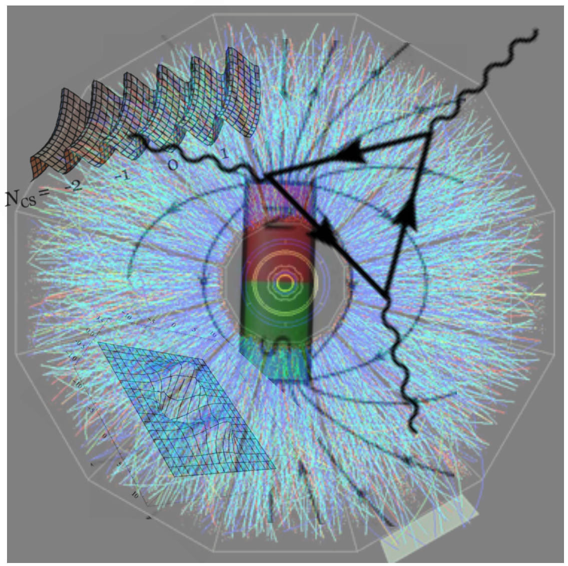
Novel Quantum Phenomena in the Subatomic Swirls



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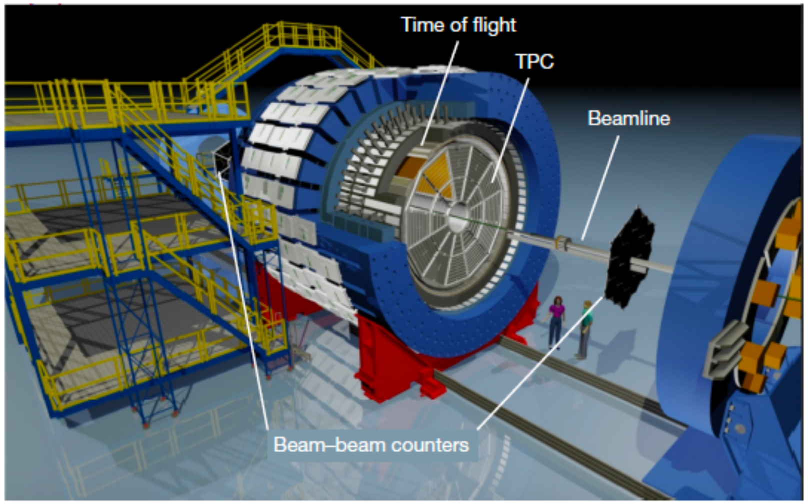
INDIANA UNIVERSITY

Research Supported by NSF & DOE

BEST COLLABORATION

The Subatomic Swirls



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*

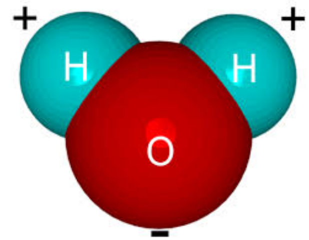
Introduction

Nuclear Physics: Exploring the Heart of Matter

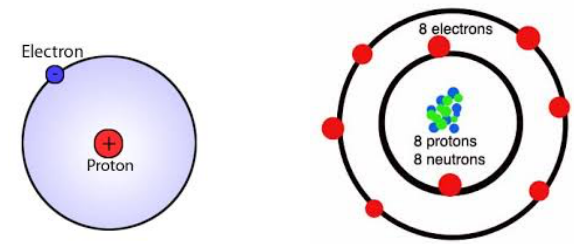
The physical world has a hierarchy of structures.

matter

molecule

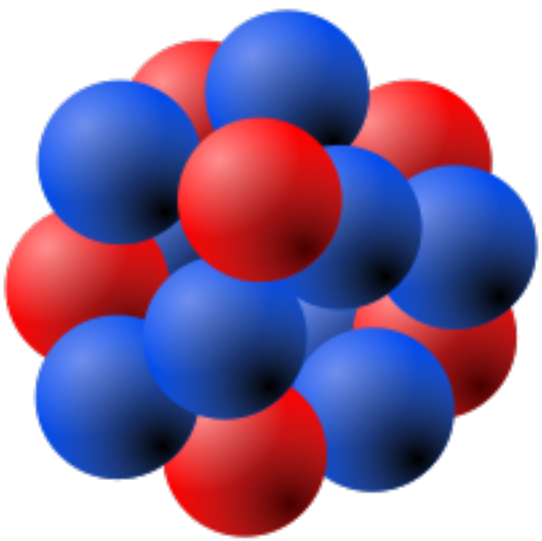


atoms



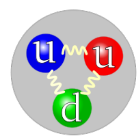
[a millionth of a mm]

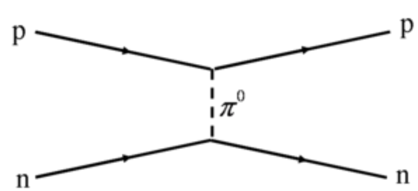
atomic nucleus



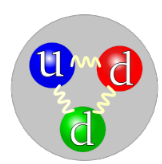
[a trillionth of a mm]

proton



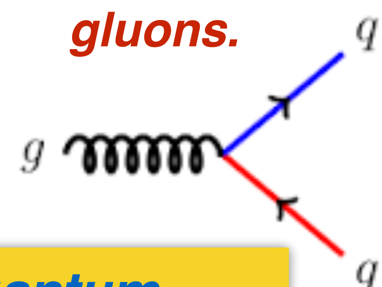


nuclear force



neutron

Most basic entities: quarks and gluons.



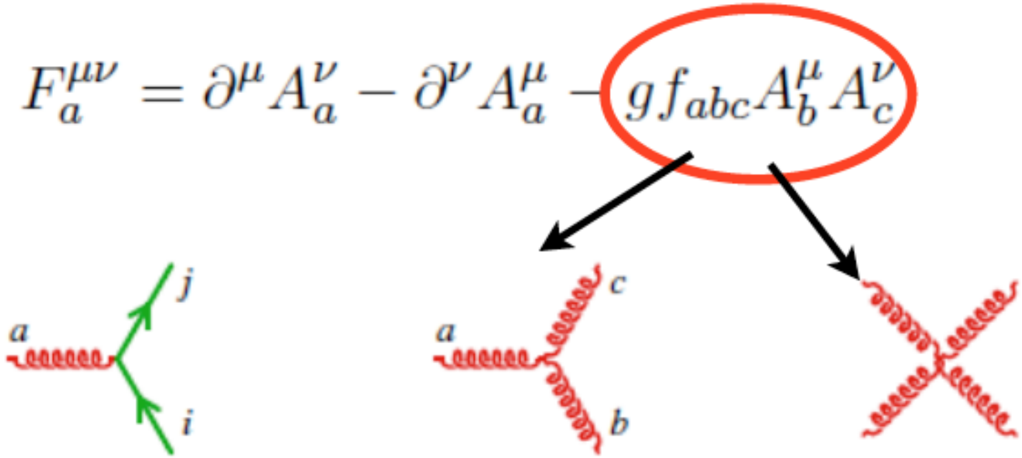
Quantum Chromodynamics (QCD)

