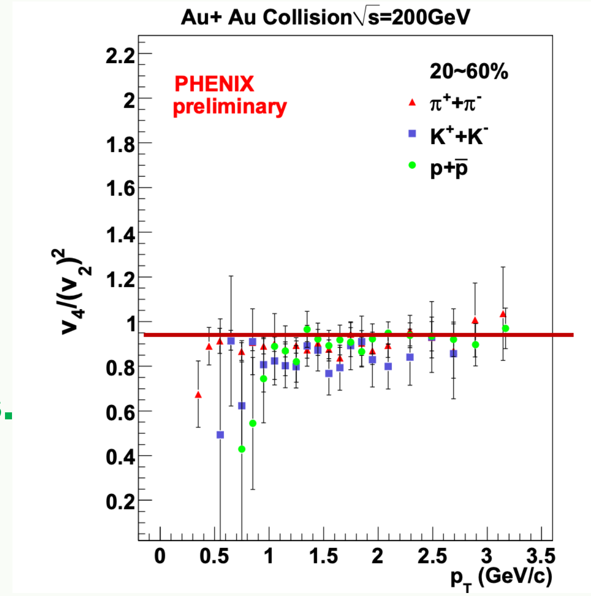


Final-state momentum anisotropy (v_n)

- **Nonlinear response of v_4**

$$v_4 = \chi_{44}\epsilon_4 + \boxed{\chi_{42}\epsilon_2^2}$$

N. Borghini ,J.-Y. Ollitrault, Phys. Lett. B 642, 227 (2006), D. Teaney and L. Yan, Phys. Rev. C 86, 044908 (2012), C. Lang and N. Borghini, Eur. Phys. J. C 74, 2955 (2014), C. Gombeaud and J.-Y. Ollitrault, Phys. Rev. C 81, 014901 (2010)



$$v_4 \sim v_2^2 \sim \epsilon_2^2$$

PHENIX, JPG (2008)

Azimuthal perturbation

- **Now, we introduce a perturbation to the temperature:**

$$T_0 \to T = T_0[1 + \boxed{\delta(\rho) S(\Theta, \phi)}],$$

- **The conservation equations then determine the corresponding perturbation to the fluid velocity:**

$$\begin{aligned} u^\mu &\to u^\mu + \delta u^\mu \\ \delta u^\mu &= \left(0, \frac{2L\tau}{L^2 + x_\perp^2}\nu_s(\rho)\boxed{\partial_\Theta S(\Theta, \phi)}, \tau\nu_s(\rho)\boxed{\partial_\phi S(\Theta, \phi)}, 0\right) + \mathcal{O}(\tau^2) \end{aligned}$$

The perturbation introduces a nontrivial ϕ dependence

where

$$\begin{aligned} \delta &= \delta_0 + \delta_0 \frac{\eta_0}{2\lambda C}(2e^\rho)^{-2/3} + \mathcal{O}(e^{2\rho}), \\ \nu_s &= -\frac{3}{2}\delta_0 + k_0 \frac{\eta_0}{\lambda C}(2e^\rho)^{-2/3} + \mathcal{O}(e^{2\rho}), \end{aligned}$$

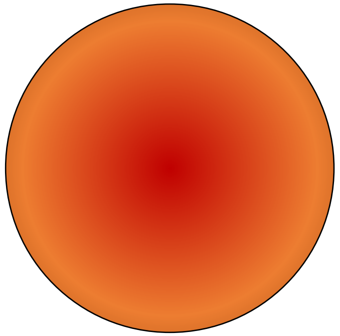
Hatta, Noronha, Torrieri, Xiao PRD (2014);
Hatta, Monnai, Xiao, PRD (2015)

Perturbation and eccentricities (I)

