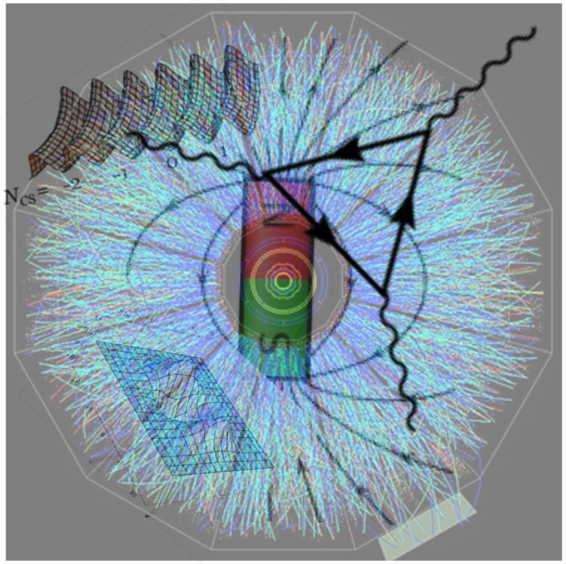
Heavy Ion Collision Theory — Selected Topics (Part II)



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Plan of the Lecture

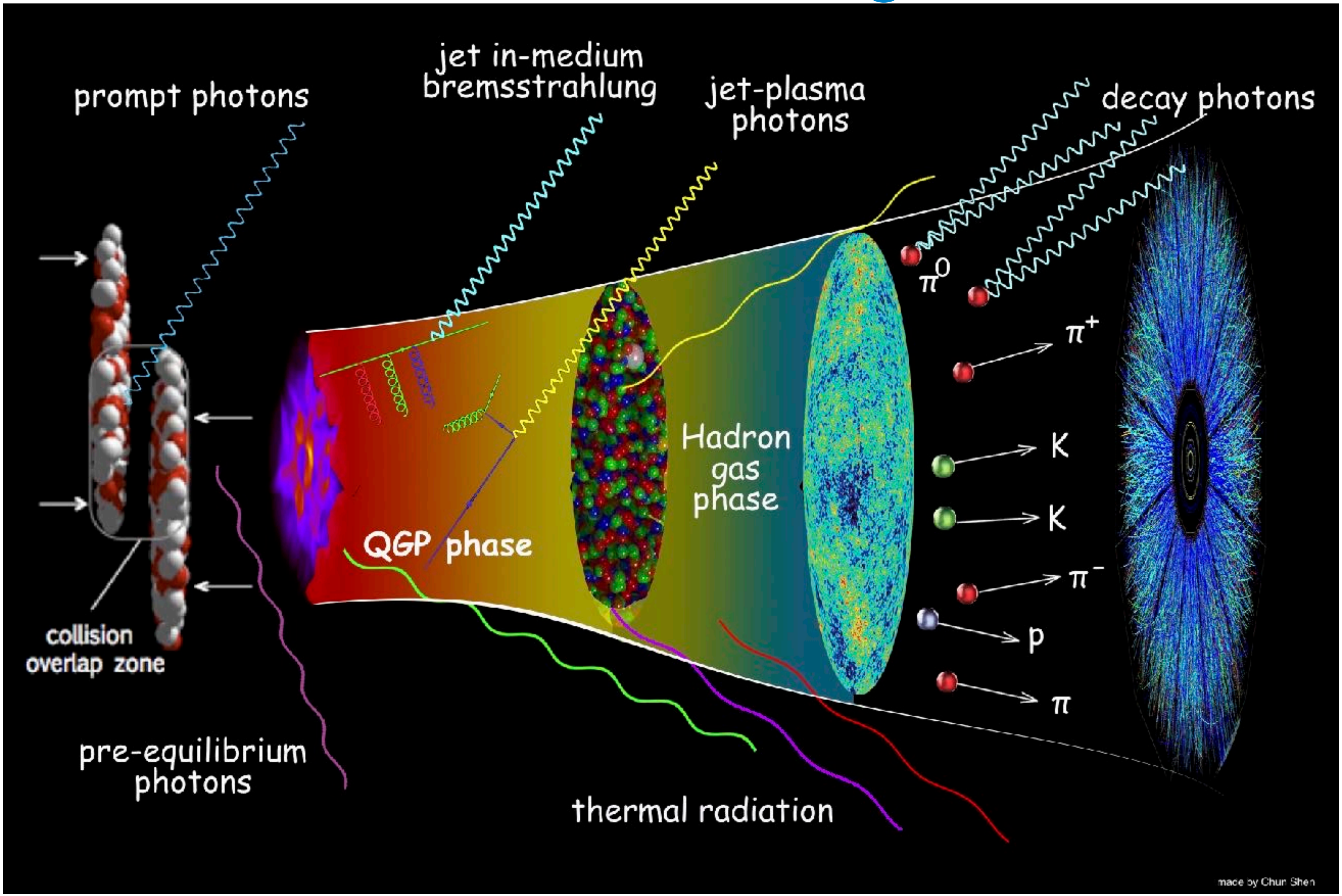
– ***Exploring a new phase of matter***

– ***Spin polarization phenomena***

– ***Anomalous transport effects***

Exploring a New Phase of Matter

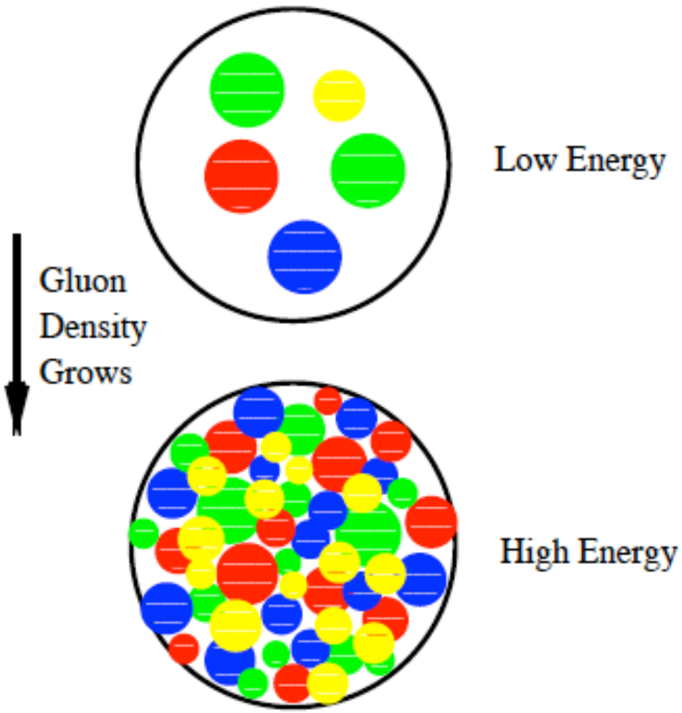
The "Little Bang"

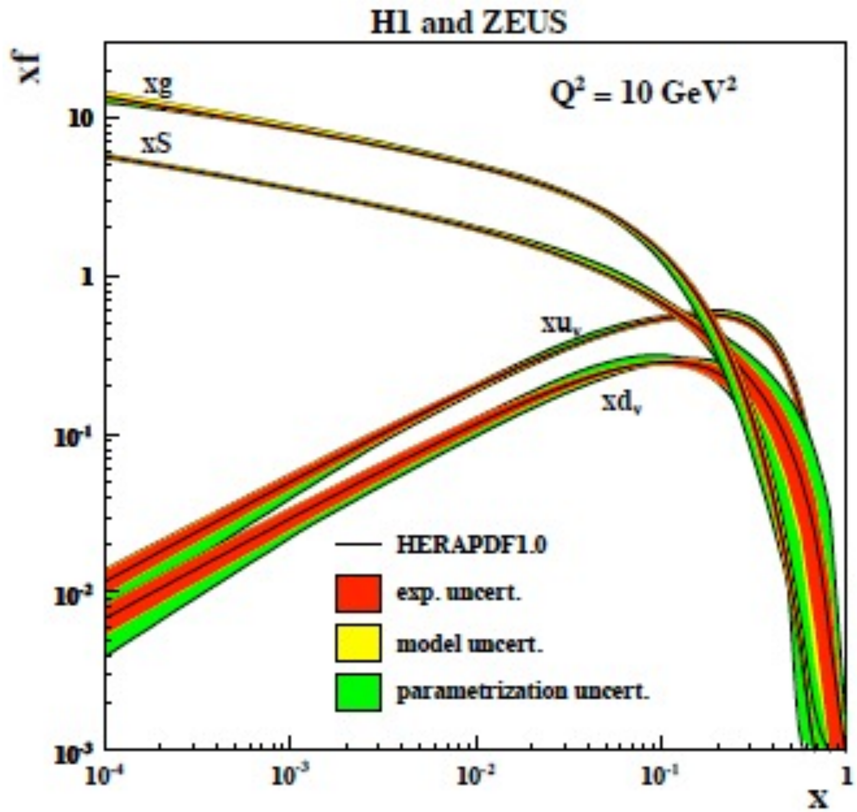


From: Chun Shen

At the Very Beginning...

Small-x part is important and dominated by gluons

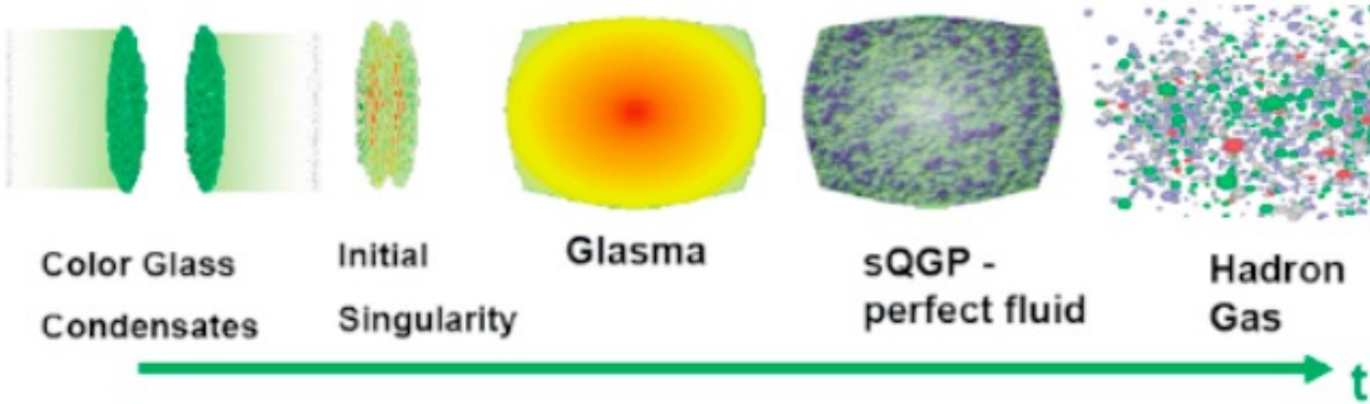




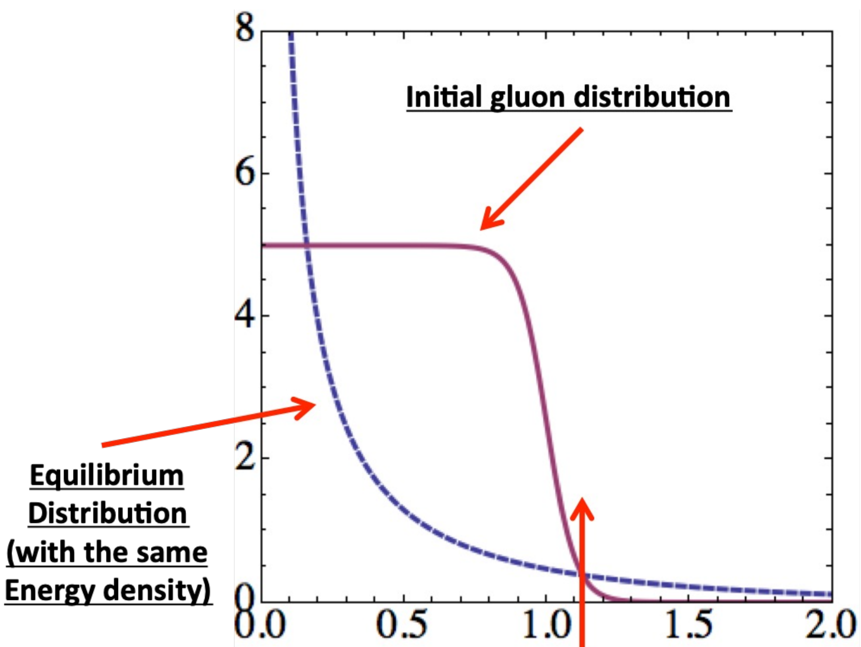
$$\boxed{Q^2 \leq \underbrace{Q_s^2}_{\text{saturation momentum}} \equiv \frac{\alpha_s x G(x, Q_s^2)}{A^{2/3}} \sim A^{1/3} x^{-0.3}}$$

See lectures by Jean-Paul, Ernst about this topic

Overpopulated Glasma



The precursor of a thermal quark-gluon plasma, known as glasma, is born as a gluon matter with **HIGH OVERPOPULATION**:



Saturation Scale Qs ~ 1 GeV or larger, weakly coupled

Very large occupation number

$$f \sim \frac{1}{\alpha_s}$$

Saturation fixes initial scale

$$\epsilon_0 \sim \frac{Q_s^4}{\alpha_s}$$

$$n_0 \sim \frac{Q_s^3}{\alpha_s}$$

$$\epsilon_0 / n_0 \sim Q_s$$

A “Small” Gap…

just after collision

glasma evolution

hydro QGP

Time

$$A \sim 1/g \qquad f < 1/g^2 \qquad f \sim 1$$

initially dominated by strong classical field

system becomes diluter

?

dominated by quanta

$$\epsilon_{initial} \approx \frac{(dN/d\eta) < p_T >}{\pi R^2 \, \tau_0}$$

Hydro start time can NOT be too late!

Kinetic Eq. Under Small Angle Approximation

$$\mathcal{D}_t f(\vec{p}) = \xi\left(\Lambda_s^2 \Lambda\right) \vec{\nabla} \cdot \left[\vec{\nabla} f(\vec{p}) + \frac{\vec{p}}{p}\left(\frac{\alpha_S}{\Lambda_s}\right) f(\vec{p})[1 + f(\vec{p})]\right]$$

Ex. Verify the fixed point and conservation laws of the above equation.

$$\Lambda\left(\frac{\Lambda_s}{\alpha_S}\right)^2 \equiv (2\pi^2) \int \frac{d^3p}{(2\pi)^3} f(\vec{p})\,[1 + f(\vec{p})]$$

$$\Lambda\frac{\Lambda_s}{\alpha_S} \equiv (2\pi^2)\, 2 \int \frac{d^3p}{(2\pi)^3} \frac{f(\vec{p})}{p}$$

Two important scales:
hard scale Lambda
soft scale Lambda_s

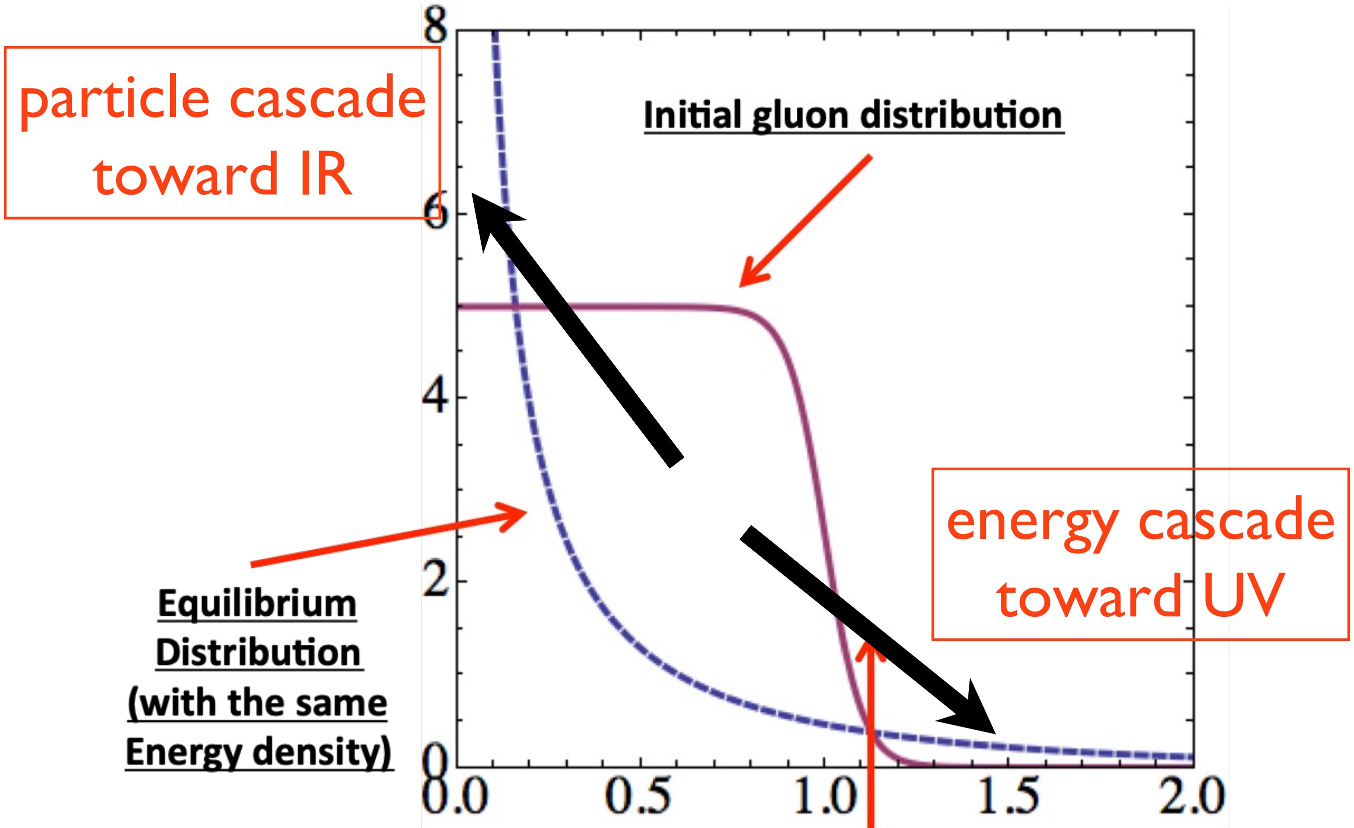
Λ : $f << 1$ for $p > \Lambda$ $\qquad \Lambda_s$: $f \sim \dfrac{1}{\alpha_s}$