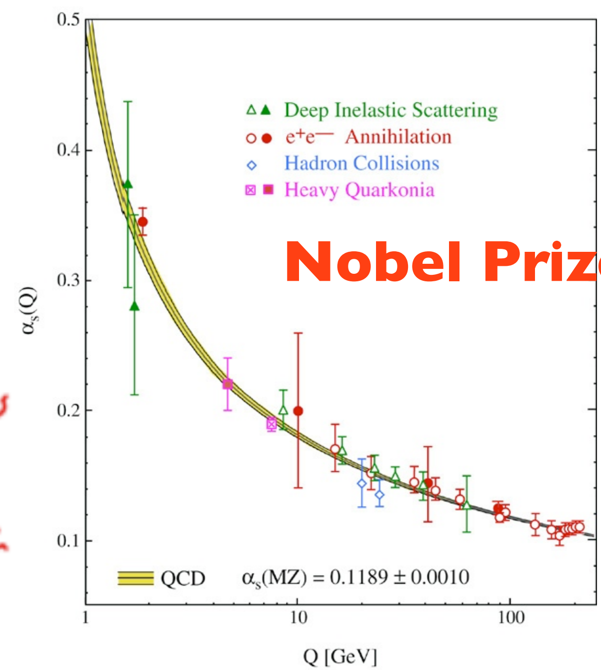
Quantum Chromodynamics (QCD)

The fundamental theory of strong nuclear force:
QCD, a non-Abelian gauge theory of quarks and gluons

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - M - g A\!\!\!/_a G^a)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$





Nobel Prize 2004

Asymptotic Freedom: coupling becomes large
at low energy or long distance scale.

$$\Lambda_{QCD} \sim 200\text{MeV} \qquad R \sim 1\,\text{fm}$$

QCD Confinement: "The Missing Particles"

Free Quark Searches

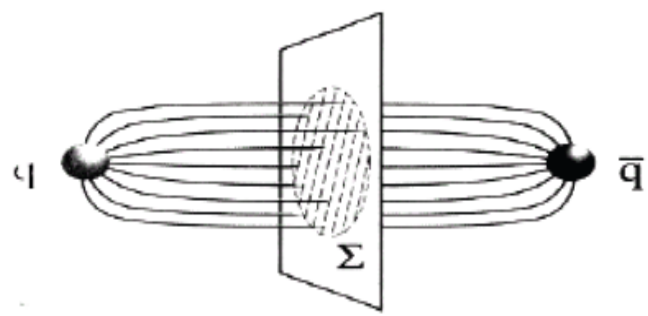
All searches since 1977 have had negative results.

from Particle Data Group

This null result is by itself a remarkable FACT of Nature.

Confinement problem:
Biggest challenge withinStandard Model!

Mathematics: one of the seven
Millennium Problems!

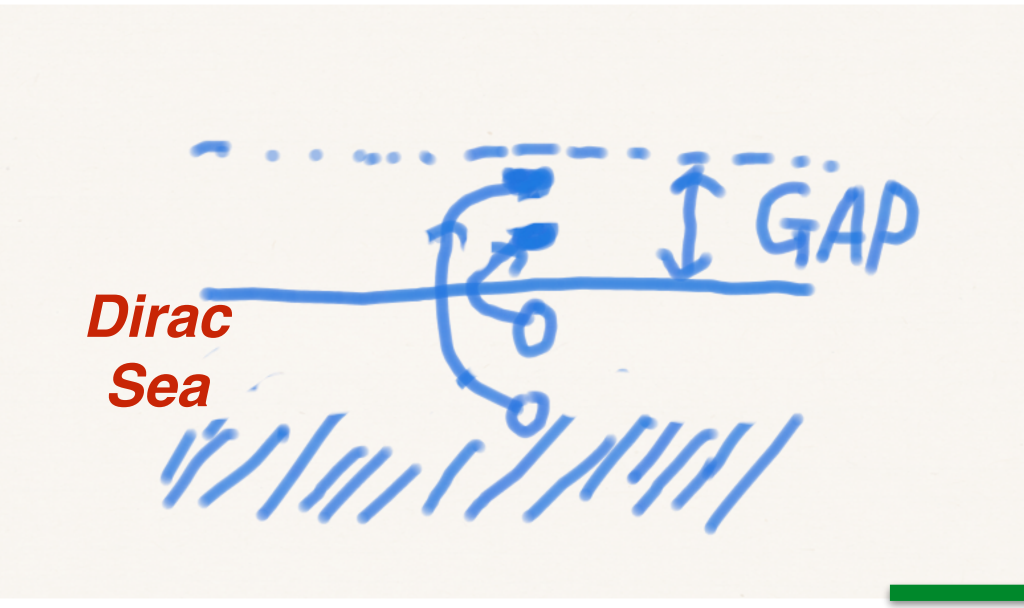


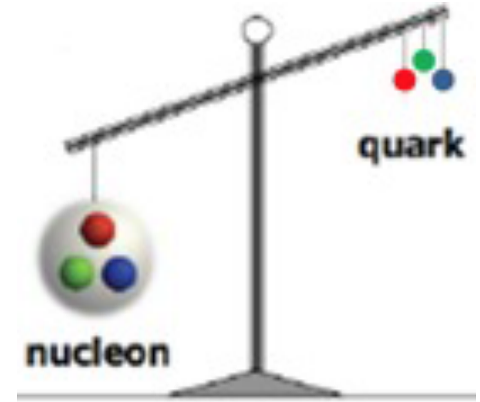
QCD dipole field

QCD vacuum as "dual superconductor" with dual Meissner effect?
Color-magnetic topological condensate?

