Spin polarization in strongly coupled fluid

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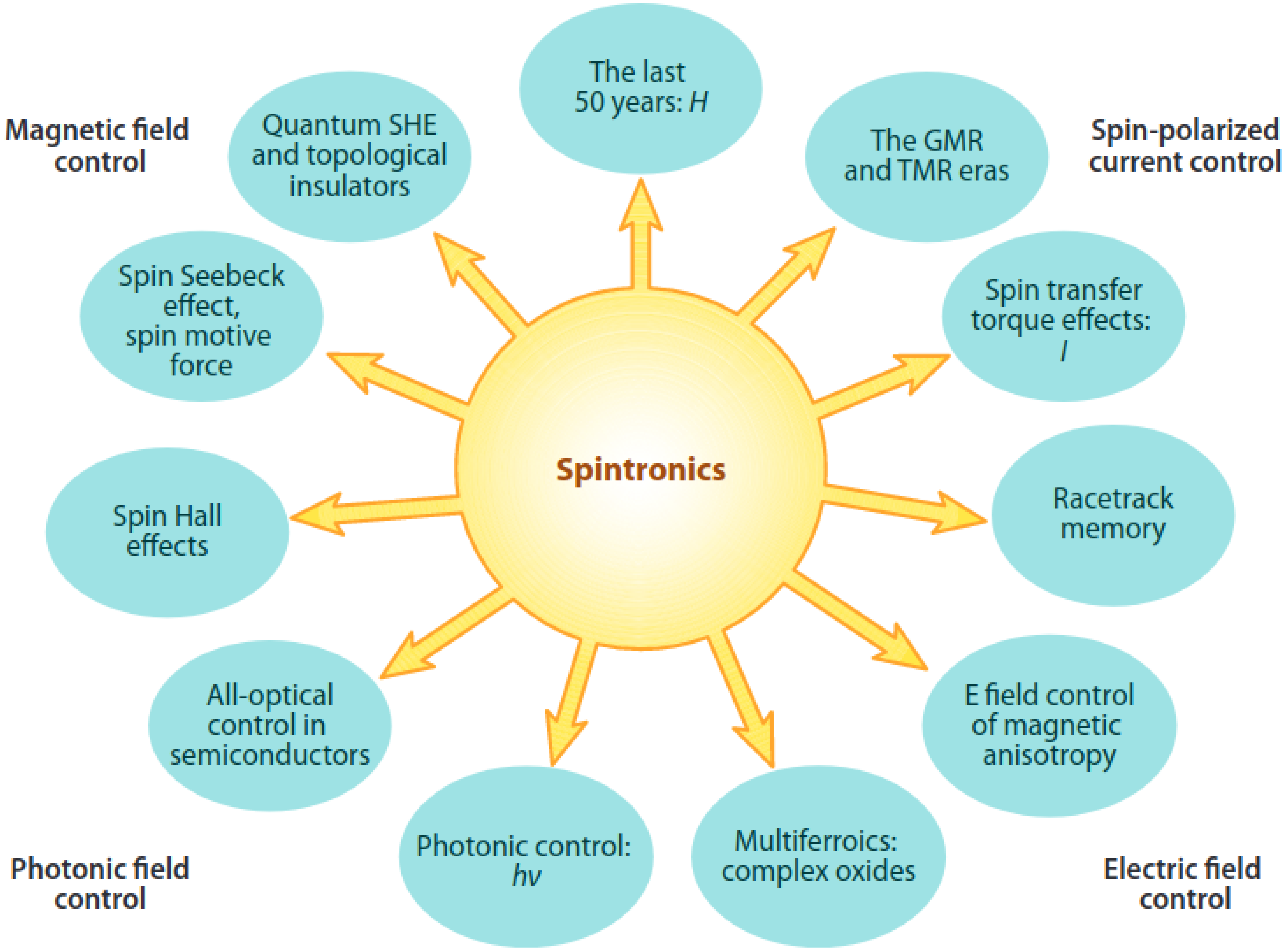
Gauge Gravity 2024, Sanya, Nov 30 – Dec 4, 2024

S.-W. Li, SL,
2412.XXXXX

Outline

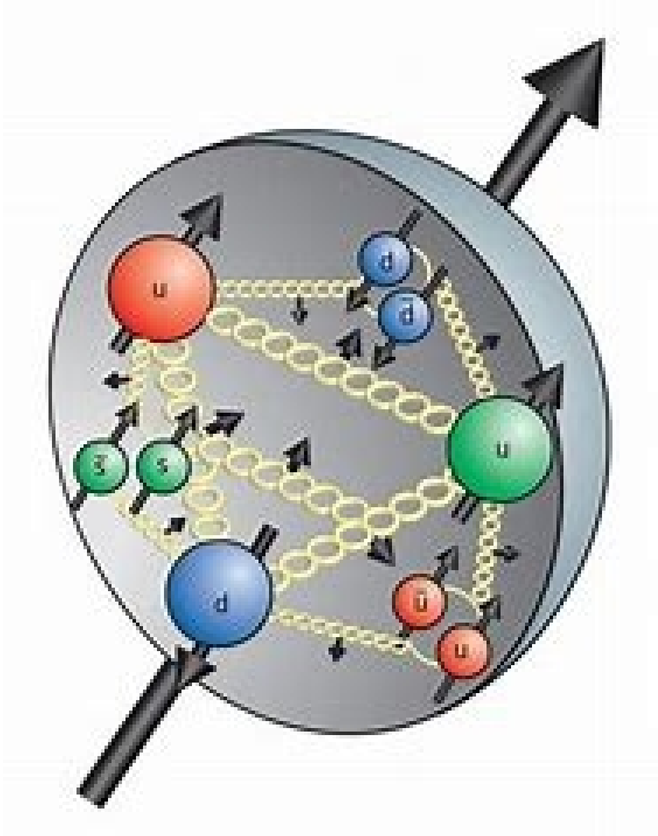
- Spin physics in different areas
- Spin in heavy ion collisions as response to hydrodynamic gradient
- Lessons from weakly coupled studies
- Holographic model for spin polarization
- Fermionic spectral function in strongly coupled fluid and spin polarization
- Conclusion and outlook