Initial glasma: $\Lambda \sim \Lambda_s \sim Q_s$

Thermalized weakly-coupled QGP: $\Lambda \sim T$, $\Lambda_s \sim \alpha_s * T$

Elastic scattering time scale $\quad t_{scat} \sim \dfrac{\Lambda}{\Lambda_s^2}$

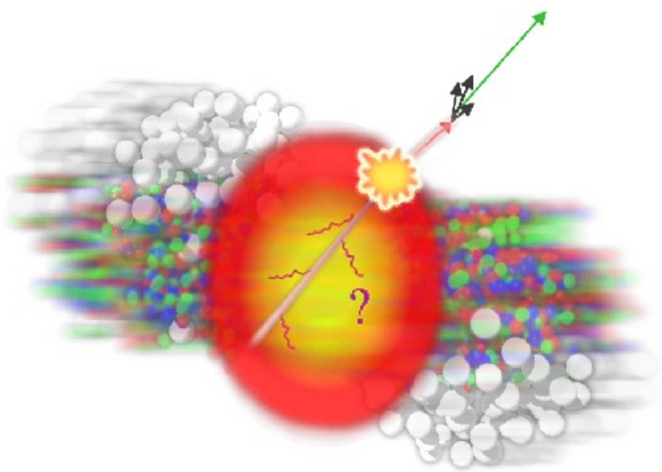
How Thermalization Proceeds

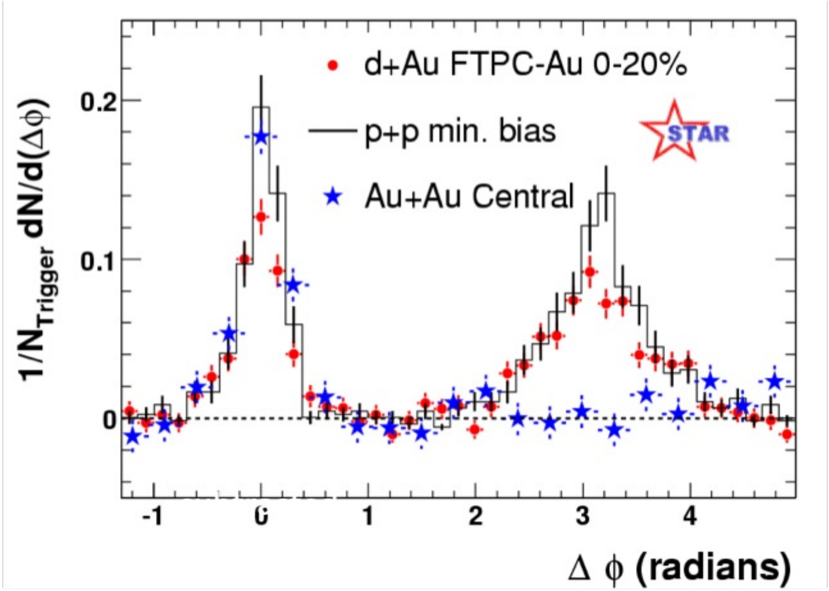


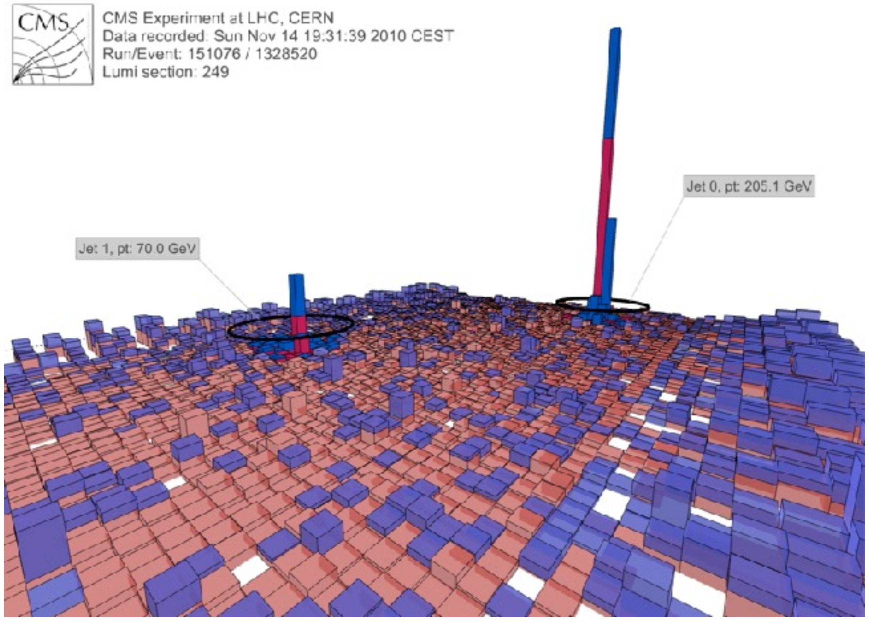
Saturation Scale Qs ~ 1 GeV or larger, weakly coupled

Initial glasma: $\Lambda \sim \Lambda_s \sim Q_s$ → Thermalized weakly-coupled QGP: $\Lambda \sim T$, $\Lambda_s \sim \alpha_s * T$

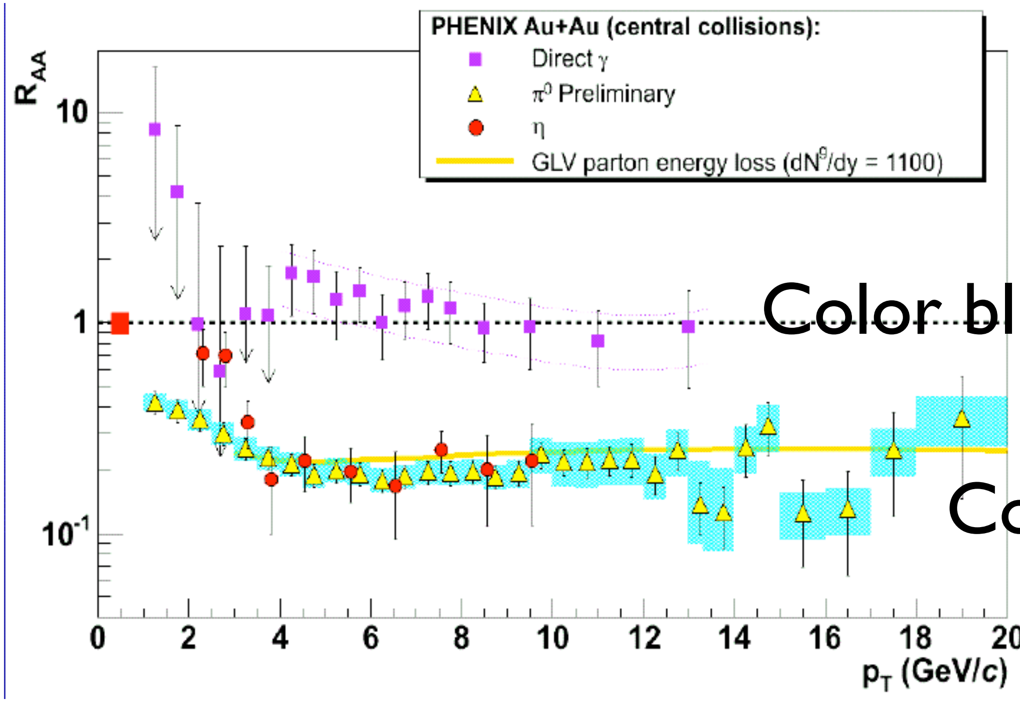
Jet Quenching





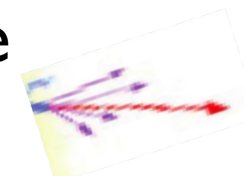


A Color-Opaque Plasma

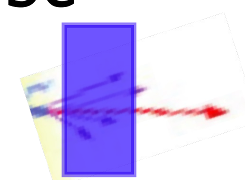


Hard probe:
Produced from initial hard scatterings; not thermally produced from QGP

Color blind probe

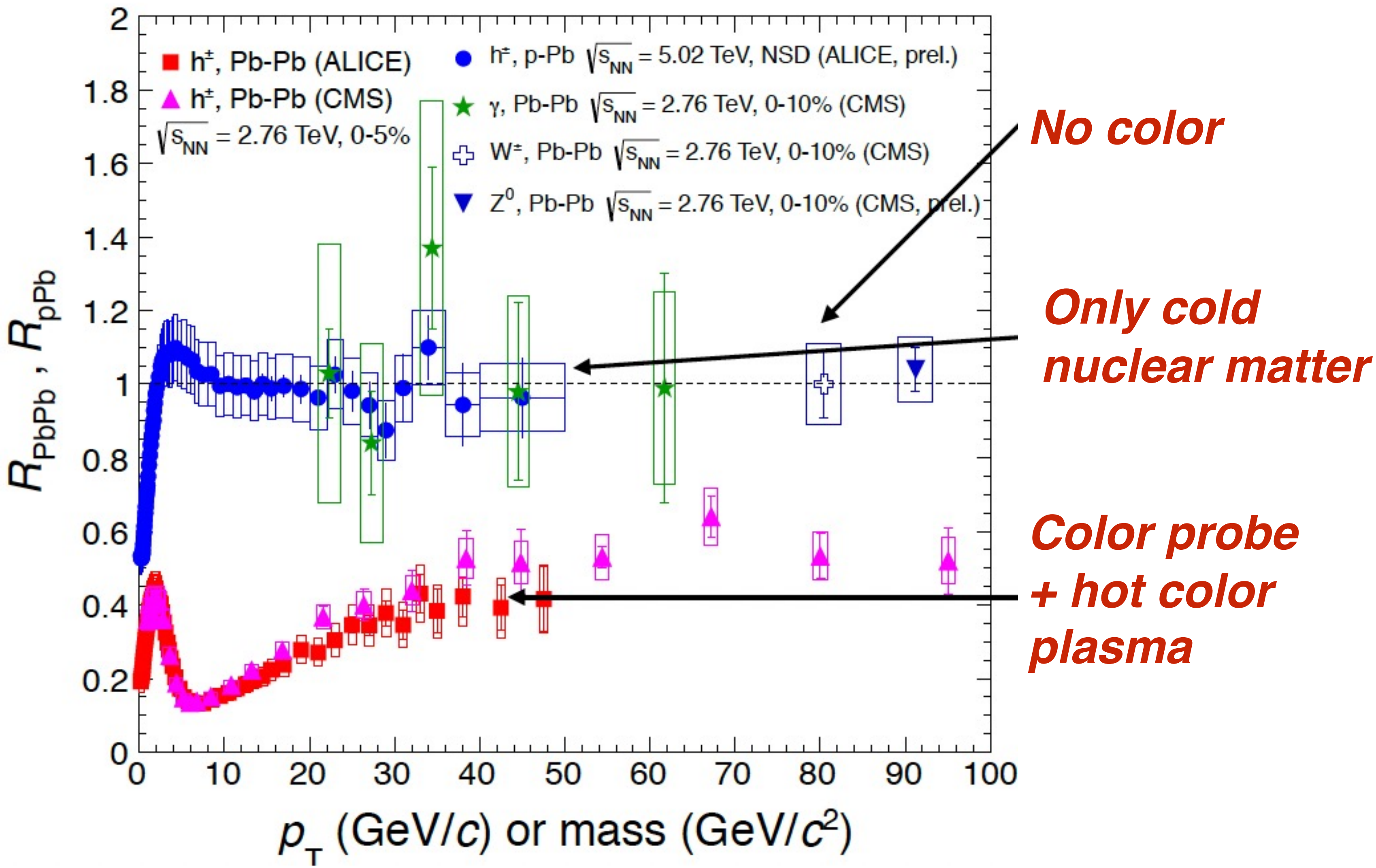


Colorful probe



A qualitatively different medium:
Jet probes color degrees of freedom in the plasma!

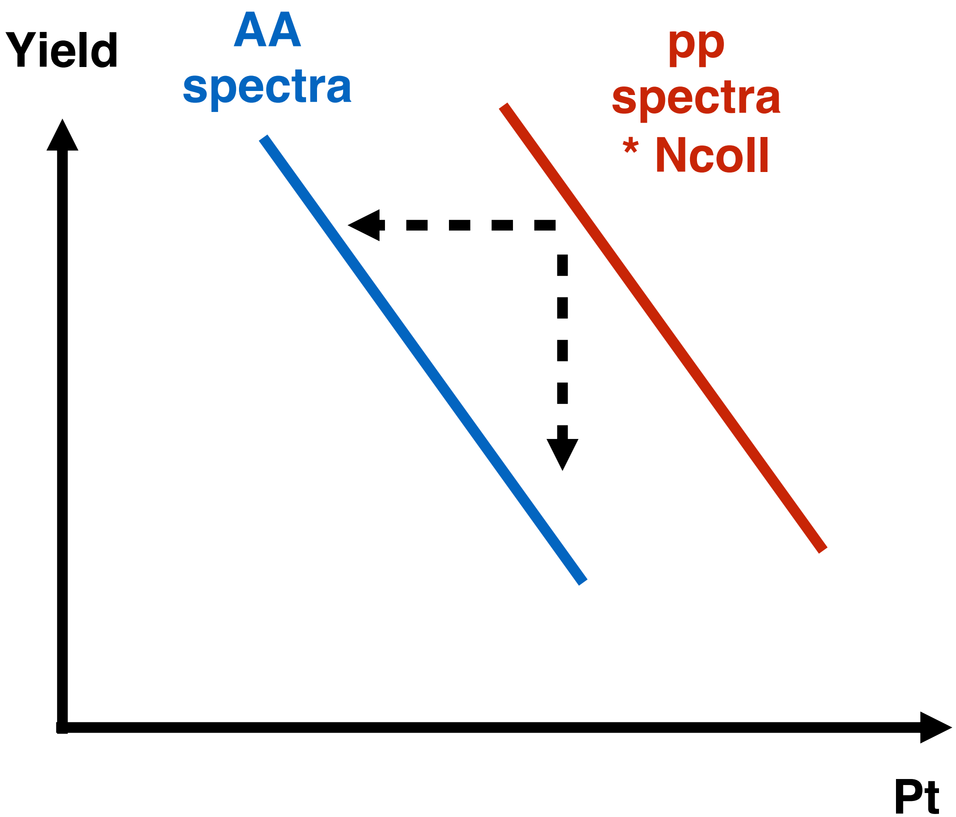
Final State Interactions



Estimating Jet Energy Loss

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

$$N_{pp} \propto \frac{1}{P^n}$$



$$\frac{dP}{dx} \propto -F(P;T,\ldots) \approx -\kappa_T \times P$$

$$P_f = P_i \times e^{-\int_L \kappa_T dx}$$

$$P_f \approx P_i \times e^{-<\kappa_T>\cdot L}$$

$$R_{AA} \approx \frac{1/(P_f \cdot e^{<\kappa_T>\cdot L})^n}{1/P_f^n}$$

$$R_{AA} \approx e^{-n\cdot<\kappa_T>\cdot L}$$

R_AA ~ 0.2 indicates very strong jet-medium coupling!

Exercise!

QGP Properties: What It Does

*** Nearly perfect fluidity: mapping fine details of initial conditions***

*** Highly opaque for a colored penetrating jet probe ~ 100GeV***

*** Screening the QCD binding force in quarkonia states***

*** Many many other interesting findings…***

With RHIC and LHC, not only we create QGP,
we've also learned a whole lot about
the properties of QGP and the dynamics of QCD !

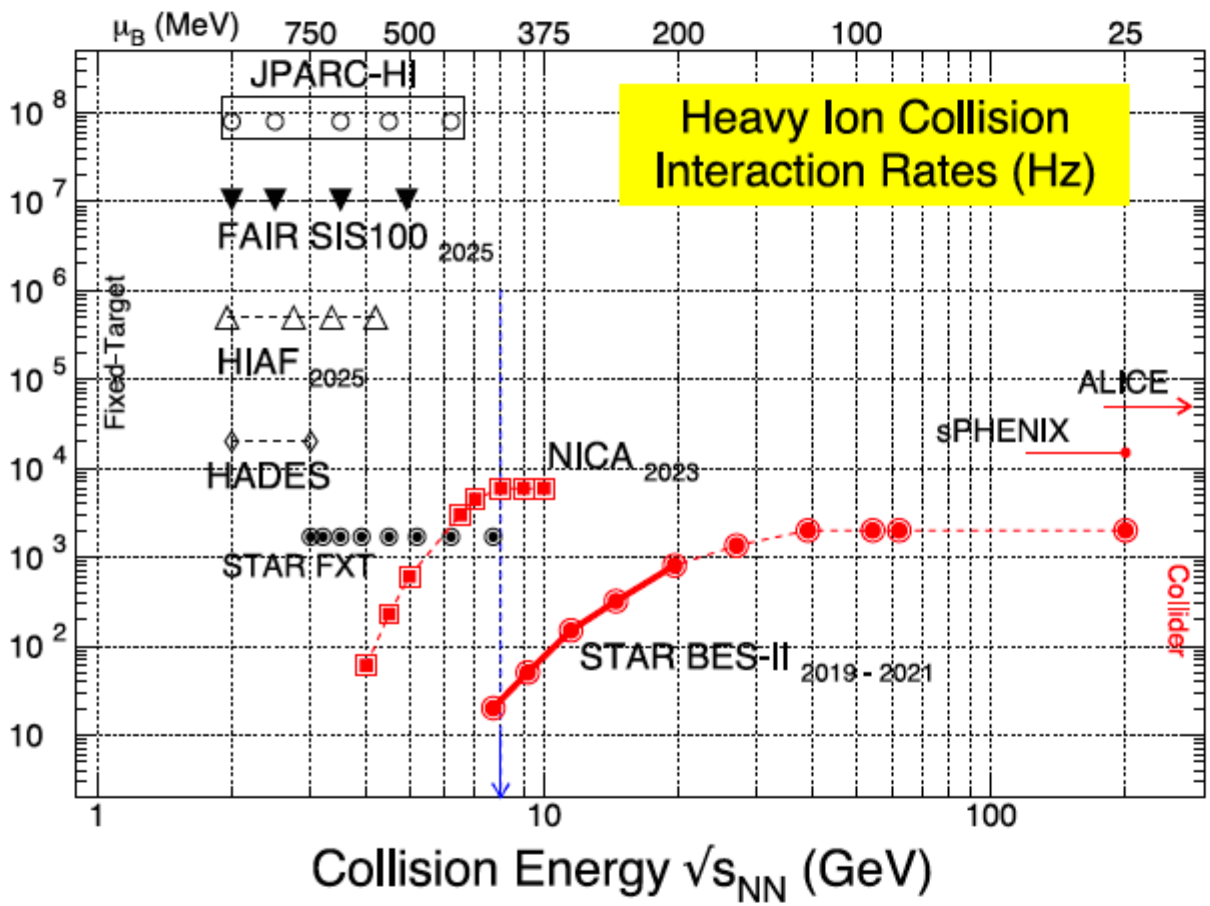
The Creative Use of QGP & HIC

The QGP (new material) & HIC (new laboratory) provide exciting opportunities for many interesting new physics

** Scanning the phase diagram of QCD*
** Universal critical phenomenon for QCD*
** Learning about initial states*
** Constraining nuclear structure*
** Producing rare particles (anti-hyper-triton, anti-alpha,…)*
** Production of light nuclei*
** Applied string theory (aka gauge/gravity duality)*
** Far from equilibrium physics*
** Understanding confinement and chiral restoration*
** Cosmology & early universe*
** spin physics and anomalous transport*
** ……*

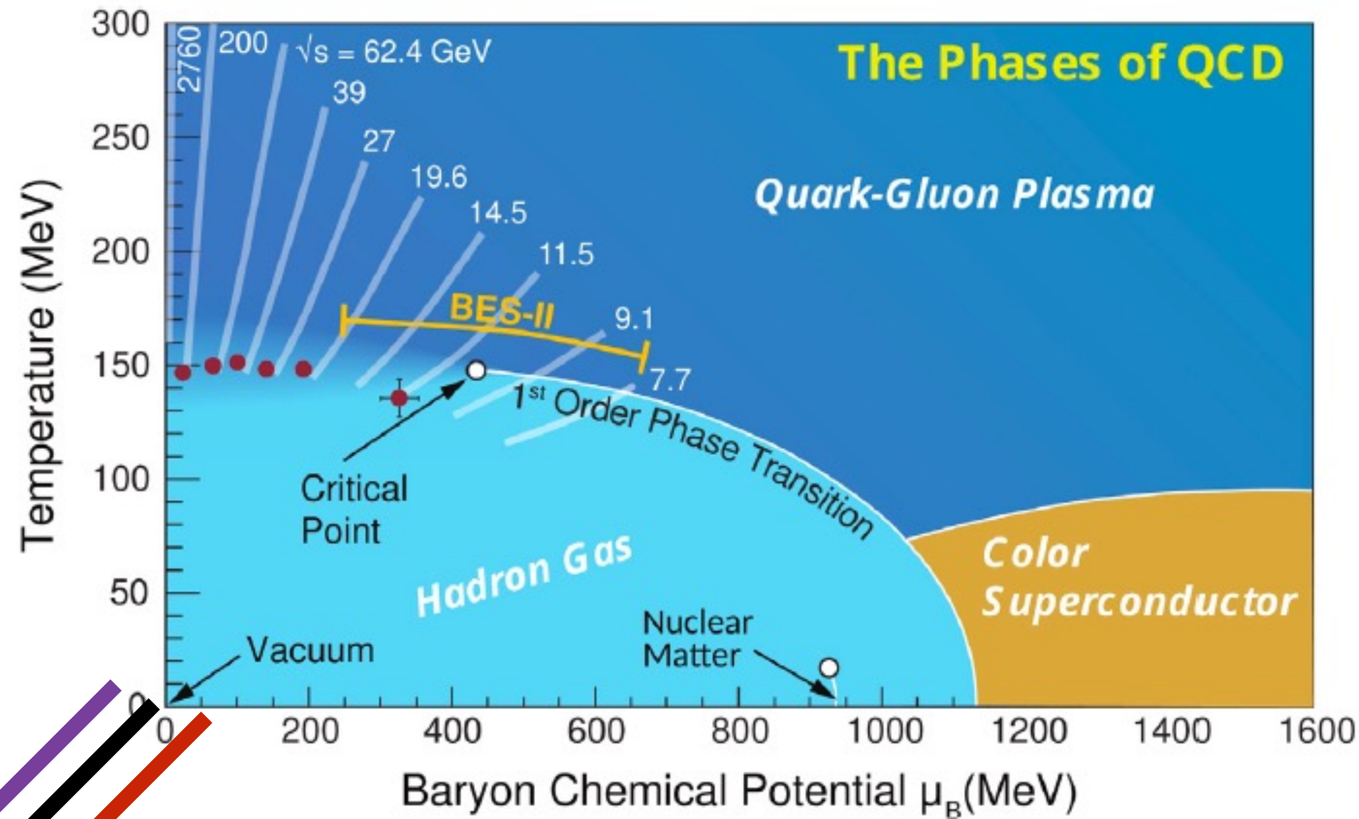
Heavy Ion Physics Programs

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.

