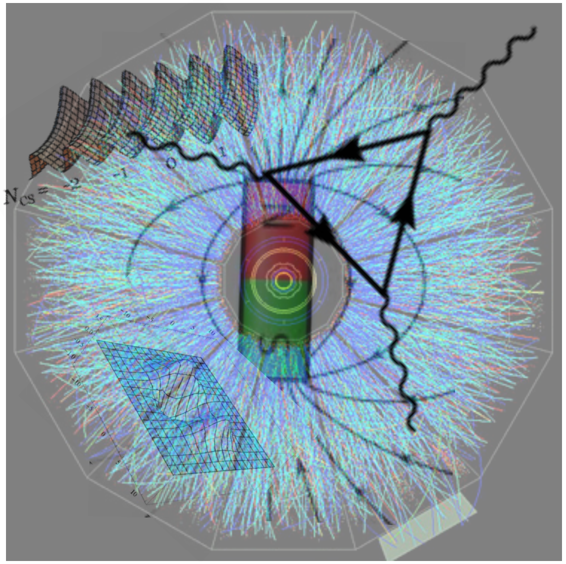
SQM2022

The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Jun 15, 2022

Novel Effects of Rotational Polarization in Relativistic Nuclear Collisions



Jinfeng Liao

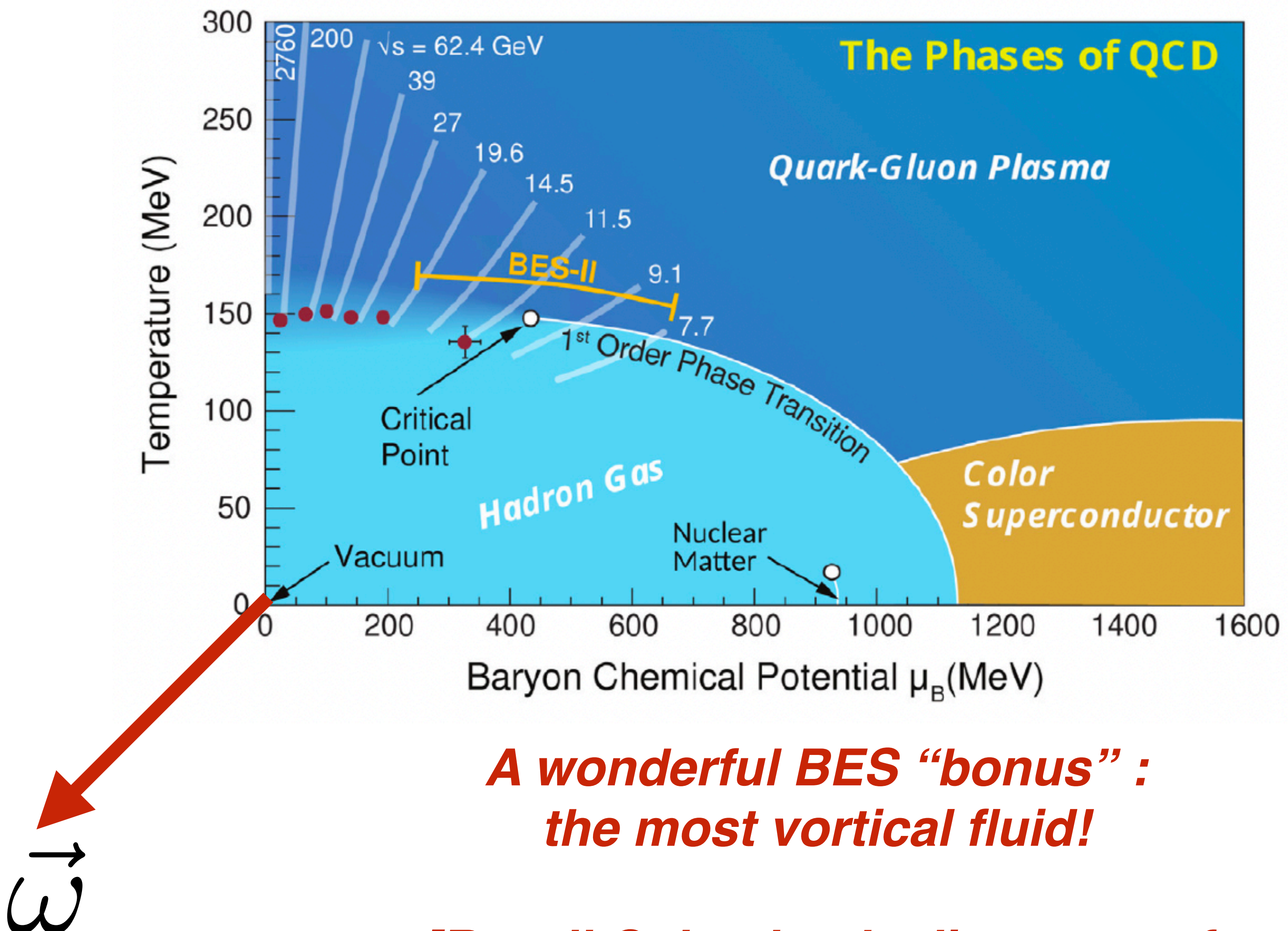
Indiana University, Physics Dept. & CEEM

INDIANA UNIVERSITY

NSF

BEST COLLABORATION

Beam Energy Scan & High Baryon Density Region



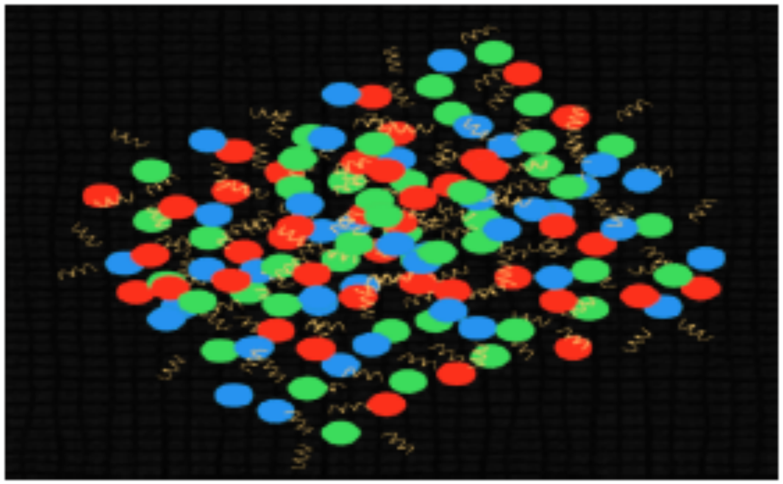
$\vec{\omega}$

A wonderful BES "bonus" :
the most vortical fluid!

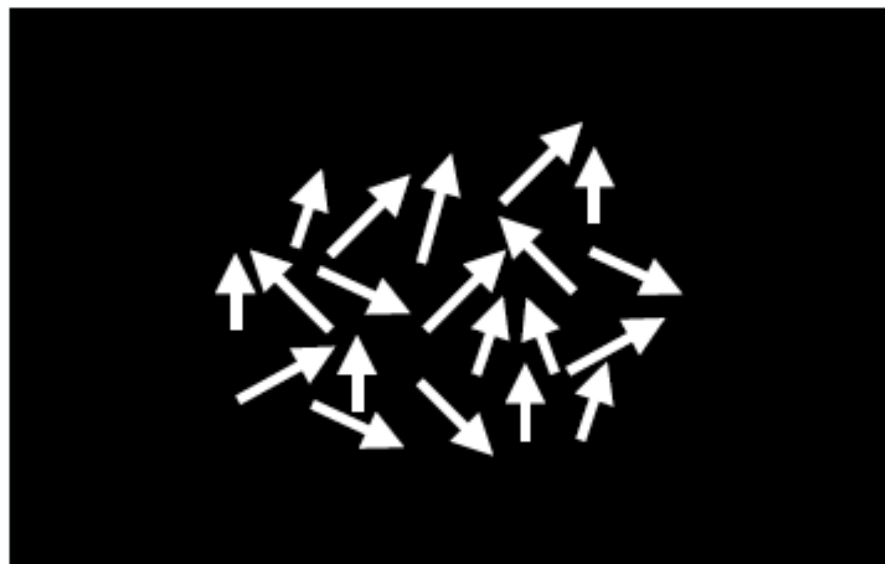
[Recall Columbus's discovery of the American continents]

A New "Handle": Rotation

A nearly perfect fluid (of energy-momentum)



What happens to the spin DoF in the fluid???



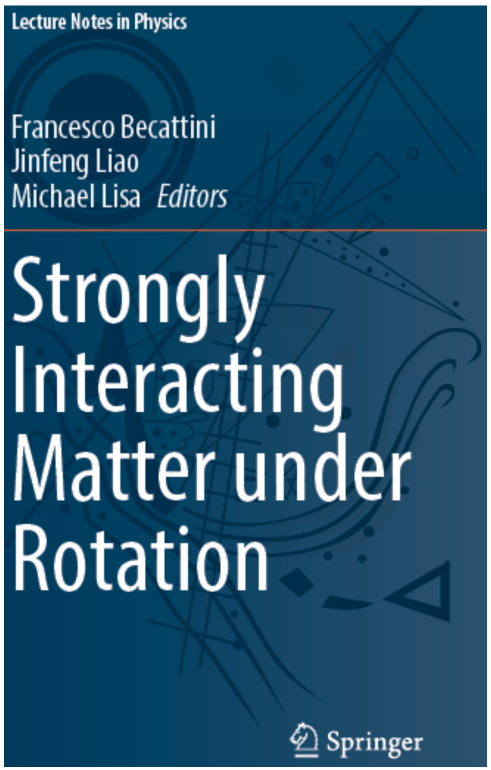
We now have a new external control on strong interaction matter: angular momentum!

Angular momentum transport, to be imaged by spin polarization.

Strongly Interacting Matter under Rotation

Opening doors for a whole new array of interesting studies:

– ***Phase structure change? Equation of state change?***
– ***Global and local polarization? Vector mesons?***
– ***Spin transport theory? Spin hydrodynamics?***
– ***Novel transport processes?***
– ***……***



A recent volume in Springer Lecture Notes in Physics!

Strongly Interacting Matter Under Rotation: An Introduction **1**

Francesco Becattini, Jinfeng Liao and Michael Lisa

Abstract

Ultrarelativistic collisions between heavy nuclei briefly generate the Quark–Gluon Plasma (QGP), a new state of matter characterized by deconfined partons last seen microseconds after the Big Bang. The properties of the QGP are of intense interest, and a large community has developed over several decades, to produce, measure, and understand this primordial plasma. The plasma is now recognized to be a strongly coupled fluid with remarkable properties, and hydrodynamics is commonly used to quantify and model the system. An important feature of any fluid is its vorticity, related to the local angular momentum density; however, this degree of freedom has received relatively little attention because no experimental signals of vorticity had been detected. Thanks to recent high-statistics datasets from experiments with precision tracking and complete kinetic coverage at collider energies, hyperon spin polarization measurements have begun to uncover the vorticity of the QGP created at the Relativistic Heavy Ion Collider. The injection of this new degree of freedom into a relatively mature field of research represents an enormous opportunity to generate new insights into the physics of the QGP. The community has responded with enthusiasm, and this book represents some of the diverse lines of inquiry into aspects of strongly interacting matter under rotation.

[arXiv:2102.00933; 2010.08937; 2009.04803; 2101.04963; 2004.04050; 2011.09974; 1908.10244; 2007.04029; 2001.00359; 2108.00586; …]

Spin & Rotational Polarization

Dirac Lagrangian in rotating frame:

$$g_{\mu\nu} = \begin{pmatrix} 1-\vec{v}^2 & -v_1 & -v_2 & -v_3 \\ -v_1 & -1 & 0 & 0 \\ -v_2 & 0 & -1 & 0 \\ -v_3 & 0 & 0 & -1 \end{pmatrix}$$

$$\vec{v} = \vec{\omega} \times \vec{x}.$$

$$\bar{\gamma}^\mu = e_a{}^\mu \gamma^a$$

$$\Gamma_\mu = \frac{1}{4} \times \frac{1}{2}[\gamma^a, \gamma^b]\Gamma_{ab\mu}$$

$$\mathcal{L} = \bar{\psi}\left[i\bar{\gamma}^\mu(\partial_\mu + \Gamma_\mu) - m\right]\psi$$

Under slow rotation:

$$\mathcal{L} = \psi^\dagger \left[i\partial_0 + i\gamma^0\vec{\gamma}\cdot\vec{\partial} + (\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times 4}\right]\psi$$

$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p} + m) - \vec{\omega}\cdot(\vec{x}\times\vec{p} + \vec{S}_{4\times 4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

Rotational polarization effect!