Spintronics in condensed matter physics



Bader+Parkin
ARCMP 2010

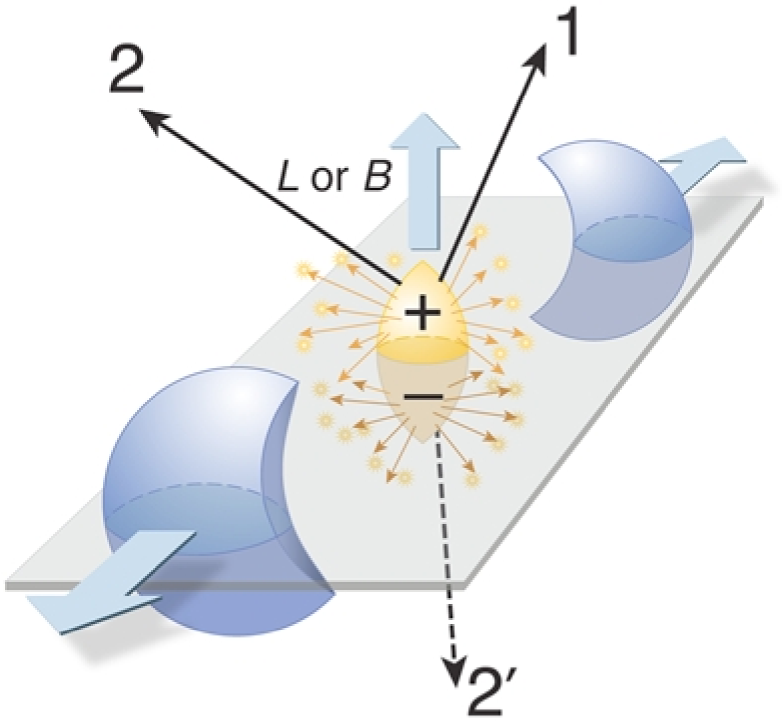
Spin in particle physics



Proton spin puzzle
(1988-now)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

Spin polarization in heavy ion collisions (HIC)



$$L_{ini} \sim 10^5 \hbar \to S_{final}$$

Liang, Wang, PRL 2005, PLB 2005

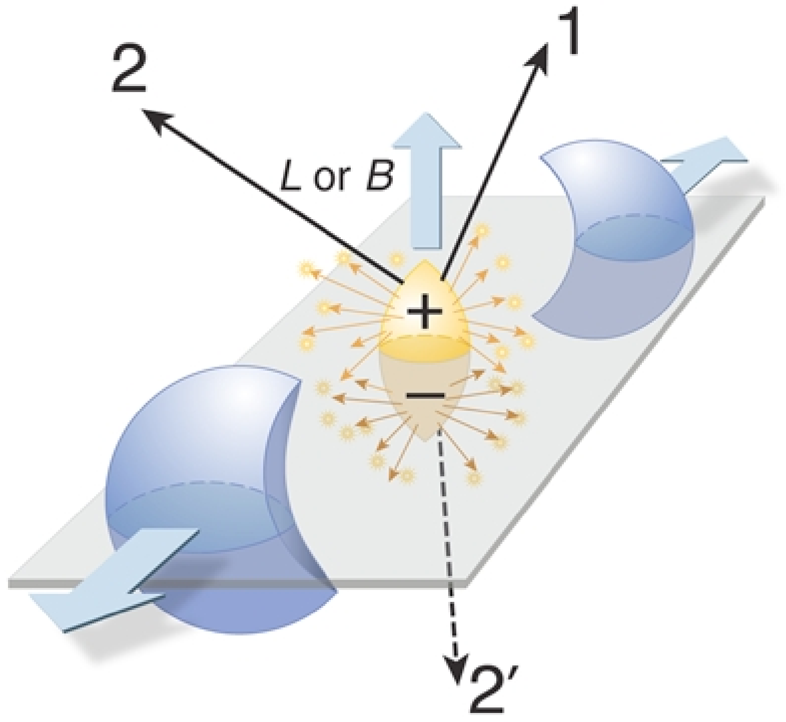
Spin polarization observed in multiple final particles: Λ, ϕ , J/ψ etc

Quark-gluon plasma (QGP) characterized by hydrodynamic gradient

→

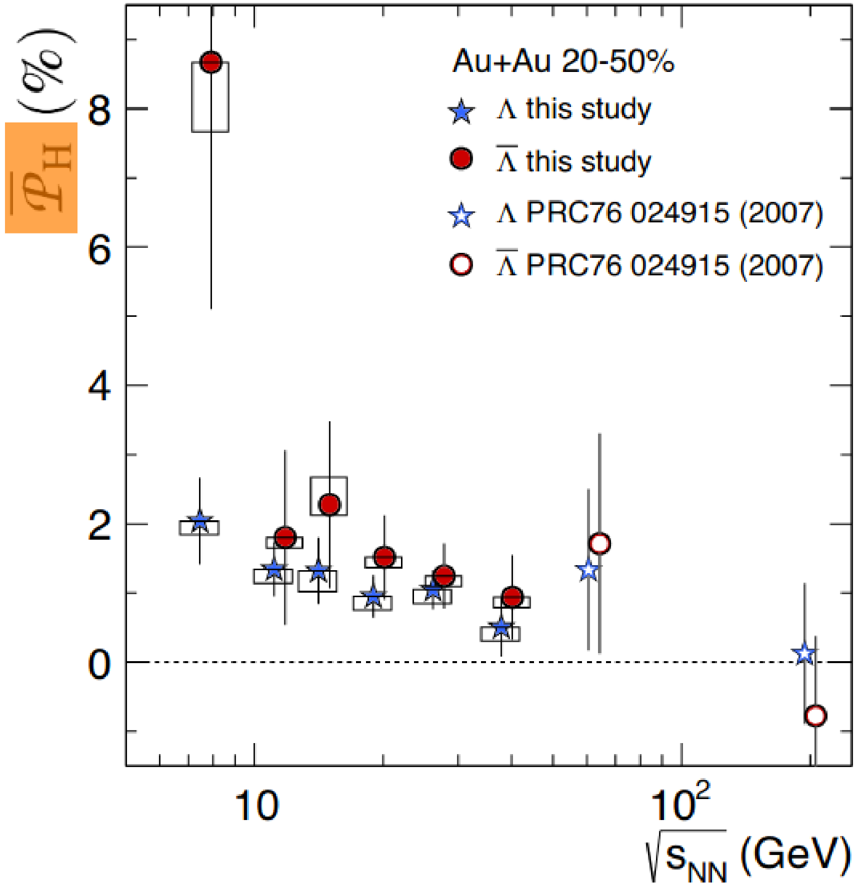
Spin polarization as response to hydrodynamic gradient