Charting the Quantum Chromo Matter



N_5 (or μ_5)

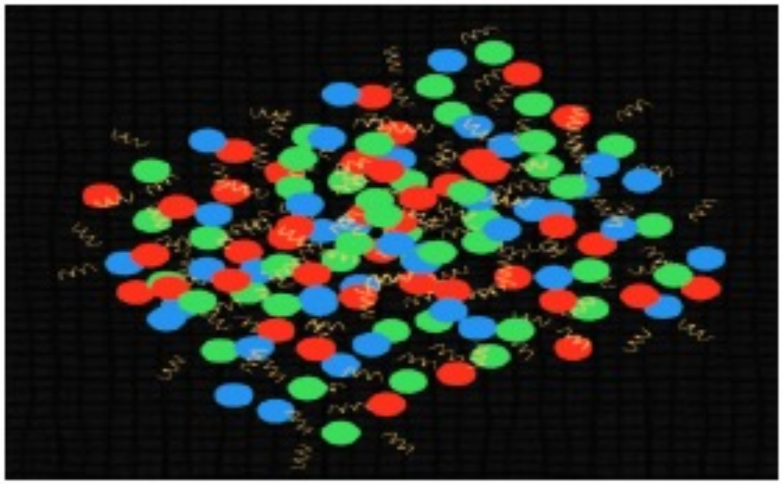
$\vec{\mathbf{B}}$ $\vec{\omega}$

Many novel dimensions for exploring Quantum Chromo Matter!

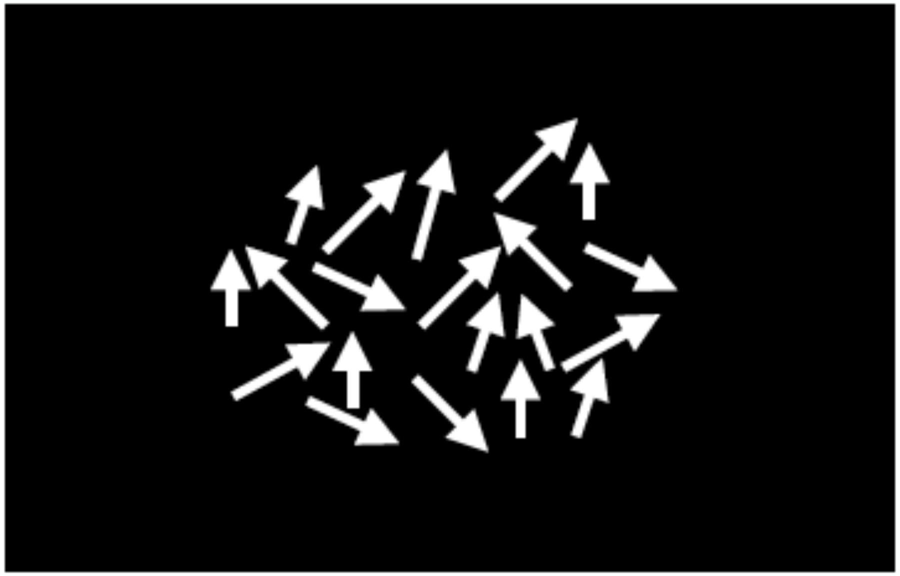
Spin Polarization Phenomena

A Quantum Fluid of Spin

A nearly perfect fluid (of energy-momentum)

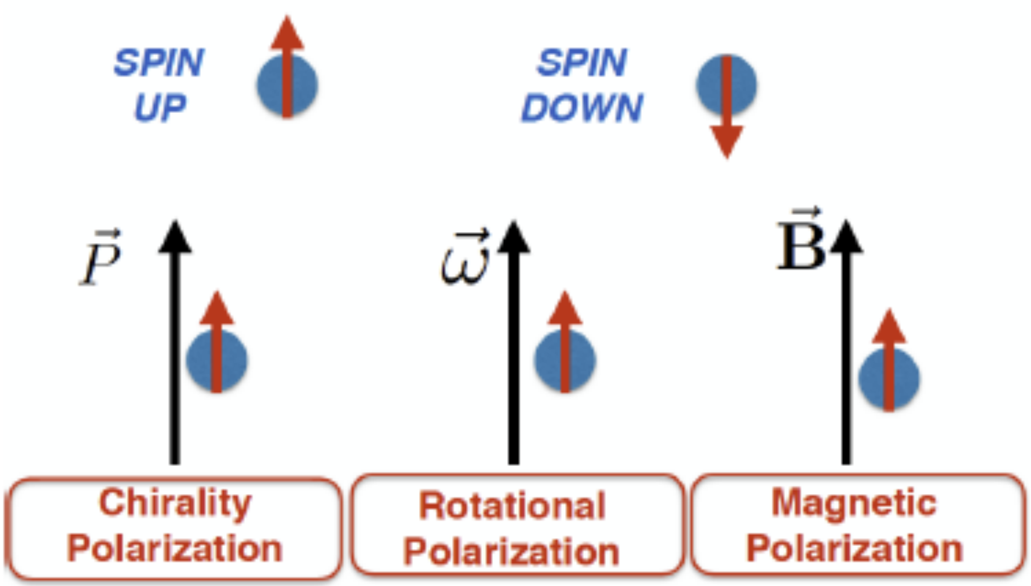


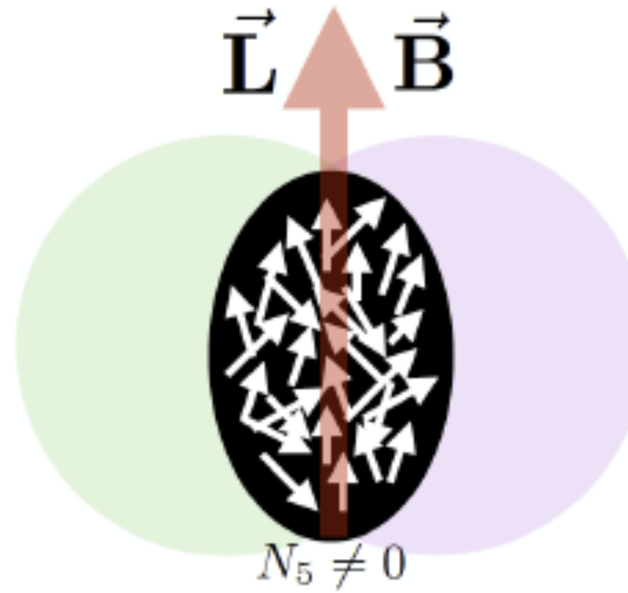
What happens to the spin DoF in the fluid???



Spin transport in a quantum fluid!

Spin @ Chirality, Vorticity and Magnetic Field



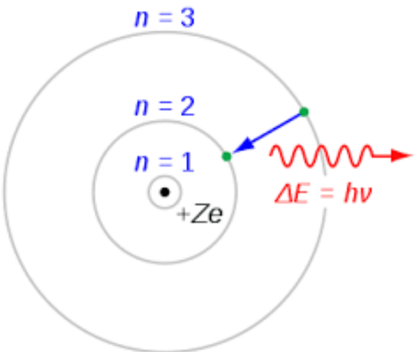


[arXiv:2004.00569]

The interplay of spin with chirality/vorticity/magnetic field —> many novel phenomena

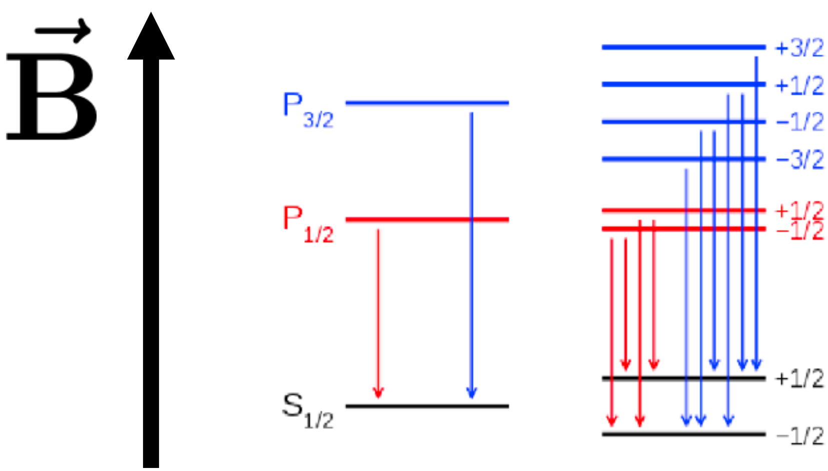
Spin: "Classically Indescribable Two-valued-ness"

Hydrogen (& alkali atoms)
[Bohr; Sommerfeld, Lande,Pauli,…]



(n, l, m)

Electron orbits in magnetic field:
Zeeman effect & Paschen-Back effect

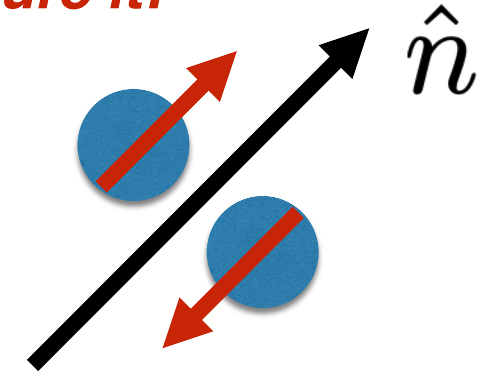


Pauli, 1923~1924:
(n, l, m, <u>s</u>)
Exclusion principle
—> <u>2</u> * (2*l +1)

Magnetic Polarization

Spin is in any direction, until you measure it!

$$\hat{\mathrm{S}} \cdot \hat{\mathrm{n}} = \frac{\hbar}{2} \begin{pmatrix} \cos\theta & \sin\theta\, e^{-i\phi} \\ \sin\theta\, e^{+i\phi} & -\cos\theta \end{pmatrix}$$

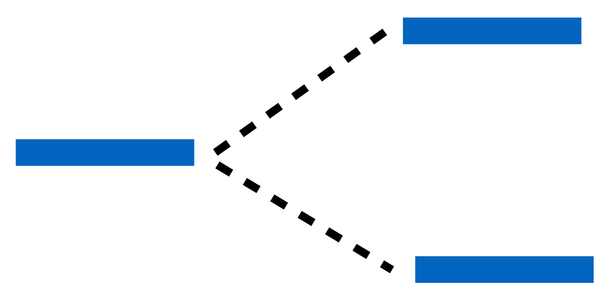


An example: electron in an external magnetic field

$$\boldsymbol{\mu}_s = \frac{g_s q\hbar}{2m} \frac{\mathbf{S}}{\hbar}$$

Magnetic moment

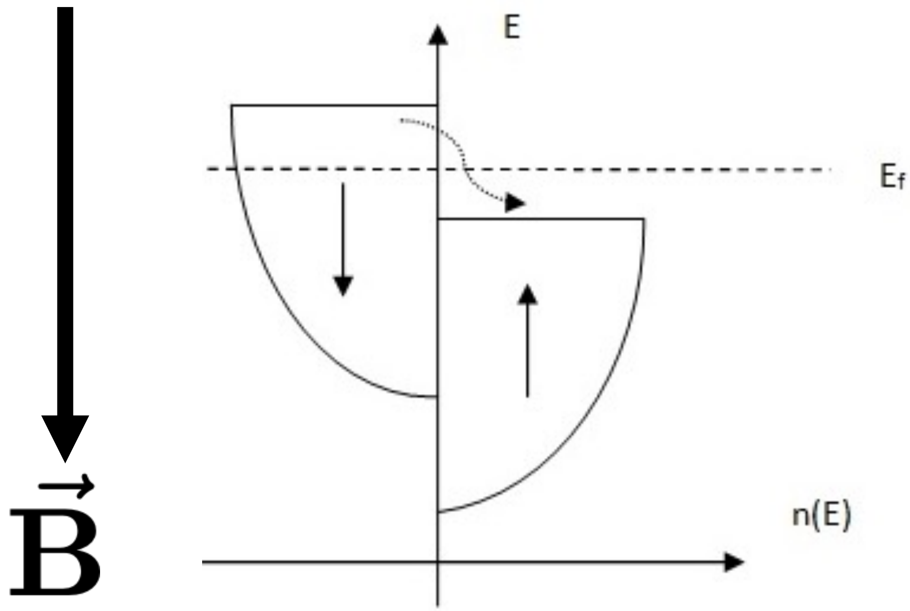
$$\hat{H}_I = -\mathrm{B} \cdot \boldsymbol{\mu}_s = \left(-\frac{g_s q\hbar}{4m}\right) \mathrm{B} \cdot \boldsymbol{\sigma}$$



Magnetization energy
(for an individual particle)

Pauli Paramagnetism: Magnetic Polarization

Magnetic polarization in a many-body system:
Particles' spins more aligned in one direction than the opposite direction.



$$n_- = \sum_E n(E) \frac{1}{e^{(E-\epsilon_B)/T}+1}$$

$$n_+ = \sum_E n(E) \frac{1}{e^{(E+\epsilon_B)/T}+1}$$

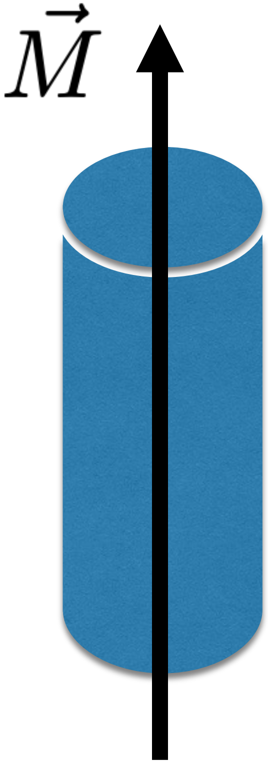
$$\vec{S} = (n_- - n_+)\frac{\hbar}{2} \approx (\#)\ \vec{\mathbf{B}}$$

$$\vec{M} \parallel \vec{S} \parallel \vec{\mathbf{B}}$$

Exercise!

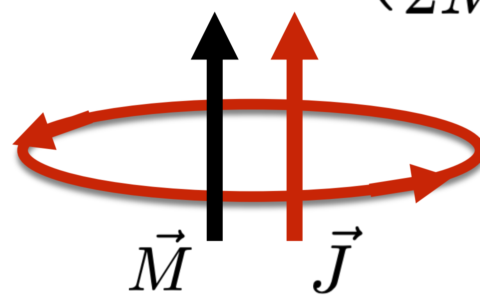
Einstein-de Hass Effect

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



Orbital contribution:

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

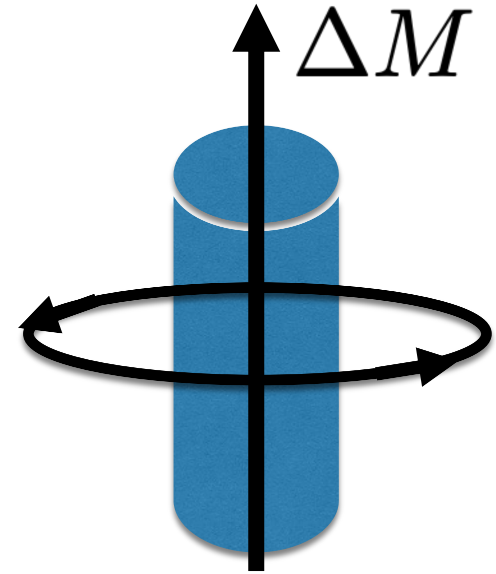


Spin contribution:

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

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

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.

The opposite should also happen:

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

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

THE

PHYSICAL REVIEW.

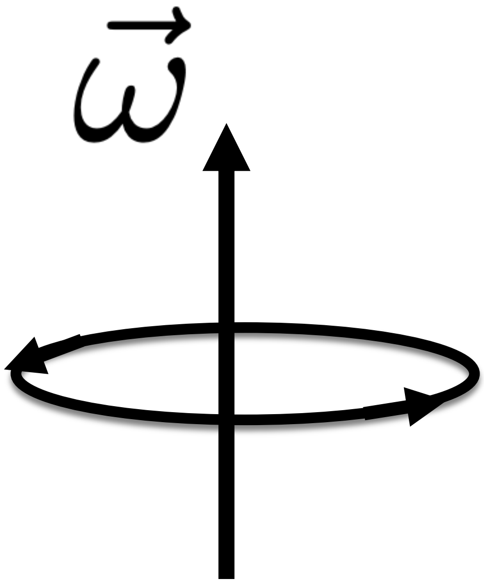
MAGNETIZATION BY ROTATION.[1]

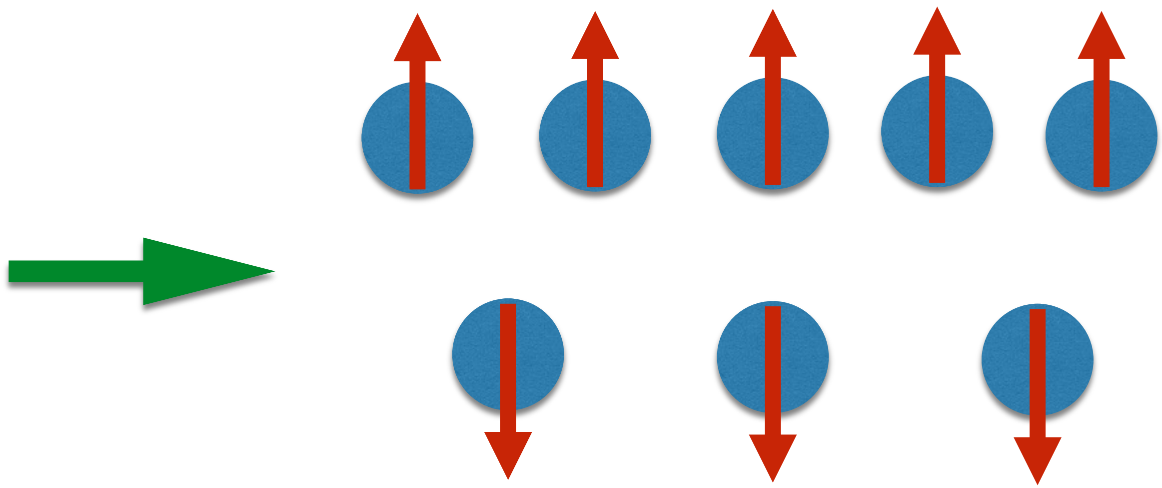
By S. J. Barnett.

§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.

Rotational Polarization

Essential assumption underlying the Barnett effect: rotational polarization





Macroscopic rotation; Global angular momentum

Microscopic spin alignment

Spin & Rotational Polarization

Dirac Lagrangian in rotating frame:

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

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

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

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

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

Under slow rotation:

$$\mathcal{L} = \psi^\dagger \left[i\partial_0 + i\gamma^0\vec{\gamma}\cdot\vec{\partial} + (\vec{\omega}\times\vec{x})\cdot(-i\vec{\partial}) + \vec{\omega}\cdot\vec{S}_{4\times4}\right]\psi$$

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

Rotational polarization effect!

[Yin Jiang, JL, PRL2016]

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

Exercise!

