# Introduction to DY’s group

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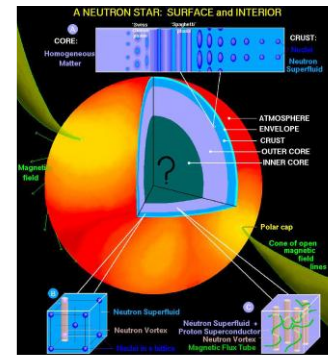
# General research interest

- To explore quantum field theories under extreme conditions such as high temperature or high density or with strong external fields.
- Physical systems in extreme conditions :

❖ From the astrophysical systems :

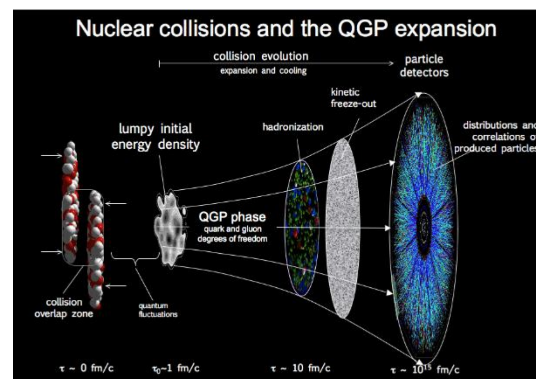

Neutron stars :

J.M. Lattimer & M. Prakash, Science 304:536-542,2004




❖ From the colliders :

Relativistic heavy ion collisions


- Focus : **Chiral** and **spin** transport in nuclear physics & astrophysics

# My group members

- Present group members : 3 postdocs


Geraint Evans (2023/09-present) :
QCD phase diagram

Haesom Sung (2025/04-present) :
heavy-ion phenomenology

Ritesh Ghosh (2025/12-present) :
QFT in extreme conditions,
heavy-ion phenomenology
(moving to Darmstadt in 2026/08 for Humboldt fellowship)

- New members (2026/05-) :

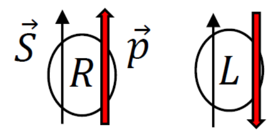
Sota Hanai (Keio Univ.) :
chiral transport theory

Nicholas Benoit (Hiroshima Univ.) :
heavy-ion phenomenology

# Quantum transport of spin and chirality

- Chiral matter formed by (approximate) massless fermions :

(e.g. light quarks in QGP)




spin momentum chirality=helicity

$\mathbf{J}_V = \mathbf{J}_R + \mathbf{J}_L$ electric current

$\mathbf{J}_5 = \mathbf{J}_R - \mathbf{J}_L$ spin current

classically:

$$\partial_\mu J^\mu_{R/L} = 0.$$

❖ Chiral anomaly : $\partial_\mu J^\mu_{R/L} = \pm \frac{\mathbf{E}\cdot\mathbf{B}}{4\pi^2} \Longrightarrow \partial_\mu J^\mu_5 = \frac{\mathbf{E}\cdot\mathbf{B}}{2\pi^2}$

S. L. Adler, Phys. Rev., 177, 2426, 1969.
J. S. Bell, & R. Jackiw, Nuovo Cim., A60, 47, 1969.

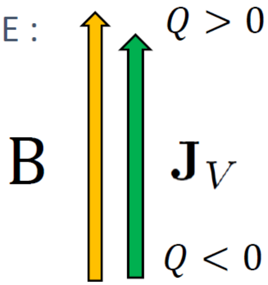
❖ Chiral magnetic/vortical effects (CME/CVE) :

$$J^\mu_{R/L} = \pm \frac{\mu_{R/L}}{4\pi^2} B^\mu \pm \left( \frac{T^2}{12} + \frac{\mu^2_{R/L}}{4\pi^2} \right) \omega^\mu$$

(in thermal equilibrium)

chiral imbalance :
$\mu_5 = \mu_R - \mu_L > 0$

CME :




CVE :
vorticity : $\boldsymbol{\omega} = \frac{1}{2} \nabla \times \boldsymbol{v}$