global spin polarization from spin-vorticity coupling



$$L_{ini} \sim 10^5\hbar \to S_{final}$$

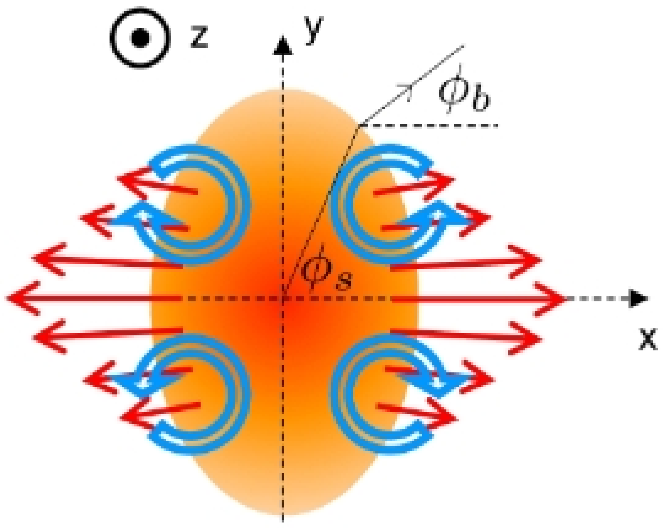
Liang, Wang, PRL 2005, PLB 2005



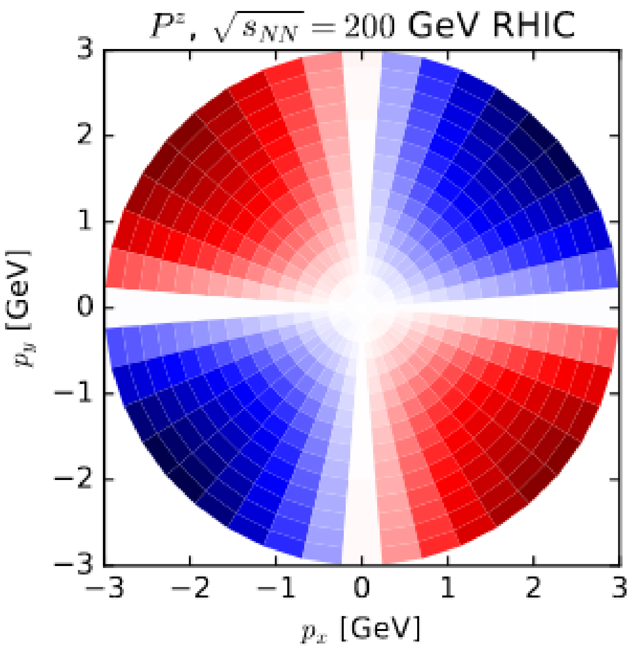
STAR collaboration, Nature 2017

$$e^{-\beta(H_0-\mathbf{S}\cdot\omega)}$$

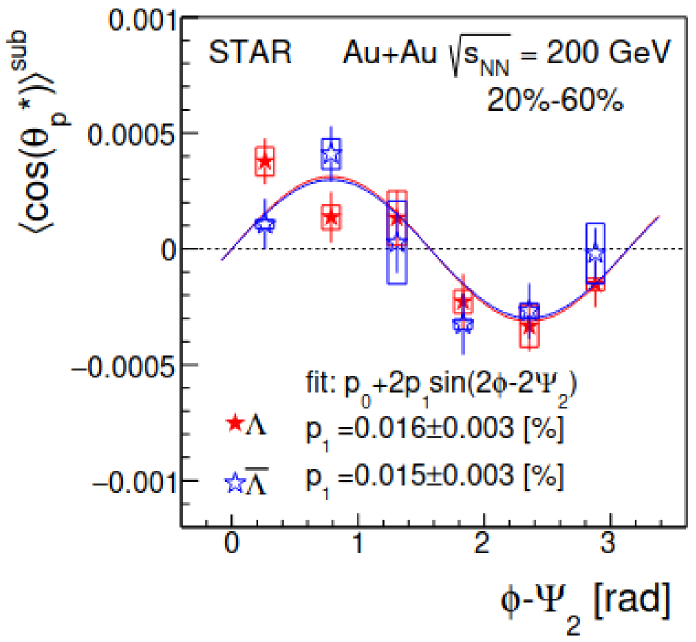
local spin polarization puzzle



$S^i \sim \omega^i$

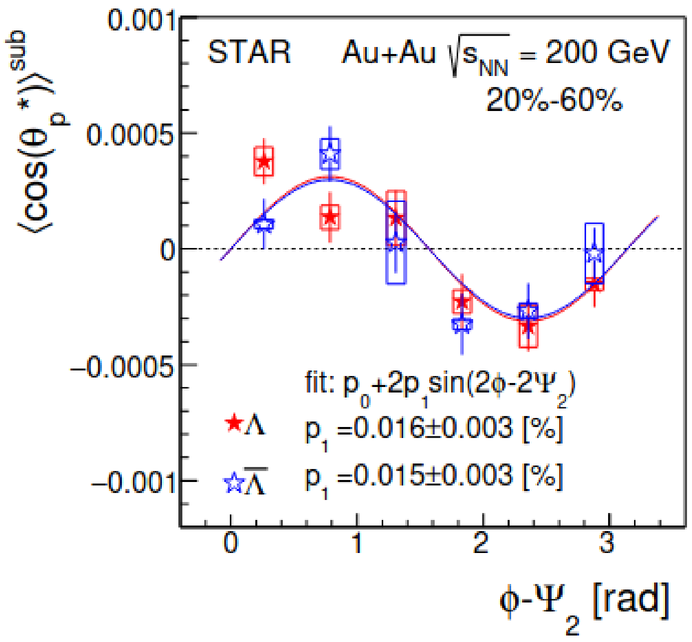


Becattini, Karpenko, PRL 2018
Wei, Deng, Huang, PRC 2019
Wu, Pang, Huang, Wang, PRR 2019
Fu, Xu, Huang, Song, PRC 2021