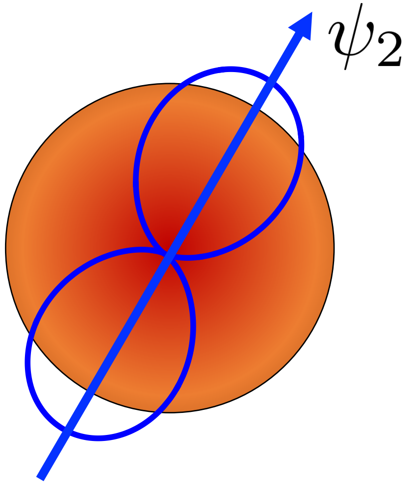
- **Fluctuations:** **In this work, we introduce azimuthal perturbations as**

$$S(\Theta,\phi) = a_2\left(\frac{2x_\perp L}{L^2+x_\perp^2}\right)^2 \boxed{\cos 2\phi} + a_4\left(\frac{2x_\perp L}{L^2+x_\perp^2}\right)^4 \boxed{\cos 4\phi},$$

- **The parameters a_2 and a_4 are related to the eccentricities,**



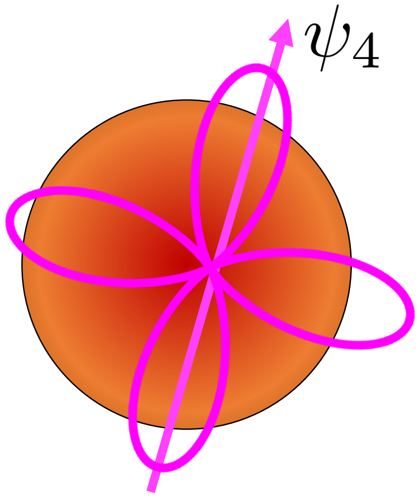
Without fluctuations



Finite a_2

⬇

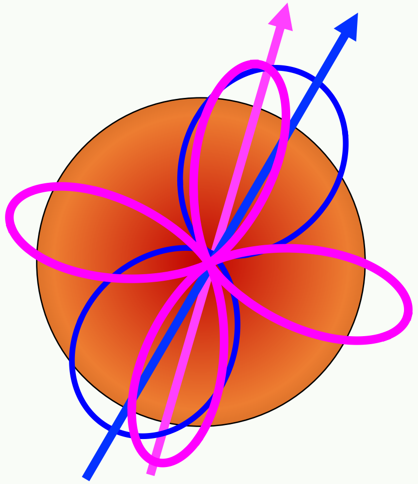
ϵ_2



Finite a_4

⬇

ϵ_4



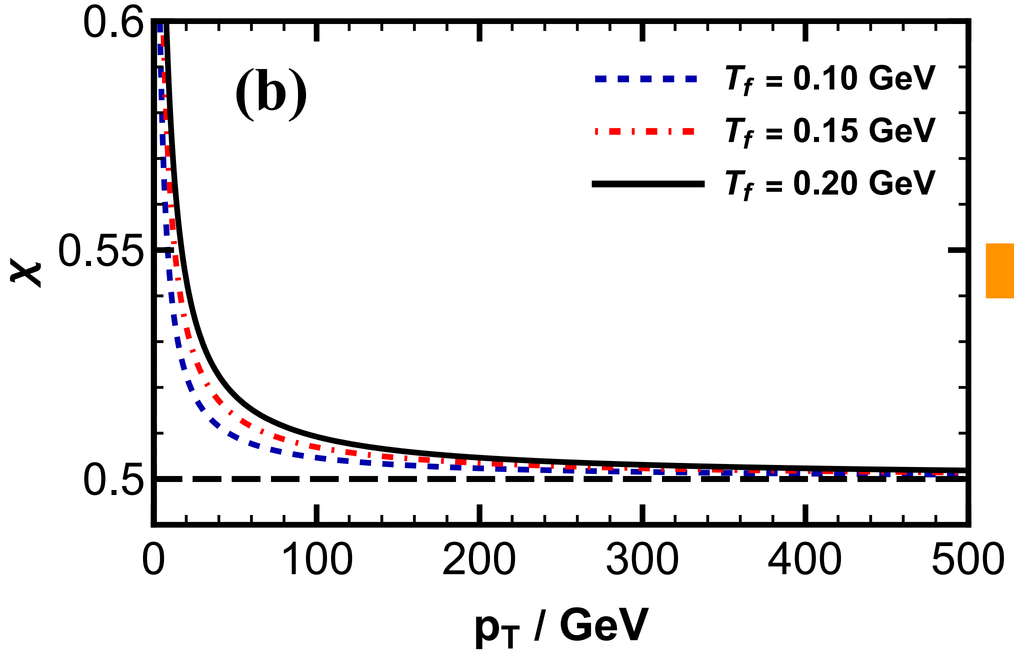
$$\begin{aligned} \epsilon_2 &= -a_2 - \frac{24}{35}a_2 a_4 + \ldots \\ \epsilon_4 &= -\frac{36}{35}a_4 \boxed{-\frac{18}{35}a_2^2} + \ldots \end{aligned}$$

Finite a_2 and a_4

The a_2 perturbation generates ϵ_4 through nonlinear coupling.