- Axial Ward identity for massive fermions : (resummed LLs, weak inhomogeneous E )

$$-iq_\mu \tilde{J}^\mu_5(q) = \frac{\boldsymbol{B}\cdot\tilde{\boldsymbol{E}}(q)}{2\pi^2} w\left( \frac{q_\parallel^2}{m^2}, \frac{|\boldsymbol{q}_\perp|^2}{|2\boldsymbol{B}|} \right) \xrightarrow[|q_\parallel^2| \ll m^2 \ll |e\boldsymbol{B}|]{} \frac{\boldsymbol{B}\cdot\tilde{\boldsymbol{E}}(q_\perp)|\boldsymbol{q}_\perp|^2}{4\pi^2|\boldsymbol{B}|}$$

K. Hattori, K. Mameda, T. Uchiyama, DY, in preparation

(modulation assisted anomaly pumping!)

- Vorticity affects the Wess-Zumino-Witten terms in ChPT.

G. Evans, N. Yamamoto, DY, PRD 113 (2026) 3, 036029 see the talk by Geraint

# Chiral kinetic theory

- Most of physical systems associated with chiral phenomena are “not” fully in equilibrium.
- Studying non-equilibrium transport is nontrivial.
- Mean-field approx. for quasi-particles : relativistic kinetic theory

$$q^\mu \Delta_\mu f(q,X) = q^\mu \mathcal{C}_\mu[f], \quad \Delta_\mu = \partial_\mu + F_{\nu\mu}\frac{\partial}{\partial q^\nu}. \Longrightarrow \partial_\mu J^\mu_{V/5} = 0, \quad \partial_\mu T^{\mu\nu} = 0.$$

Boltzmann equation — charge & momentum conservation

- Quantum corrections such as **magnetic-moment coupling**, **chiral anomaly** etc. are missing.

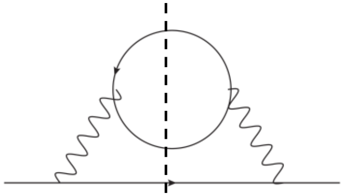
❑ Chiral kinetic theory (CKT) :

$$\delta\left(q^2 - \hbar\frac{B\cdot q}{q\cdot n}\right)\left\{\left[q\cdot\Delta + \hbar\frac{S^{\mu\nu}_{(n)}E_\mu}{(q\cdot n)}\Delta_\nu + \hbar S^{\mu\nu}_{(n)}(\partial_\mu F_{\rho\nu})\partial^\rho_q\right]f^{(n)}_q - \tilde{\mathcal{C}}\right\} = 0,$$

$$\tilde{\mathcal{C}} = q\cdot\mathcal{C} + \hbar\frac{S^{\mu\nu}_{(n)}E_\mu}{(q\cdot n)}\mathcal{C}_\nu + \hbar S^{\alpha\beta}_{(n)}\left((1-f^{(n)}_q)\Delta_\alpha\Sigma^<_\beta - f^{(n)}_q\Delta_\alpha\Sigma^>_\beta\right).$$

M. Stephanov & Y. Yin, PRL. 109, 162001 (2012)
D. T. Son & N. Yamamoto, PRL. 109, 181602 (2012)
J.-W. Chen, et al., PRL. 110, 262301 (2013)
D. T. Son & N. Yamamoto, PRD. 87, 085016 (2013)
Y. Hidaka, S. Pu, DY, PRD 95, 091901 (2017), PRD 97, 016004 (2018)
Review : Y. Hidaka, S. Pu, Q, Wang, DY, PPNP 127, 103989 (2022)

$$\Longrightarrow \partial_\mu J^\mu_{R/L} = \pm\frac{\mathbf{E}\cdot\mathbf{B}}{4\pi^2}$$



e.g., 2-2 scattering

✓ The covariant form with both background EM fields and collision term can be derived from quantum field theory!