Spin & Rotational Polarization

Eigenstates of Dirac Hamiltonian in rotating frame:

$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p} + m) - \vec{\omega}\cdot(\vec{x}\times\vec{p} + \vec{S}_{4\times 4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

$$\longrightarrow \quad \hat{H},\ \hat{p}_z,\ \hat{\vec{p}}_t^{\,2},\ \hat{J}_z,\ \text{and}\ \hat{h}_t \equiv \gamma^5\gamma^3\vec{p}_t\cdot\vec{S}_{4\times 4}$$

$$u_{k_z,k_t,n,s} = \sqrt{\frac{E_k+m}{4E_k}}e^{ik_z z}e^{in\theta}\begin{pmatrix} J_n(k_t r) \\ s e^{i\theta}J_{n+1}(k_t r) \\ \frac{k_z - isk_t}{E_k+m}J_n(k_t r) \\ \frac{-sk_z+ik_t}{E_k+m}e^{i\theta}J_{n+1}(k_t r)\end{pmatrix},$$

$$v_{k_z,k_t,n,s} = \sqrt{\frac{E_k+m}{4E_k}}e^{-ik_z z}e^{in\theta}\begin{pmatrix} \frac{k_z - isk_t}{E_k+m}J_n(k_t r) \\ \frac{sk_z-ik_t}{E_k+m}e^{i\theta}J_{n+1}(k_t r) \\ J_n(k_t r) \\ -s e^{i\theta}J_{n+1}(k_t r)\end{pmatrix},$$

$$E_k \equiv \sqrt{k_z^2 + k_t^2 + m^2}$$

$$E = \pm E_k - (n + 1/2)\omega$$

Rotational polarization energy

[Yin Jiang, JL, PRL2016]

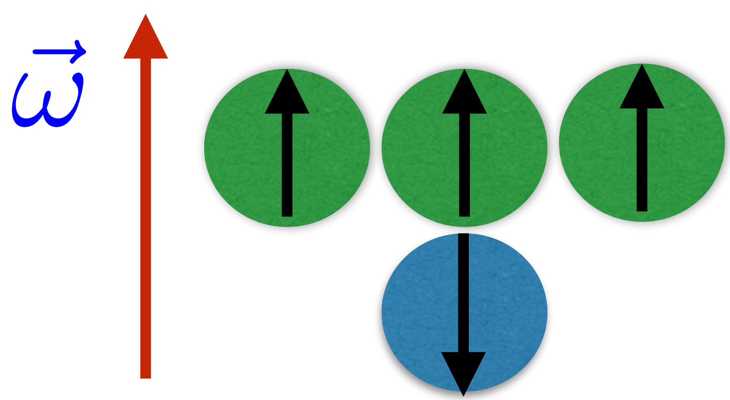
Rotational Polarization in Thermal System

$$\hat{H} = \gamma^0(\vec{\gamma}\cdot\vec{p}+m) - \vec{\omega}\cdot(\vec{x}\times\vec{p}+\vec{S}_{4\times4}) = \hat{H}_0 - \vec{\omega}\cdot\hat{\vec{J}}$$

Rotational polarization effect!

For thermally produced particles: "equal-partition" of angular momentum

$$dN \propto e^{\frac{\vec{\omega}\cdot\vec{J}}{T}}$$



Rotational Polarization in Condensed Matter

Spin hydrodynamic generation

R. Takahashi, M. Matsuo, M. Ono, K. Harii, H. Chudo, S. Okayasu, J. Ieda, S. Takahashi, S. Maekawa & E. Saitoh

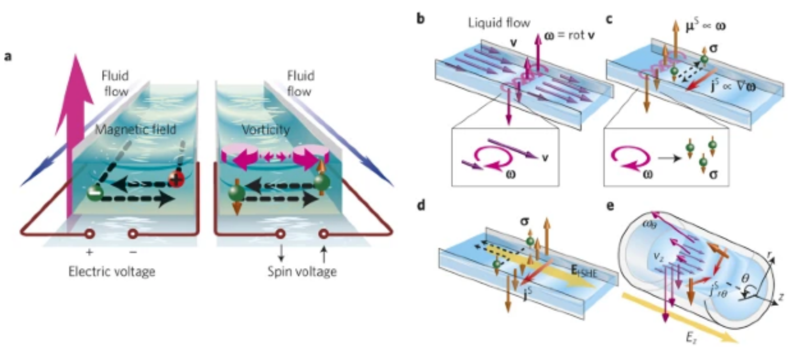
Nature Physics **12**, 52–56(2016) | Cite this article

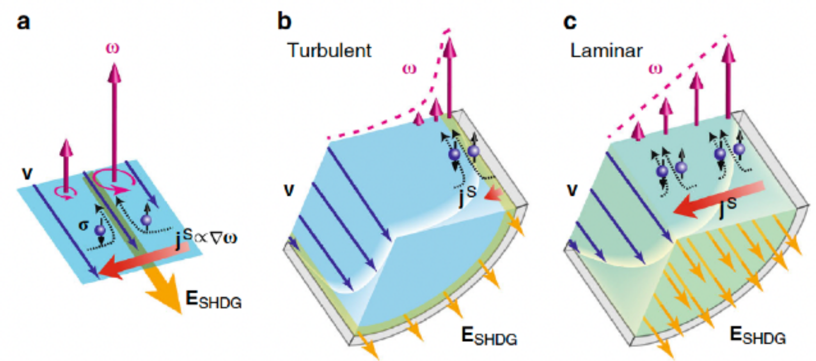
Giant spin hydrodynamic generation in laminar flow

R. Takahashi, H. Chudo, M. Matsuo, K. Harii, Y. Ohnuma, S. Maekawa & E. Saitoh

Nature Communications **11**, Article number: 3009 (2020) | Cite this article

Viscous fluid flow —> vorticity —> spin polarization



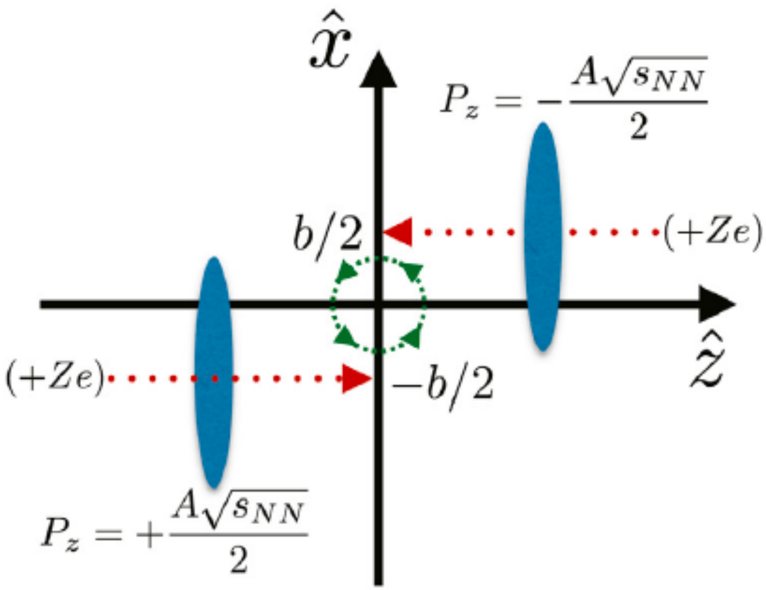


"Fluid Spintronics": Based on spin-fluid-vorticity coupling

Plan for the Rest of the Talk

- *Phenomenology of rotational polarization in heavy ion collisions: global polarization of hyperons*
- *Nontrivial effects of rotational polarization on the phase structures of matter*
- *Theoretical understanding of angular momentum in hydrodynamic framework*

Angular Momentum in Heavy Ion Collisions



Huge angular momentum for the system in non-central collisions at high energy

$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

Liang & Wang ~ 2005: spin-orbital coupling
orbital L —> spin polarization via partonic collision processes

Becattini, et al ~ 2008, 2013: A fluid dynamical scenario

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma d\Sigma \cdot p\varpi_{\nu\rho} n_F (1 - n_F)}{\int_\Sigma d\Sigma \cdot p n_F} \qquad \varpi_{\mu\nu} = \frac{1}{2}\left[\partial_\nu\left(\frac{1}{T}u_\mu\right) - \partial_\mu\left(\frac{1}{T}u_\nu\right)\right]$$

“Rotating” Quark-Gluon Plasma

$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$

PHYSICAL REVIEW C **94**, 044910 (2016)

Rotating quark-gluon plasma in relativistic heavy-ion collisions

Yin Jiang,[1] Zi-Wei Lin,[2] and Jinfeng Liao[1,3]

[1]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 North Milo B. Sampson Lane, Bloomington, Indiana 47408, USA*

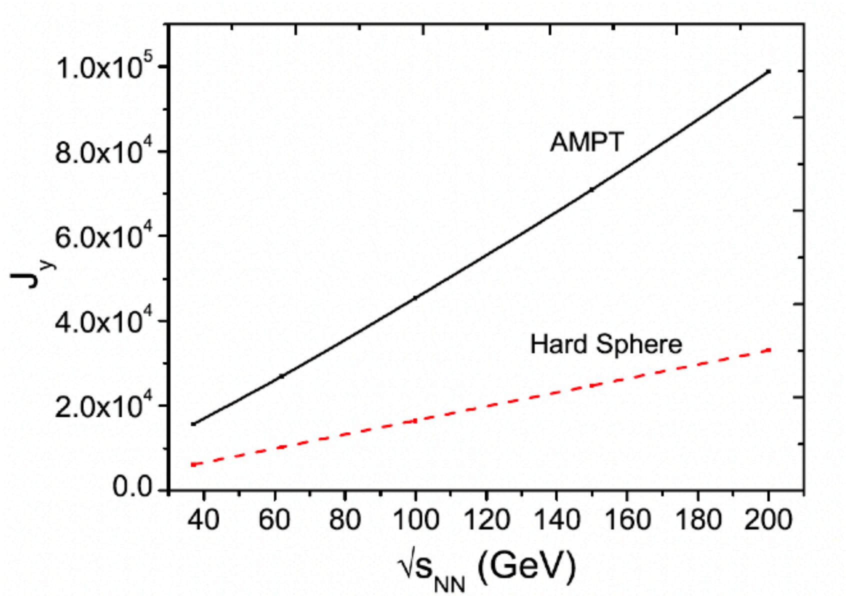
[2]*Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*

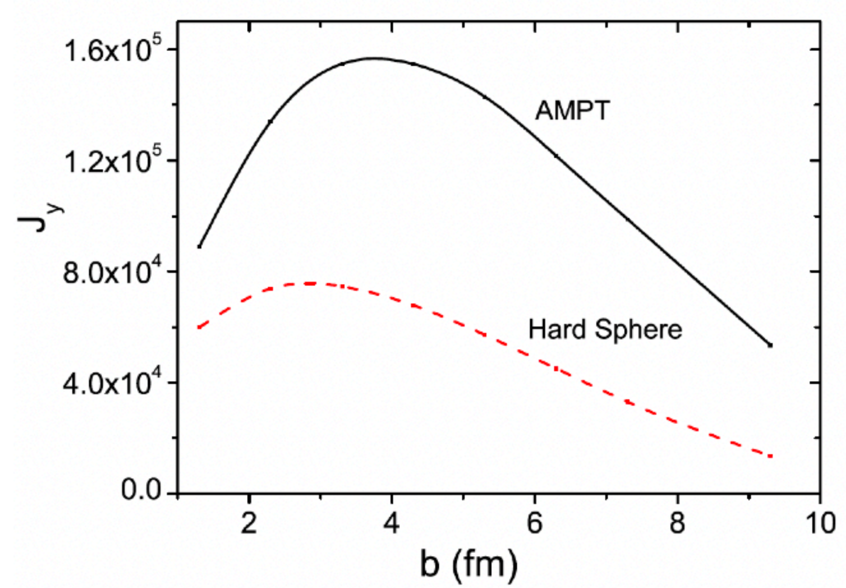
[3]*RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, New York 11973, USA*

What fraction stays in QGP?
— up to ~20%, depending on collision energy.