Nonlinear hydrodynamic response

$$v_2 = \chi_{22}\epsilon_2,$$
$$v_4 = \chi_{44}\epsilon_4 + \boxed{\chi_{42}\epsilon_2^2} = \chi_{44}\epsilon_4 + \boxed{\chi v_2^2} \qquad \chi \equiv \chi_{42}/\chi_{22}^2$$



In the large p_T limit

$$\boxed{\frac{v_4}{v_2^2} = \frac{1}{2} + \mathcal{O}(p_T^{-1}).}$$

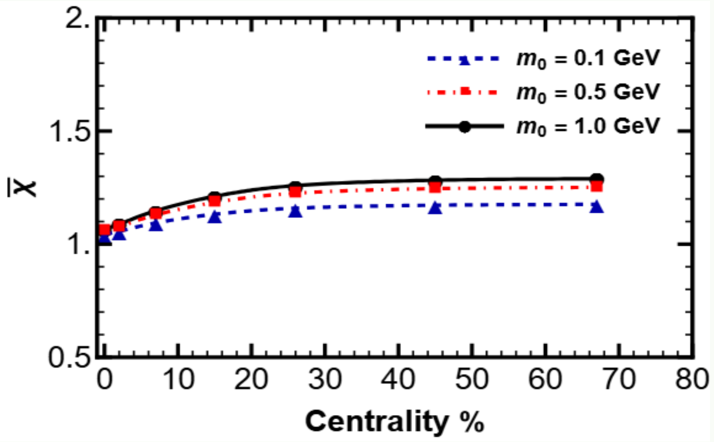
The nonlinear response approaches a universal value at large p_T .

Consistent with previous hydrodynamic simulations.

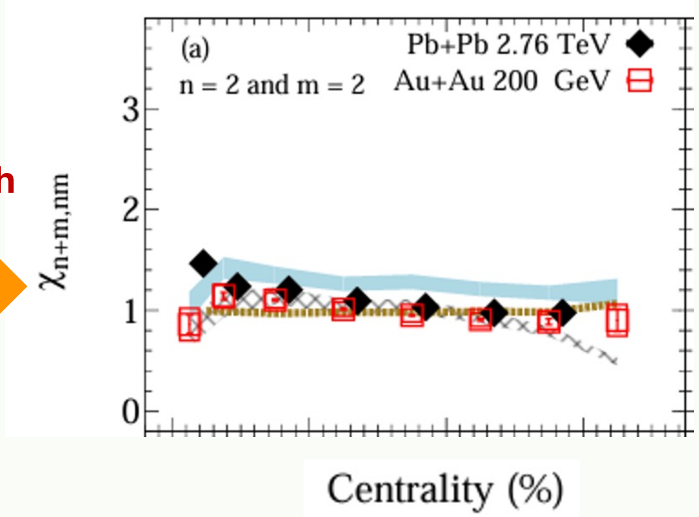
N. Borghini ,J.-Y. Ollitrault, Phys. Lett. B 642, 227 (2006),
D. Teaney and L. Yan, Phys. Rev. C 86, 044908 (2012)
C. Lang and N. Borghini, Eur. Phys. J. C 74, 2955 (2014)
C. Gombeaud and J.-Y. Ollitrault, Phys. Rev. C 81, 014901 (2010)