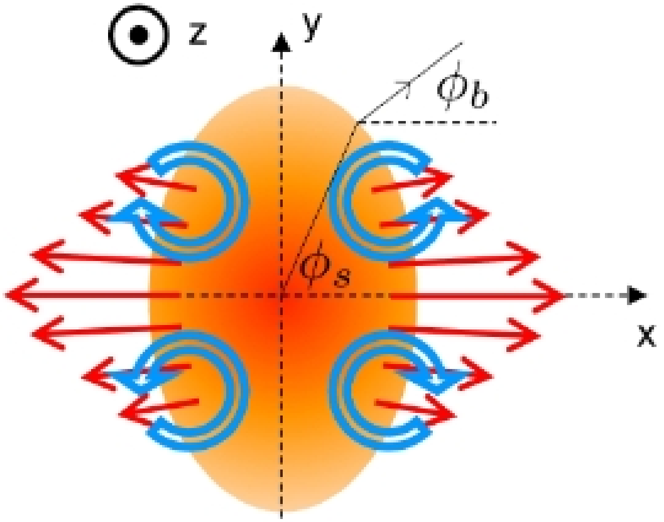


STAR collaboration, PRL 2019

local spin polarization from spin-vorticity/shear coupling



STAR collaboration, PRL 2019



Hidaka, Pu, Yang, PRD 2018
Liu, Yin, JHEP 2021
Becattini, et al, PLB 2021

vorticity + shear

$$S^i \sim \omega^i$$

$$S^i \sim \epsilon^{ijk}\hat{p}_k\hat{p}_l\sigma_{jl}$$

$$S^z \sim \left(\langle p_y^2\rangle - \langle p_x^2\rangle\right)\partial_y u_x$$

Spin-shear coupling gives correct sign

Theoretical frameworks for spin polarization

- Quantum kinetic theory: kinetic theory extended to include spin
- pro: applies to general off-equilibrium state
- con: relies on quasi-particle picture

- Spin hydrodynamics: hydrodynamics extended to include spin assuming slow relaxation of spin

Yarom’s talk

QGP may be strongly coupled

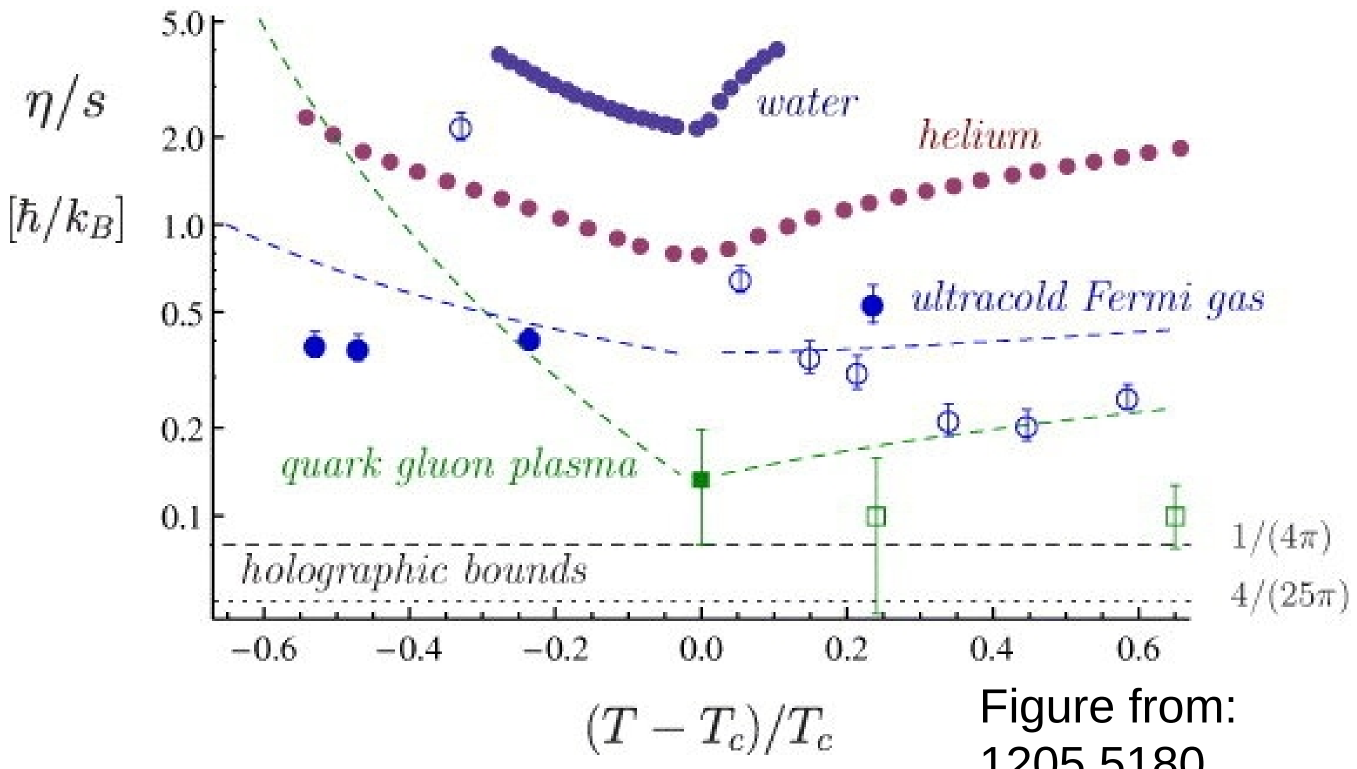


Figure from: 1205.5180

Question:
spin polarization in strongly coupled fluid w/o quasi-particle?