Chiral Symmetry: Spontaneous Breaking

$m_\pi \approx 140 MeV \, , \, m_n \approx 940 MeV$



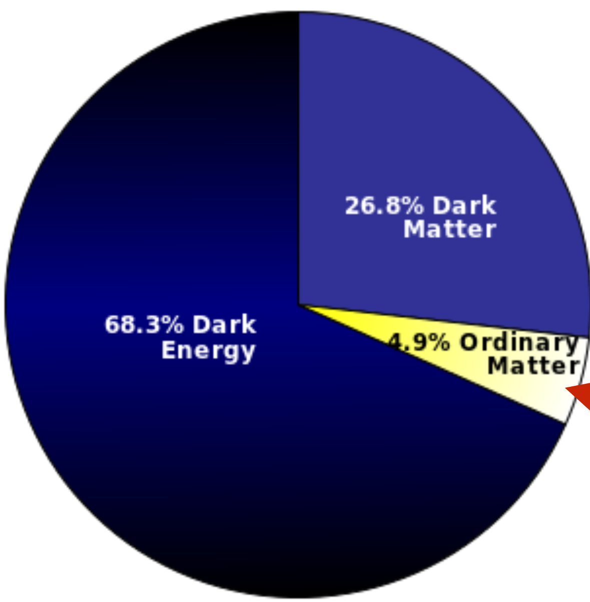


$$M = m - 2G \langle \bar{\psi} \psi \rangle$$

Constituent mass

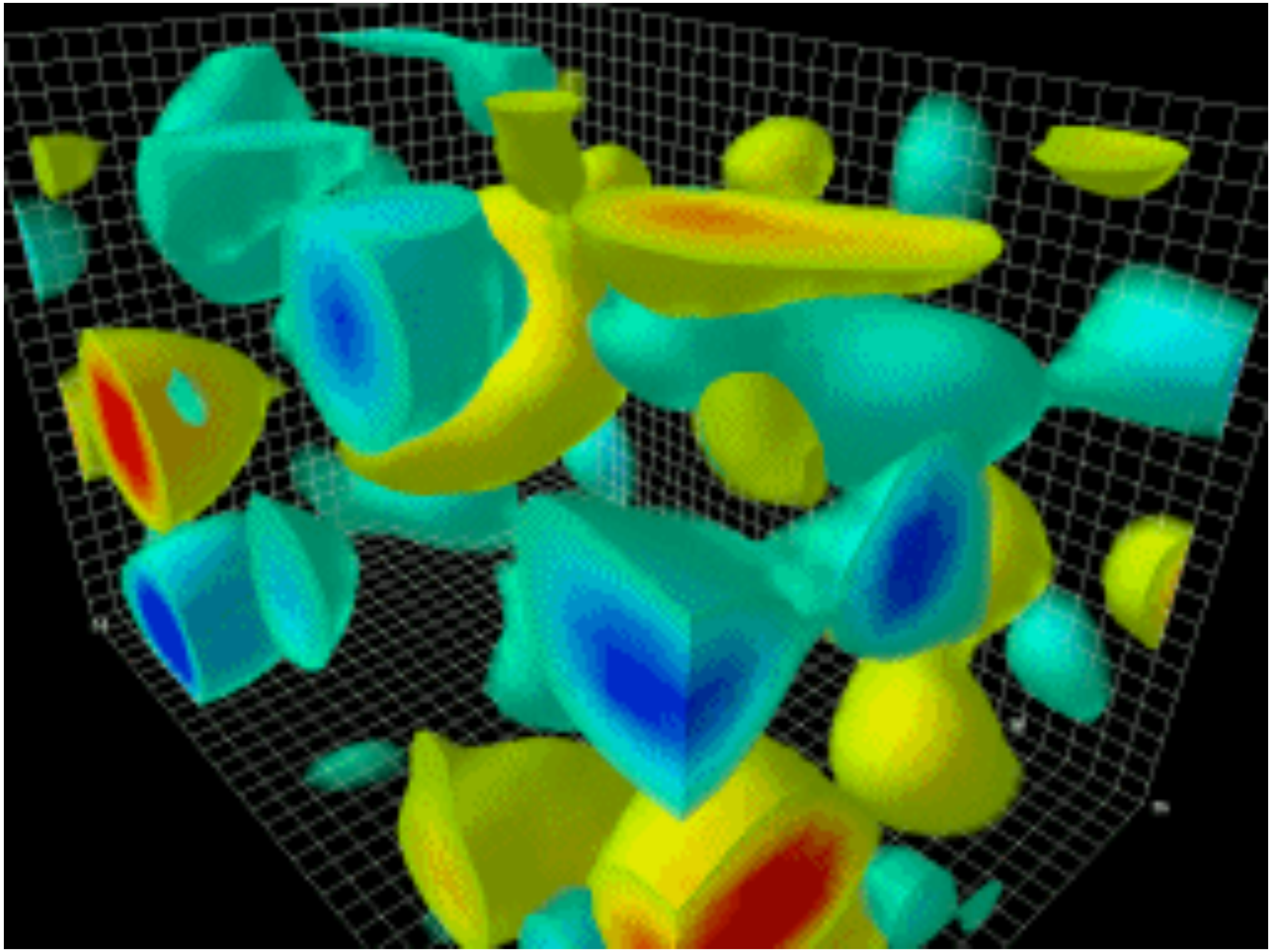
Lagrangian (SM) mass

Vacuum condensate



It accounts for 99% of the mass of our visible matter in universe.

QCD as Topological Material



Instantons

$$Q_w = \frac{1}{32\pi^2}\int d^4x\,(gG_a^{\mu\nu})\cdot(g\tilde{G}^a_{\mu\nu})$$

Emergent Phenomena in QCD

F. Wilczek @ QM2014

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

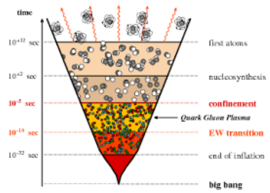
In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

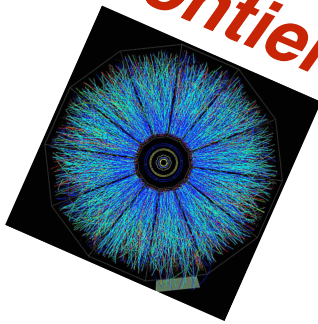
It *embodies* many deep aspects of relativistic quantum field theory (confinement, asymptotic freedom, anomalies/instantons, spontaneous symmetry breaking ...)

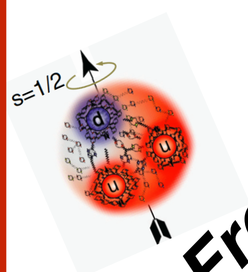
NP as Quantum Chromo Material Science

Temperature

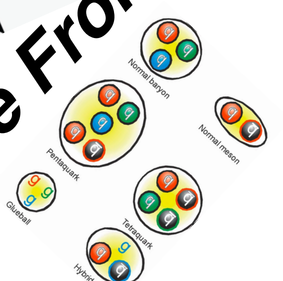
"Hot Frontier"

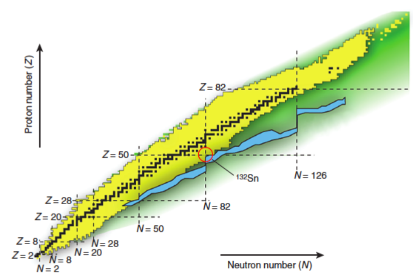


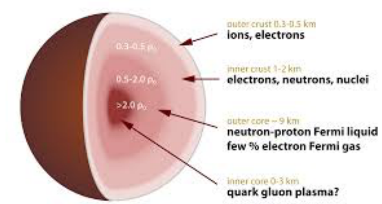




"Force Frontier"







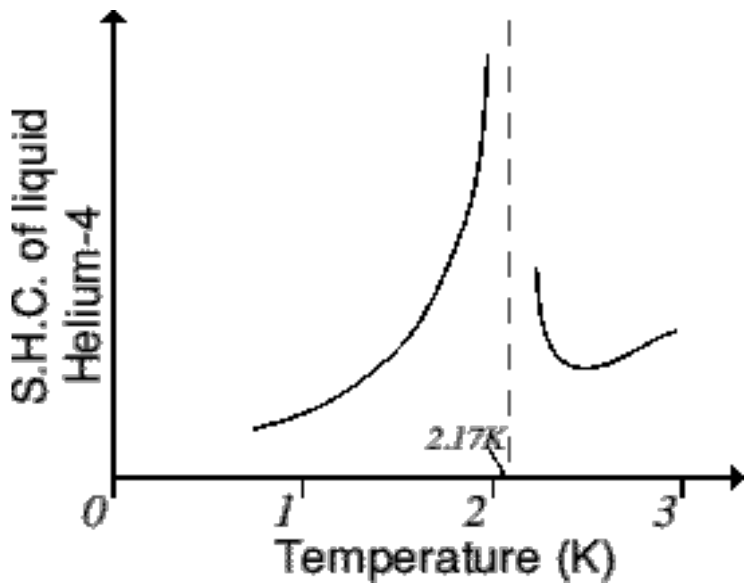
"Dense Frontier"

Baryon Density

This talk will focus on the "hot frontier".