# Chiral transport in CCSN

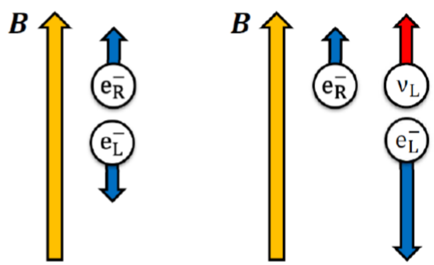
- Neutrino absorption (weak int.) : $\bar{\Gamma}_q^{\lessgtr} \approx \bar{\Gamma}_q^{(0)\lessgtr} + \bar{\Gamma}_q^{(\omega)\lessgtr}(q\cdot\omega) + \bar{\Gamma}_q^{(B)\lessgtr}(q\cdot B)$,

$\nu_{\rm L}^{\rm e}(q) + {\rm n}(k) \rightleftharpoons {\rm e_L}(q') + {\rm p}(k')$

N. Yamamoto & DY, APJ 895 (2020), 1

vorticity & magnetic field corrections :
breaking spherical symmetry & axisymmetry

- **Effective CME** from neutrino radiation (far from equilibrium) : N. Yamamoto, DY, PRL 131, 012701 (2023)




(a) $\boldsymbol{j}_B = \boldsymbol{0}$ (b) $\boldsymbol{j}_B \neq \boldsymbol{0}$

$$j_B^\mu(x) \approx e^2 \int \frac{{\rm d}^4 q}{(2\pi)^3} \frac{\delta(q^2)}{q_0} \left(B^\mu q\cdot\partial_q - q\cdot B\partial_{\bar{q}}^\mu\right) \delta f_{\rm W}^{(\rm e)} = \xi_B B^\mu,$$

$\Delta t \nearrow \Rightarrow \xi_B \nearrow$

(neutrino emission time)

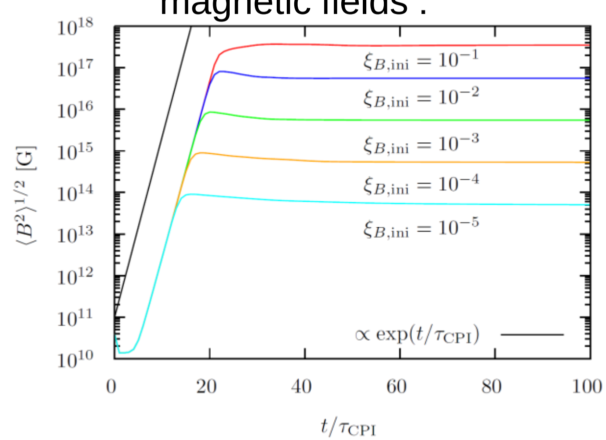
- Chiral plasma instability :

M. Joyce, M. E. Shaposhnikov, PRL **79**, 1193 (1997)
Y. Akamatsu, N. Yamamoto, PRL 111, 052002 (2013)

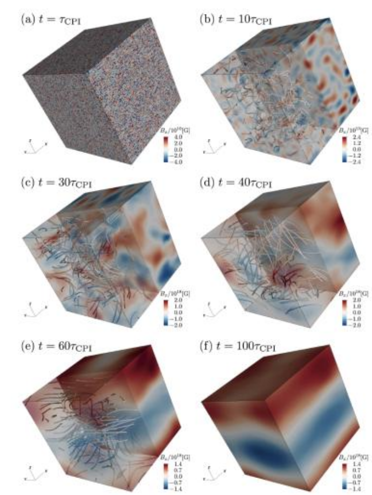
Helicity conservation :

axial charge ⇒ magnetic helicity

Dynamical amplification of magnetic fields :



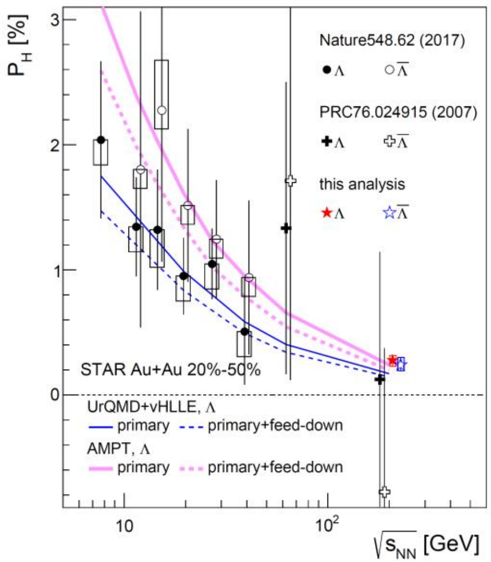

Inverse cascade :