Centrality dependence and scaling behavior

- **Centrality denpendence**



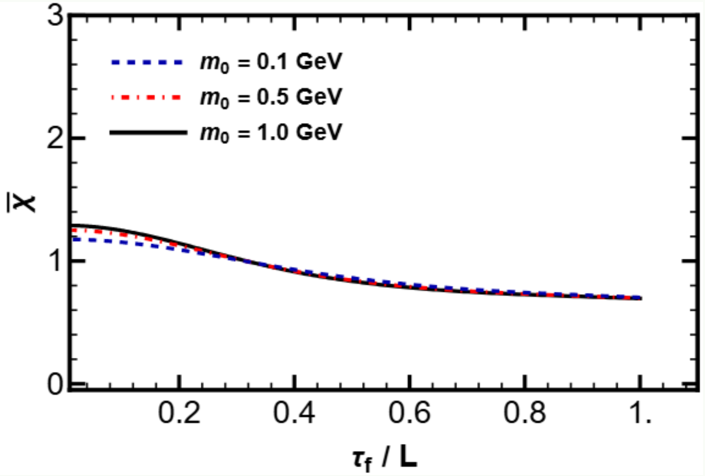
Consistent with STAR data



Parameters are fixed by fitting the integrated v2 in Au+Au collisions at 200 GeV .

Hatta, Noronha, Torrieri, B.W.Xiao, PRD (2014);Hatta, Monnai, B.W.Xiao, PRD(2015)
R. S. Bhalerao, J.P. Blaizot, N. Borghini, J.Y. Ollitrault, Phys. Lett. B(2005)

- **Scaling behavior**



Assume $\bar{\chi} \propto (\tau_f/L)^a$, two scaling regimes emerge, separated around $\tau_f/L = 0.3$.

$\tau_f/L \leq 0.3$: $\mathbf{a} \approx -0.06$. $\bar{\chi}$ is nearly constant
$\tau_f/L \geq 0.3$: $\mathbf{a} \approx -0.3$.

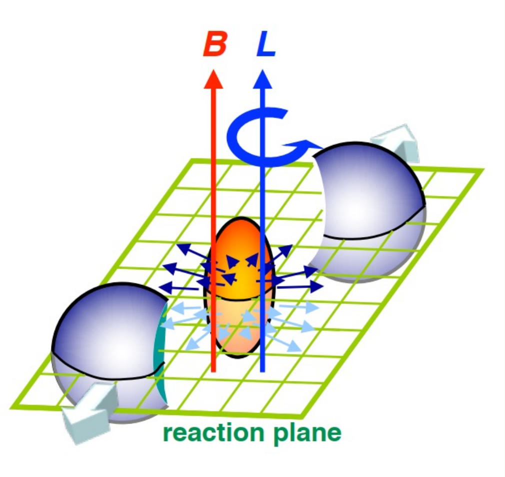
From Flow to Polarization

K. Fukushima, S. Pu, D.-L. Wang, arXiv:2608.03945 (2026)

Puzzle: How does initial state affect polarization?

Initial state

Initial orbital angular momentum



Final state

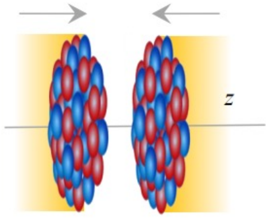
Fluid profile near the freeze-out hypersurface

Polarization induced by
thermal vorticity
热涡旋

$$S^{\mu}_{\rm thermal} \sim \epsilon^{\mu\nu\alpha\beta} p_{\nu} \partial_{\alpha} \frac{u_{\beta}}{T}$$

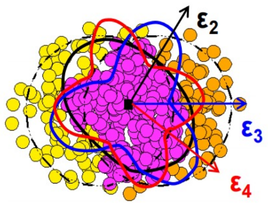
Basic idea: from initial state to polarization

Collision



Nuclear structure and fluctuations

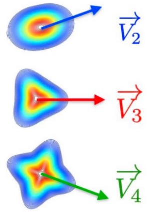
Initial state



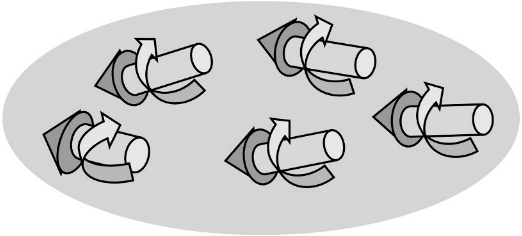
Initial-state spatial anisotropy (ϵ_n)

Anisotropic pressure gradients

Final state



Final-state momentum anisotropy (v_n)