Quark-Gluon Plasma (QGP):
A Subatomic Quantum Fluid

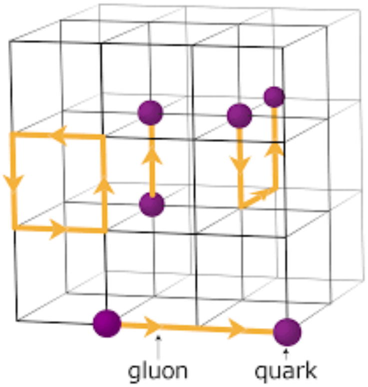
QCD in Hot Environment



The "super" side is hard, and let's attack the lambda point from the "right side", when the system is just about to condense!

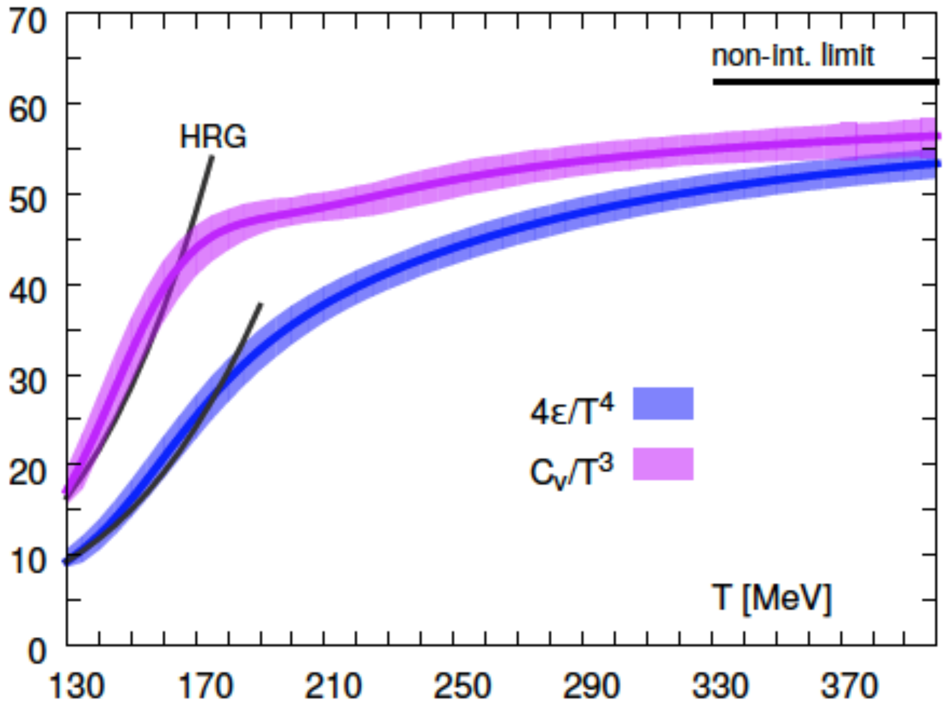
Why don't we do the same for QCD?!
QCD at extreme temperatures:
At high enough T >> Lambda_QCD
A transition to a quark-gluon plasma (QGP) !
[mid ~ late 1970's]

QGP: A New Phase of Matter



from Lattice QCD

RHIC LHC



$$\epsilon = 47.5 \times \frac{\pi^2}{30} T^4$$

free QGP

a relativistic
pion gas

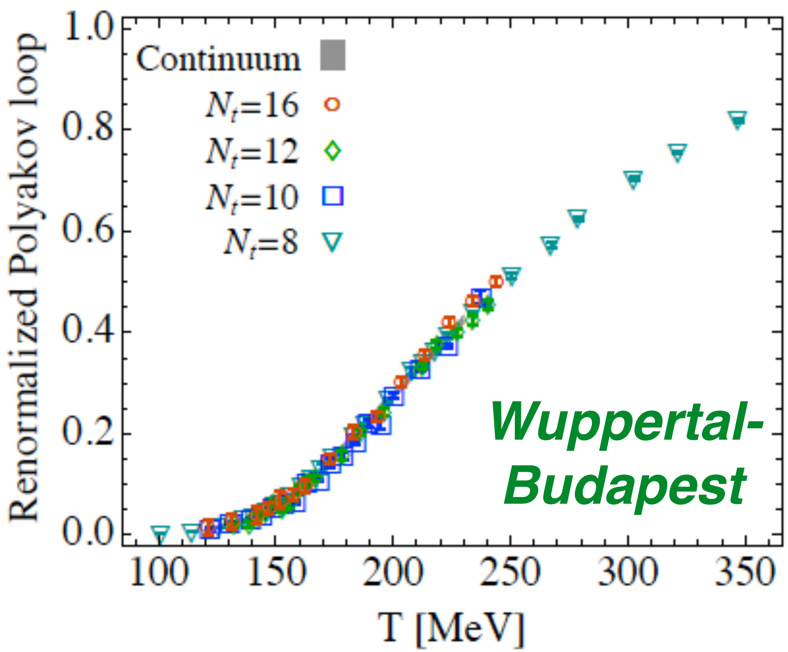
$$\epsilon = 3 \times \frac{\pi^2}{30} T^4$$

More precisely,
Hadron Resonance Gas

* ***Two benchmarks at low/high T***
* ***A transition regime in the middle***
* ***Crossover (instead of a phase transition)***

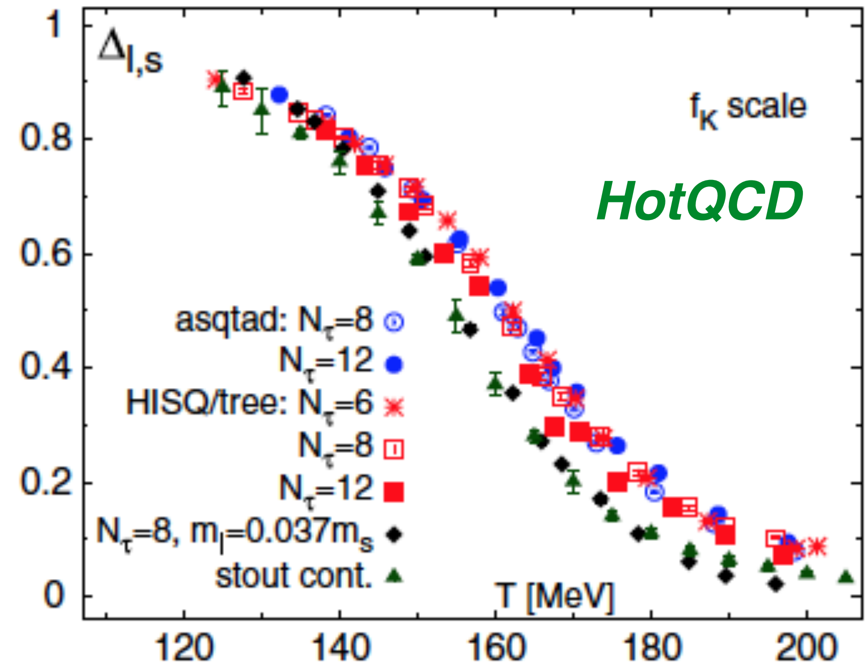
QGP: A New Phase of Matter

The liberated quarks & gluons



$$|\langle P\rangle| = \left|\frac{1}{L_\sigma^3}\sum_x \langle P(x)\rangle\right| \rightarrow e^{-\beta F_q} \quad (L_\sigma \rightarrow \infty)$$