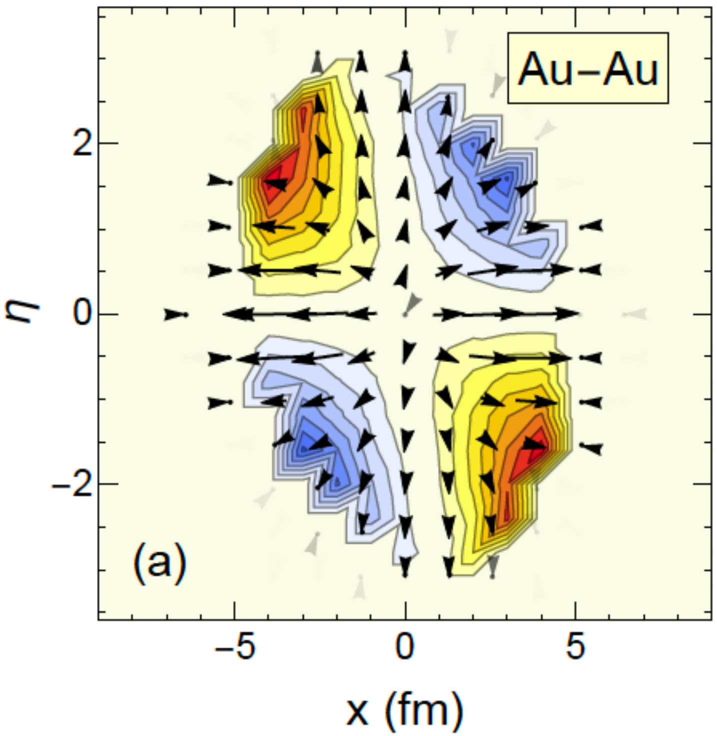
Is this portion conserved?
—YES!

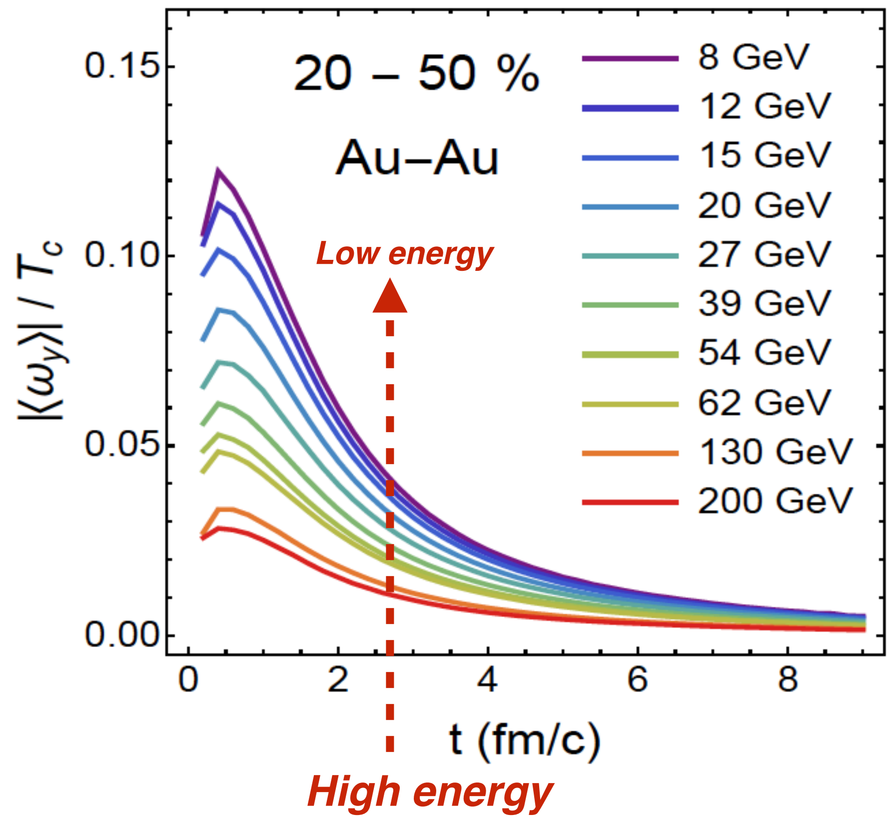
How QGP accommodates this angular momentum?
— Fluid vorticity!





Nontrivial Vorticity Structures





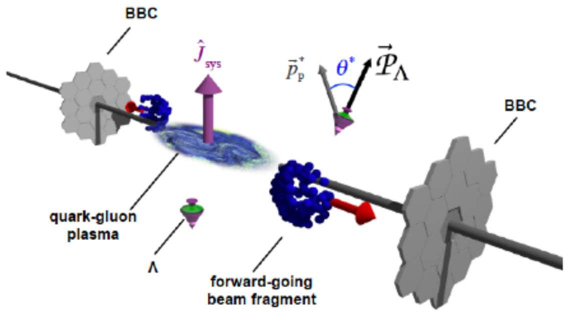
Sizable vorticity in QGP, due to the global orbital angular momentum.

It could be manifested via spin-fluid coupling.

Jiang, Lin, JL, PRC2016; Deng, Huang, PRC2016; ……

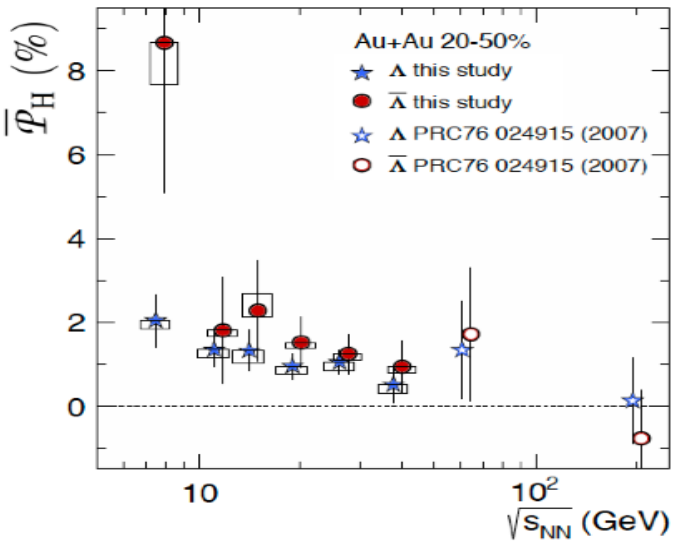
Vorticity @ O(10) GeV >> Vorticity @ O(100) GeV

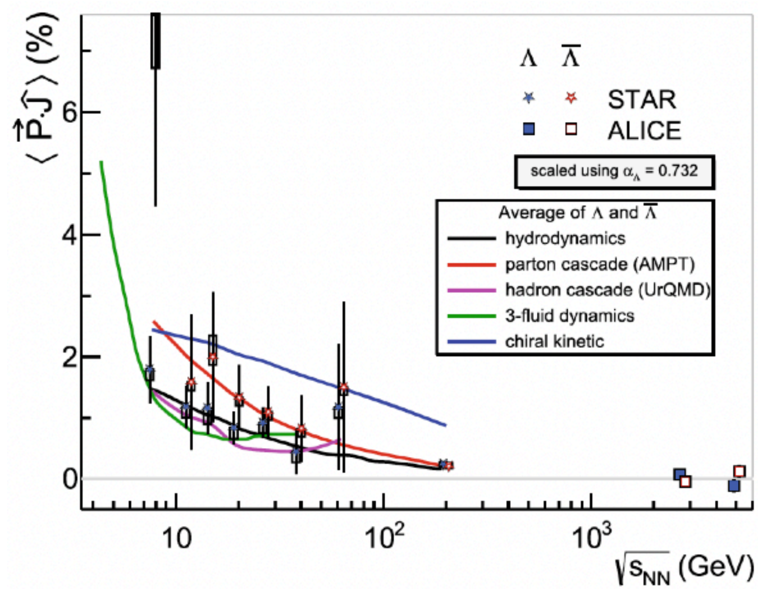
Spin Polarization in the Subatomic Swirls



STAR Collaboration, Nature 2017

The most vortical fluid!





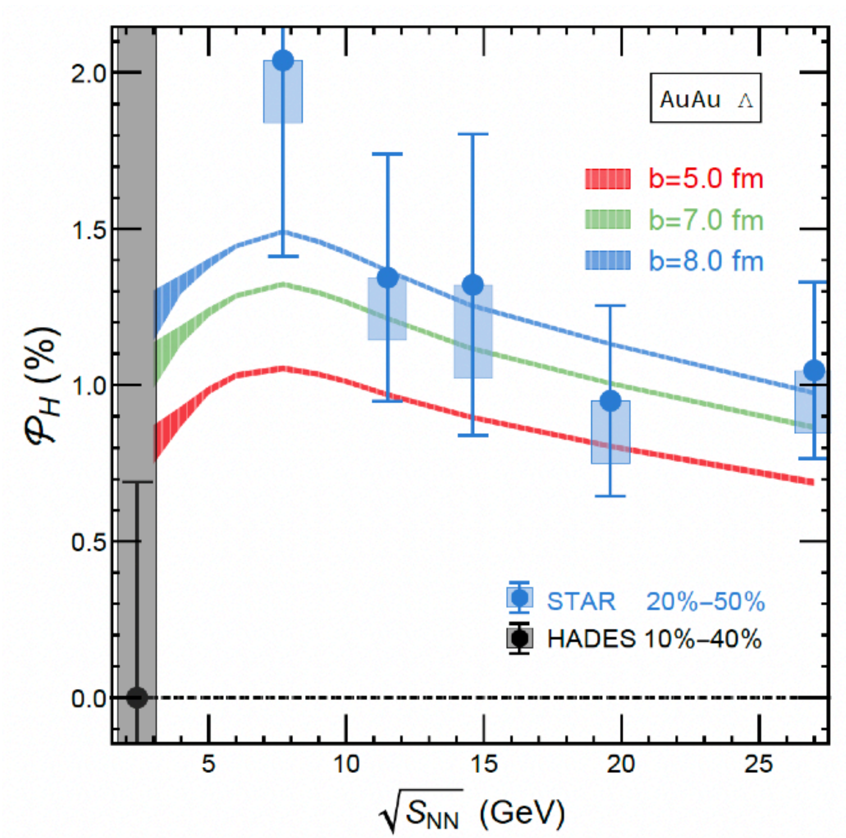
$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$

Many calculations based on hydro or transport models

Many new developments since then, see e.g. various talks at this conference

Trend of Global Polarization toward O(1) GeV

The Question: Trend for global hyperon polarization @ O(1~10) GeV ???



Yu Guo, et al, PRC2021 arXiv:2105.13481

AMPT calculations predict non-monotonic behavior in the dependence of global polarization on beam energy —> maximum around 7.7 GeV

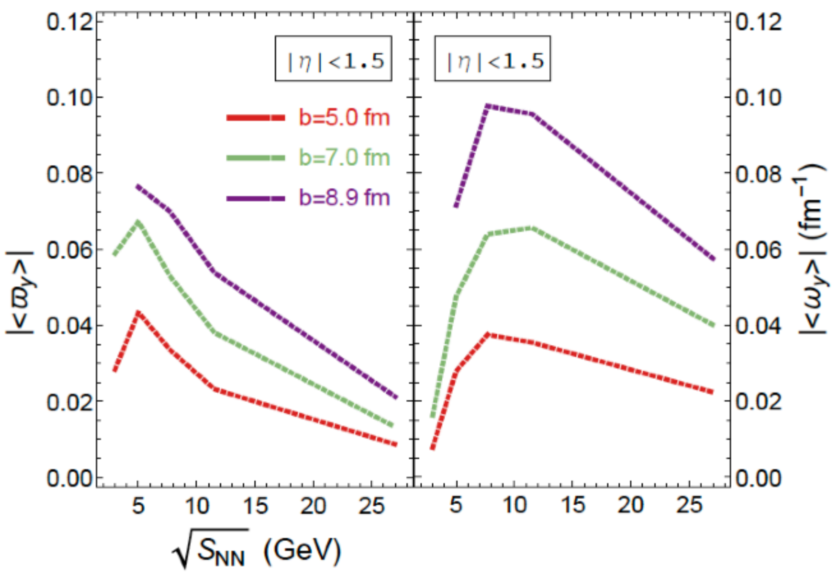
See also results for differential dependence and local polarization in the paper.

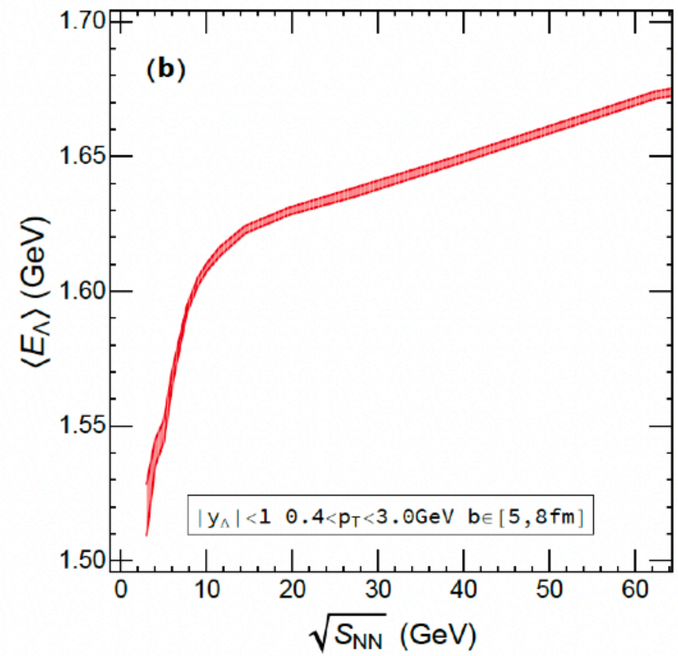
Understanding the Trend

"Thermal model" formula for spin d.o.f.