[Yin Jiang, JL, PRL2016]

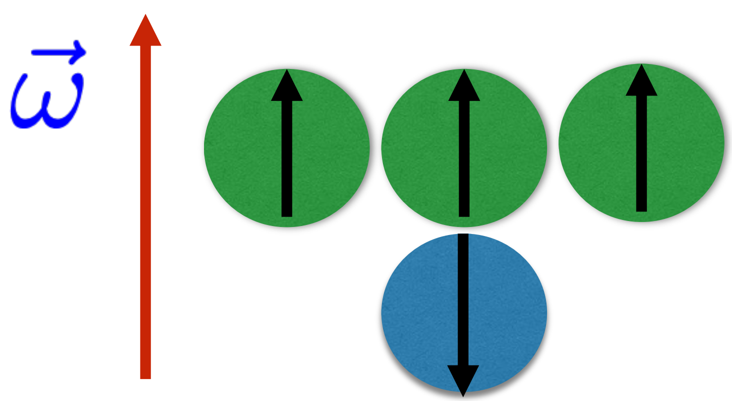
Rotational Polarization in Thermal Source

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

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

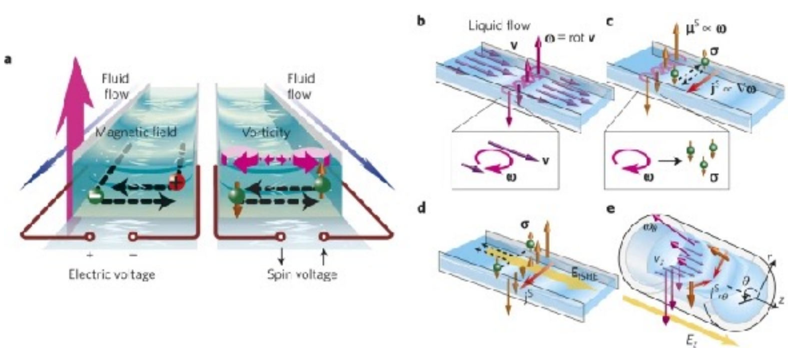
Nature Physics **12**, 52–56(2016) | Cite this article

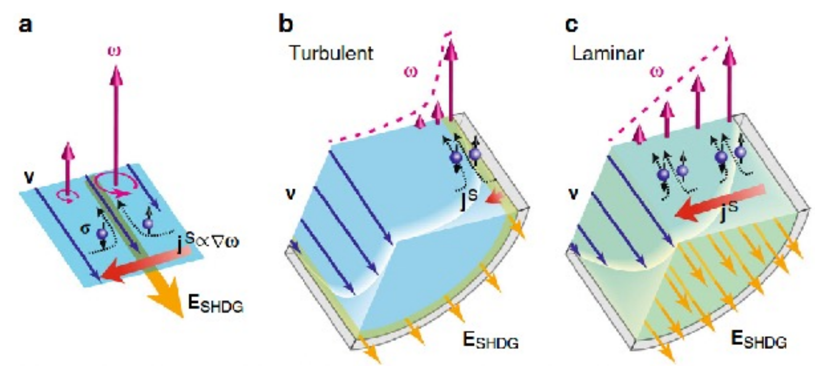
Viscous fluid flow —> vorticity —> spin polarization

Giant spin hydrodynamic generation in laminar flow

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

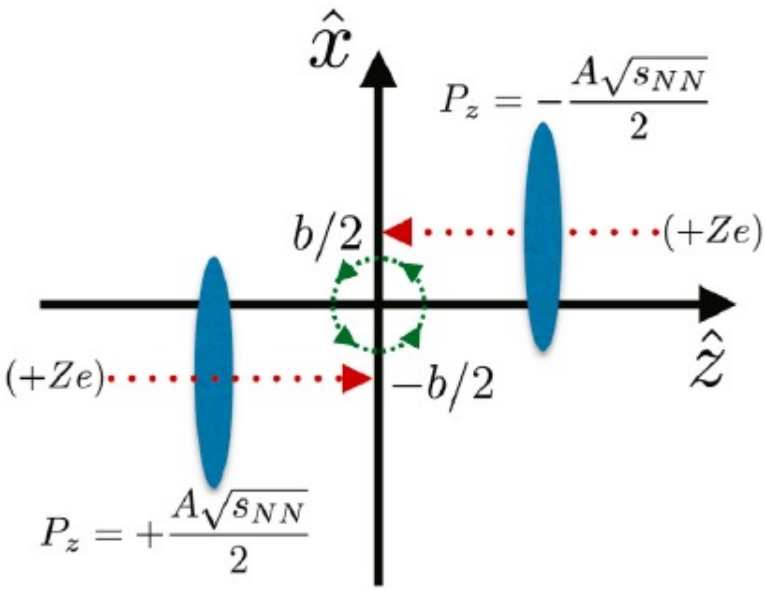
Nature Communications **11**, Article number: 3009 (2020) | Cite this article





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

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

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

“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*

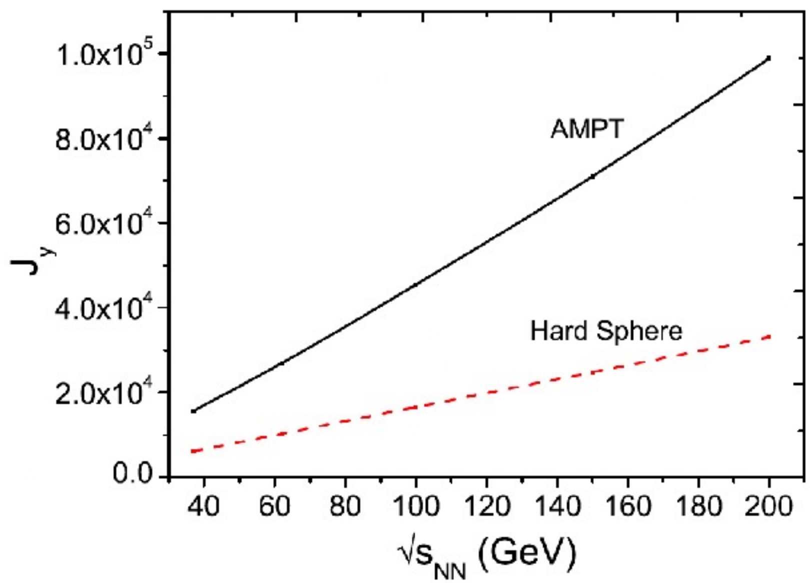
[2] *Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA*

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

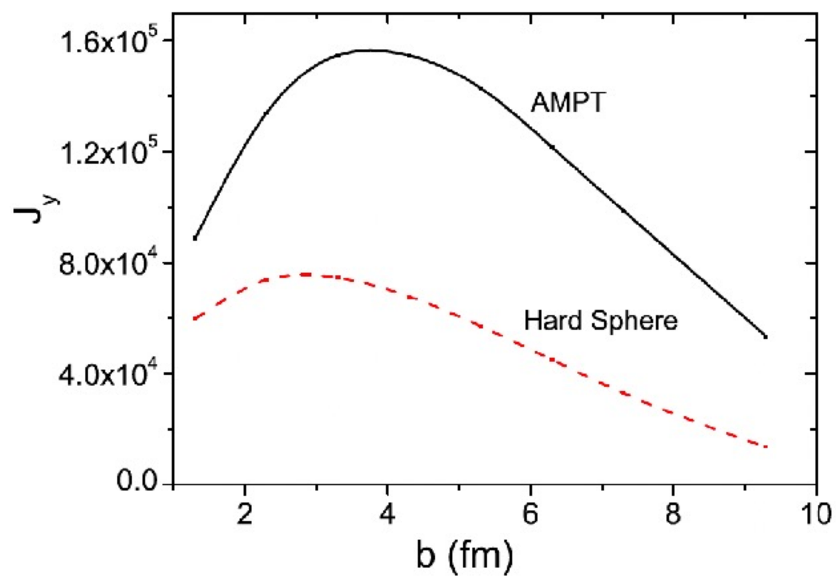
What fraction stays in QGP?
— up to ~20%, depending on collision energy.

Is this portion conserved?
—YES!

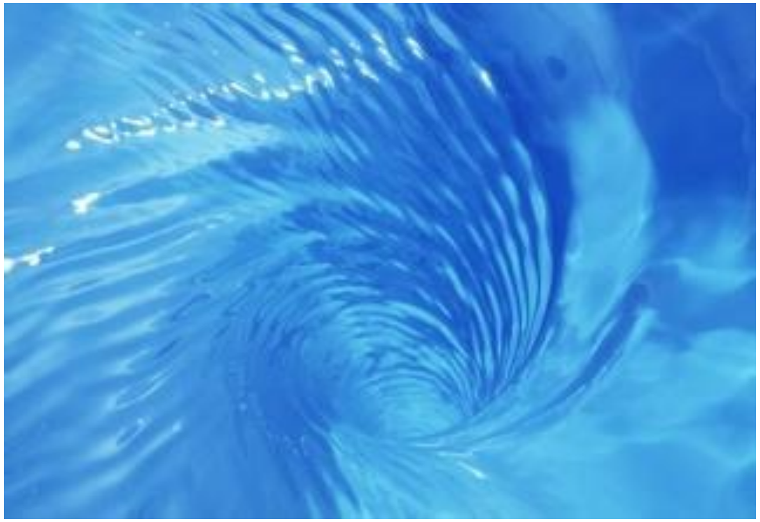
How QGP accommodates this angular momentum?
— Fluid vorticity!



Exercise!



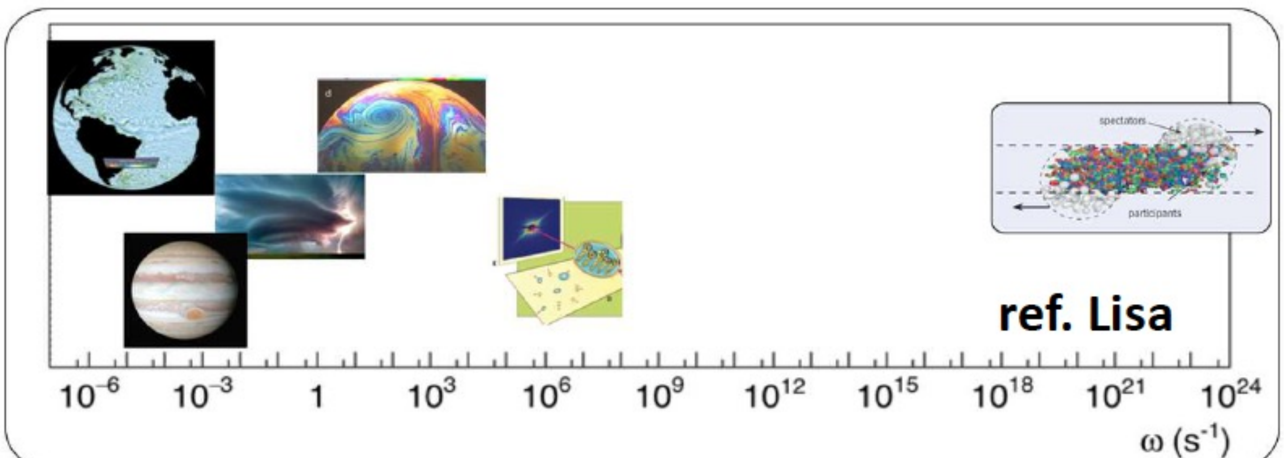
Quantifying Fluid Rotation



$$\vec{\mathbf{v}}$$

NR $\vec{\omega} = \frac{1}{2}\nabla \times \vec{\mathbf{v}}$

Rel. $\Omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$



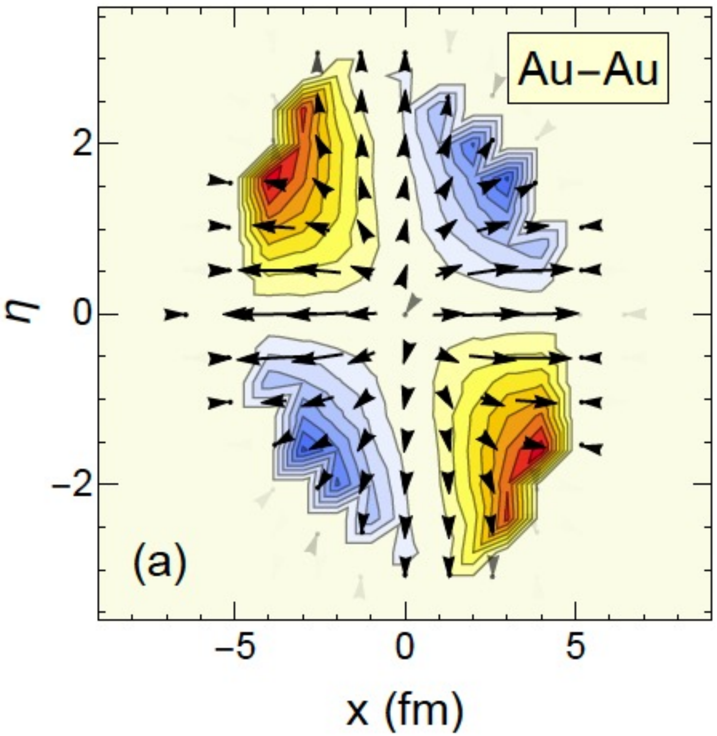
Heavy ion collisions:

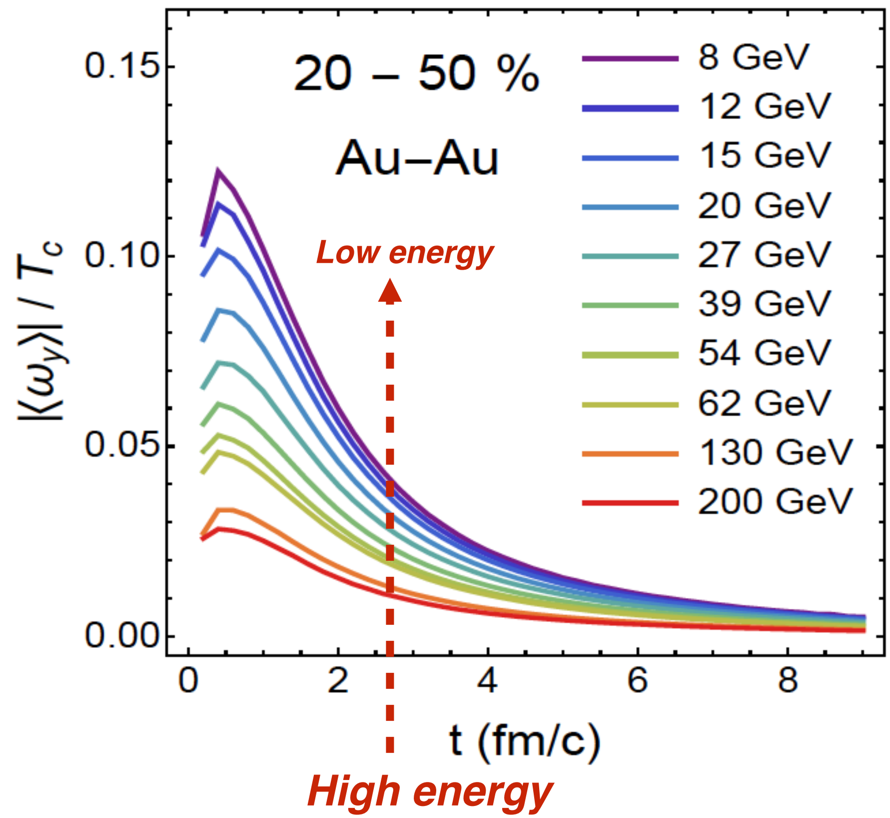
$v \sim 0.1\,c$

$\partial \sim \mathrm{fm}^{-1}$

$\omega \sim 10^{22}\,\mathrm{s}^{-1}$

Nontrivial Vorticity Structures





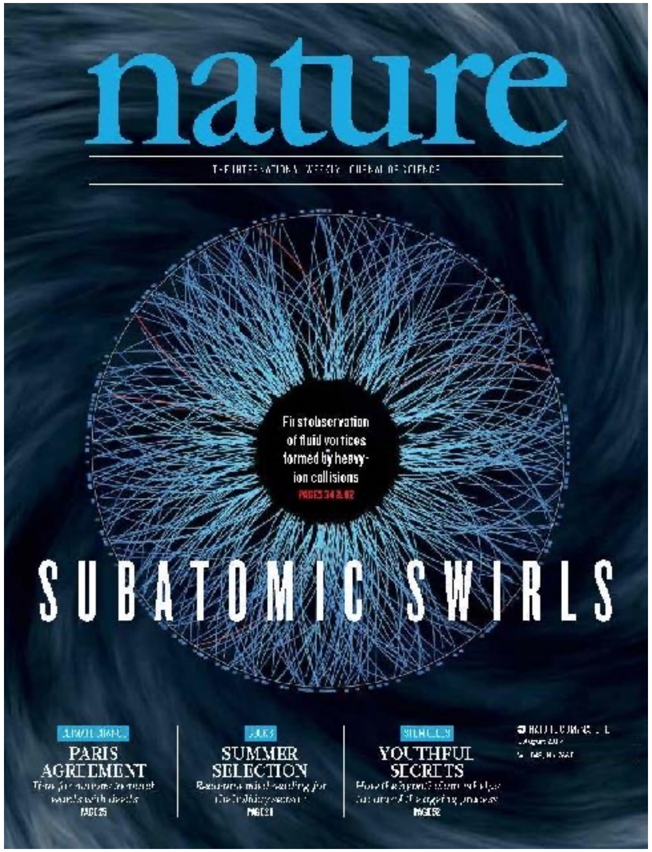
Sizable vorticity in QGP, due to the global orbital angular momentum.

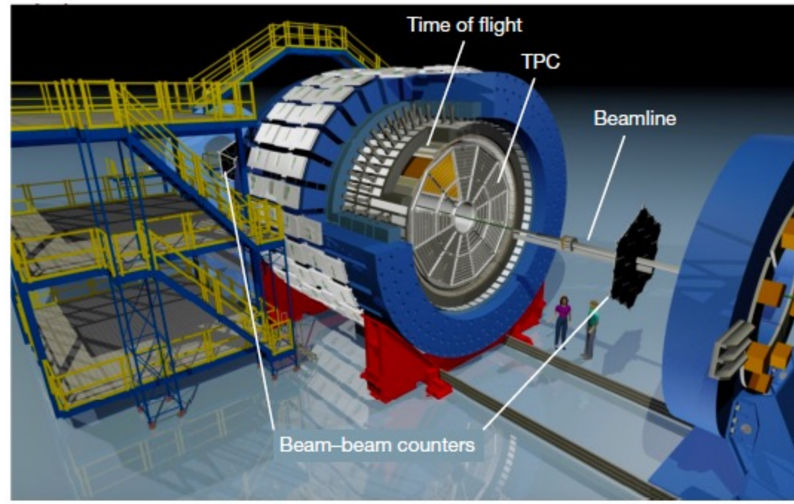
It could be manifested via spin-fluid coupling.

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

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

The Most Vortical Fluid





An exciting discovery from STAR Collaboration at RHIC: The most vortical fluid!

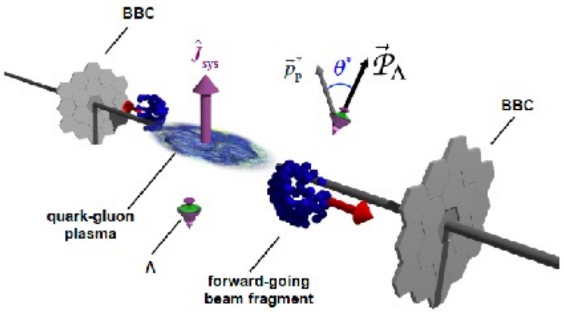
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

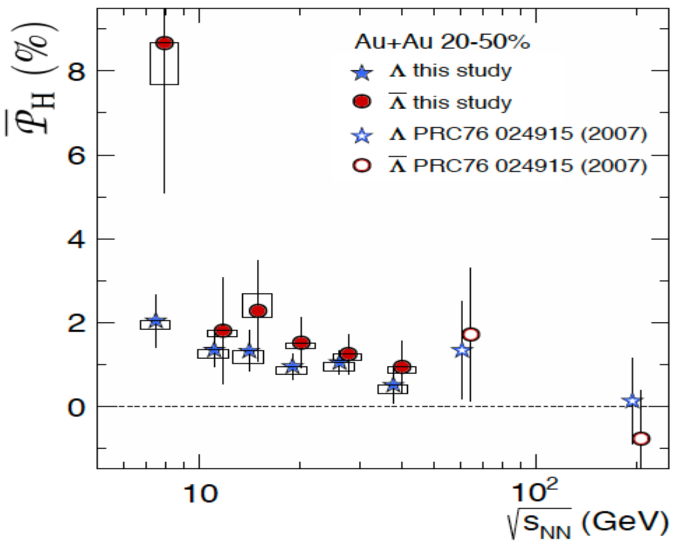
The STAR Collaboration*

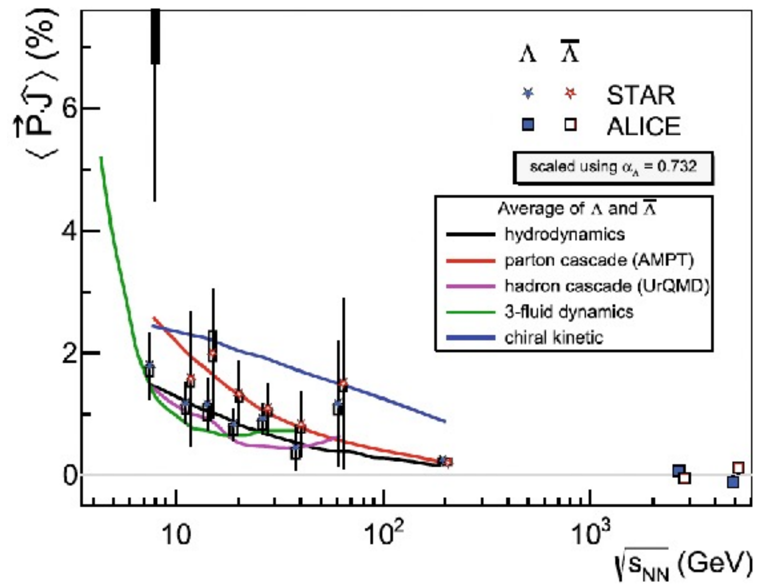
Spin Polarization in the Subatomic Swirls



STAR Collaboration, Nature 2017

The most vortical fluid!