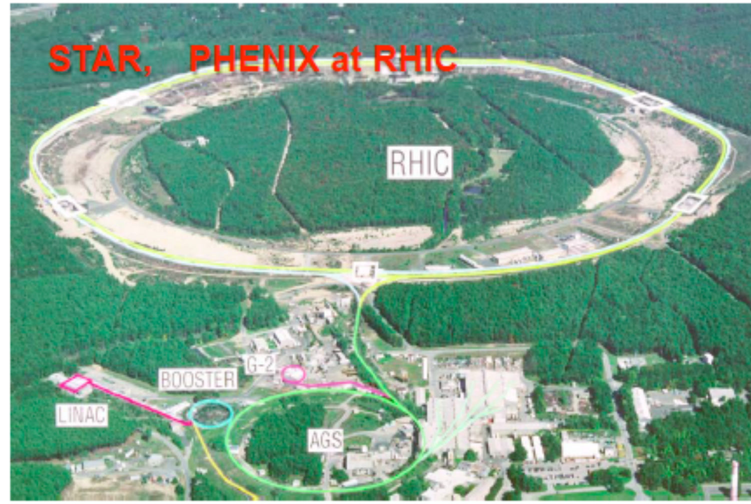
The restored chiral symmetry



The high T phase of QCD matter (a few hundred MeV & up) is a distinctive new phase, the quark-gluon plasma (QGP).

Little Bangs in Heavy Ion Collisions (HIC)

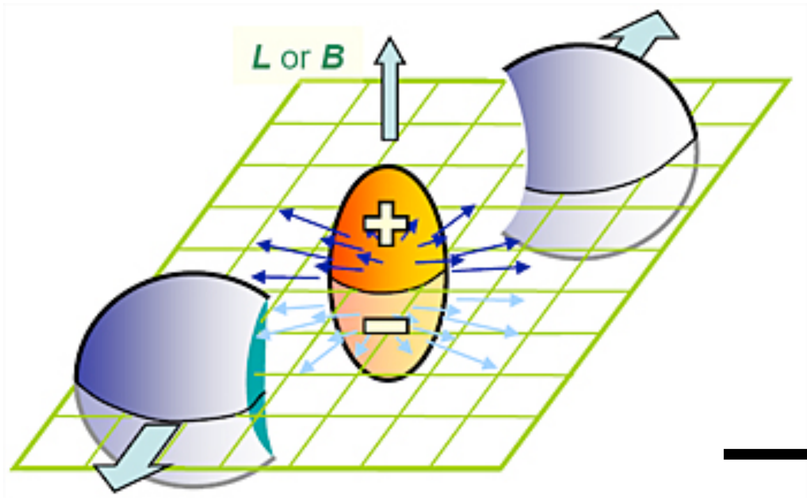
An artistic presentation:
“nuclei as heavy as bulls,
colliding into new phase of matter”



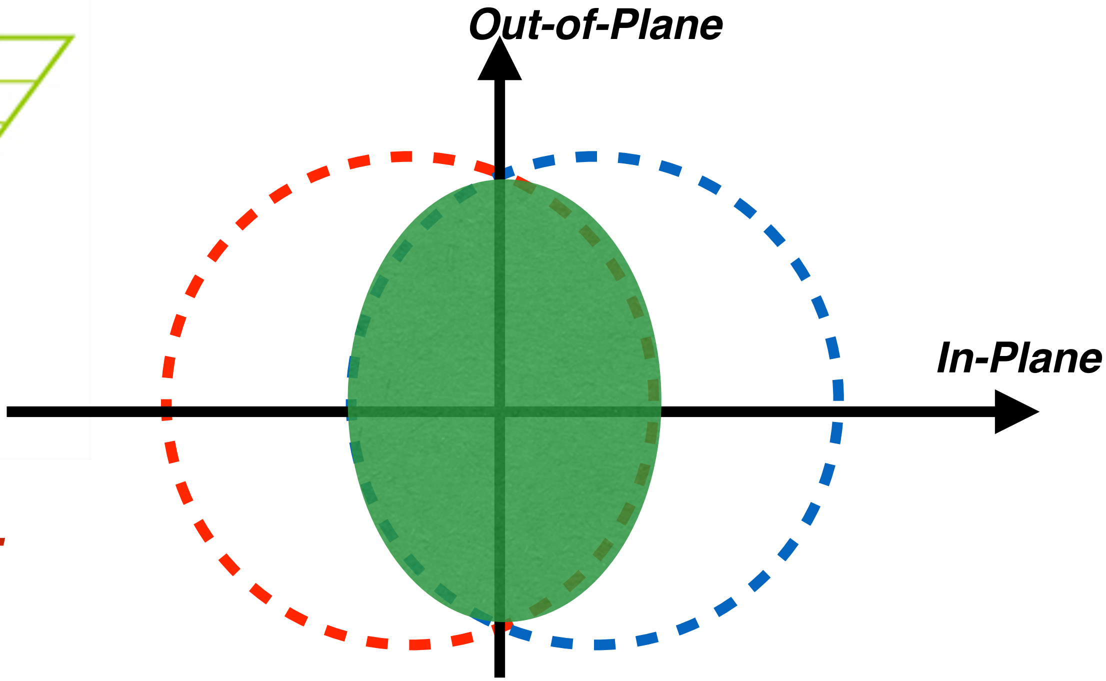
Relativistic Heavy Ion Collider

Large Hadron Collider

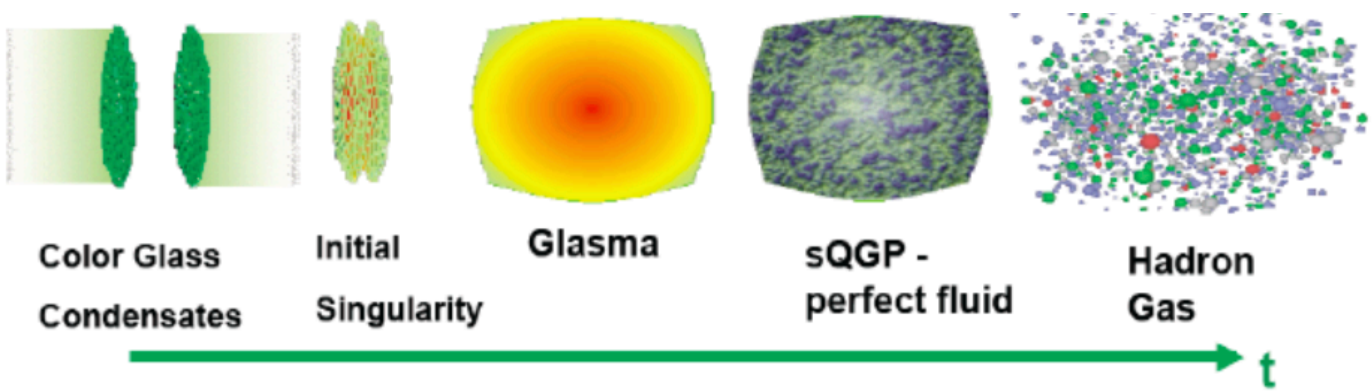
The Setup of Heavy Ion Collision

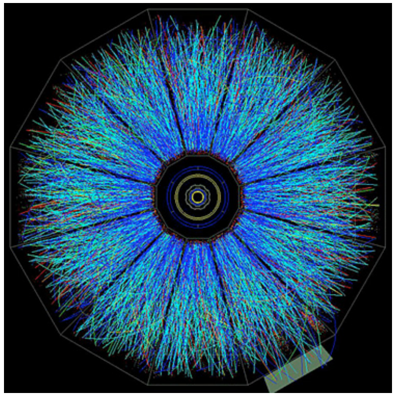


A typical off-central collision.