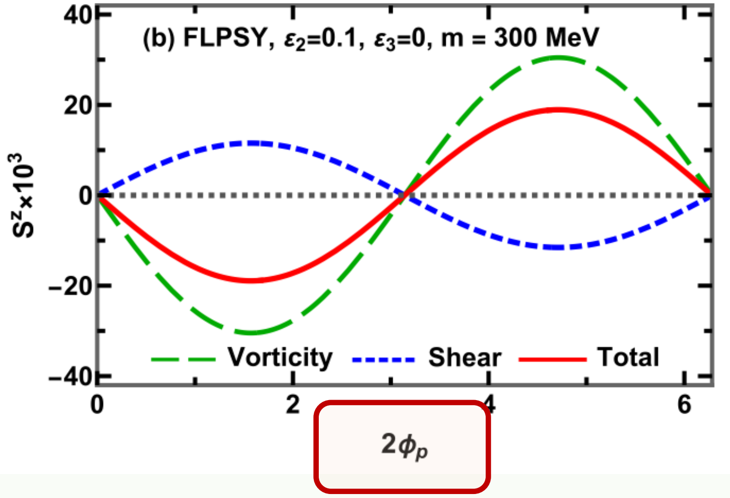


Polarization?

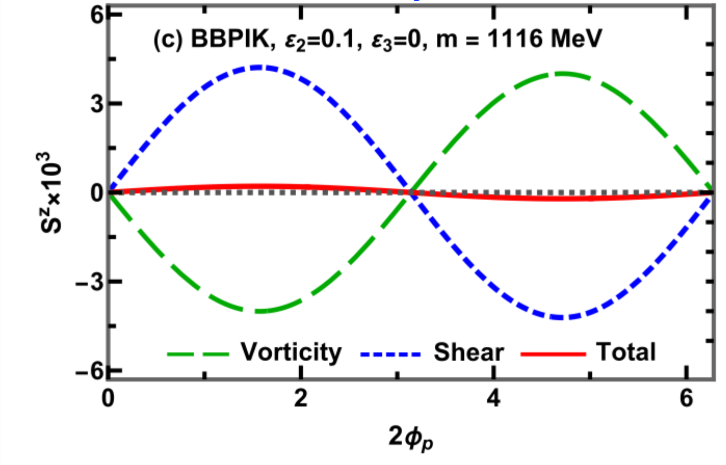
Results (I)

A finite initial eccentricity ϵ_2 generates longitudinal polarization.