Lessons from quantum kinetic theory

$$S^i \sim \left(\beta\omega^i + \epsilon^{ijk}\hat{p}_l\hat{p}_k\beta\sigma_{jl} + \partial_i\beta\right)$$

vorticity shear T-grad

free theory in local equilibrium state

Hidaka, Pu, Yang 2016, 2017

$$\Delta S^i \sim F(p,T)\epsilon^{ijk}\hat{p}_k\hat{p}_l\sigma_{jl}$$

similarly for T-grad, but not for vorticity!

$$\delta f \sim \frac{\partial_i f^{\rm leq}}{g^4} \quad \eta \sim \frac{1}{g^4}$$

dependence on coupling cancels at LO!

interacting theory in steady (off-equilibrium) state

SL, Wang, 2022, 2024

Holographic model for fermions

$$S = i \int d^{D+1}x \sqrt{-g}\bar{\psi}\left(\Gamma^M \nabla_M - m\right)\psi,$$

Iqbal, Liu 2009

bulk Dirac fermion ⟷ boundary Weyl fermion

spin 1/2 lump of quark-gluon

$$\psi = \begin{pmatrix} \psi_R \\ \psi_L \end{pmatrix}$$

$$\psi_L = Az^{-m} + Bz^{m+1} \qquad \psi_R = Cz^{1-m} + Dz^m$$

source for m>0

$$-D = G_R(\omega, \vec{p})\, A.$$

Fluid-gravity background

$$ds^2 = -2u_\mu(x)dx^\mu dr - r^2 f(b(x)r)u_\mu u_\nu dx^\mu dx^\nu + r^2 P_{\mu\nu}dx^\mu dx^\nu$$ local equilibrium

$$+ 2r^2 bF(br)\sigma_{\mu\nu}dx^\mu dx^\nu + \frac{2}{3}ru_\mu u_\nu \partial_\lambda u^\lambda dx^\mu dx^\nu - ru^\lambda \partial_\lambda(u_\mu u_\nu)dx^\mu dx^\nu$$ steady state

Bhattacharyya et al 2008

$$O(\partial^0) \qquad O(\partial)$$

$$T^{\mu\nu} = (\pi T)^4 (\eta^{\mu\nu} + 4u^\mu u^\nu) - 2(\pi T)^3 \sigma^{\mu\nu}$$

η

local equilibrium steady state

σ_{ij} ~~$\partial_0 b = \frac{1}{3}\partial_i u_i$~~ $\partial_i b = \partial_0 u_i$

naively spin respond to shear & T-grad only

Spectral function generalities

$$\rho_{\alpha\beta} = \int d^4x e^{iP\cdot x} \langle \{\chi_\alpha(x), \chi^\dagger_\beta(0)\}\rangle$$

$$S_{R,\alpha\beta} = \int d^4x e^{iP\cdot x} i\theta(x^0) \langle \{\chi_\alpha(x), \chi^\dagger_\beta(0)\}\rangle$$

$$S_{A,\alpha\beta} = -\int d^4x e^{iP\cdot x} i\theta(-x^0) \langle \{\chi_\alpha(x), \chi^\dagger_\beta(0)\}\rangle$$

$$\rho = S_R - S_A = 2\mathrm{Im} S_R$$

for state invariant under T-reversal

true for local equilibrium state
false for steady state

Equilibrium spectral function

$$S_R(P) = \frac{\Delta_+(P)}{2}(1 + \hat{p} \cdot \sigma) + \frac{\Delta_-(P)}{2}(1 - \hat{p} \cdot \sigma)$$

particle plasmino

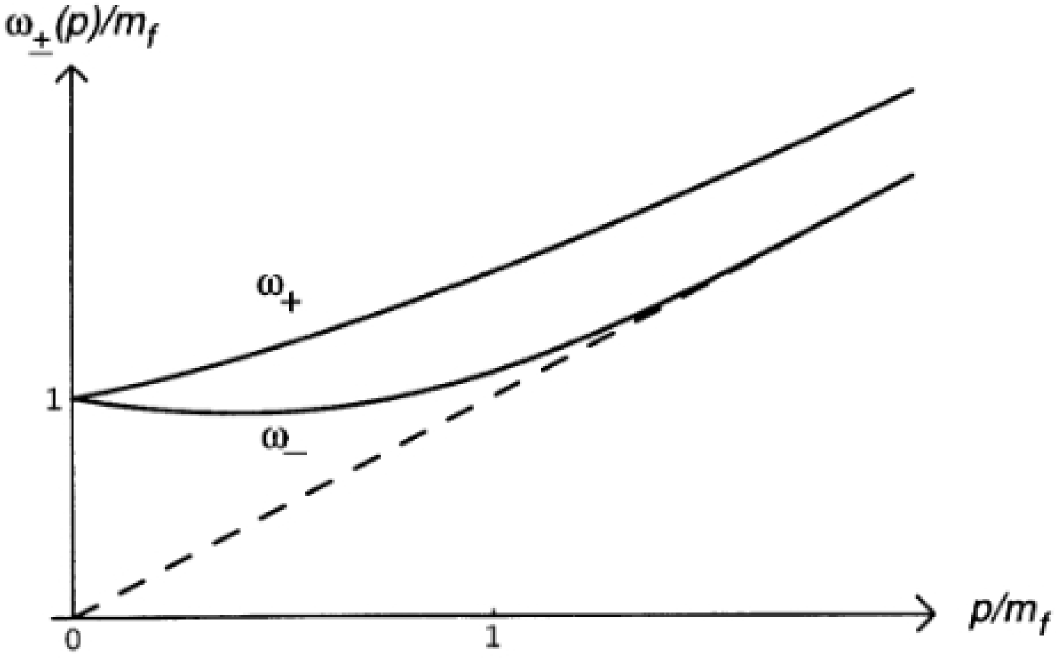
$$\mathrm{Im}\Delta_+(\omega, p) = \mathrm{Im}\Delta_-(-\omega, p).$$

oddness of spectral function

Equilibrium spectral function: weak coupling

$$S_R(P) = \frac{\Delta_+(P)}{2}(1 + \hat{p}\cdot\sigma) + \frac{\Delta_-(P)}{2}(1 - \hat{p}\cdot\sigma)$$