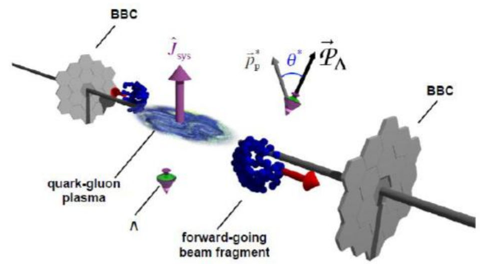

J. Matsumoto, N. Yamamoto, DY, PRD 105, 123029 (2022)
reviews : K. Kamada, N. Yamamoto, DY, PPNP 129 (2023) 104016

# Global & local Λ polarization in HIC

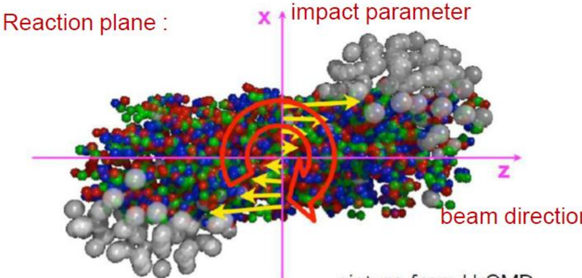
- The global polarization of Λ hyperons was measured in heavy ion collisions
  ⇨ spin polarization of the strange quarks




L. Adamczyk et al. (STAR), Nature 548, 62 (2017)




Reaction plane :




picture from UrQMD

❖ Successfully described by the **global equilibrium** assumption from **vorticity** :

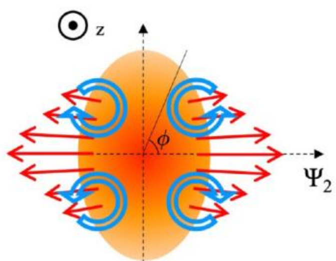
F. Becattini, et al., Ann. Phys. 338, 32 (2013)
R. Fang, et al., PRC 94, 024904 (2016)

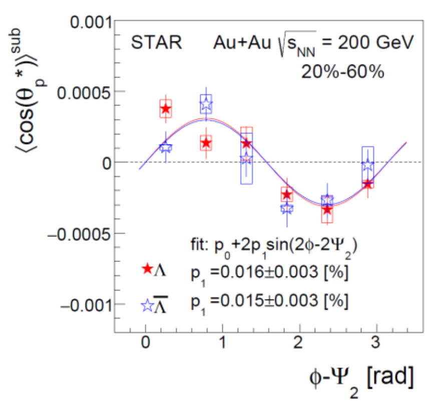
$$\mathcal{P}^\mu(p) = \frac{\int d\Sigma_x \cdot p f_p^{(0)}(1 - f_p^{(0)})\epsilon^{\mu\nu\rho\sigma} p_\nu \omega_{\rho\sigma}}{8M_\Lambda \int d\Sigma_x \cdot p f_p^{(0)}}, \quad \omega_{\rho\sigma} = \frac{1}{2}\left(\partial_\rho\left(\frac{u_\sigma}{T}\right) - \partial_\sigma\left(\frac{u_\rho}{T}\right)\right).$$

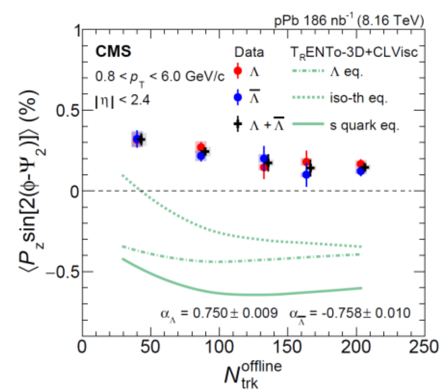
thermal vorticity

- More complicated for local pol :

new effects needed!