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma d\Sigma \cdot p\varpi_{\nu\rho} n_F(1-n_F)}{\int_\Sigma d\Sigma \cdot p n_F}$$

$$\varpi_{\mu\nu} = \frac{1}{2}\left[\partial_\nu\left(\frac{1}{T}u_\mu\right) - \partial_\mu\left(\frac{1}{T}u_\nu\right)\right]$$

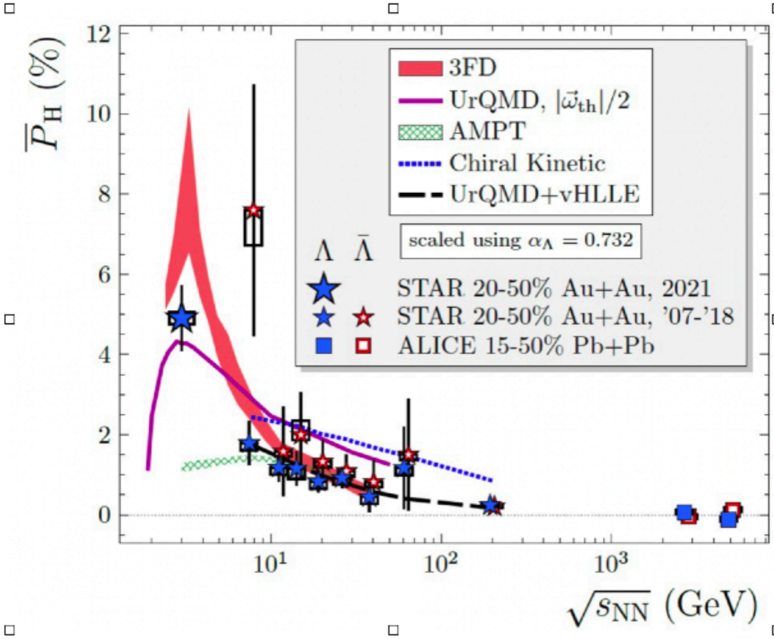




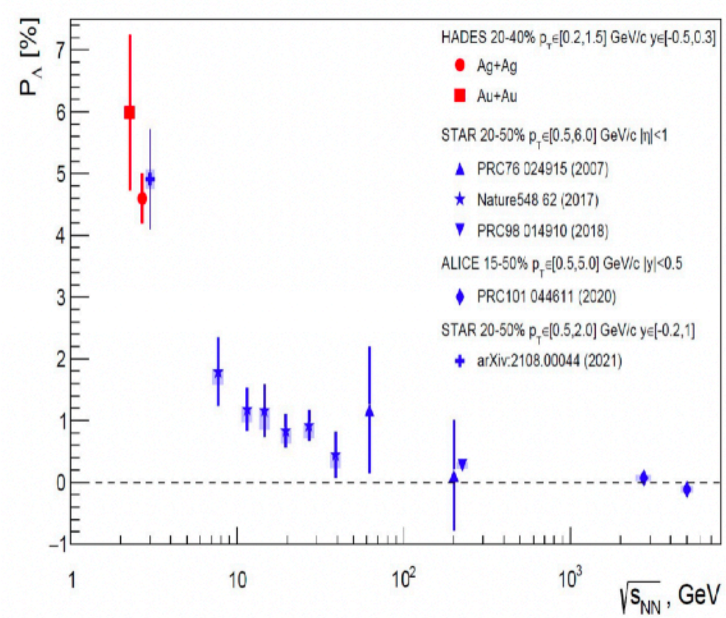
The decrease of polarization toward O(1) GeV region is due to the decrease in both vorticity and the produced hyperon energy.

STAR & HADES New Results

STAR, arXiv:2108.00044



Kornas @ Chirality 2021



Surprisingly large signal at 2.4~3 GeV …

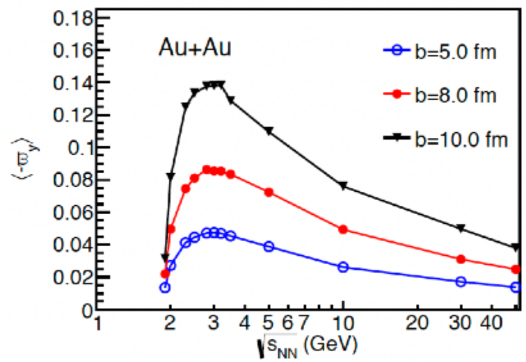
Recall that this regime is VERY close to the threshold:

$$L_y = \frac{1}{2} A b \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

Digesting the New Data

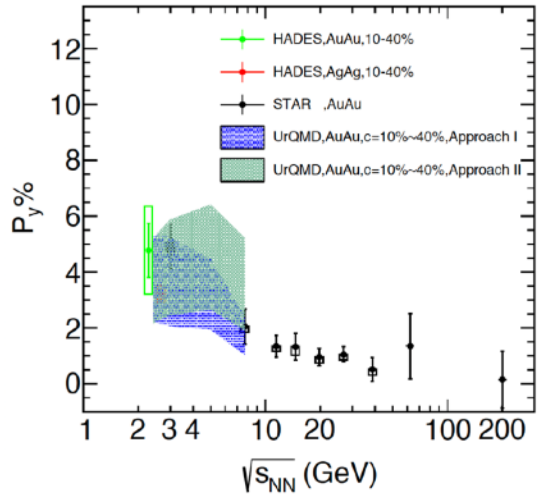
URQMD

Deng, Huang, Ma, Zhang, arXiv:2001.01371



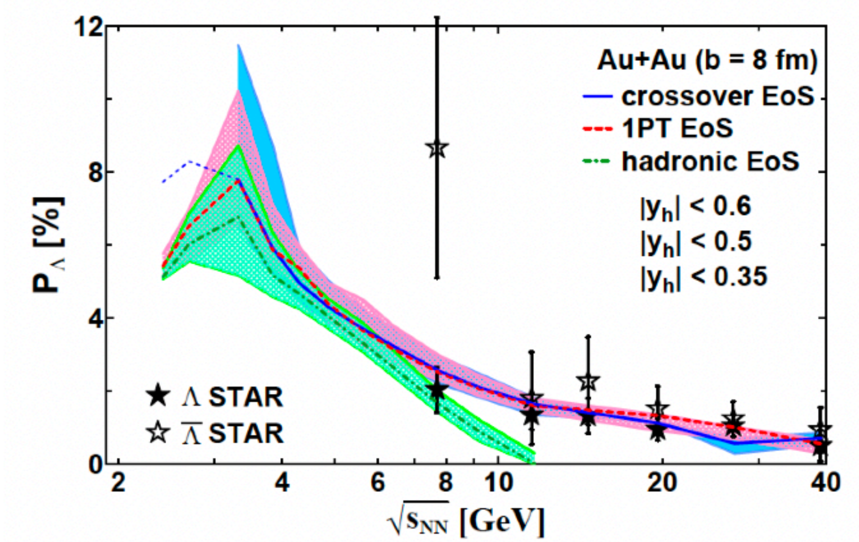
— URQMD & AMPT results for vorticity are similar.

Deng, Huang, Ma, arXiv:2109.09956



3FD

Ivanov, arXiv:2012.07597



— Many model details could be quite different and need to be understood

— Likely having more spectator-participant interactions and angular momentum transport

Digesting the New Data

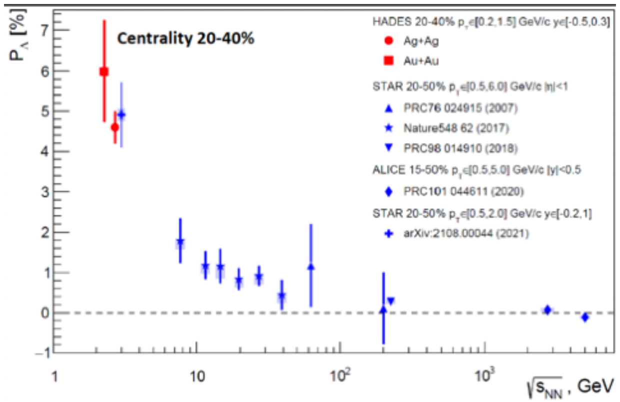
What can go "wrong" in calculating the hyperon global polarization?

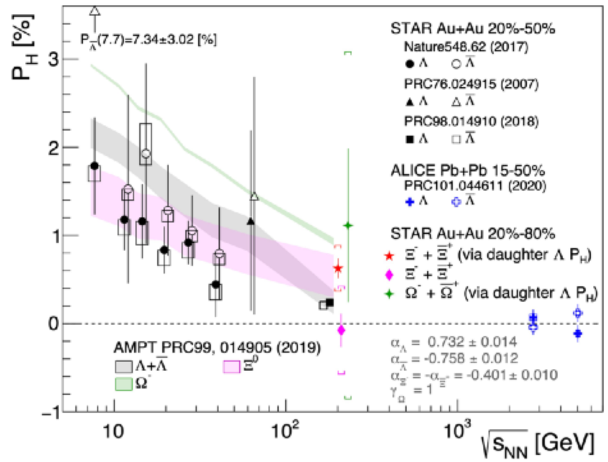
$$S^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_{\sigma} \frac{\int_{\Sigma} \mathrm{d}\Sigma \cdot p \varpi_{\nu\rho} n_F (1 - n_F)}{\int_{\Sigma} \mathrm{d}\Sigma \cdot p n_F}$$

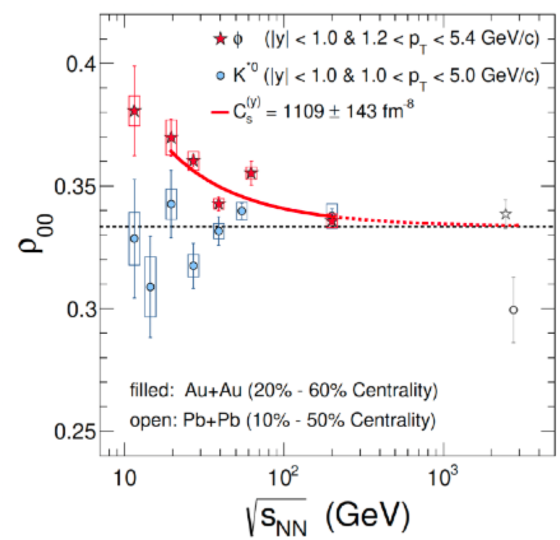
— complete failure of fluid-vorticity-polarization scenario
— substantial out-of-equilibrium correction
— inaccurate bulk fluid property (e.g. thermal vorticity)
— particle production mechanism (e.g. hadronic versus partonic)

The low AMPT signal could indicate: A shift of dominance in hyperon production from partonic coalescence to direct hadronic reaction.