particle plasmino



$$\mathrm{Im}\Delta_\pm \sim \delta(p_0 - \omega_\pm)$$

poles

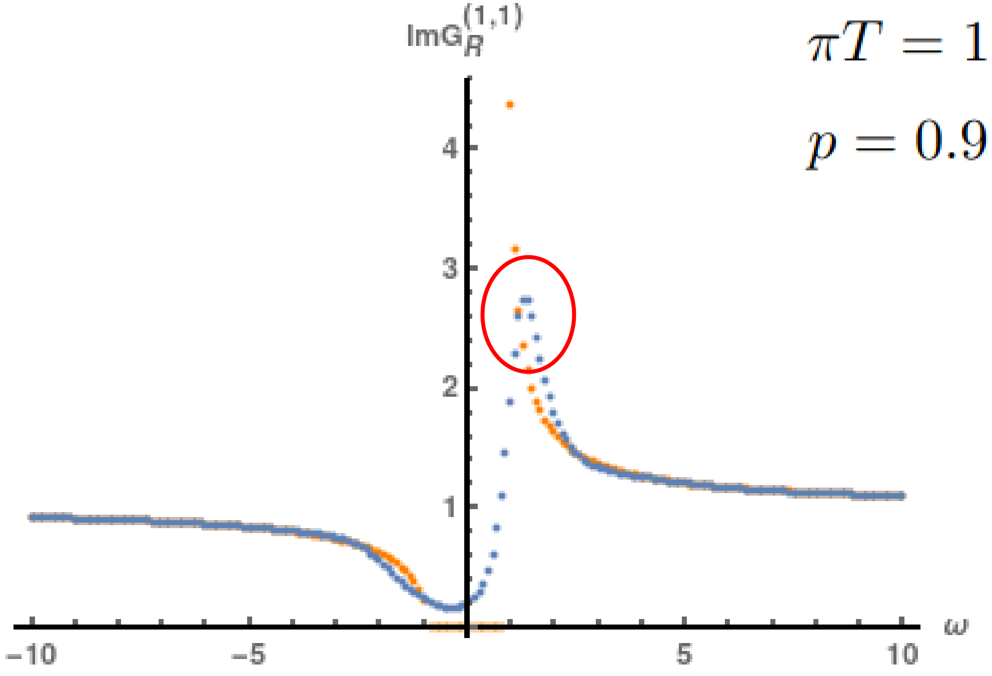
Equilibrium spectral function: strong coupling

$$S_R(P) = \frac{\Delta_+(P)}{2}(1+\hat{p}\cdot\sigma) + \frac{\Delta_-(P)}{2}(1-\hat{p}\cdot\sigma)$$

p along z

particle plasmino

$G_R^{1,1} = \Delta_+ \quad G_R^{2,2} = \Delta_-$



$\pi T = 1$

$p = 0.9$

blue: equilibrium
orange: vacuum

singularity in vacuum

$\mathrm{Im}\Delta_+ \sim (\omega - p)^{-1/2}$ Iqbal, Liu 2009

particle peak in medium
no plasmino

Seo, Sin, Zhou, 2013

Structure of hydrodynamic gradient correction

$$S_R(P) = \frac{\Delta_+(P)}{2}(1+\hat{p}\cdot\sigma) + \frac{\Delta_-(P)}{2}(1-\hat{p}\cdot\sigma)$$

$$\delta S_R(P) = \frac{\delta\Delta_+(P)}{2}(1+\hat{p}\cdot\sigma) + \frac{\delta\Delta_-(P)}{2}(1-\hat{p}\cdot\sigma)$$
$$+ A(P)\omega_\perp^i\sigma^i + B(P)\epsilon^{ijk}p_j\frac{\partial_k b}{b}\sigma^i + C(P)\epsilon^{ijk}\hat{p}_k\hat{p}_l\sigma_{jl}\sigma^i$$
$$+ D(P)\epsilon^{ijk}\hat{p}_j\omega_k\sigma^i + F(P)\hat{p}_j\sigma_{ij}\sigma^i + G(P)\frac{\partial_\perp^i b}{b}\sigma^i$$

$\delta\Delta_\pm$ correction to spectral density

A, B, C, D, F, G: correction to spin polarization

Splitting of corrections

$$ds^2 = -2u_\mu(x)dx^\mu dr - r^2 f(b(x)r)u_\mu u_\nu dx^\mu dx^\nu + r^2 P_{\mu\nu} dx^\mu dx^\nu$$ local equilibrium

$$+ 2r^2 bF(br)\sigma_{\mu\nu} dx^\mu dx^\nu + \frac{2}{3} r u_\mu u_\nu \partial_\lambda u^\lambda dx^\mu dx^\nu - r u^\lambda \partial_\lambda (u_\mu u_\nu) dx^\mu dx^\nu$$ steady state

$$\left(\Gamma^M \nabla_M - m\right)\psi = 0$$

local equilibrium $O(\partial)$ correction to Dirac spinor

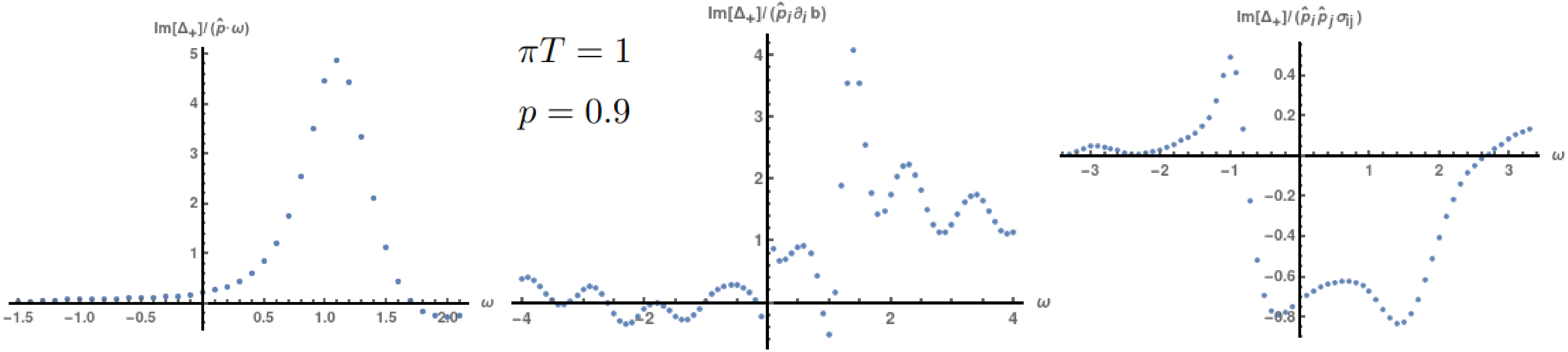
→ response to vorticity, shear, T-grad

steady state $O(\partial)$ correction to Dirac equation

→ response to shear, T-grad

Correction in local equilbrium state

$$\delta S_R(P) = \frac{\delta\Delta_+(P)}{2}(1+\hat{p}\cdot\sigma) + \frac{\delta\Delta_-(P)}{2}(1-\hat{p}\cdot\sigma)$$