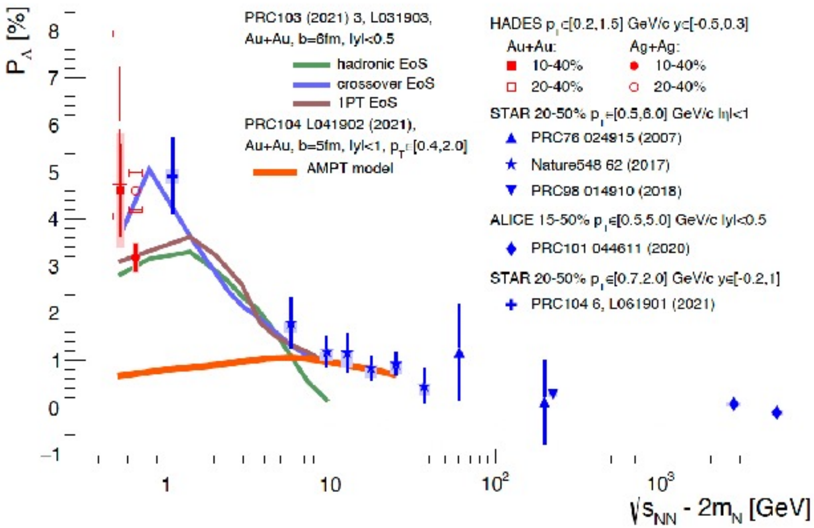


$$\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$$

Many calculations based on hydro or transport models

Highly Polarized Fluid at Low Beam Energy

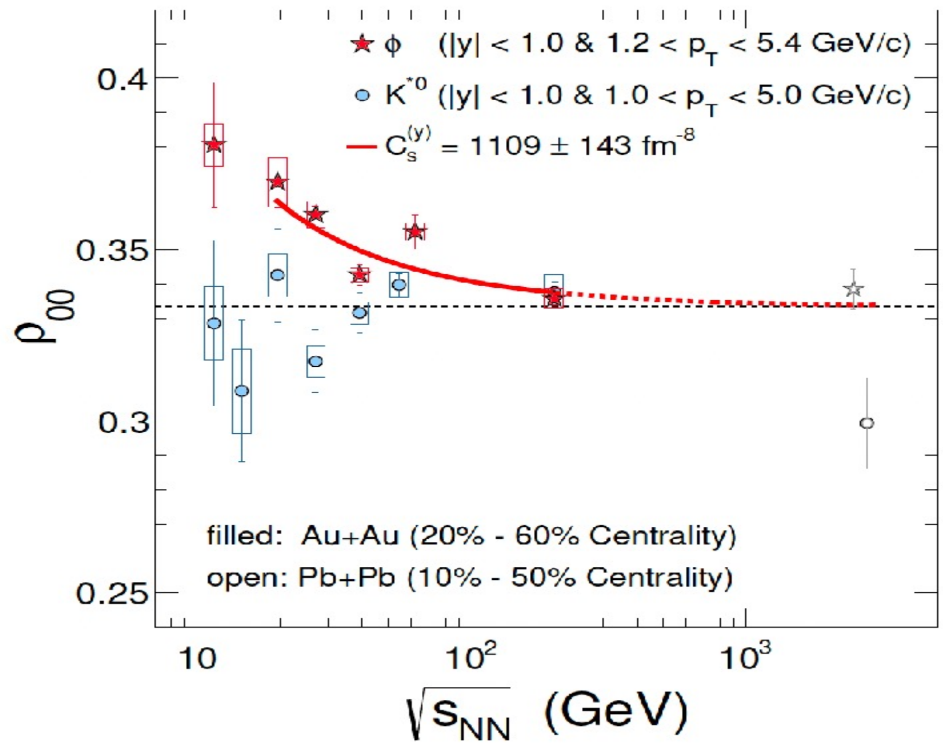
HADES, arXiv: 2207.05160



Surprisingly large signal even very close to threshold?!

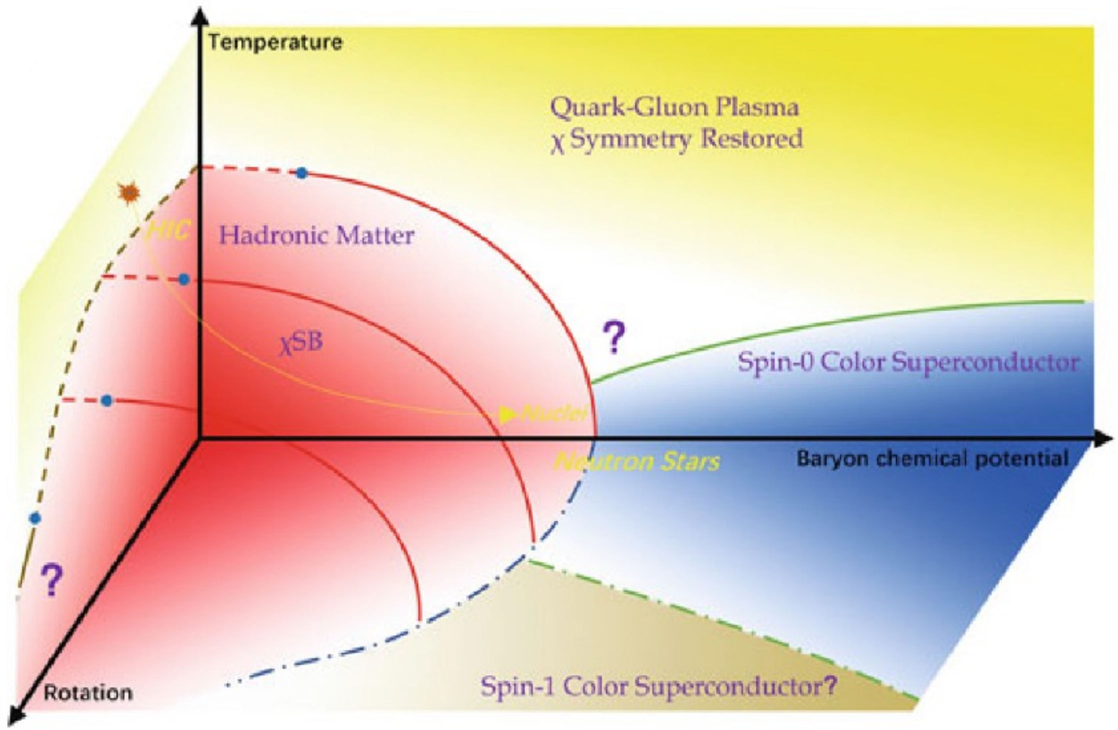
$$L_y = \frac{1}{2} A b \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

STAR, Nature 2023, arXiv: 2204.02302



Many other measurements (e.g. local polarization, other vector mesons, LHC, etc)

Phase Structures under Rotation



from arXiv: 2108.00586

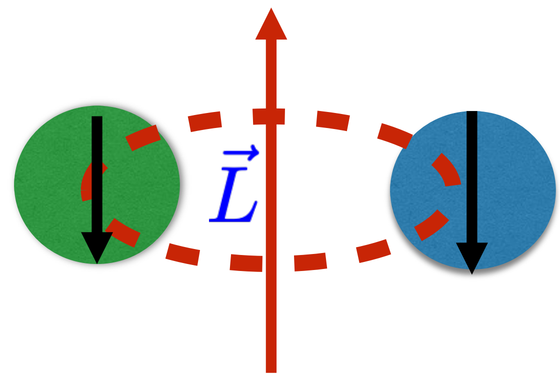
Rotation tends to align both spin and orbital angular momentum to align with global angular momentum.

Fermion Pairing under Rotation

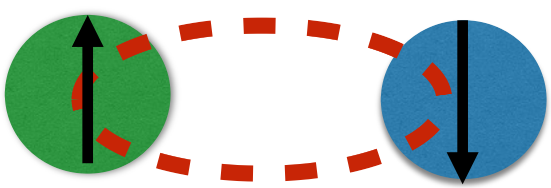
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, …

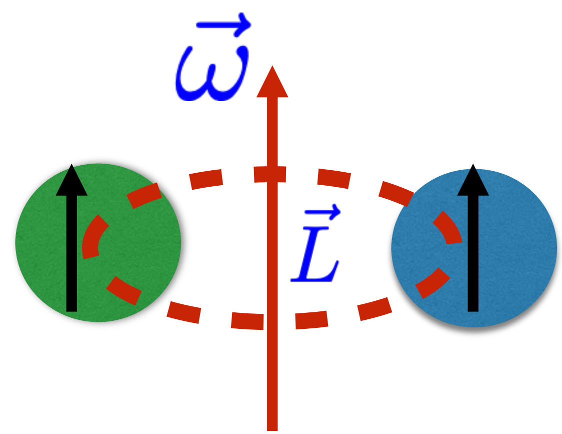
We consider scalar pairing state, with J=0.

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



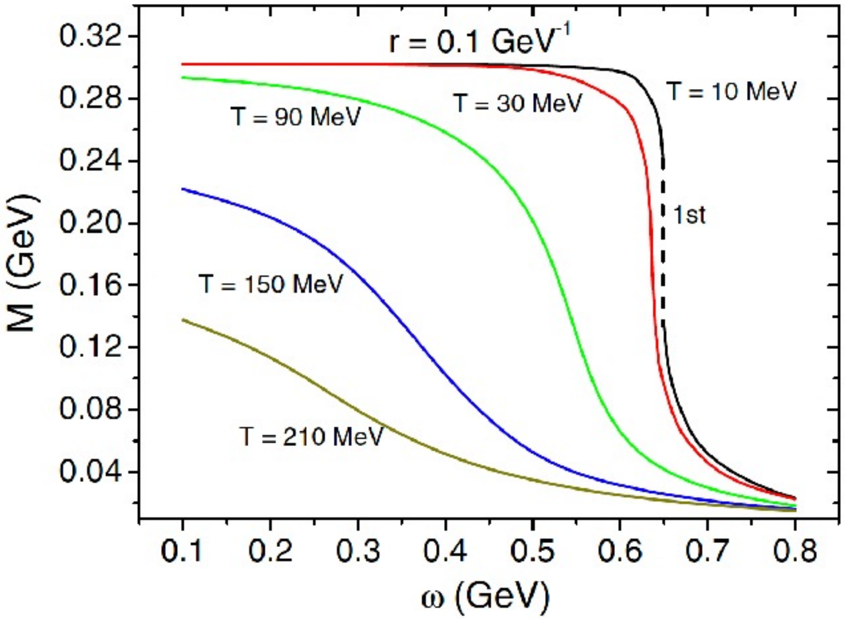
Rotation tends to polarize ALL angular momentum, both L and S, thus suppressing scalar pairing.



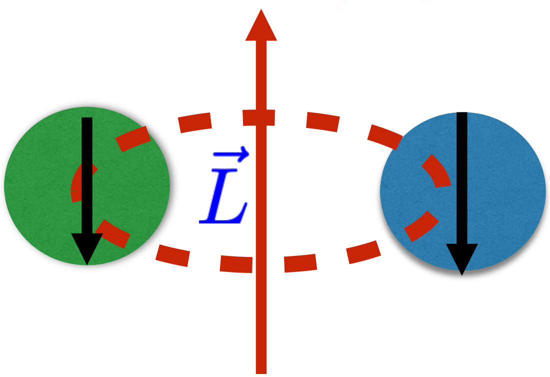


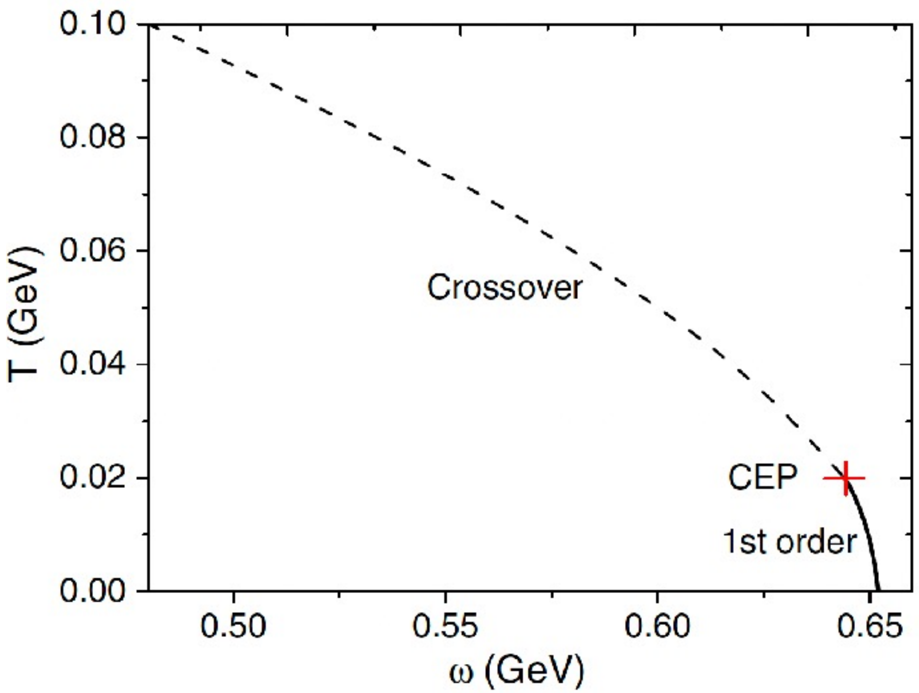
[Yin Jiang, JL, PRL2016]

Chiral Condensate under Rotation



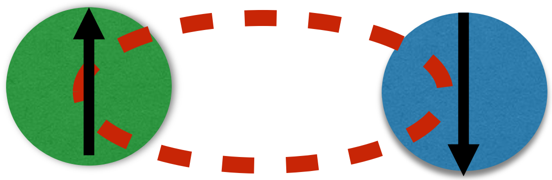
Chiral condensate: scalar-isoscalar pairing



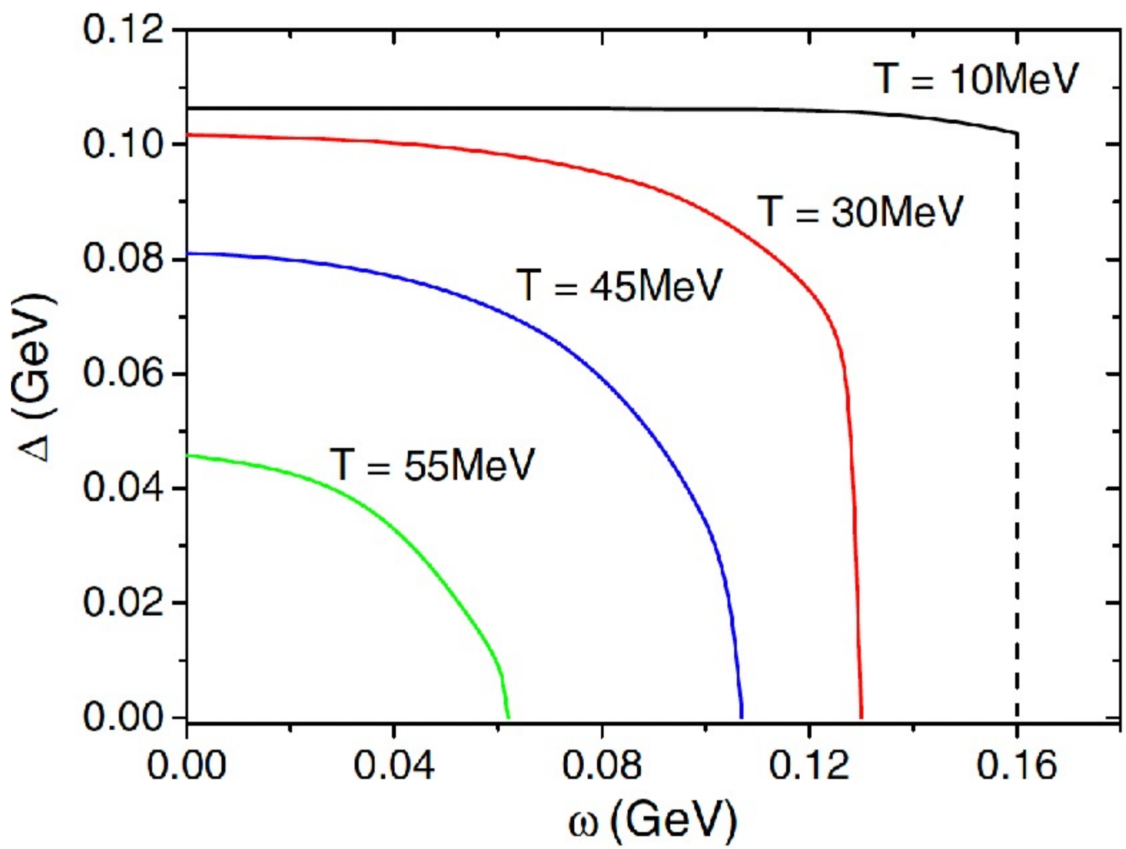


[Yin Jiang, JL, PRL2016]

Color Superconductor under Rotation



Color superconductivity:
scalar-isoscalar pairing

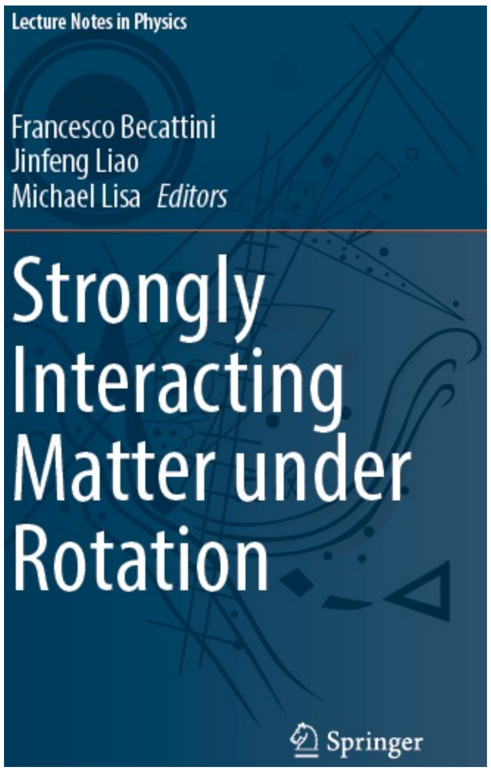


[Yin Jiang, JL, PRL2016]

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; …]

Anomalous Transport Effects

Spin & Chirality

Dirac fermion in massless limit: chirality well defined

$$\mathcal{L} \to \bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + \bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R$$

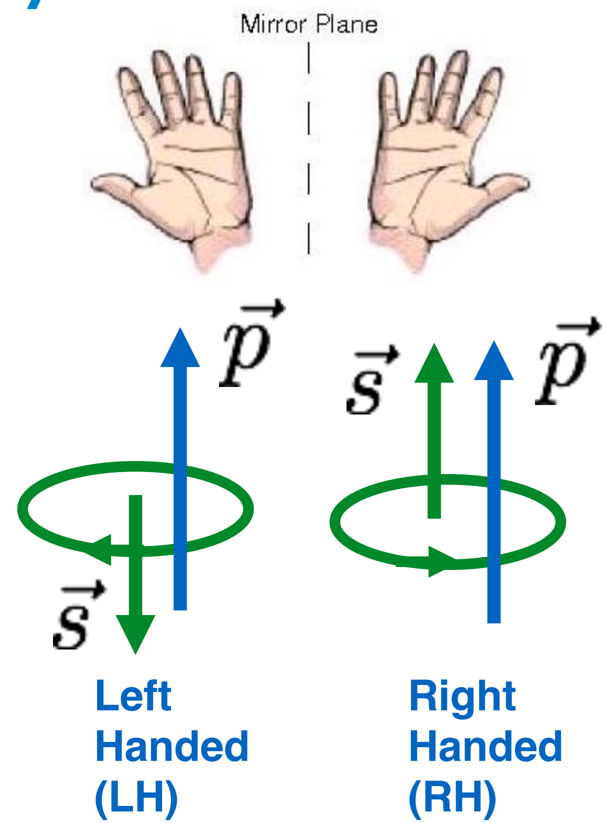
Axial symmetry
—> classical conserved axial current

Specific correlation between spin and momentum!!