Exciting New Regime @ Low Energy: Highly Polarized Strong Interaction Matter







Going from O(100)GeV down to O(1)GeV:

— the disappearance of partonic collectivity in a nearly perfect QGP fluid

— strong increase of fireball angular momentum, in opposite trend to J_y or J_y/y_beam

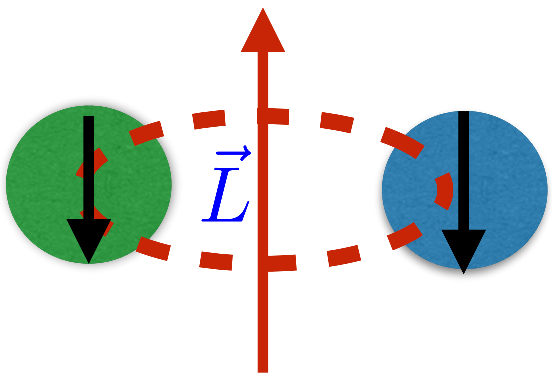
— maybe the appearance of spin collectivity in a high-polarization strong interaction fluid

Phase Structures under Rotation

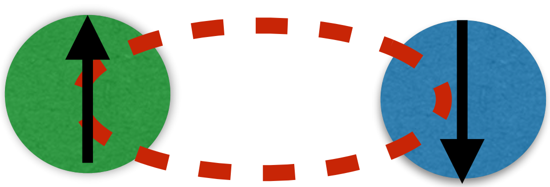
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, …

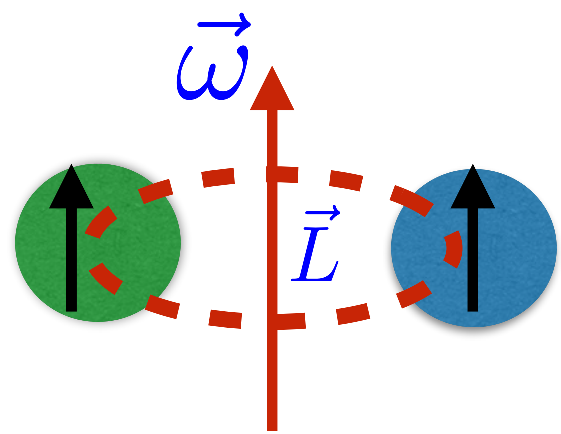
First consider scalar pairing state, with J=0.

$$\vec{S} = \vec{s}_1 + \vec{s}_2 \qquad \vec{J} = \vec{L} + \vec{S}$$



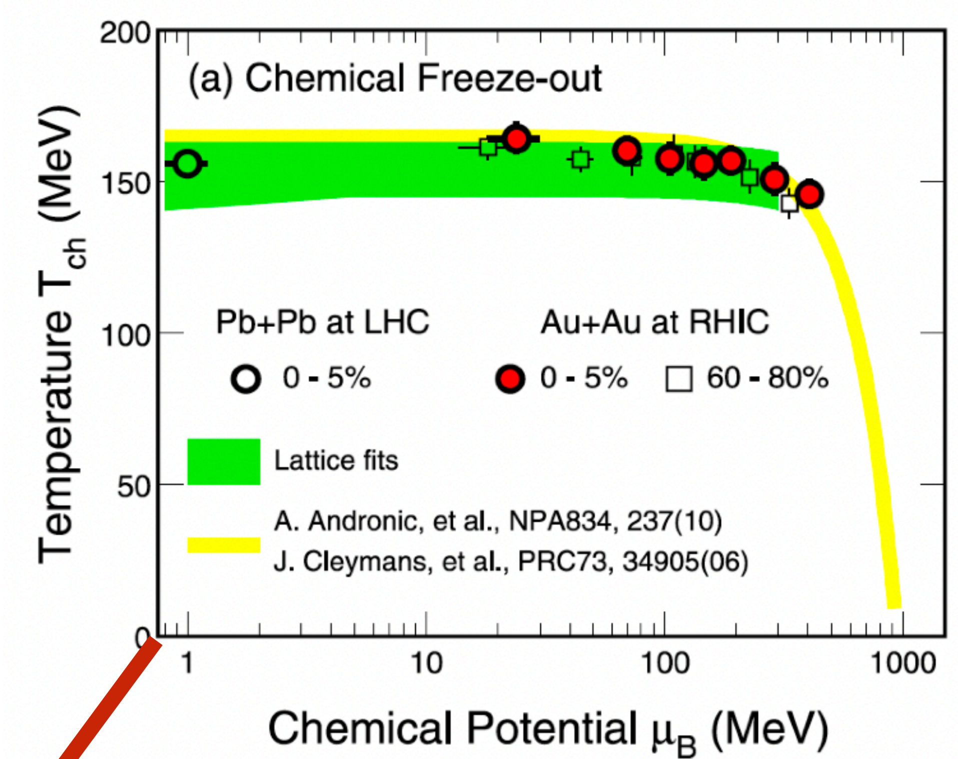
Rotation tends to polarize ALL angular momentum, both L and S, thus suppressing scalar pairing, E.g. chiral condensate and scalar diquark condensate





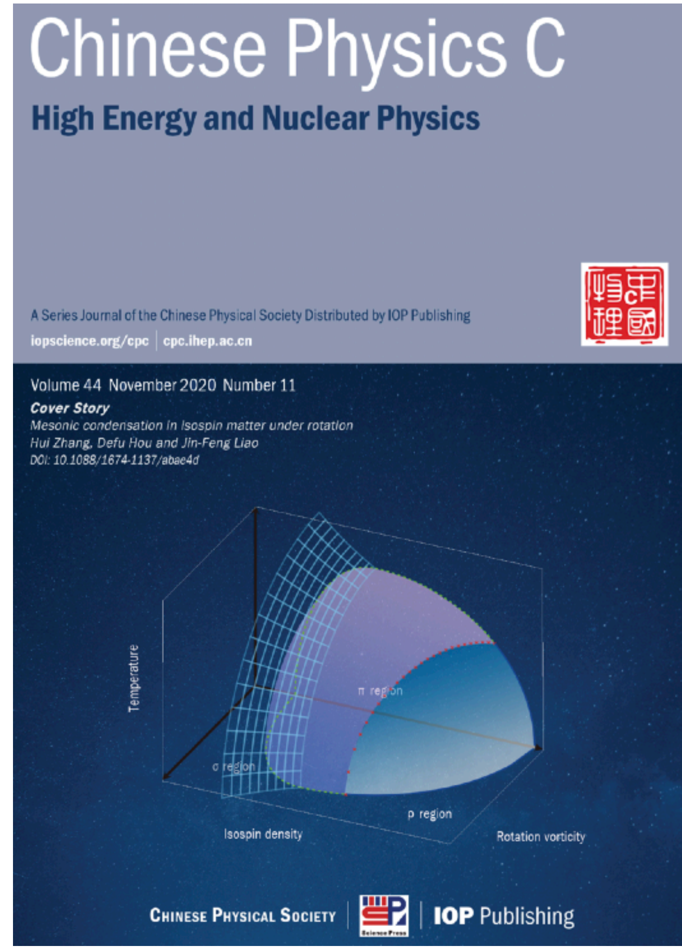
[Yin Jiang, JL, PRL2016]

Isospin Matter under Rotation



$\vec{\omega}$

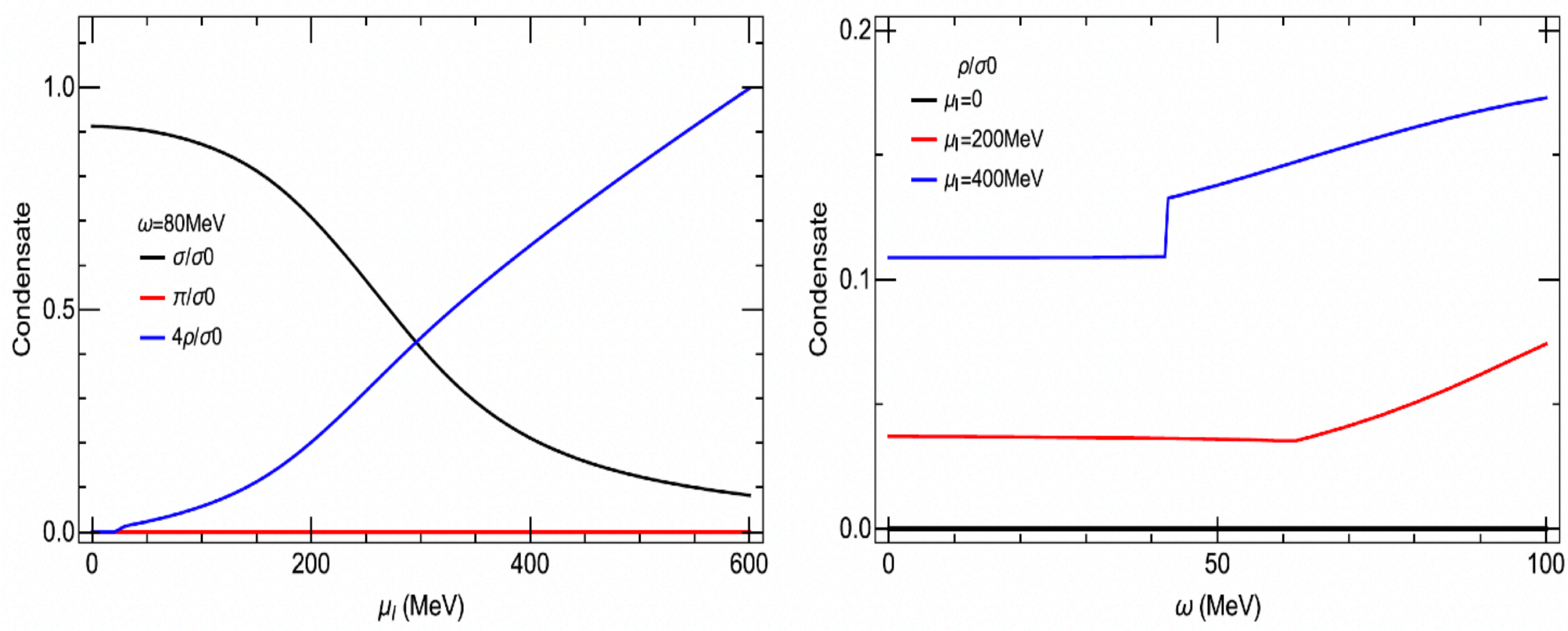
Finite isospin density for both low energy collisions and neutron stars



[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

Isospin Matter under Rotation

Vacuum: sigma condensate;
Static isospin matter: pion superfluidity;
Isospin matter under rotation: emergence of rho condensate!
This effect is more significant at high baryon density.



[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

Isospin Matter under Rotation

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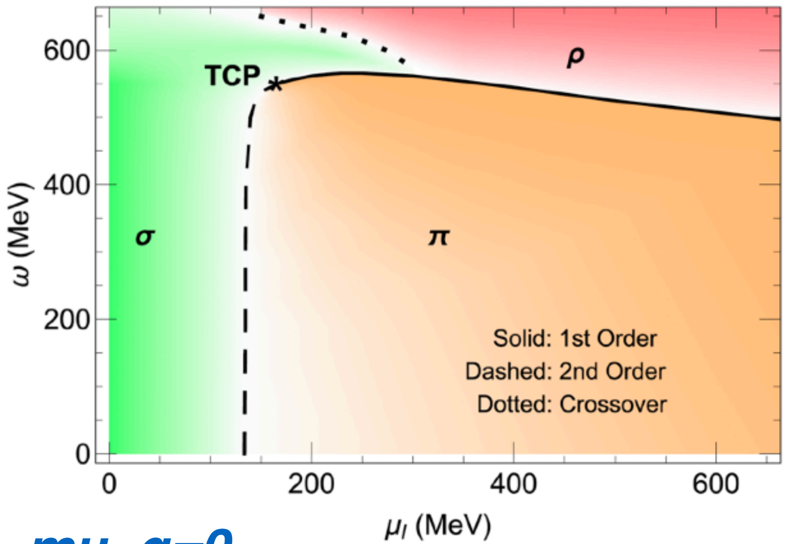
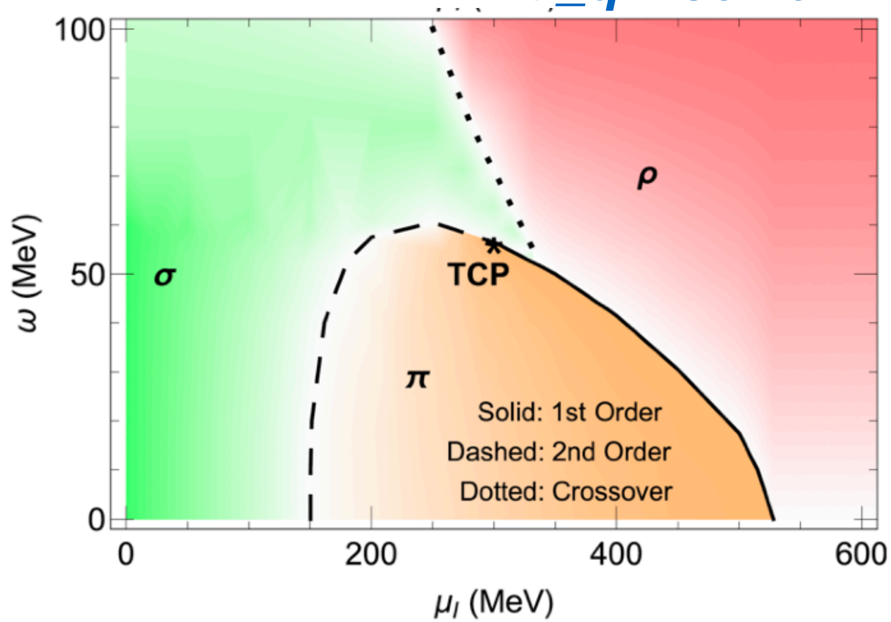


mu_q=0

mu_q=250MeV



Rich phase structures of isospin matter under rotation;
Relevant to low energy HIC or neutron star matter;
Implications for particle polarization / dileptons?!

[Hui Zhang, Defu Hou, JL, CPC44(2020)11,111001]

Relativistic Viscous Hydro with Ang. Mom.