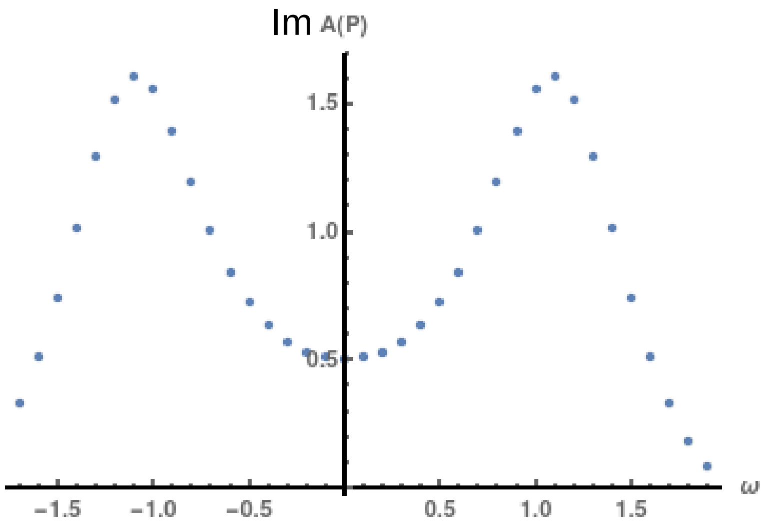
vorticity T-grad shear

Correction in local equilbrium state

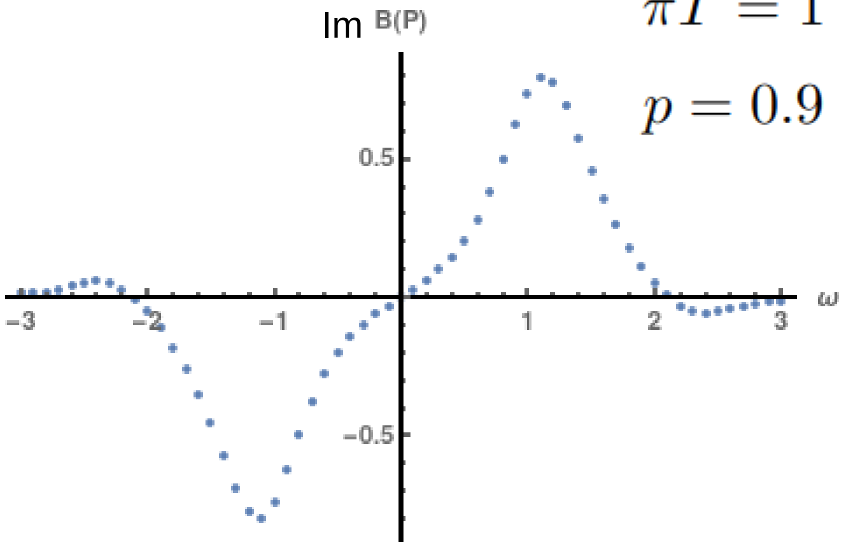
$$\delta S_R(P) = A(P)\omega_\perp^i \sigma^i + B(P)\epsilon^{ijk} p_j \frac{\partial_k b}{b} \sigma^i + C(P)\epsilon^{ijk} \hat{p}_k \hat{p}_l \sigma_{jl} \sigma^i$$