A (large) mass term spoils all that:

$$m\bar{\Psi}\Psi = m\left(\bar{\Psi}_L \Psi_R + \bar{\Psi}_R \Psi_L\right)$$

$$\partial_\mu J_5^\mu = 2im\bar{\Psi}\gamma^5\Psi$$



In QCD:

$$\underset{\text{Constituent}}{M} = \underset{\text{SM}}{m} - 2G\underset{\text{Chiral condensate}}{\langle\bar{\psi}\psi\rangle}$$

(Nearly) chiral quarks only upon chiral restoration

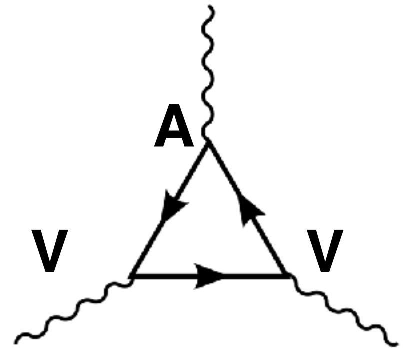
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

Classical axial symmetry broken at QM level:

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

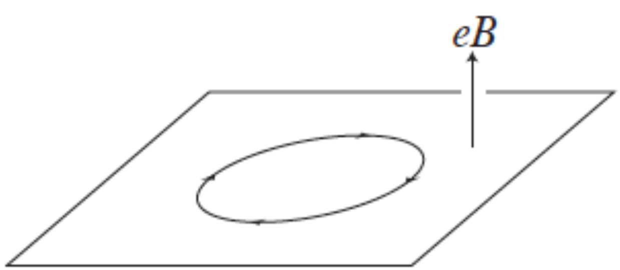


[e.g. pi0—> 2 gamma]

* C_A is universal anomaly coefficient

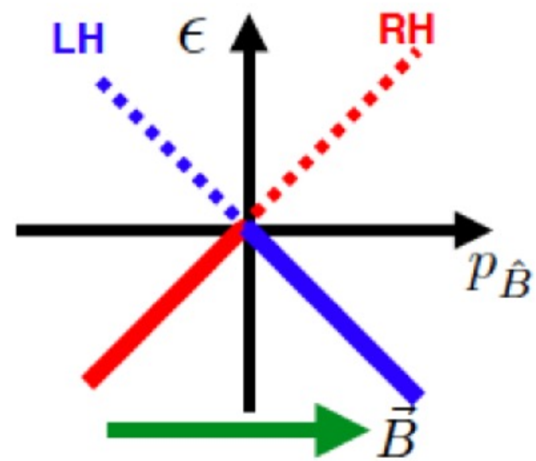
* Anomaly is intrinsically QUANTUM effect

We could intuitively understand this from Landau level



$$E_n^2 = p_z^2 + 2nB$$

Exercise!



Lowest-Landau-Level (LLL): LLL is chiral!

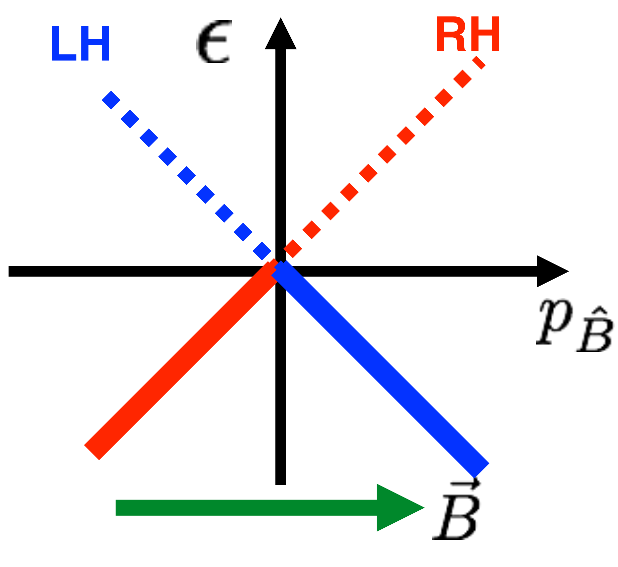
Chiral Anomaly

Chiral anomaly is a fundamental aspect of QFT with chiral fermions.

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

$$J_5^\mu = J_R^\mu - J_L^\mu$$



Illustrated with Lowest-Landau-Level (LLL) picture: the LLL is chiral!

Chiral Magnetic Effect (CME): Macroscopic Chiral Anomaly

Chirality & Anomaly & Topology

$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

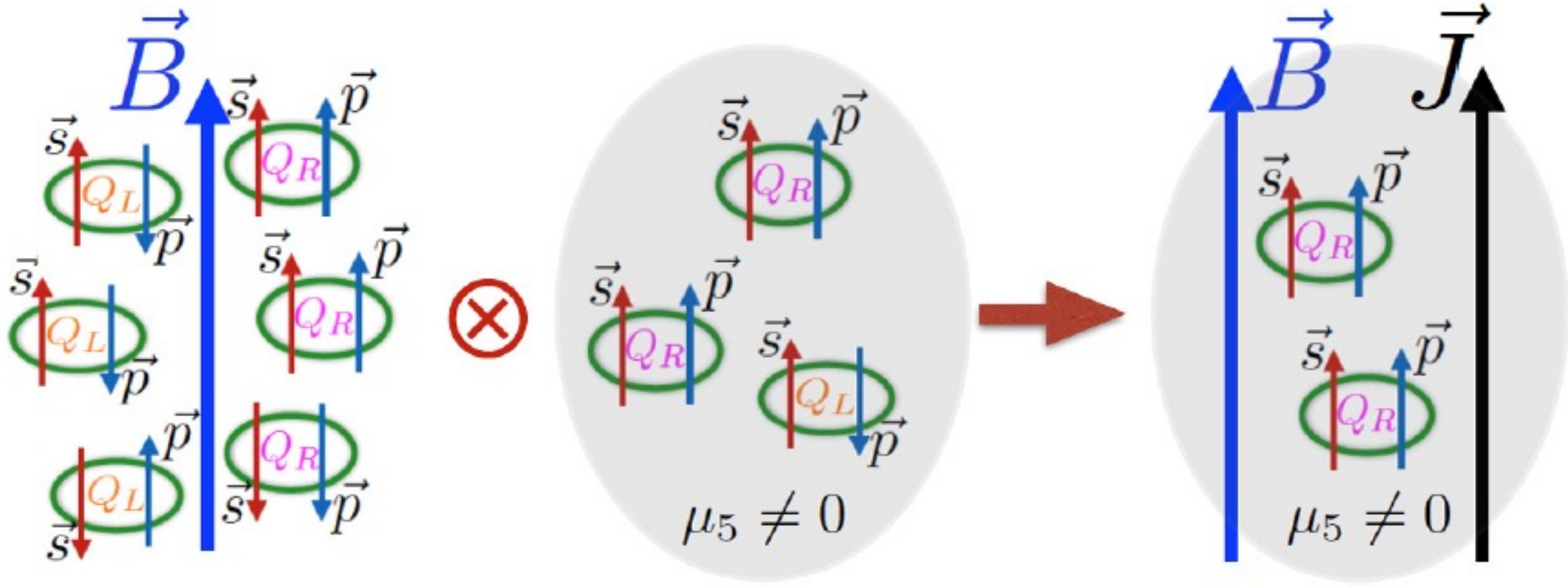
Electric Current

Magnetic Field

Q.M. Transport

[Kharzeev, Fukushima, Warringa, McLerran, …]

CME: Interplay of B- and Chirality- Polarizations



[arXiv:1511.04050]

Intuitive understanding of CME:

Magnetic Polarization —>
correlation between micro.
SPIN & EXTERNAL FORCE

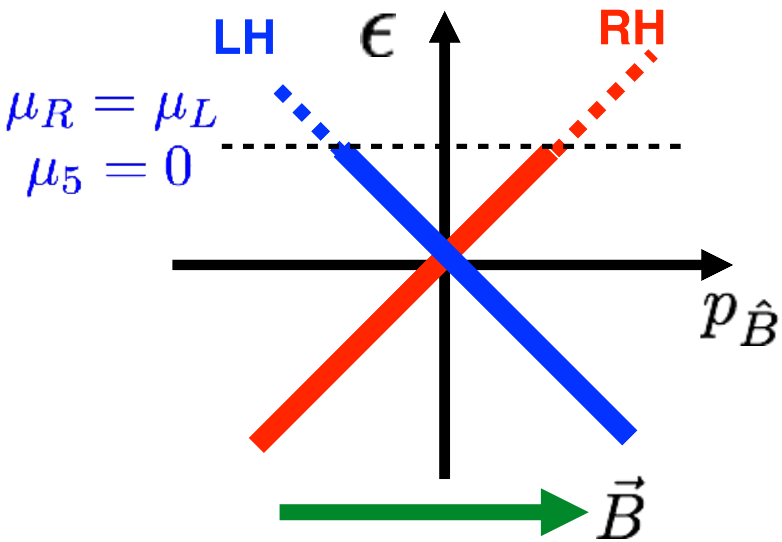
$\otimes$

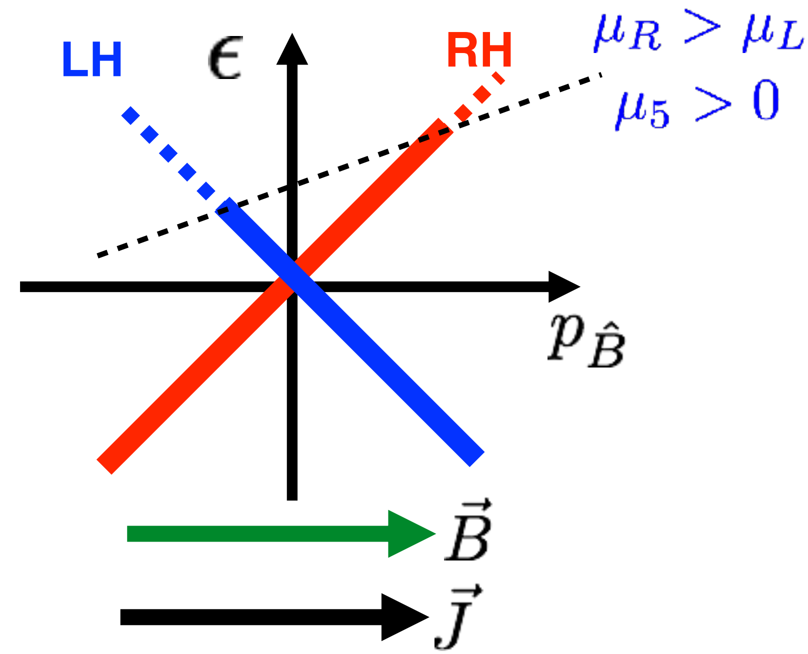
Chirality Polarization —>
correlation between directions of
SPIN & MOMENTUM

Transport current along magnetic field

$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Connecting CME with Anomaly





One may recognize deep connection between CME & anomaly.

$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$

The CME conductivity is

**** fixed entirely by quantum anomaly***

**** T-even, non-dissipative***

**** universal from weak to strong coupling***

Macroscopic effect of chiral anomaly!

CME <=> Chiral Anomaly

Anomaly --> $\partial^\mu j^5_\mu = \frac{q^2}{2\pi^2} \boldsymbol{E}\cdot\boldsymbol{B}$ $\frac{dN_5}{dtd^3x} = \frac{q^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B}$

Chirality --> $\int d^3x \boldsymbol{j}_{el}\cdot\boldsymbol{E} = \mu_5 \frac{dN_5}{dt} = \frac{q^2\mu_5}{2\pi^2}\int d^3x \mathrm{B}\cdot\boldsymbol{E}$

$\boldsymbol{E}\to 0$ $\boldsymbol{j}_{el} = (q^2\mu_5/2\pi^2)\boldsymbol{B}$

* This is a non-dissipative current!
* Indeed the chiral magnetic conductivity is P-odd but T-even!
(In contrast the Ohmic conductivity is T-odd and dissipative.)

Analogy between B Field and Rotation

Fluid velocity field

$$\vec{V}$$

Fluid vorticity

$$\vec{\omega} = \vec{\nabla} \times \vec{V}$$

EM vector field

$$\vec{A}$$

Magnetic field

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

At classical level:

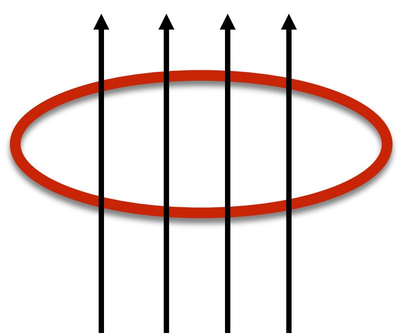
$$\vec{F}_{Lorentz} = e\,\vec{v} \times \vec{B}$$

(Lorentz force)

$$\vec{F}_{cor} = 2m\,\vec{v} \times \vec{\omega}$$

(Coriolis force)

$$\vec{\omega}\ or\ \vec{B}$$



At quantum level:

$$\phi_B = e \int \vec{B} \cdot d\vec{S}$$

(Aharonov-Bohm effect)

$$\phi_\omega = 2m \int \vec{\omega} \cdot d\vec{S}$$

(Sagnac effect)

An angular momentum from rotation and a magnetic flux generate a similar quantum phase of topological character.

B/Omega Analogy: Chiral Vortical Effect

In a Parity-Odd medium, vectors & axial vectors can be mixed up, and one can be generated from the other.

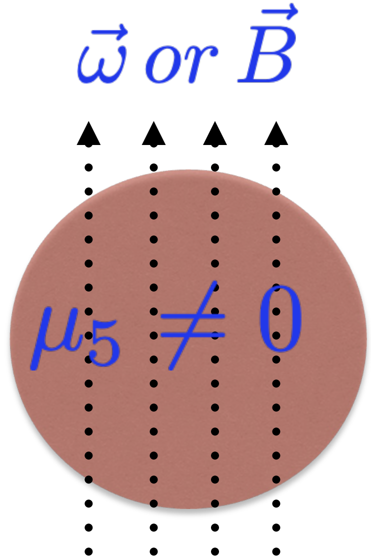
For rotating fluid:

$$\vec{V} \cdot \vec{\omega} \neq 0$$

$$\omega \to V \parallel \omega$$

Chiral Vortical Effect

$$\vec{J} \propto \mu_5 (\mu \vec{\omega})$$



For EM field:

$$\vec{E} \cdot \vec{B} \neq 0$$

$$\vec{B} \to \vec{E} \parallel \vec{B}$$

Chiral Magnetic Effect

$$\vec{J} \propto \mu_5 (e\vec{B})$$

Intuitive understanding of CME & CVE:

rotational polarization or magnetic polarization —> correlation between micro. SPIN & EXTERNAL FORCE

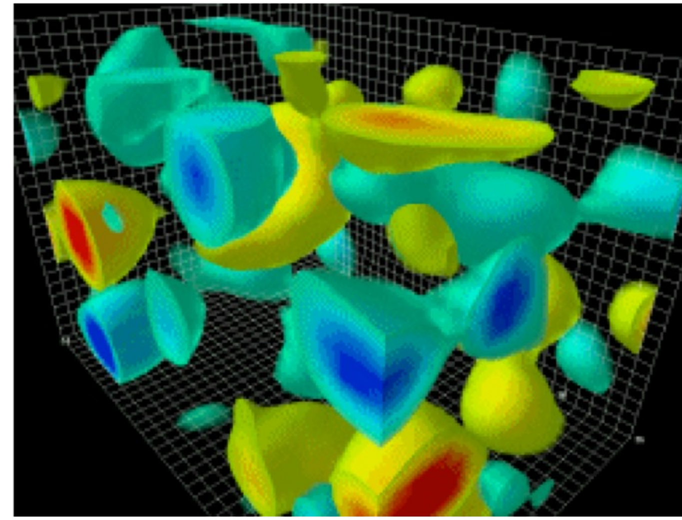
$\otimes$

Chiral imbalance —> correlation between directions of SPIN & MOMENTUM

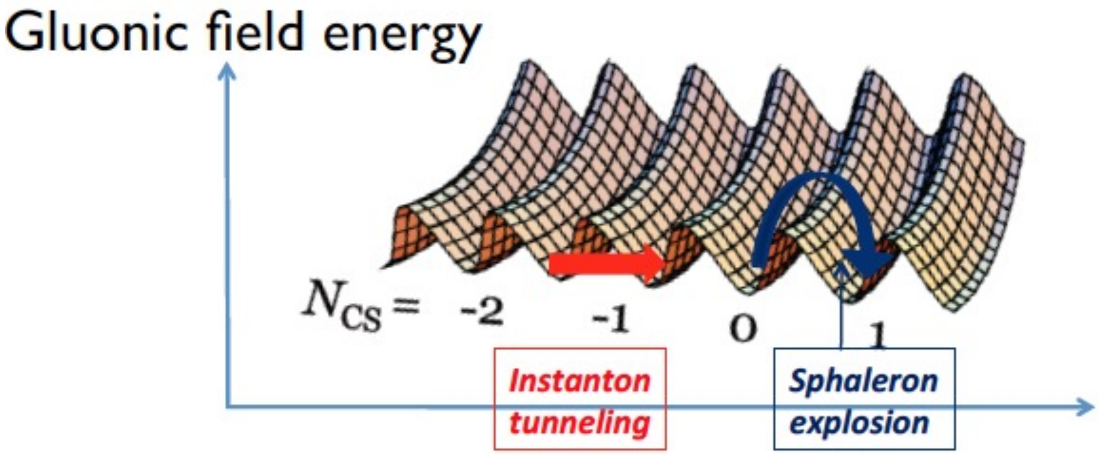
$\longrightarrow$ ***Current along external force!***

Topological Objects Provide E-dot-B

Topological objects in QCD are known to exist and play vital roles. [e.g. 't Hooft, hep-th/0010225]



Lattice QCD Visualization

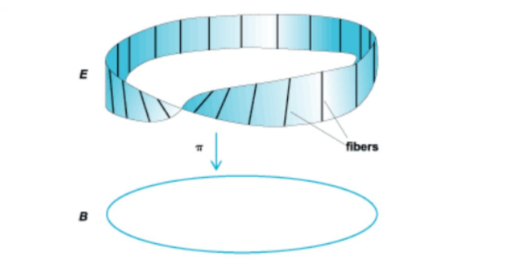


$$N_{CS} = \frac{1}{16\pi^2}\int d^3x\,\epsilon^{ijk}\left(A_i^a\partial_j A_k^a + \frac{1}{3}\epsilon^{abc}A_i^a A_j^b A_k^c\right)$$

$$\boxed{Q_w = \frac{g^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}_a^{\mu\nu}} \sim \vec{E}^a \cdot \vec{B}^a$$

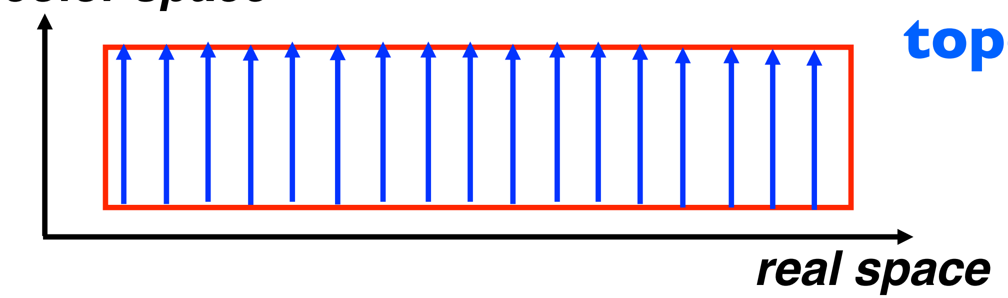
P & CP ODD

Topological Objects Provide E-dot-B



Möbius strip, the simplest nontrivial example of a fiber bundle

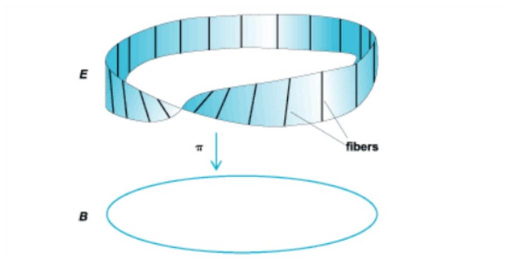
The Mobius Strip is a neat example to illustrate the gauge field topology.