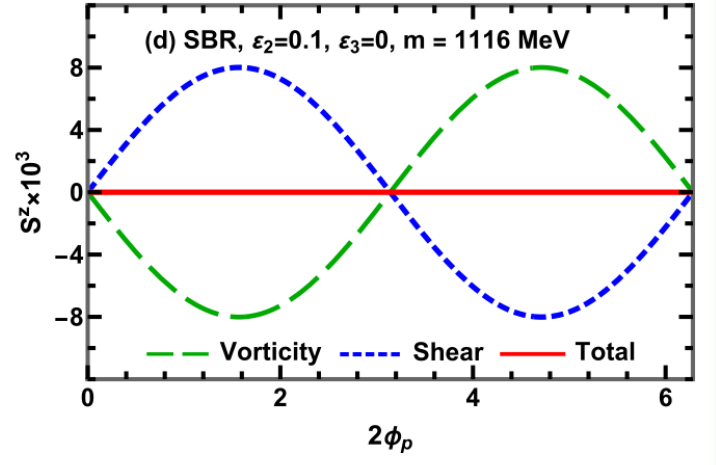
s quark equilibrium



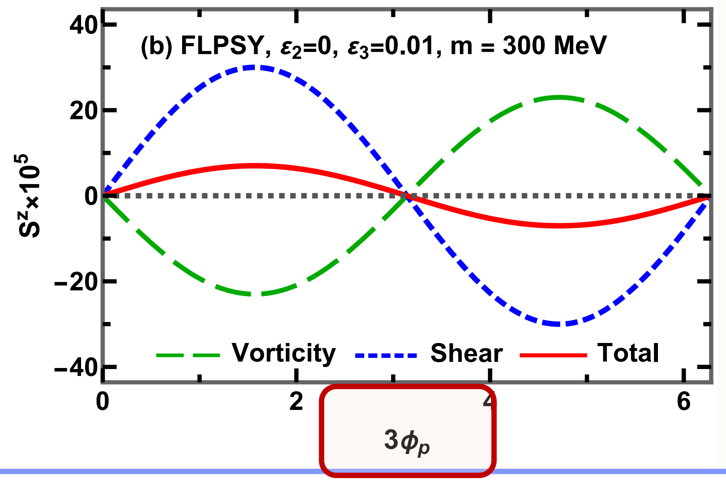
Isothermal equilibrium

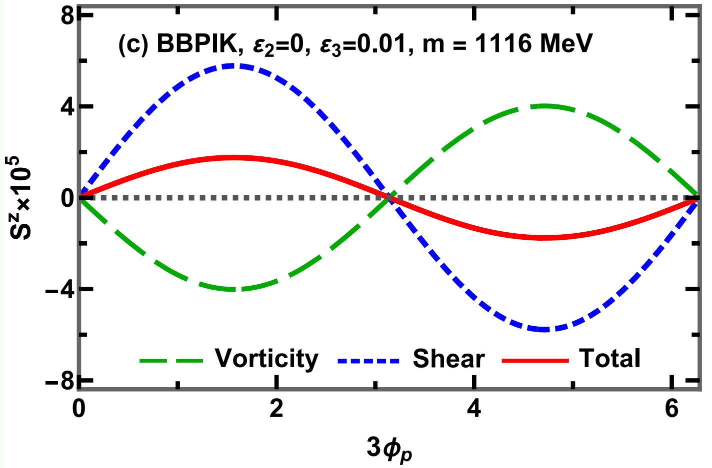


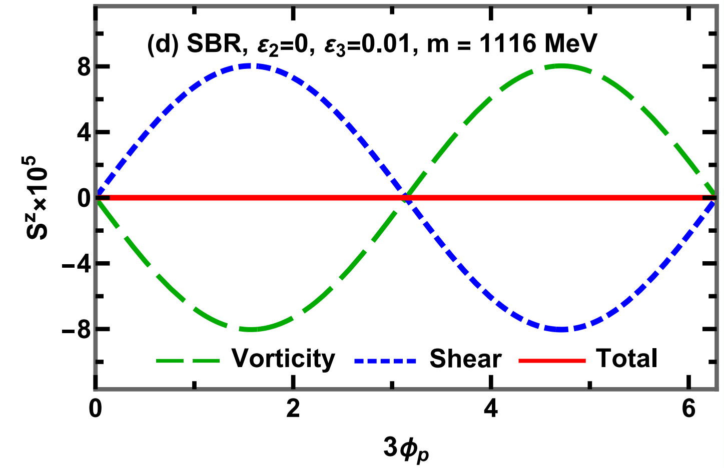
Improved isothermal equilibrium



A finite initial eccentricity ϵ_3 generates longitudinal polarization.







Results (II)

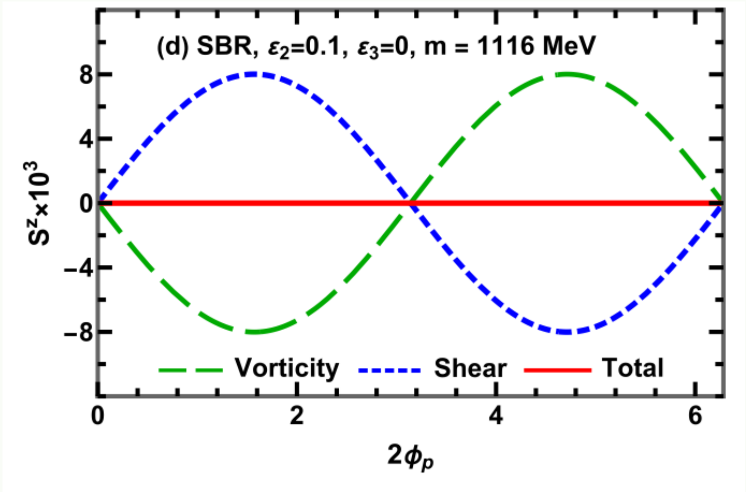
(1) Initial-state geometry -> eccentricity -> flow ->polarization

- **In our setup, zero initial eccentricity leads to zero polarization.**
- **A finite ϵ_2 gives $sin(2\phi_p)$ modulation, a finite ϵ_3 gives $sin(3\phi_p)$ modulation.**

(2) Thermal vorticity and thermal shear contribute with opposite signs.