Relativistic Viscous Hydrodynamics with Angular Momentum

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[1] *Key Laboratory of Quark and Lepton Physics(MOE) and Institute of Particle Physics, central China Normal University , Wuhan, 430079, China.*

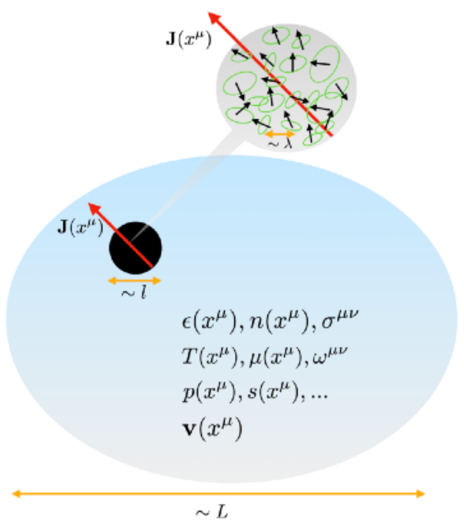
[2] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA.*

[3] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China.*

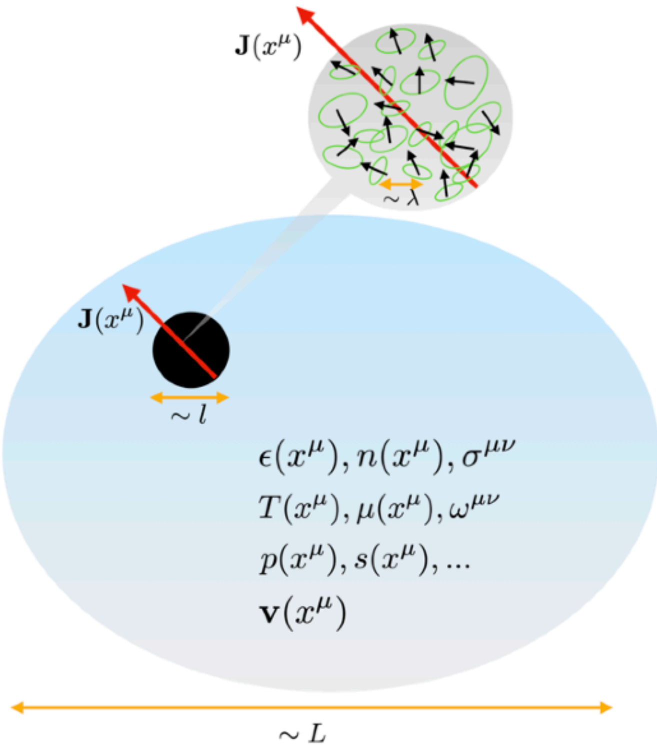
(Dated: February 25, 2022)

Hydrodynamics is a general theoretical framework for describing the long-time large-distance behaviors of various macroscopic physical systems, with its equations based on conservation laws such as energy-momentum conservation and charge conservation. Recently there has been significant interest in understanding the implications of angular momentum conservation for a corresponding hydrodynamic theory. In this work, we examine the key conceptual issues for such a theory in the relativistic regime where the orbital and spin components get entangled. We derive the equations for relativistic viscous hydrodynamics with angular momentum through Navier-Stokes type of gradient expansion analysis and find five new transport coefficients for angular momentum diffusion modes.

[arXiv:2105.04060]



Goal: Navier-Stokes Program for Ang. Mom.



$\lambda \ll l \ll L$, a coarse-graining process

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

$$\partial_\mu J^{\mu\alpha\beta} = 0,$$

$$J^{\mu\alpha\beta} = \left(x^\alpha T^{\mu\beta} - x^\beta T^{\mu\alpha}\right) + \Sigma^{\mu\alpha\beta}.$$

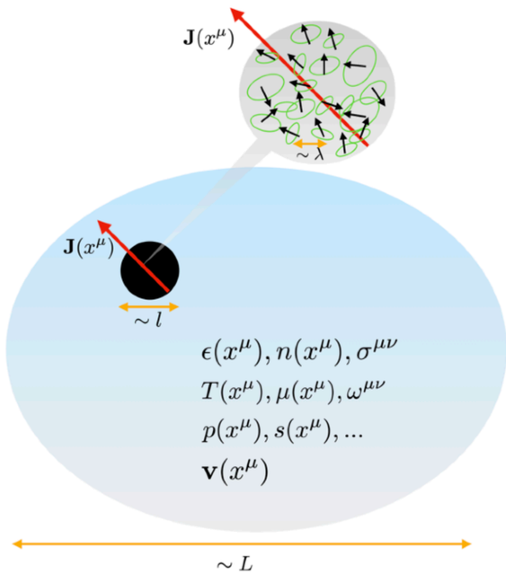
We choose to deal with only the conserved quantities, i.e. angular momentum.

Local angular momentum current $\Sigma^{\mu\alpha\beta}$

Local angular momentum density $\sigma^{\alpha\beta}(x^\mu)$

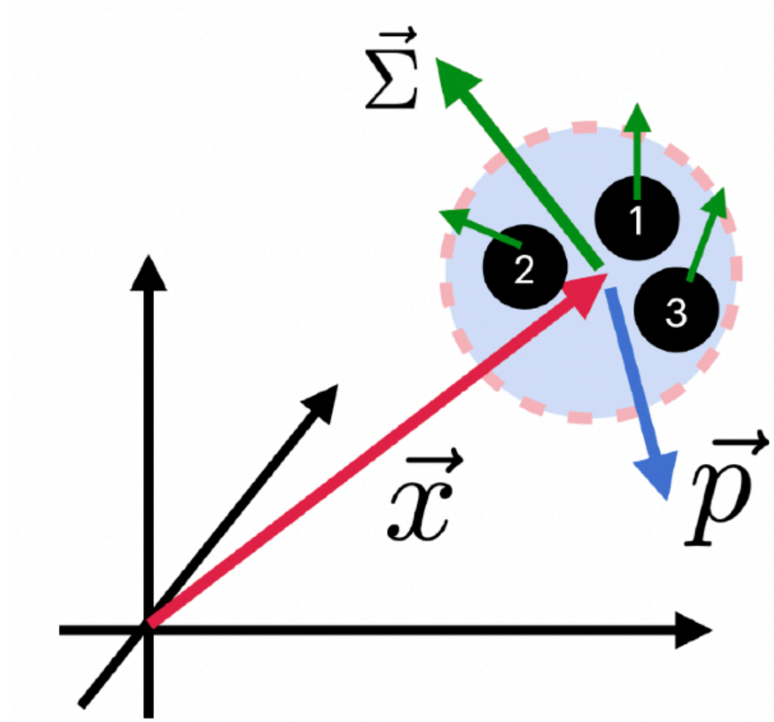
Local angular momentum chemical potential $\omega_{\alpha\beta}(x^\mu)$

Decomposition of Fluid Cell Angular Momentum



$\lambda \ll l \ll L$, a coarse-graining process

$$J^{\mu\alpha\beta} = \left(x^\alpha T^{\mu\beta} - x^\beta T^{\mu\alpha}\right) + \Sigma^{\mu\alpha\beta} .$$



Conceptually, it may NOT be feasible to further separate the spin part out of the local angular momentum of a coarse-grained fluid cell.

$$\vec{\mathbf{J}} = \vec{\mathbf{x}} \times \vec{\mathbf{p}} + \sum_{i=1,2,3} \left(\vec{\mathbf{x}}'_i \times \vec{\mathbf{p}}'_i + \vec{\mathbf{s}}_i\right).$$

$$\vec{\mathbf{\Sigma}} = \sum_{i=1,2,3} \left(\vec{\mathbf{x}}'_i \times \vec{\mathbf{p}}'_i + \vec{\mathbf{s}}_i\right)$$

Viscous Hydro with Ang. Mom.

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - p\Delta^{\mu\nu} + \widetilde{T}^{\mu\nu} \,,$$
$$N^\mu = n u^\mu + \widetilde{N}^\mu \,,$$
$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + \widetilde{\Sigma}^{\mu\alpha\beta} \,,$$
$$S^\mu = s u^\mu + \widetilde{S}^\mu .$$

Let us first focus on entropy current:

$$S^\mu = p\beta^\mu + \beta_\nu T^{\mu\nu} - \alpha N^\mu - \beta\omega_{\alpha\beta}\Sigma^{\mu\alpha\beta}$$

Leading order:

$$\partial_\mu S^\mu_{(0)} = 2\beta\omega_{\alpha\beta}\widetilde{T}^{\alpha\beta}_{(a)} \,. \quad \Rightarrow \quad \widetilde{T}^{\alpha\beta}_{(a)} = 0.$$

Next order (2nd-gradient):

$$\begin{aligned}\partial_\mu S^\mu &= \partial_\mu \left(p\beta^\mu + \beta_\nu T^{\mu\nu} - \alpha N^\mu - \beta\omega_{\alpha\beta}\Sigma^{\mu\alpha\beta}\right) \\ &= \widetilde{T}^{\mu\nu}\partial_\mu\beta_\nu - \widetilde{N}^\mu\partial_\mu\alpha - \widetilde{\Sigma}^{\mu\alpha\beta}\partial_\mu\left(\beta\omega_{\alpha\beta}\right) ,\end{aligned}$$

$$\partial_\mu S^\mu \geq 0.$$

Viscous Hydro with Ang. Mom.: Eckart Frame

$$u_E^\mu = \frac{N^\mu}{\sqrt{N^\nu N_\nu}},$$

Write down all allowed Lorentz structures to the correct order of gradient expansion

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\,\Delta^{\mu\nu} + 2u^{(\mu}q^{\nu)} + \pi^{\mu\nu},$$
$$N^\mu = n u^\mu,$$
$$\Sigma^{\mu\alpha\beta} = u^\mu \sigma^{\alpha\beta} + 2u^{[\alpha}\Delta^{\mu\beta]}\Phi + 2u^{[\alpha}\tau_{(s)}^{\mu\beta]} + 2u^{[\alpha}\tau_{(a)}^{\mu\beta]} + \Theta^{\mu\alpha\beta}.$$

Plug these into the entropy current divergence and look for conditions of positivity:

$$\partial_\mu S^\mu = \partial_\mu \left(p\beta^\mu + \beta_\nu T^{\mu\nu} - \alpha N^\mu - \beta\omega_{\alpha\beta}\Sigma^{\mu\alpha\beta}\right) = \widetilde{T}^{\mu\nu}\partial_\mu\beta_\nu - \widetilde{N}^\mu\partial_\mu\alpha - \widetilde{\Sigma}^{\mu\alpha\beta}\partial_\mu\left(\beta\omega_{\alpha\beta}\right),$$

$$\partial_\mu S^\mu \geq 0.$$

Viscous Hydro with Ang. Mom.: Eckart Frame

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p+\Pi)\,\Delta^{\mu\nu} + 2u^{(\mu}q^{\nu)} + \pi^{\mu\nu},$$
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$$\partial_\mu S^\mu \geq 0.$$

$$\Pi = -\zeta\theta,$$
$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle},$$
$$q^\mu = \lambda T\left(\frac{\nabla^\mu T}{T} - Du^\mu\right)$$
$$= -\frac{\lambda n T^2}{\epsilon+p}\left[\nabla^\mu\left(\frac{\mu}{T}\right) + \frac{\sigma^{\alpha\beta}}{n}\nabla^\mu\left(\frac{\omega_{\alpha\beta}}{T}\right)\right]$$

$$\Phi = -\chi_1 u^\alpha \nabla^\beta\left(\frac{\omega_{\alpha\beta}}{T}\right), \tag{25}$$
$$\tau_{(s)}^{\mu\beta} = -\chi_2 u^\alpha\left[\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} + \Delta^{\mu\rho}\Delta^{\beta\gamma}\right) - \frac{2}{3}\Delta^{\mu\beta}g^{\rho\gamma}\right]\nabla_\gamma\left(\frac{\omega_{\alpha\rho}}{T}\right) \tag{26}$$
$$\tau_{(a)}^{\mu\beta} = -\chi_3 u^\alpha\left(\Delta^{\beta\rho}\Delta^{\mu\gamma} - \Delta^{\mu\rho}\Delta^{\beta\gamma}\right)\nabla_\gamma\left(\frac{\omega_{\alpha\rho}}{T}\right), \tag{27}$$
$$\Theta^{\mu\alpha\beta} = -\chi_4\left(u^\beta u^\rho \Delta^{\alpha\delta} - u^\alpha u^\rho \Delta^{\beta\delta}\right)\Delta^{\mu\gamma}\nabla_\gamma\left(\frac{\omega_{\delta\rho}}{T}\right) + \chi_5 \Delta^{\alpha\delta}\Delta^{\beta\rho}\Delta^{\mu\gamma}\nabla_\gamma\left(\frac{\omega_{\delta\rho}}{T}\right). \tag{28}$$

Five new positive angular momentum transport coefficients:

$\chi_1, \chi_2, \chi_3, \chi_4$ and χ_5

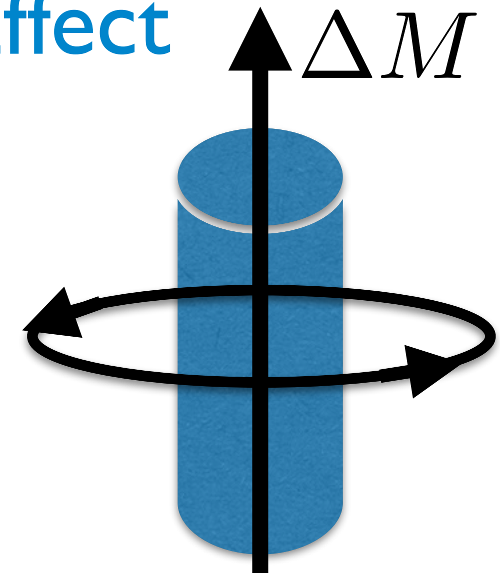
Summary

- *A new regime of study for strong interaction matter:*

  Large angular momentum as external control;
- *Nontrivial fluid vorticity structures and induced global and local polarization phenomena, especially at low energy;*
- *New and rich phase structures under rotation;*
- *Development of hydrodynamic theoretical framework with angular momentum;*
- *Many more interesting questions to be fully explored!*

Backup Slides

A Long Story: Barnett Effect



SEPTEMBER 24, 1909] SCIENCE 413

Lehrbuch der Kristalloptik, by E. B. Wilson; "Notes"; "New Publications."