# of twisting before gluing:
topological charge |Q ~ E-dot-B|

Two ways of twisting:
LH vs RH (+ or - |Q|)

Topological Objects Provide E-dot-B



Möbius strip, the simplest nontrivial example of a fiber bundle

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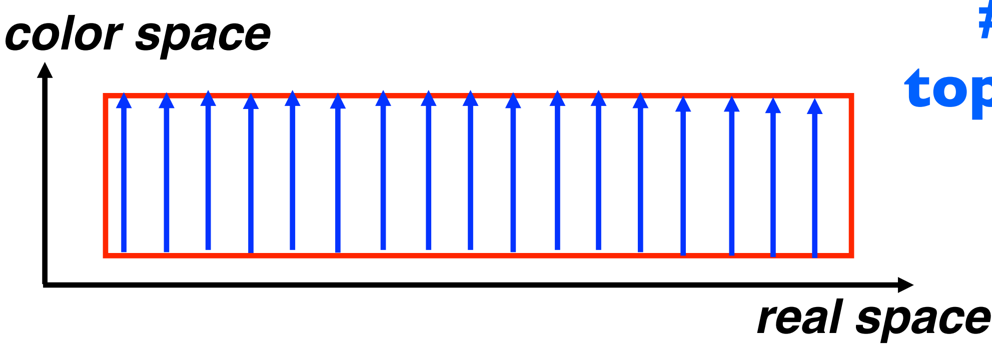
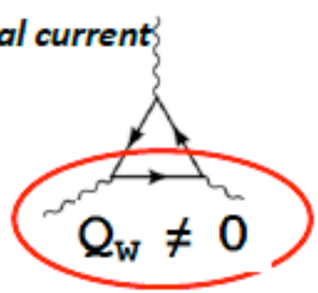


# of twisting before gluing: topological charge |Q ~ E-dot-B|

Two ways of twisting: LH vs RH (+ or - |Q)



$$\partial^\mu j^5_\mu = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

$$\boxed{(N^f_L - N^f_R) = 2Q_w}$$

Nonzero topological charge generates chirality change

Chirality imbalance <——> QCD topological fluctuations!

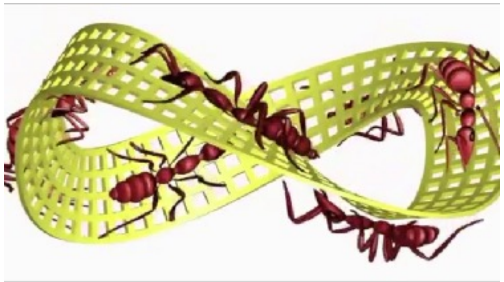
A Deep Mathematical Connection

Atiyah-Singer Index Theorem

Abel Prize 2004

Theorem (M.F. Atiyah and I.M. Singer): *Let $P(f) = 0$ be a system of differential equations. Then*

$$\textit{analytical index}(\mathrm{P}) = \textit{topological index}(\mathrm{P}) .$$



$$N_R - N_L = N_5 = 2Q_w$$

Net chirality <—> topo fluctuations & chiral restoration

Probing topology & chirality is of fundamental interest!

More Chiral Transport Phenomena

- *Chiral separation effect (CSE)*
- *Chiral electric separation effect (CESE)*
- *Chiral vortical effect (CVE)*
- *Chiral magnetic/vortical waves*
- *Chiral plasma instabilities*
- *……*

Strong Interdisciplinary Interests

- *Condensed matter: CME in semimetals*
- *Astrophysics: leptons in supernova / compact star*
- *Cosmology: analogy beween Baryo-genesis and Chiro-genesis*
- *Plasma physics: MHD with CME & magnetic helicity*
- *Quantum information: devices based on CME*
- *QFT & many-body theory: new "playground" (chiral transport theory; chiral hydrodynamics; ...)*

Exciting Progress: See Recent Reviews

Kharzeev & JL, Nature Reviews Physics 3(2021)1, 55-63

Bzdak, Esumi, Koch, JL, Stephanov, Xu, arXiv:1906.00936 [Phys. Rep. 853 (2020) 1-87].

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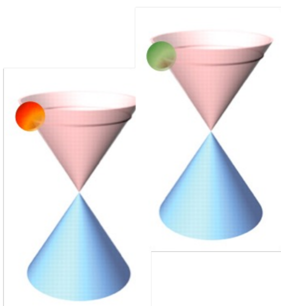
Miransky & Shovkovy, Phys. Rept. 576(2015)1.

New Territory of CME Physics: 3D Semimetals

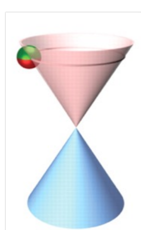
e anomalous transport phenomena are universal phenomena across
undaries of disciplines, encompassing a wide range of chiral systems!

Weyl semimetal
(non-degenerated bands)

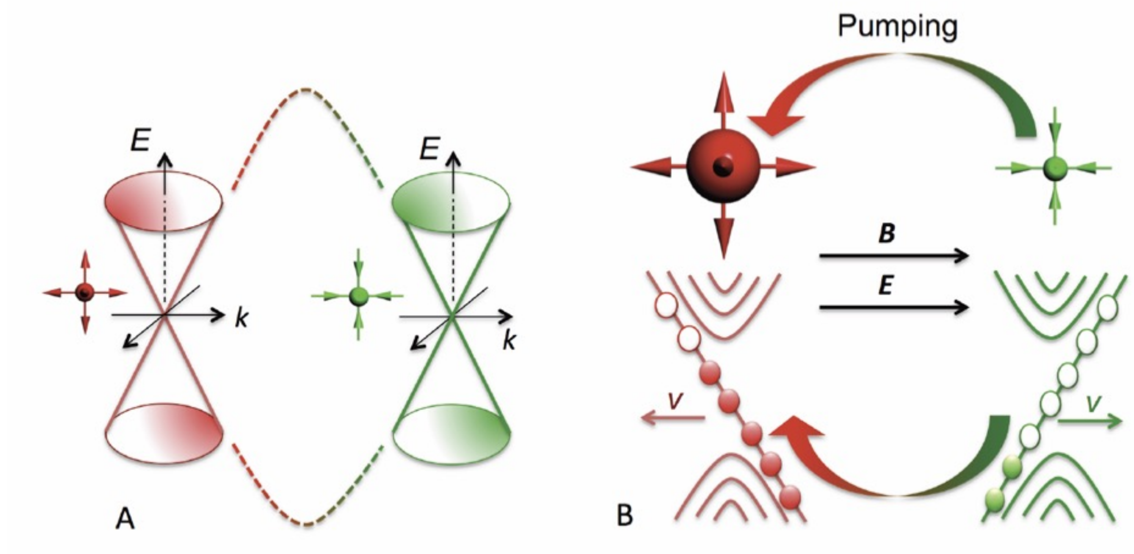


TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



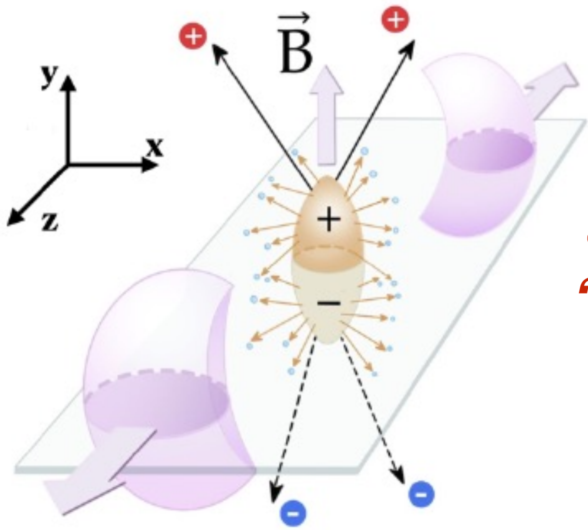
$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

$$dQ_5/dt = \int_{\vec{x}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

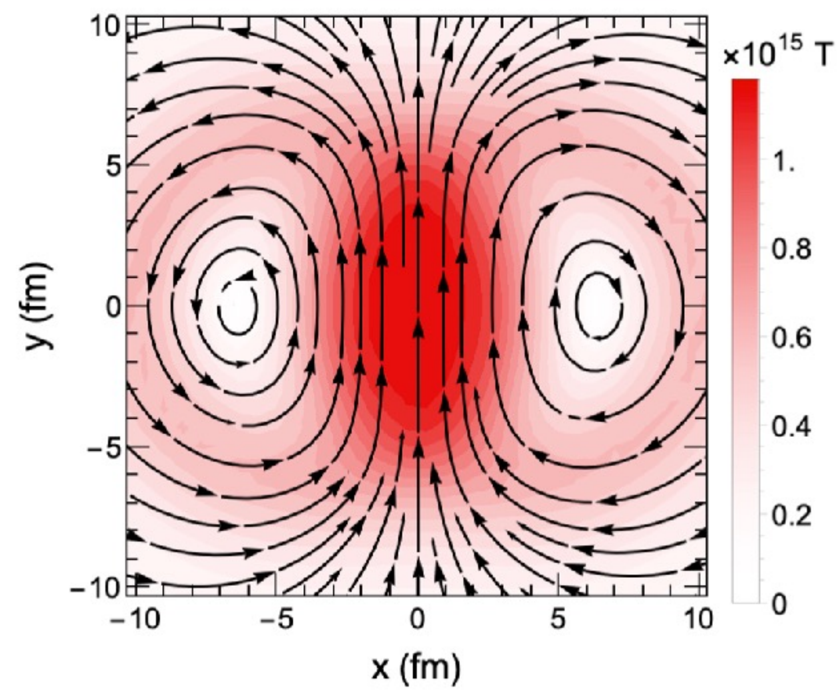
CME has been observed via negative magnetoresistance!

See review in e.g. RMP90, no. 1, 015001 (2018).

Heavy Ion Collision: the Most Magnetized Fluid



Subatomic "lightning"!



The strongest B field ~ 10^15 Tesla

$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

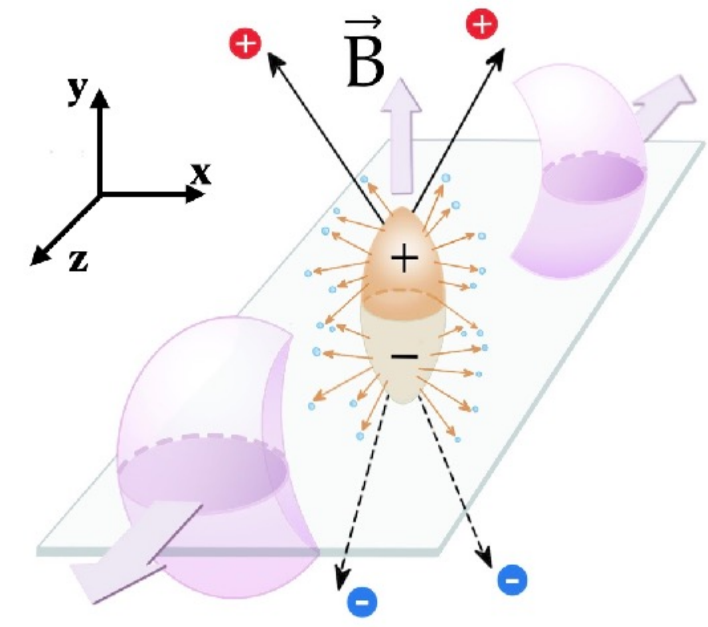
Exercise!

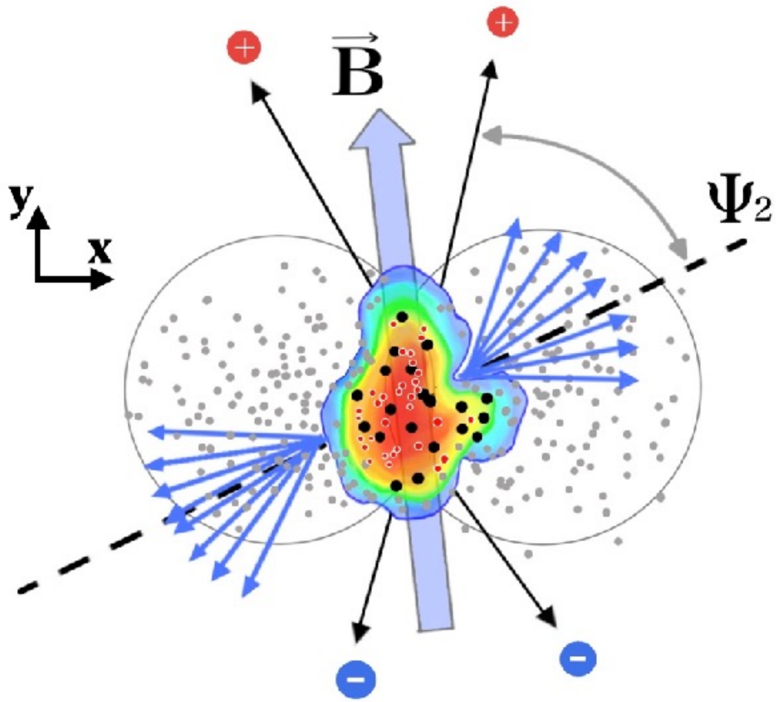
However: maybe short-lived

Interesting new ways to probe and constrain in-medium B fields: Conserved charge fluctuations, Ding et al; Directed flow; Spin polarization splitting; …

Looking for CME Signals in Nuclear Collisions

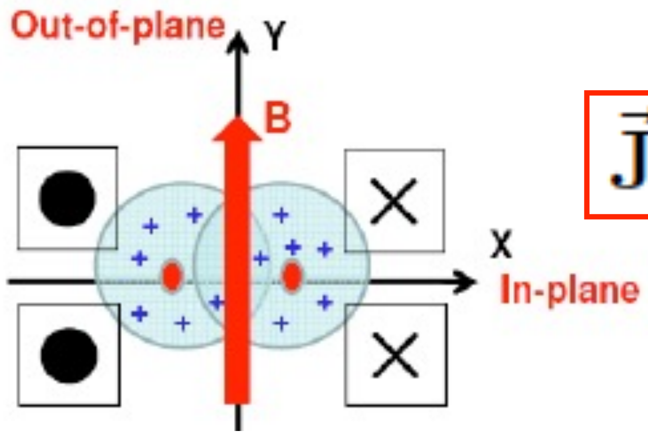
CME transport induces a charge dipole distribution along magnetic field direction in the QGP fluid.



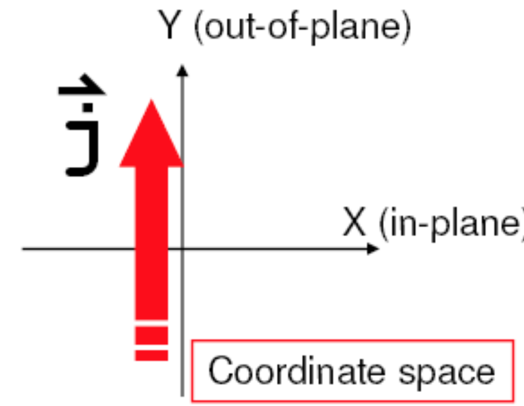


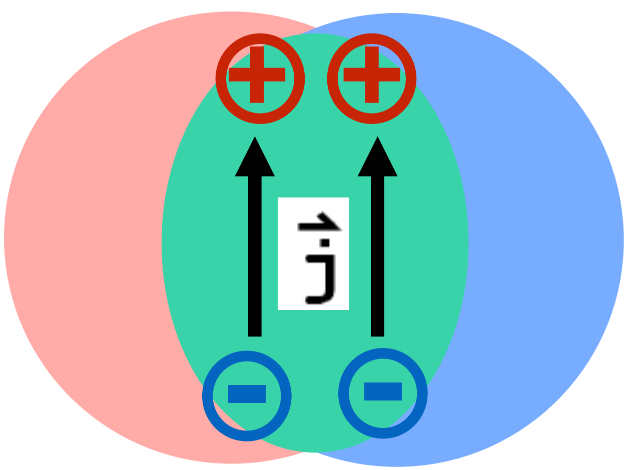
A specific emission pattern of charged particles along B field:
Same-sign hadrons emitted preferably side-by-side;
Opposite-sign hadrons emitted preferably back-to-back.

From CME to Charge Separation

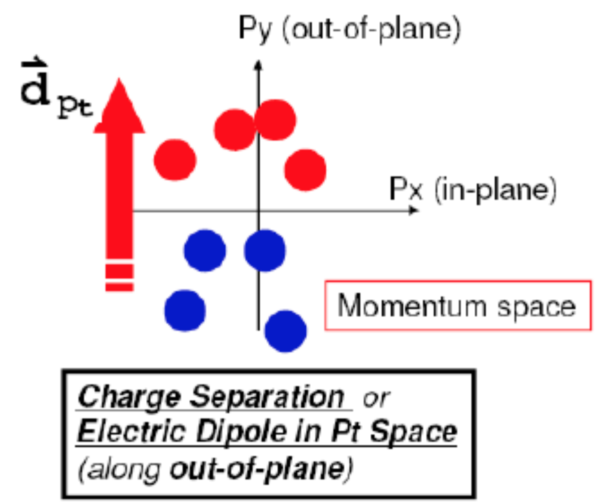


$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$





strong radial blast:
position —> momentum



$$\frac{dN_\pm}{d\phi} \propto \ldots + a_\pm \sin(\phi - \Psi_{RP})$$

$$< a_\pm > \sim \pm < \mu_5 > B$$

[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

Charge Separation Observable

$$\frac{dN_\pm}{d\phi} \propto ... + a_\pm \sin(\phi - \Psi_{RP})$$

$$< a_\pm > \sim \pm < \mu_5 > B \to 0$$

The dipole flips e-by-e and averages to zero (no global P-violation)

[Voloshin, 2004]

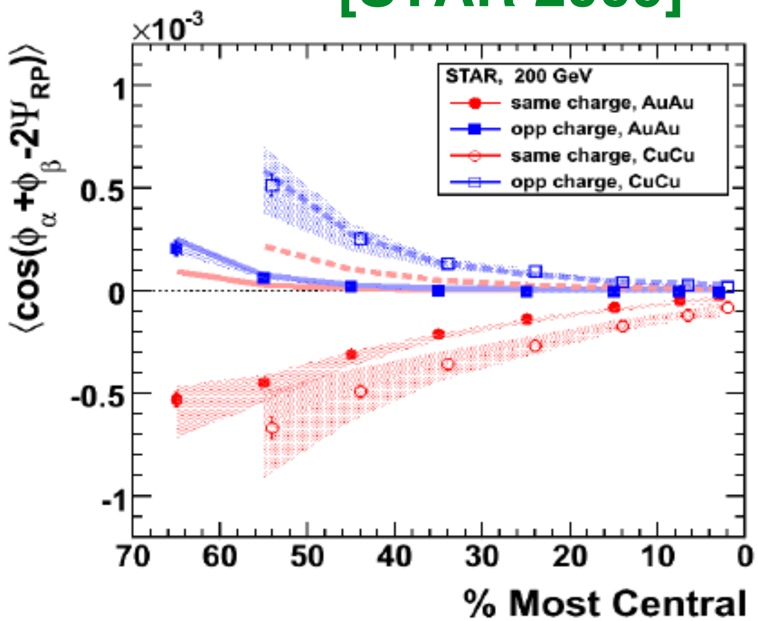
$$\gamma = \langle cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$$

known to be very small

The hope was: these two cancel out to be negligible…

what we are looking for

[STAR 2009]



As it was pointed out later, the backgrounds turn out to be NOT negligible…

[Bzdak, Koch, JL, 2009, 2010; Wang; Pratt, …]

Fluid Dynamics That Knows Left & Right

Normal Hydrodynamics

$$\partial_\mu J^\mu = 0$$

$$J^\mu = n u^\mu + \nu^\mu$$

Viscous Current

$$\nu^\mu = \frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right)$$

Diffusion

$$+ \frac{\sigma}{2} E^\mu$$

Conduction

Anomalous Hydrodynamics

$$\partial_\mu J^\mu = C_A E^\mu B_\mu$$

Anomaly

$$J^\nu = n u^\mu + \nu^\mu + \nu_a^\mu$$

Viscous Current — *Anomalous Current*

$$\nu^\mu = \frac{\sigma T}{2} \Delta^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right)$$