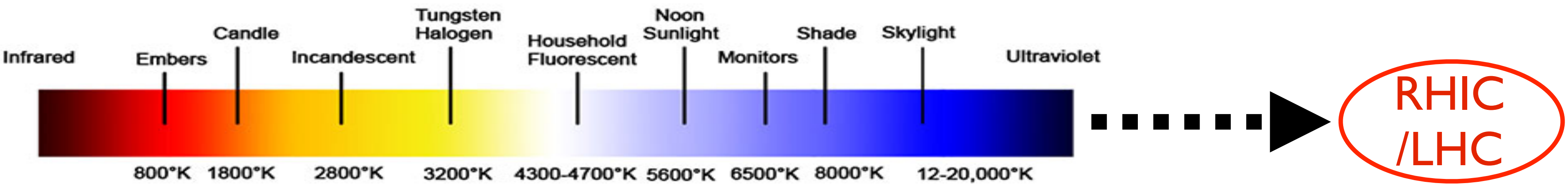


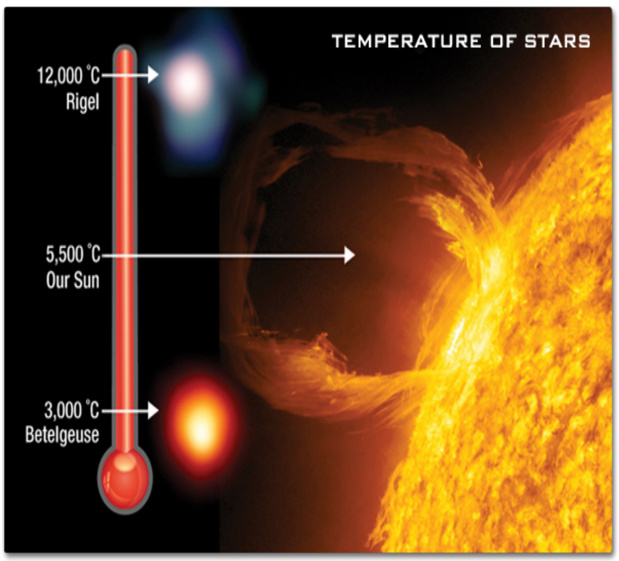
Quark-gluon plasma is created in such collisions!

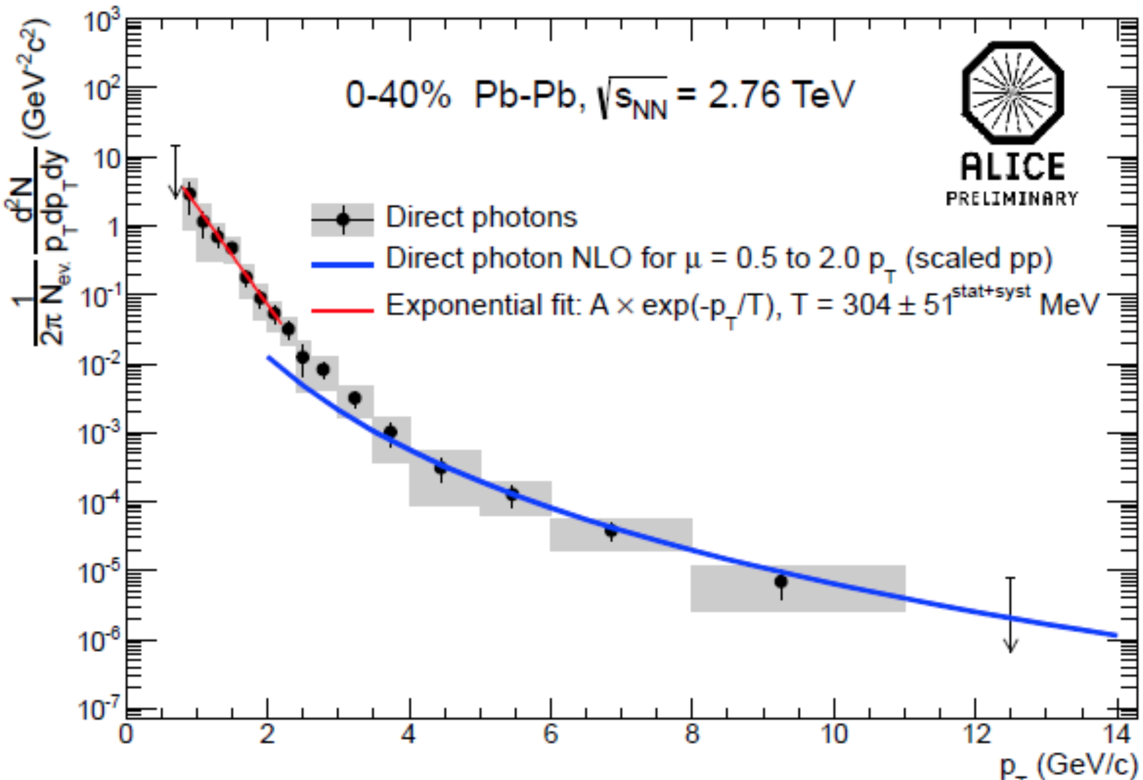




QGP Shining Brightly!