# QKT for relativistic massive fermions

- **Quantum kinetic theory (QKT)** : tracking the **axial-current density** in phase space
  ⇨ (spin is no longer aligned with momentum)

❑ Spin pol. spectra : $\mathcal{P}^\mu(\boldsymbol{p}) = \frac{\int d\Sigma\cdot p\,\mathcal{J}^\mu_5(\boldsymbol{p},x)}{2m\int d\Sigma\cdot\mathcal{N}(\boldsymbol{p},x)}, \quad \mathcal{J}^\mu_5(\boldsymbol{p},x)\propto\int dp_0\mathcal{A}^\mu(p,x)$

$\mathcal{A}^\mu = 2\pi\Big(\delta(p^2-m^2)\tilde{a}^\mu + \hbar\delta'(p^2-m^2)e\tilde{F}^{\mu\nu}p_\nu f_V\Big)$ ( $\tilde{a}^\mu(p,x)$: effective spin four vector)

- **Axial kinetic theory (AKT)** : scalar/axial-vector kinetic eqs. (SKE/AKE)

K. Hattori, Y. Hidaka, DY, PRD 100 (2019), 096011
DY, K. Hattori, Y. Hidaka, JHEP 20, 070 (2020)
Review : Y. Hidaka, S. Pu, Q, Wang, DY, PPNP 127, 103989 (2022)

➢ SKE : $p\cdot\Delta f_V = \mathcal{C}[f_V], \quad \Delta_\mu = \partial_\mu + eF_{\nu\mu}\partial^\nu_p.$

standard Boltzmann (Vlasov) eq. entangled $f_V$ & $\tilde{a}^\mu$ $\widehat{AB} = A^< B^> - A^> B^<.$

➢ AKE : $p\cdot\Delta\tilde{a}^\mu + eF^{\nu\mu}\tilde{a}_\nu - \frac{\hbar}{2}\epsilon^{\mu\nu\rho\sigma}p_\rho(\partial_\sigma eF_{\beta\nu})\partial^\beta_p f_V = q_\nu\widehat{\Sigma^\nu_V\tilde{a}^\mu} + \cdots + \frac{\hbar}{2}\epsilon^{\mu\nu\rho\sigma}q_\nu(\Delta_\sigma\widehat{\Sigma_{V\rho})f_V},$

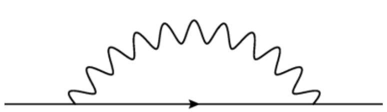
✓ Dynamically generate spin pol. from EM fields or spin-orbit int. in collisions!

❑ **Self-energy corrections** on QKT : N. Yamamoto, DY ,PRD 109, 056010 (2024)
S. Fang, S. Pu, DY, PRD 109, 034034 (2024), PRD 112 (2025) 1, 014038.

We mostly consider $\Sigma^{\lessgtr}_\mu$ related to $\mathrm{Im}(\Sigma^{\mathrm{r/a}}_\mu)$ for scattering. How about $\bar{\Sigma}_\mu = \mathrm{Re}(\Sigma^{\mathrm{r/a}}_\mu)$ ?

$q^2 = 0 \to q^2 = 2q\cdot\bar{\Sigma} = m^2_{\mathrm{th}}$ ⟹ $F^{eff}_{\mu\nu}$ : $\bar{F}_{\mu\nu} = \partial_{[\mu}\bar{\Sigma}_{V\nu]}$ effective background EM fields

**(change onshell condition)**



⟹ neutrino spin Hall effect

radioactive corrections on quark spin polarization in QGP

# Spin transport from color fields

- QKT for quarks with **chromo-electromagnetic** fields : DY, JHEP 06, 140 (2022) B. Müller, DY, PRD 105, L011901 (2022)

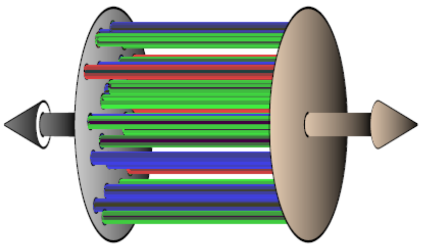
⇨ spin transport from **color-field correlators** for color-singlet observables