(3) In the improved isothermal equilibrium formalism, the thermal-vorticity and thermal-shear contributions cancel exactly.

Improved isothermal equilibrium

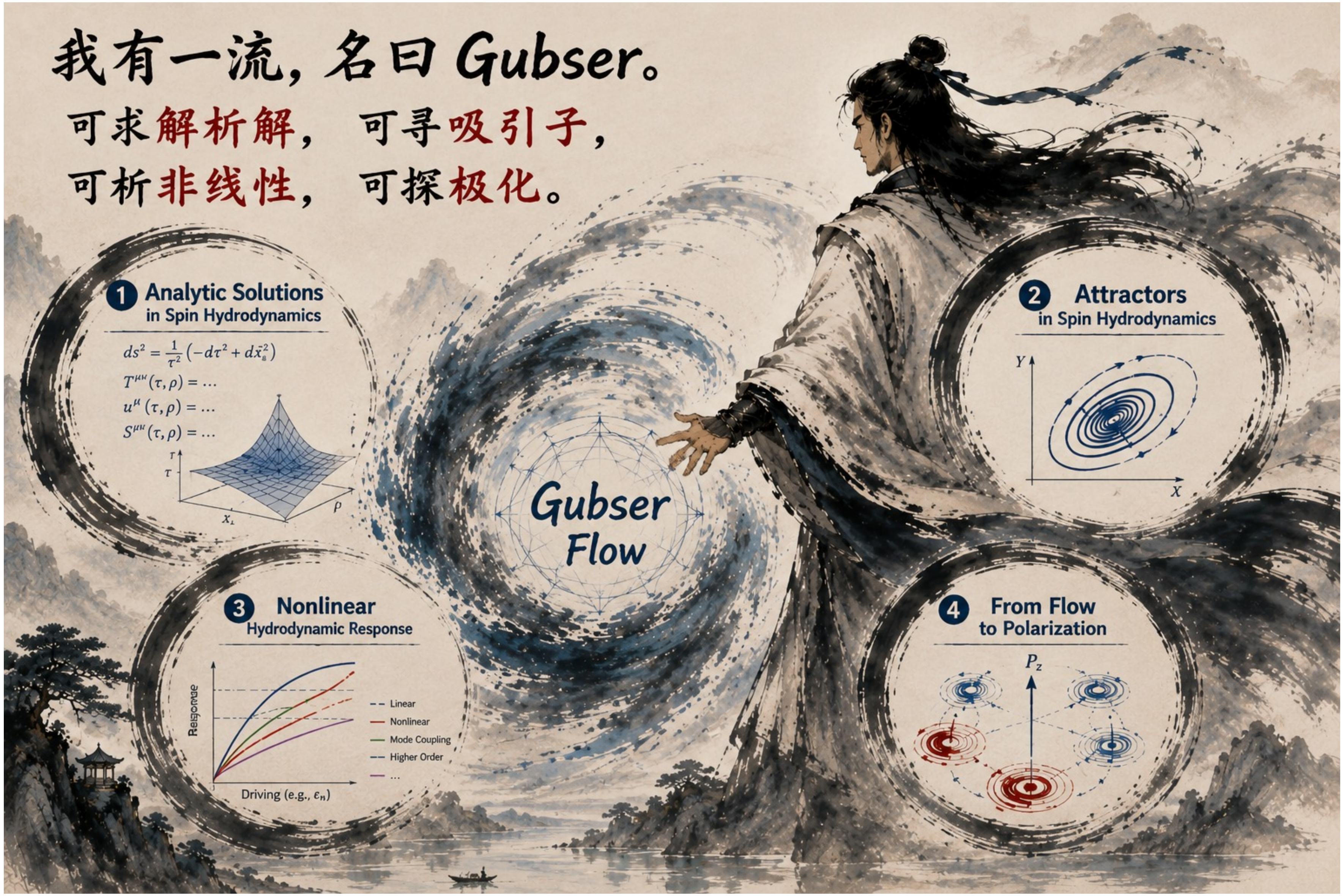


Summary

Summary

Spin hydrodynamics

Azimuthal Perturbations



Outlook

Although Gubser flow is a powerful tool, realistic hydrodynamic simulations are still indispensable.