SPECIAL ARTICLES

ON MAGNETIZATION BY ANGULAR ACCELERATION

Some time ago, while thinking about the origin of the earth's magnetism, it occurred to me that any magnetic substance must, according to current theory, become magnetized by receiving an angular velocity.

Thus consider a cylinder of iron or other substance constituted of atomic or molecular systems whose individual magnetic moments

fectly definite and unquestionable, but exceedingly difficult to account for, viz., a magnetization along the rod in a definite direction independent of the direction of rotation and of the direction of the original residual magnetism of the rod. It was not due to the jarring of the cylinder as it was rotated in the earth's field, nor to a possible minute change in the direction of its axis produced by the pull of the motor. In magnitude this effect was several times as great as the other, which became manifest only at the higher of the two speeds used.

Second Series. *October, 1915* *Vol. VI., No. 4*

THE

PHYSICAL REVIEW.

MAGNETIZATION BY ROTATION.[1]

BY S. J. BARNETT.

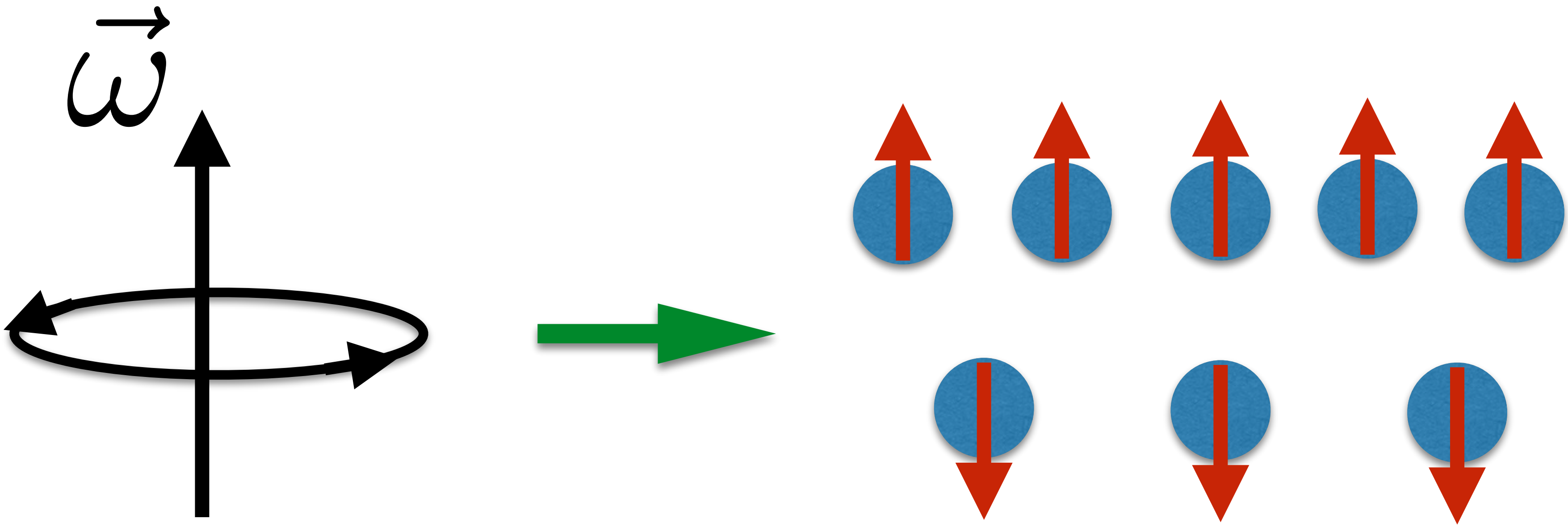
§1. In 1909 it occurred to me, while thinking about the origin of terrestrial magnetism, that a substance which is magnetic (and therefore, according to the ideas of Langevin and others, constituted of atomic or molecular orbital systems with individual magnetic moments fixed in magnitude and differing in this from zero) must become magnetized by a sort of molecular gyroscopic action on receiving an angular velocity.

Rotating solid sample —> magnetization

$$\Delta J \Rightarrow \Delta M$$

In Short: Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization

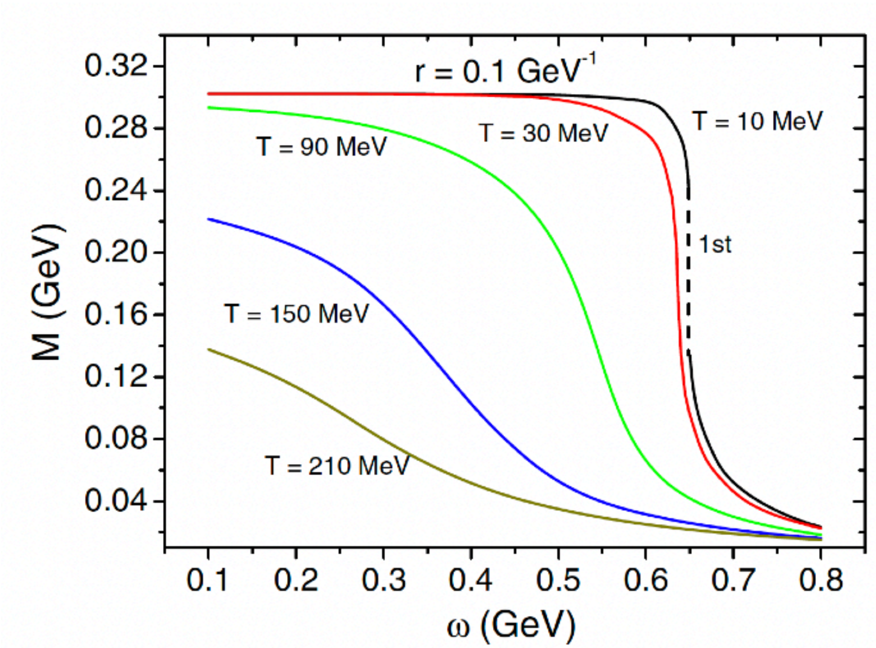


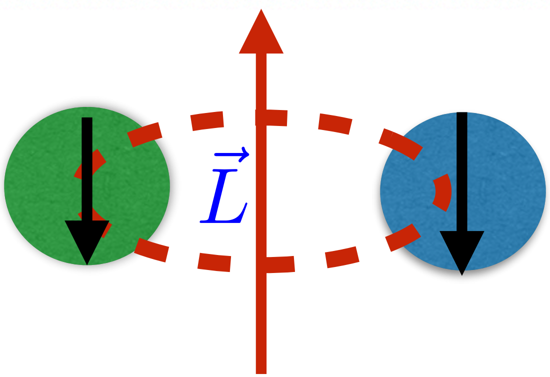
Macroscopic rotation; Global angular momentum

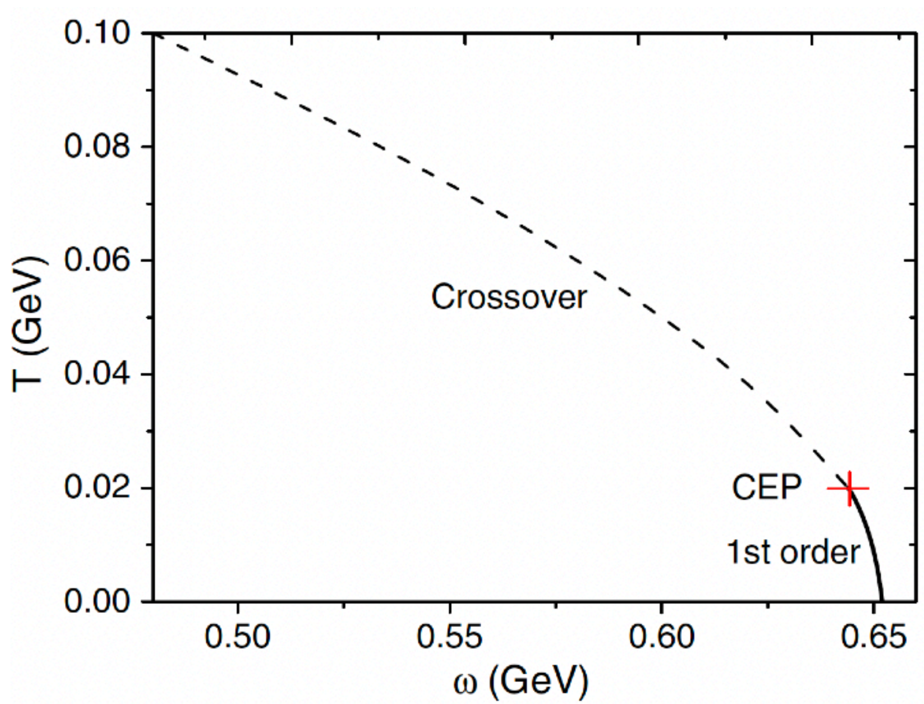
Microscopic spin alignment

It however is tricky to be directly observed for a flowing fluid.

Chiral Condensate under Rotation

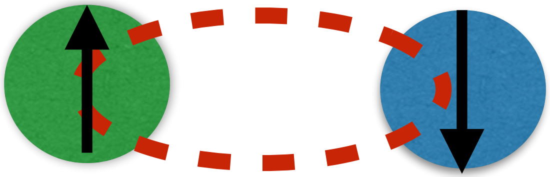


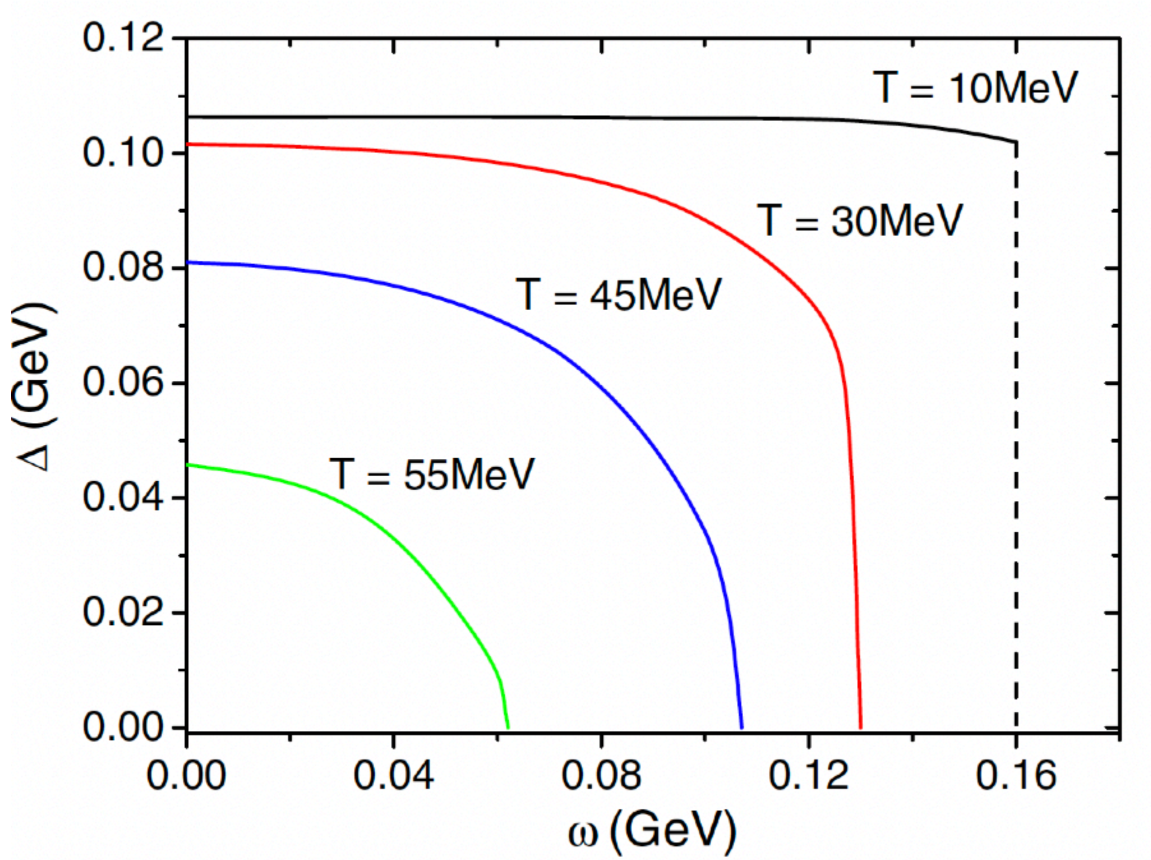




[Yin Jiang, JL, PRL2016]