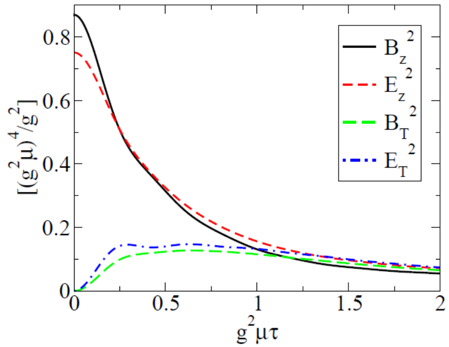
- Strong color fields from the **glasma** phase in HIC :

Reviews : F. Gelis et al., Ann.Rev.Nucl.Part.Sci.60:463-489,2010
J. Berges et al., Rev. Mod. Phys. 93 (2021) 3, 035003

$$D_\mu \boxed{F^{\mu\nu,a}} = \delta^{\nu+}\,\delta(x^-)\boxed{\rho^a(x_\perp)}$$

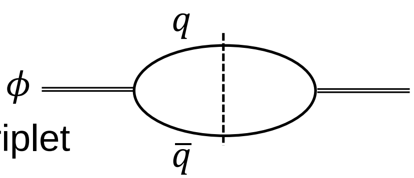
soft gluons hard partons






T. Lappi, PLB 643 (2006) 11-16

❑ Spin alignment of vector mesons from quark coalescence :




spin triplet

$$\delta\rho_{00} = \rho_{00} - \frac{1}{3} \sim \langle \boldsymbol{\mathcal{P}}^a \cdot \boldsymbol{\mathcal{P}}^a \rangle \sim \langle \boldsymbol{B}^a \cdot \boldsymbol{B}^a \rangle$$

spin correlation from color fields affects the spin-dependent spectra of vector mesons A. Kumar, B. Müller, DY, PRD 107, 076025 (2023) DY, PRD 110, 056005 (2025)

❑ Local spin polarization of $\Lambda$ :

$$\boldsymbol{\mathcal{P}} \sim \boxed{(\boldsymbol{p}\times\boldsymbol{u})(\langle \boldsymbol{B}^a\cdot\boldsymbol{B}^a\rangle + \langle \boldsymbol{E}^a\cdot\boldsymbol{E}^a\rangle)}$$

H. Sung, B. Müller, DY, arXiv: 2507.23210

see the talk by Haesom

# Ongoing projects & future prospect

- **QKT** is a powerful theoretical tool to study the spin transport and applicable with different interactions.

  ⇨ Capture the spin-orbit int. (like p-wave scattering, but from the **transport** instead of the cross section)

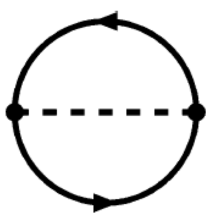
- Some ongoing projects :

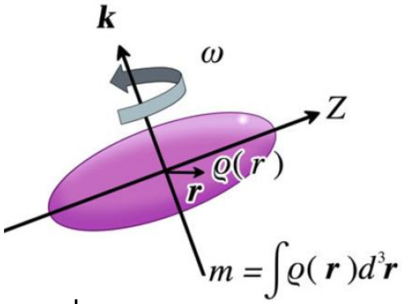
➢ Spin dependent EoS for nuclear matter :

with Ritesh, P. Gubler, T. Naito

ChEFT (one-pion exchange + iterated) :

$\bar{E} = \bar{E}_0(\rho) + a|\boldsymbol{S}|^2 + b\boldsymbol{S}\cdot\boldsymbol{\omega}$

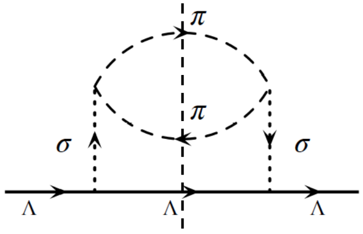





➢ Spin transport in rotational hadron gas :

with Haesom, Ritesh

Spin-orbit int. from collisions : $\mathcal{C}^{(n_r)}_{2\mu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}p^{\beta}(\partial^{\nu}\widehat{\Sigma^{\alpha}_{V})f_{V}}$




- Future goals :

➢ Simulations for the glasma effects on spin polarization

➢ Chiral transport + collective flavor oscillation for neutrinos

➢ Applying QKT to other physical systems?