Diffusion

$$+ \frac{\sigma}{2} E^\mu$$

Conduction

$$\nu_a^\mu = \xi_B B^\mu$$

CME

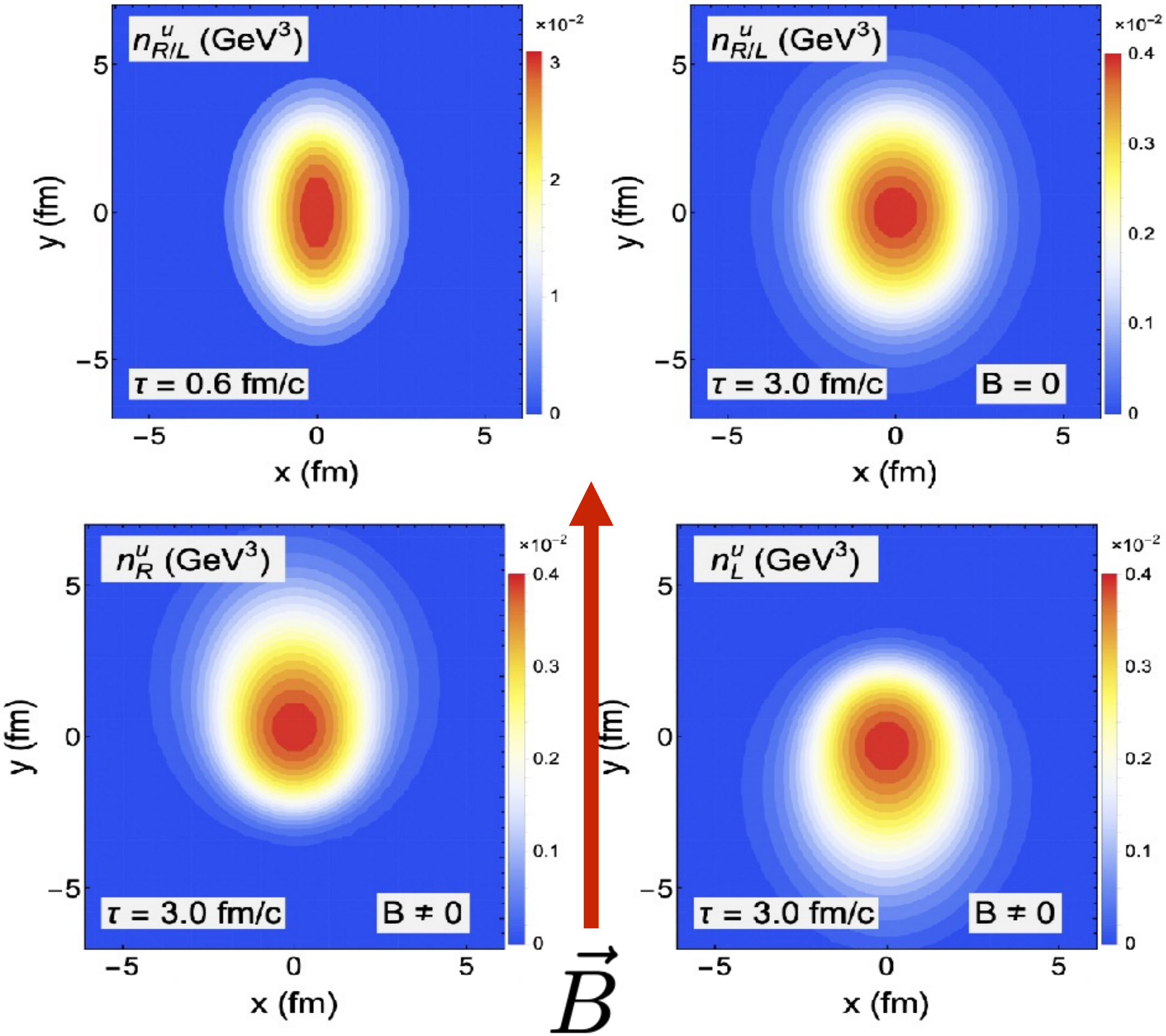
$$+ \xi \, \omega^\mu$$

CVE

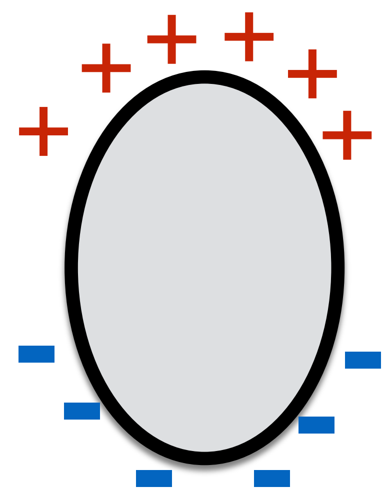
[Son, Surowka, 2009;…]

It would be remarkable to actually "see" this new hydrodynamics at work in real world materials!

Fluid Dynamics That Knows Left & Right



Chirality imbalance
—>
R/L asymmetry
—>
charge asymmetry



Anomalous-Viscous Fluid Dynamics (AVFD)

[arXiv:1611.04586; 1711.02496; 1910.14010]

Have We Seen the CME?

- *First measurement ~ 2009 by STAR;*
- *Efforts in the past ~14 yrs by STAR, ALICE, CMS @ RHIC and LHC*
- *Search from ~10GeV to ~5440GeV beam energies*
- *Various colliding systems from small to large systems*

It proves to be a very difficult search:
Very small signal contaminated by very strong background correlations!

$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

We are not alone!
Think about many other famous searches, e.g. for Higgs, gravitational wave, temperature fluctuations of CMB, EDM, WIMP, 2-beta decay, …

It took some 20+ years to finally discover quark-gluon plasma itself in heavy ion collisions!

Significant Progress in the Search

$$\gamma = \gamma^{CME} + \gamma^{bkg}$$

Flow driven ***Nonflow***

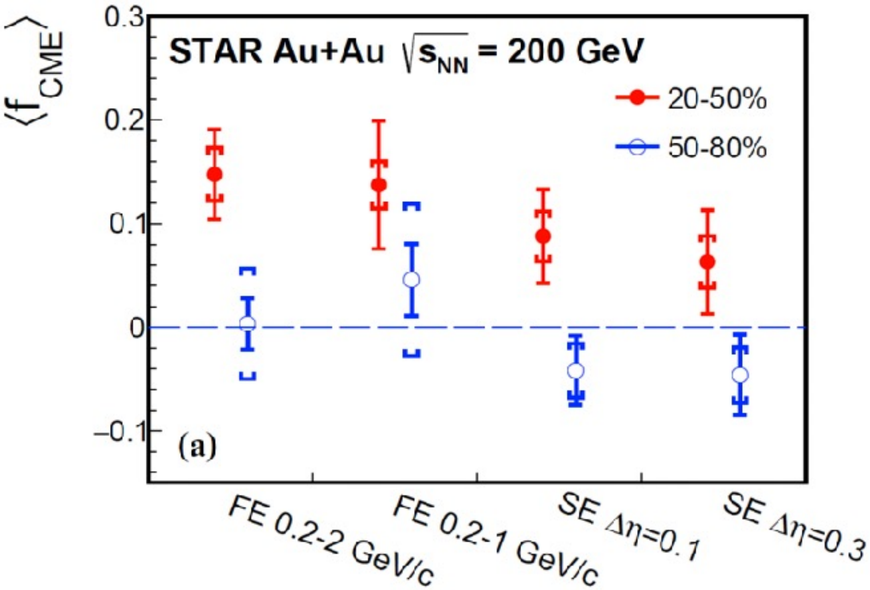
We've come a long way in fighting with the backgrounds
— recognizing the dominance of flow driven backgrounds (2009~2015)

— developing exp methods as well as theoretical calculations to quantify and remove the flow driven backgrounds (2015~2021)

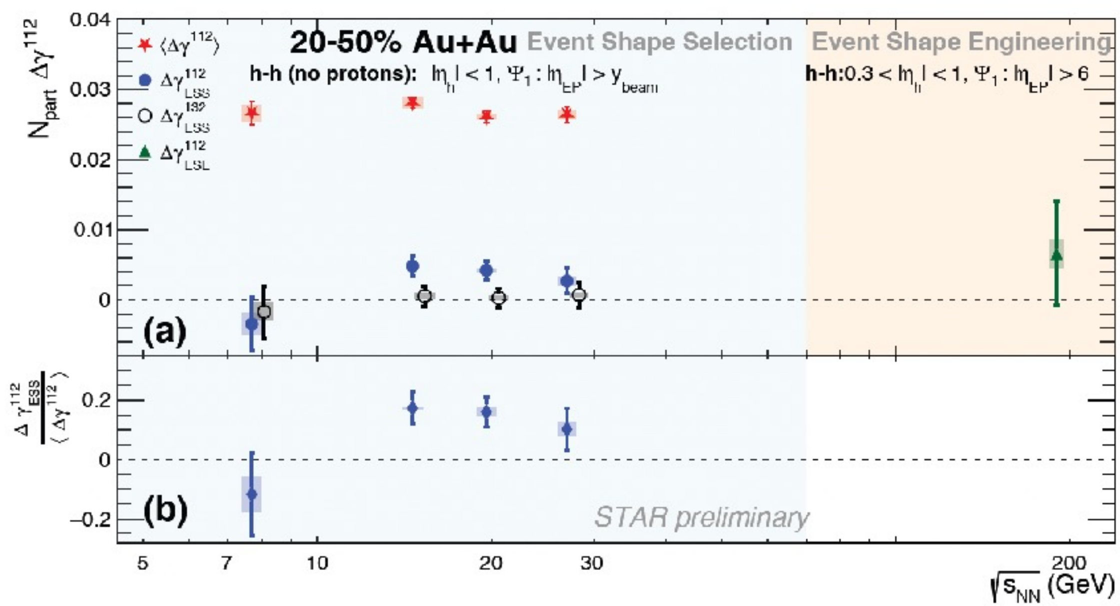
— studying nonflow for final extraction of CME signal (2021~now)

AuAu Collisions

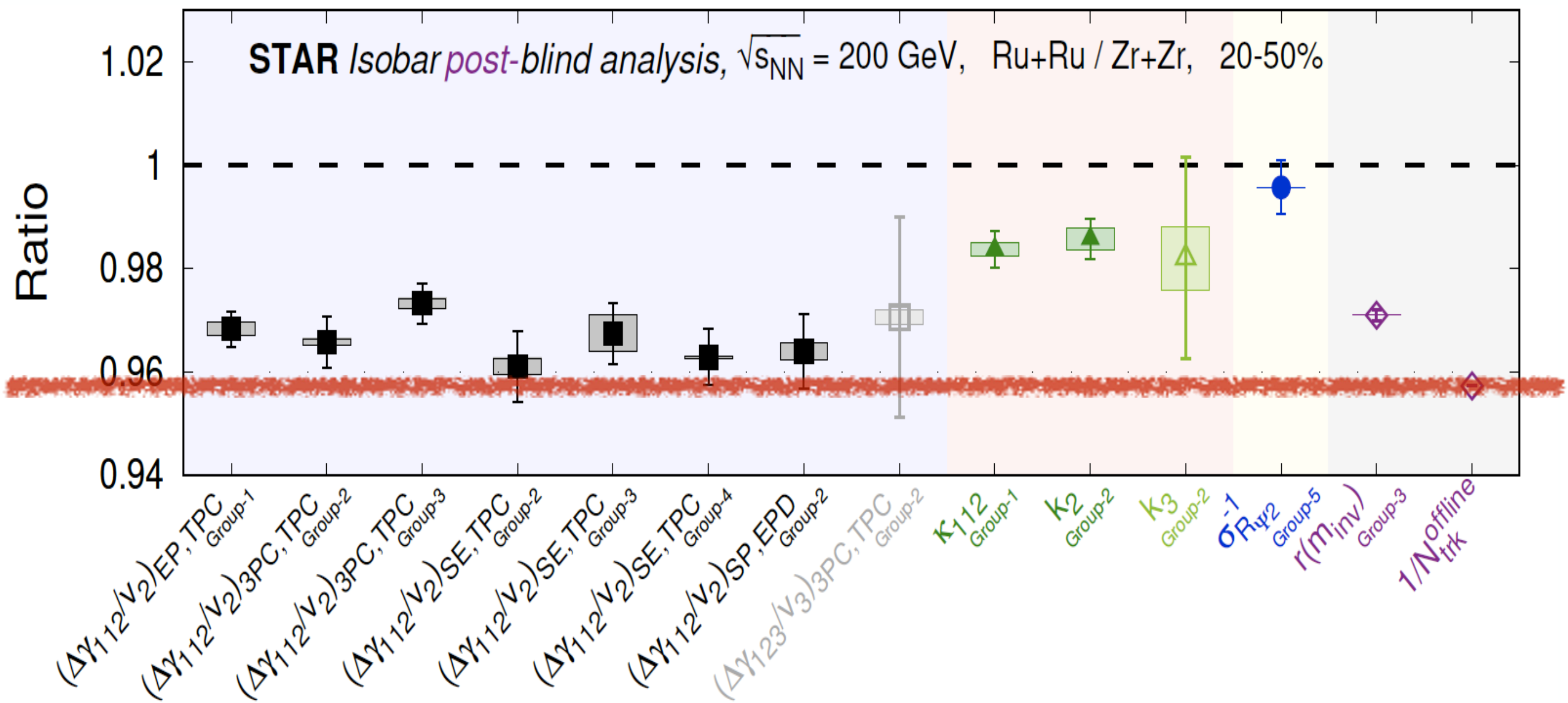
STAR, arXiv:2106.09243



About 3-sigma level of CME signal found in AuAu collisions!



Isobar Collisions



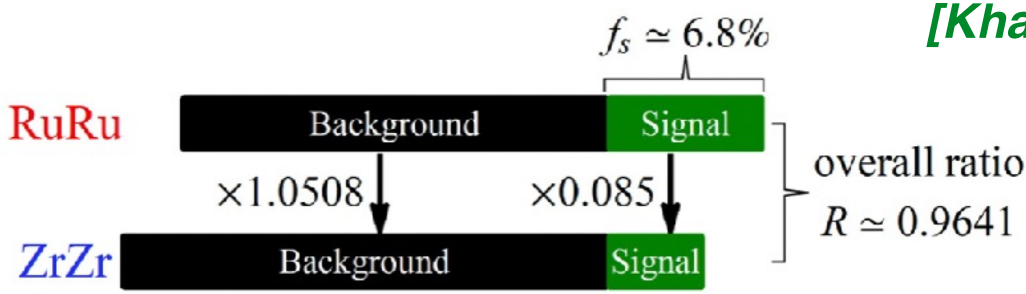
There appears room for potential CME signal above the 1/N line!
Need accurate calibration of the true baseline!

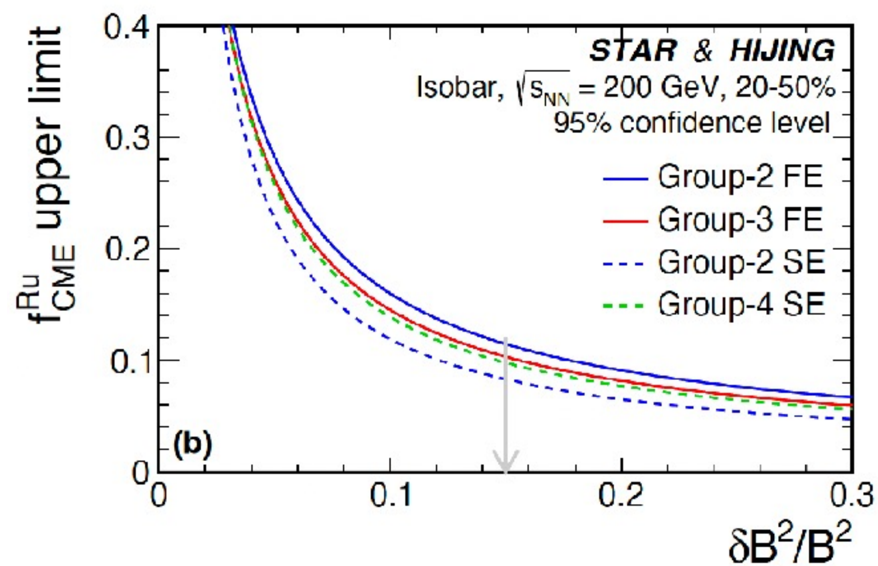
$$\gamma_{bkg} \propto \frac{1}{N_{ch}} \qquad N_{ch}^{Ru} > N_{ch}^{Zr} \qquad \frac{\gamma_{bkg}^{Ru}}{\gamma_{bkg}^{Zr}} < 1$$

Isobar Collisions

– ***Theoretical analysis suggests a nonzero signal in isobar collisions***

[Khazeev, JL, Shi, arXiv:2205.00120]





– ***Upper limits have been set by STAR for isobar collisions.***
– ***Consistent with theoretical expectations***
– ***Indicating a still better chance for the search in AuAu collisions***

Have We Seen the CME?

arXiv:2405.05427
(for QGP 6 ed. by XN Wang)

Chiral Magnetic Effect in Heavy Ion Collisions: The Present and Future

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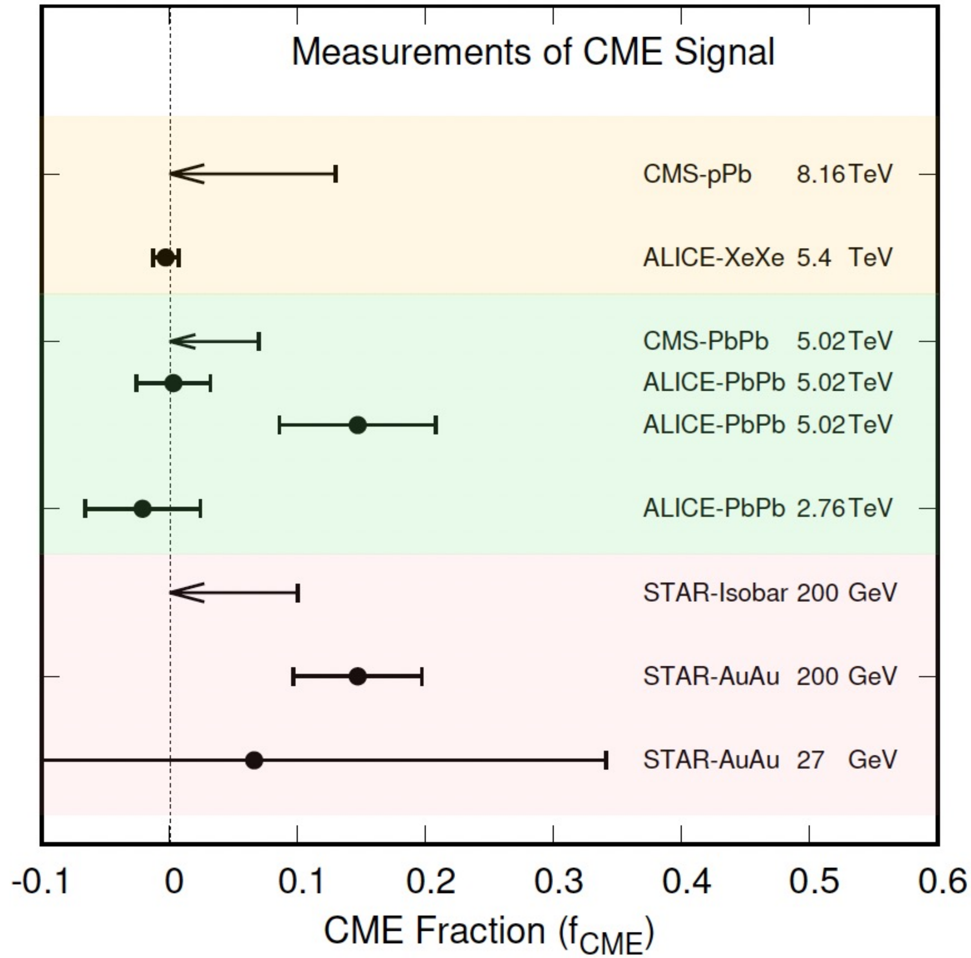
The chiral magnetic effect (CME) is a collective quantum phenomenon that arises from the interplay between gauge field topology and fermion chiral anomaly, encompassing a wide range of physical systems from semimetals to quark-gluon plasma. This review, with a focus on CME and related effects in heavy ion collisions, aims to provide an introductory discussion on its conceptual foundation and measurement methodology, a timely update on the present status in terms of experimental findings and theoretical progress, as well as an outlook into the open problems and future developments.



The key issue at stake:
Can we find it in heavy ion collisions?
— Not conclusive yet, but very promising!