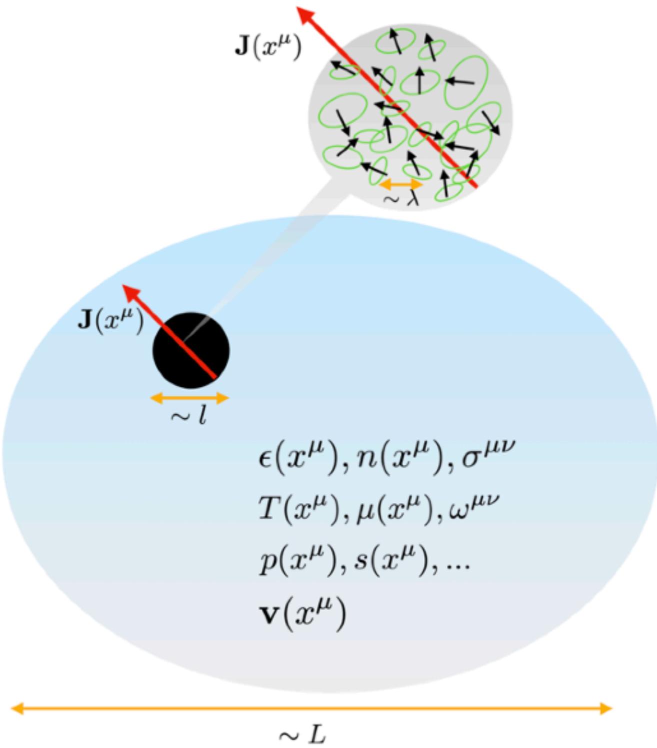
Color Superconductor under Rotation





[Yin Jiang, JL, PRL2016]

Ideal Hydrodynamics



$\lambda \ll l \ll L$, a coarse-graining process

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

$$T^{\mu\nu}_{(0)} = \epsilon u^\mu u^\nu - p\Delta^{\mu\nu},\ N^\mu_{(0)} = n u^\mu.$$

$$\epsilon = -p + Ts + \mu n$$

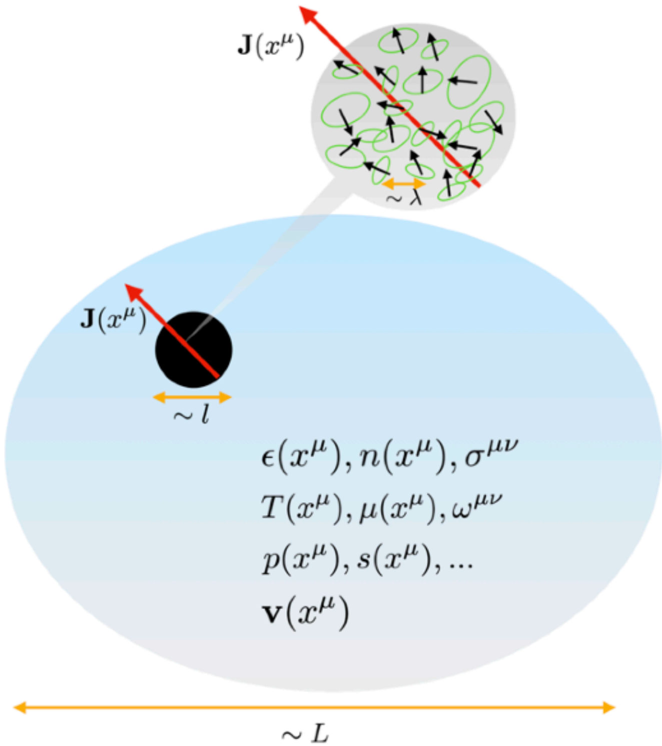
$$S^\mu_{(0)} = s u^\mu$$

$$\partial_\mu S^\mu_{(0)} = \partial_\mu (s u^\mu) = 0$$

Microscopic physics enters via thermodynamic relations (i.e. EOS).

See e.g. Landau and Lifshitz

Navier-Stokes Viscous Hydrodynamics



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

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - p\Delta^{\mu\nu} + \widetilde{T}^{\mu\nu},$$
$$N^\mu = n u^\mu + \widetilde{N}^\mu,$$
$$S^\mu = s u^\mu + \widetilde{S}^\mu.$$

$$\partial_\mu S^\mu \geq 0.$$

$\lambda \ll l \ll L$, a coarse-graining process

$$\Pi = -\zeta\theta,$$
$$\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle},$$
$$q^\mu = \lambda T\left(\frac{\nabla^\mu T}{T} - Du^\mu\right)$$

See e.g. Landau and Lifshitz

Microscopic physics also enters via transport coefficients in viscous terms.

Ideal Hydro with Ang. Mom.

$$T^{\mu\nu}_{(0)} = \epsilon u^\mu u^\nu - p\Delta^{\mu\nu},\ N^\mu_{(0)} = n u^\mu.$$

$$\Sigma^{\mu\alpha\beta}_{(0)} = \sigma^{\alpha\beta} u^\mu.$$

$$\partial_\mu J^{\mu\alpha\beta}_{(0)} = \sigma^{\alpha\beta}\theta + D\sigma^{\alpha\beta} = 0.$$

Generalized thermodynamics:

$$\epsilon = -p + Ts + \mu n + \omega_{\alpha\beta}\sigma^{\alpha\beta}$$

It is straightforward to verify: no entropy generation

$$\partial_\mu S^\mu_{(0)} = \partial_\mu \left(s u^\mu \right) = 0.$$

Viscous Hydro with Ang. Mom.: Landau Frame

$$u_L^\mu = \frac{T^\mu_\nu u_L^\nu}{\sqrt{u_L^\alpha T_\alpha^\beta T_{\beta\gamma} u_L^\gamma}}$$

$$T^{\mu\nu} = \epsilon u_L^\mu u_L^\nu - (p + \Pi)\,\Delta_L^{\mu\nu} + \pi^{\mu\nu},$$

$$N^\mu = n u_L^\mu - n\frac{q^\mu}{\epsilon + p},$$

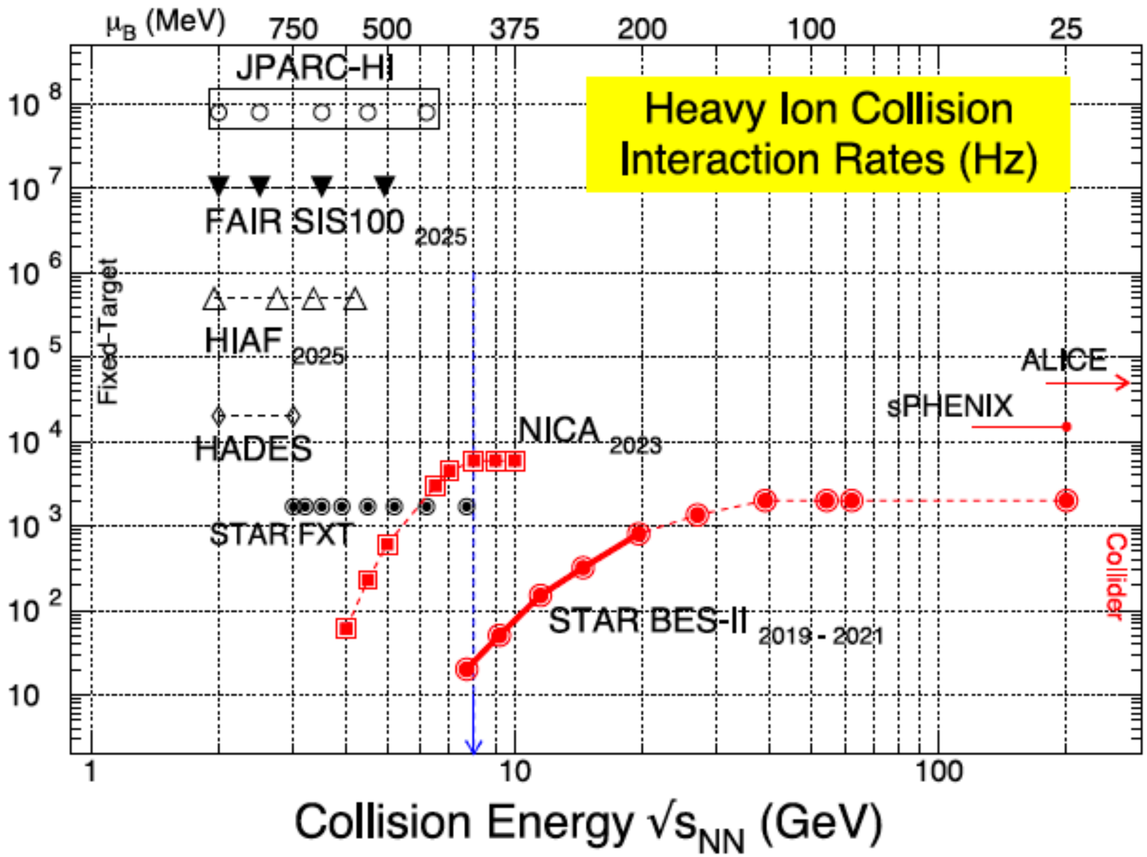
$$\Sigma^{\mu\alpha\beta} = u_L^\mu \sigma^{\alpha\beta} - \frac{q^\mu}{\epsilon + p}\sigma^{\alpha\beta} + 2u_L^{[\alpha}\Delta_L^{\mu\beta]}\Phi + 2u_L^{[\alpha}\tau_{(s)}^{\mu\beta]} + 2u_L^{[\alpha}\tau_{(a)}^{\mu\beta]} + \Theta^{\mu\alpha\beta}.$$

Following the same procedure, one obtains essentially the same consistent results.

High-Polarization Matter in Low Energy Collisions

Relativistic nuclear collisions have been and will continue to be done from O(1) GeV to O(1000) GeV beam energy!

"Mapping the Phases of Quantum Chromodynamics with Beam Energy Scan", Bzdak, Esumi, Koch, JL, Stephanov, Xu, Phys. Rep. 853(2020)1-87.

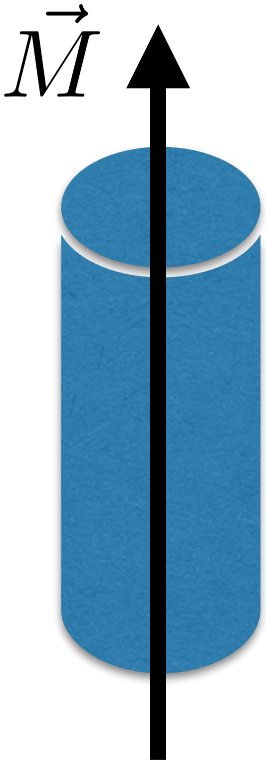


High Polarization Matter: Exciting new regime!

Potentially a new, interesting and integral component of a rich and diverse low energy nuclear collision physics program.

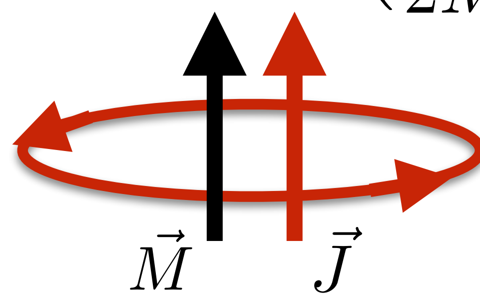
Einstein-de Hass Effect

Richardson,~1908; Einstein-de Hass,~1915:
Change of a free body's magnetic momentum —>
Mechanical rotation of the sample



Orbital contribution:

$$\Delta M = \left(\frac{q}{2M}\right)\Delta J$$



Spin contribution:

$$\Delta M = \left(\frac{2 \times q}{2M}\right)\Delta J$$

Barnett (OSU), ~1915:
1st correct measurement, supporting the g~2,
Indicating dominant spin contributions in magnetization.