$\pi T = 1$

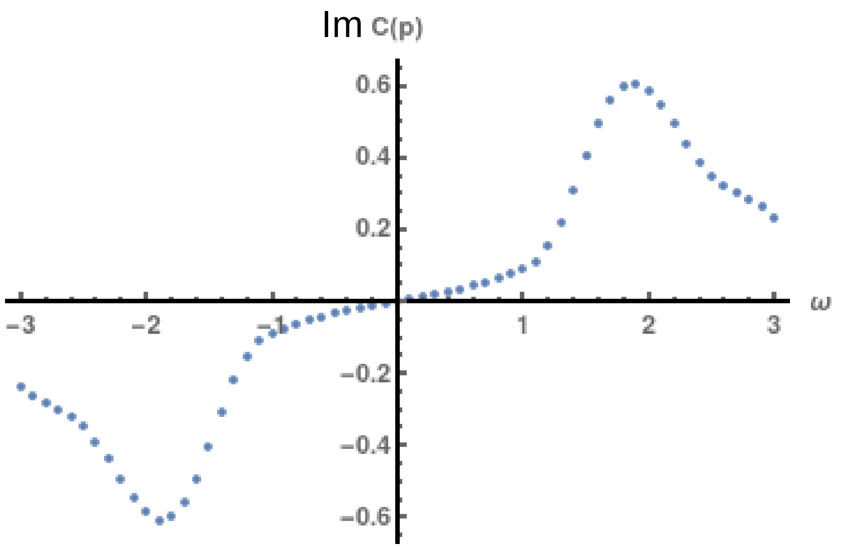
$p = 0.9$



vorticity



T-grad



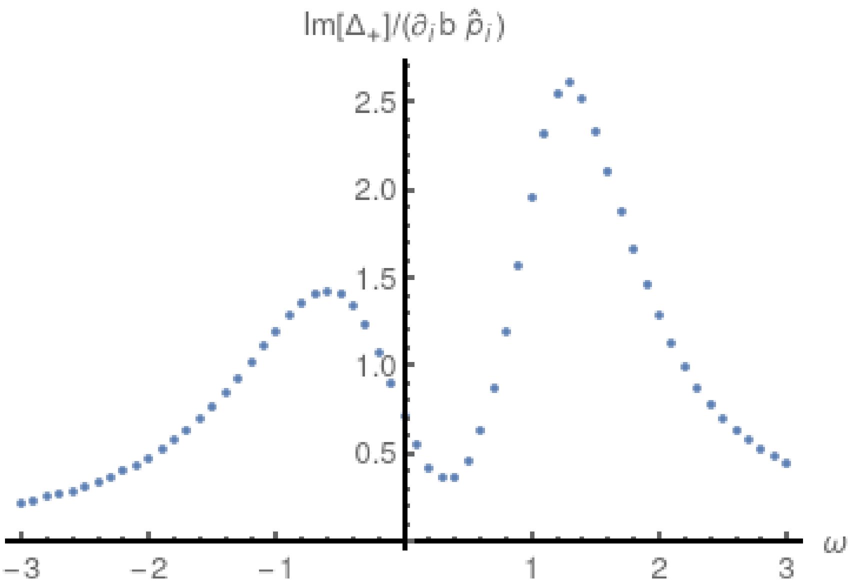
shear

Correction in steady state

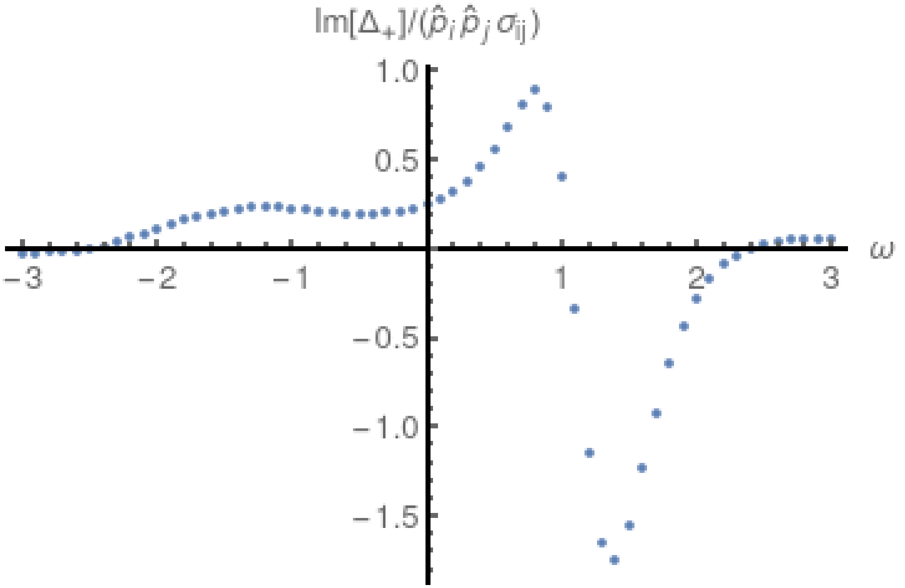
$$\delta S_R(P) = \frac{\delta\Delta_+(P)}{2}(1+\hat{p}\cdot\sigma) + \frac{\delta\Delta_-(P)}{2}(1-\hat{p}\cdot\sigma)$$

$\pi T = 1$

$p = 0.9$



T-grad



shear

$S_A \neq S_R^*$

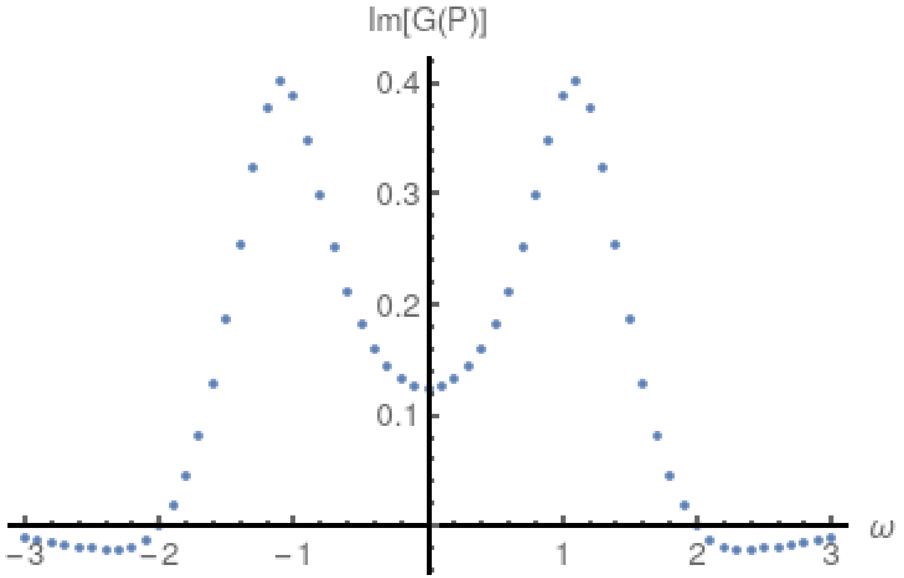
non-invariance
under T-reversal

Correction in steady state

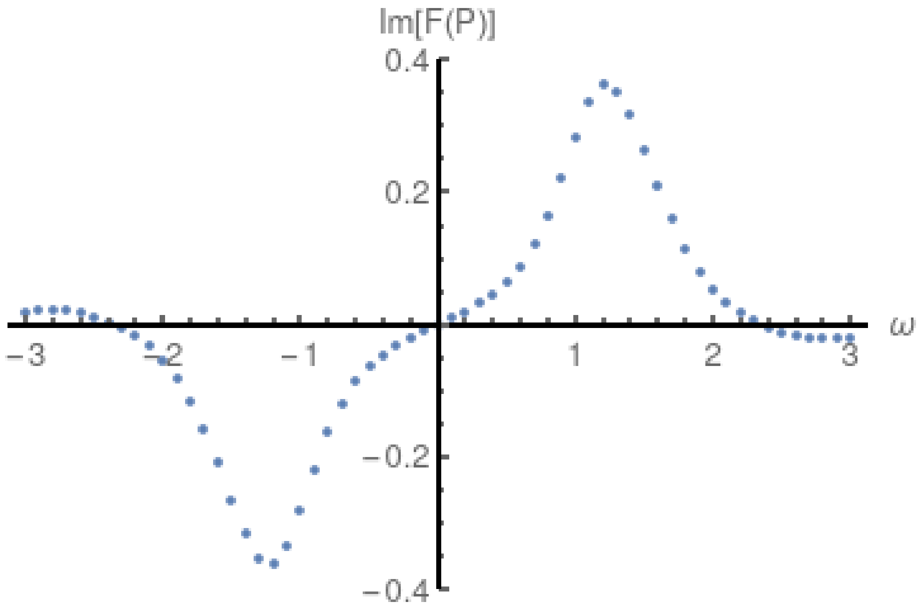
$$\delta S_R(P) = F(P)\hat{p}_j \sigma_{ij}\sigma^i + G(P)\frac{\partial_\perp^i b}{b}\sigma^i$$

$\pi T = 1$

$p = 0.9$



T-grad



shear

Conclusion

- Spin polarization of Weyl spinor studied using bulk fermion in fluid-gravity background.
- Splitting of contributions in local equilibrium state and steady state. Spin response to all hydro gradient found.
- Non-invariance under T-reversal seen in spin-T-grad coupling in steady state.

Outlook

- Bulk fermion in Schwinger-Keldysh contour extended fluid-gravity background.

Thank you!