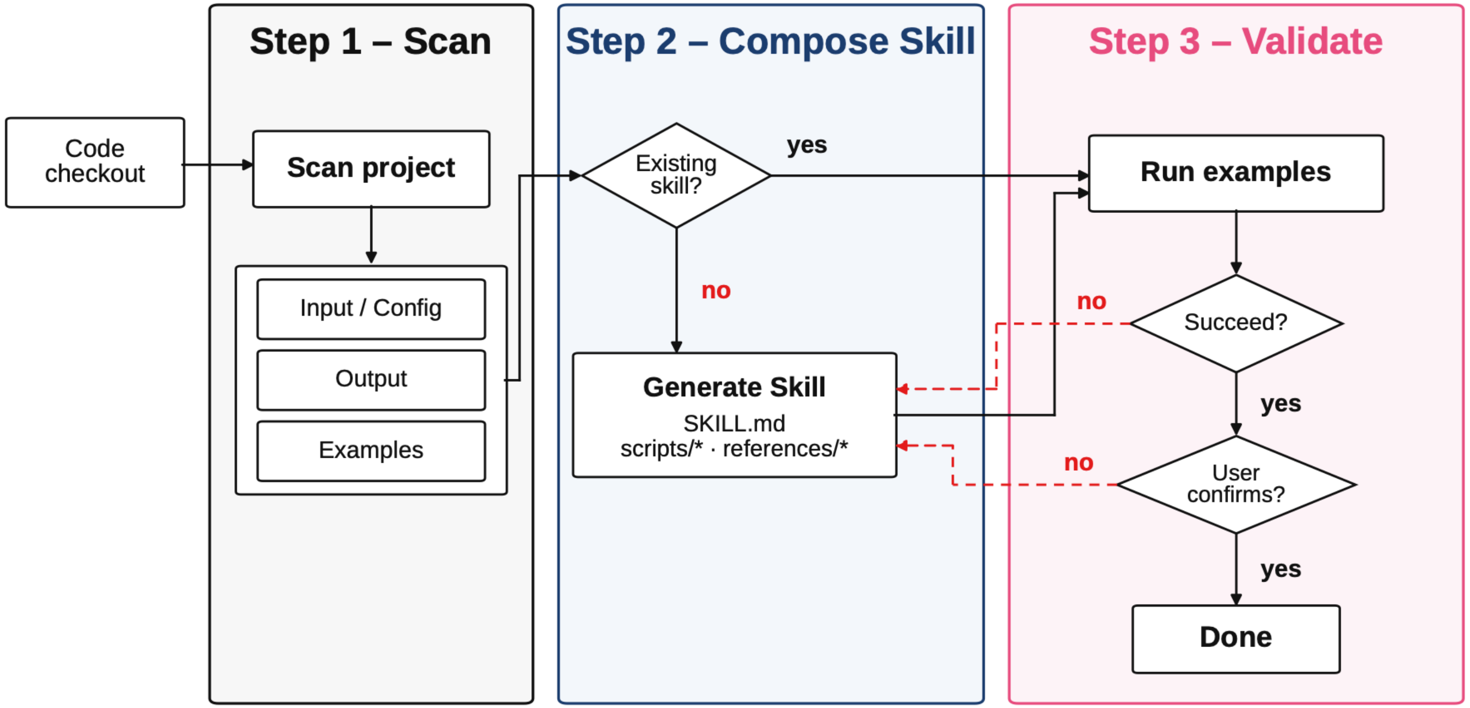
Hydrodynamic simulations require repeated coding, testing, and validation. This can consume enormous amounts of time and human effort.

What if AI could automate this process?

CLVisc Agent

CLVisc Agent for autonomous relativistic hydrodynamics studies

Q. Wang, L.G. Pang, SP, X. N. Wang, arXiv: 2607.27822



Possible tools include:

Kimi Code (国产AI)

Codex

…

Thank you for your time!

Any comments and suggestions are welcome!

Backup