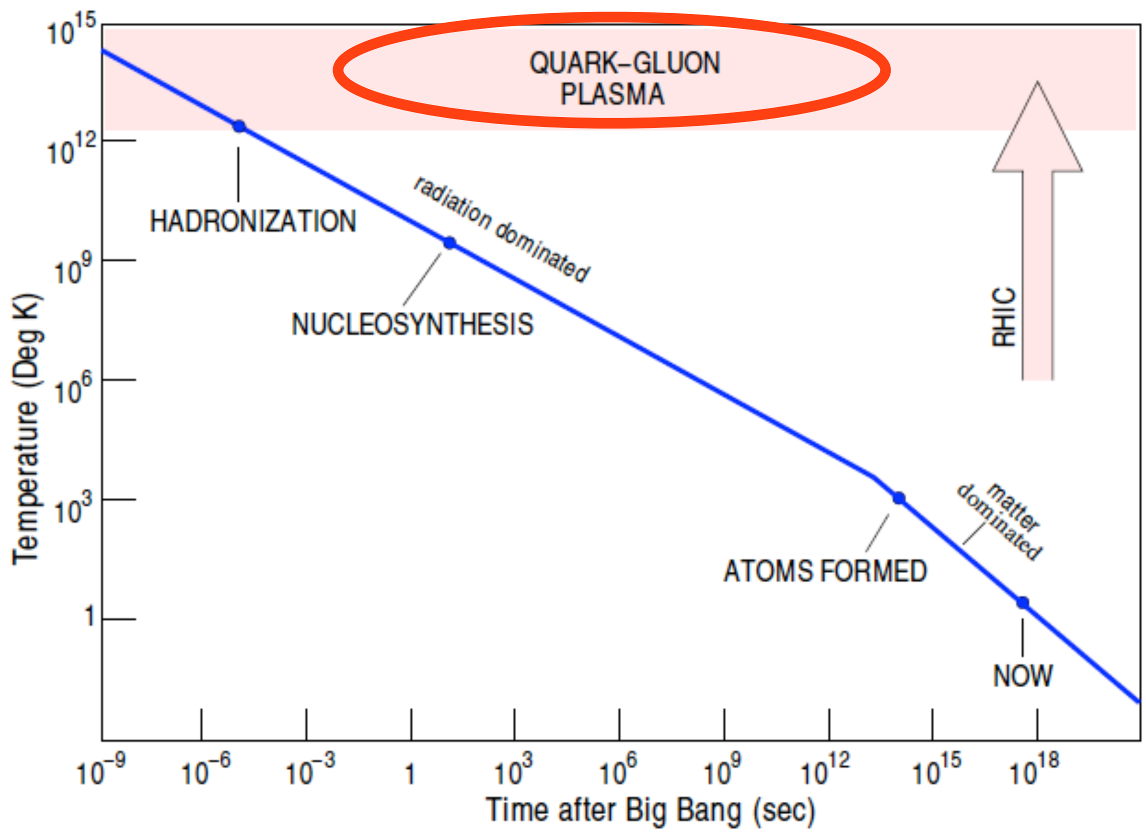




QGP is hot stuff: about trillion degrees !
Official Guinness World Record:
the highest man-made temperature!

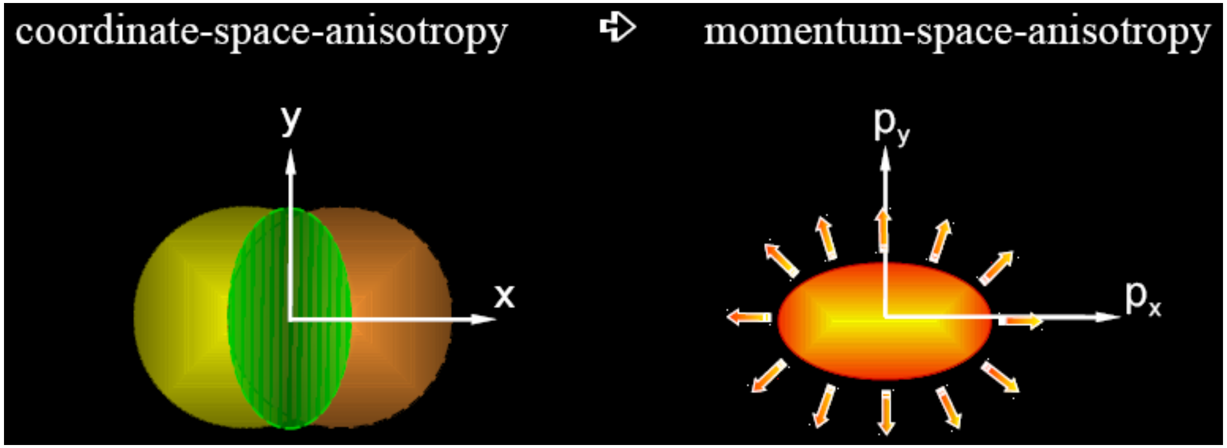
QGP: An Old Phase of Matter

The highest ever temperature was in the beginning of universe. The QGP temperature was available back then.

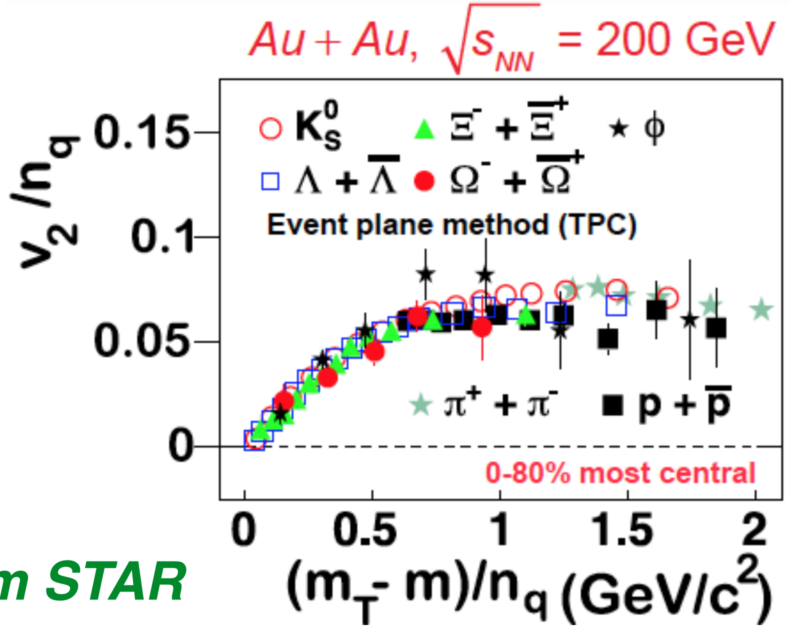


The quark-gluon plasm is an old phase of matter!

Anisotropic Explosion: Elliptic Flow



$$\frac{dN}{dP_t\, d\phi} = \frac{dN}{dP_t}\left[1 + 2\, v_2\,(P_t)\cos(2\phi) + \ldots\right]$$



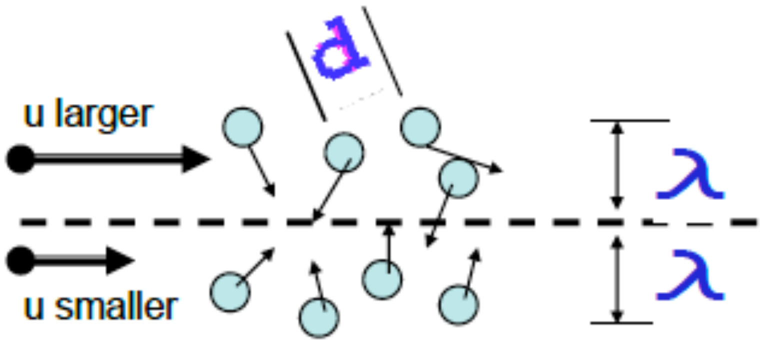
from STAR

relativistic hydrodynamics @ 1~ 10 fm scale.

This response is very sensitive to fluid dissipation

$$1 \leq 4\pi(\eta/s)_{QGP} \leq 2.5$$

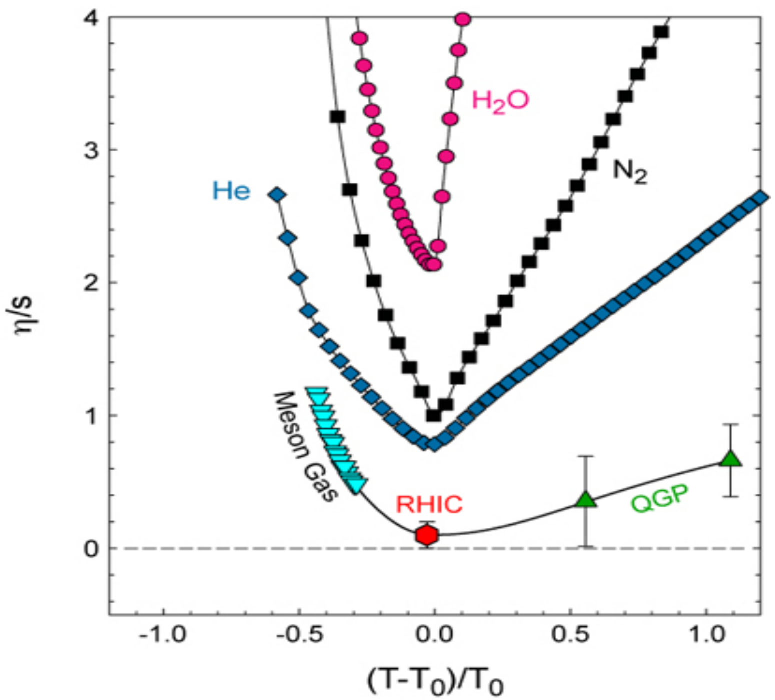
QGP: Nearly Perfect Quantum Liquid



$$\eta \sim \rho v_T \lambda \sim n p_T \lambda$$

$$s \sim n$$

$$\eta/s \sim p_T\lambda \sim \lambda/\lambda_{dB}$$



QGP is a quantum fluid:

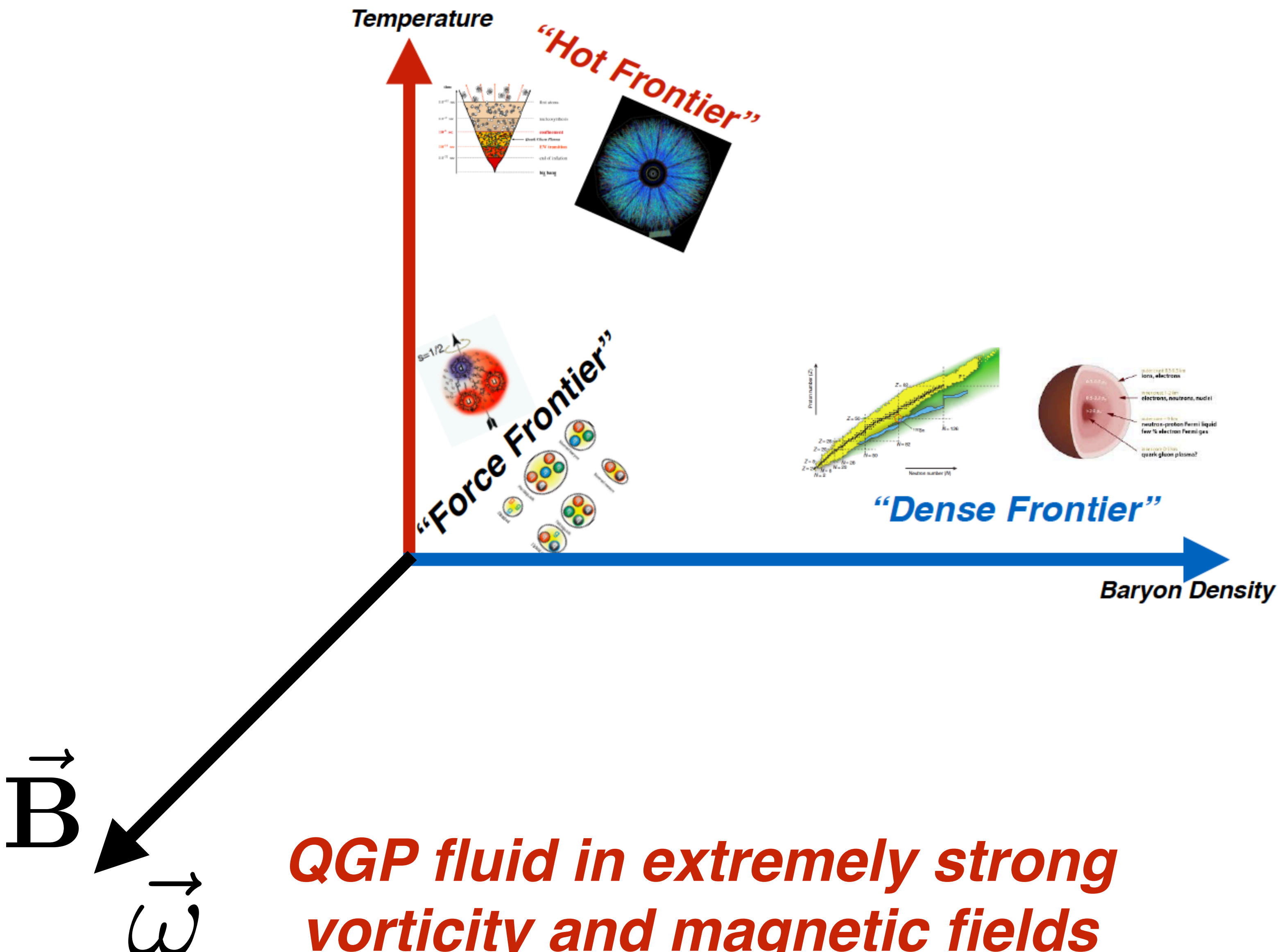
$$\lambda_{M.F.P.} \sim \lambda_{de\ Broglie}$$

[A recent ravel: cold atomic gas with infinite scattering length]

It has nearly perfect fluidity: less dissipative than known substance; very close to conjectured lower bound.

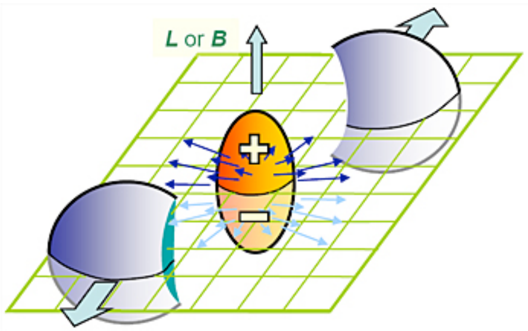
Vorticity & Magnetic Field

Fascinating New Frontiers

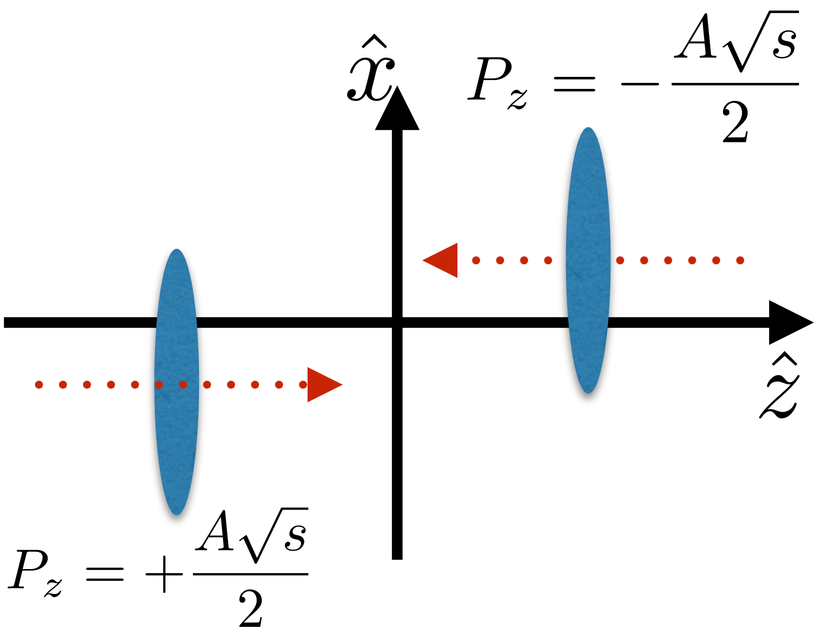


QGP fluid in extremely strong vorticity and magnetic fields

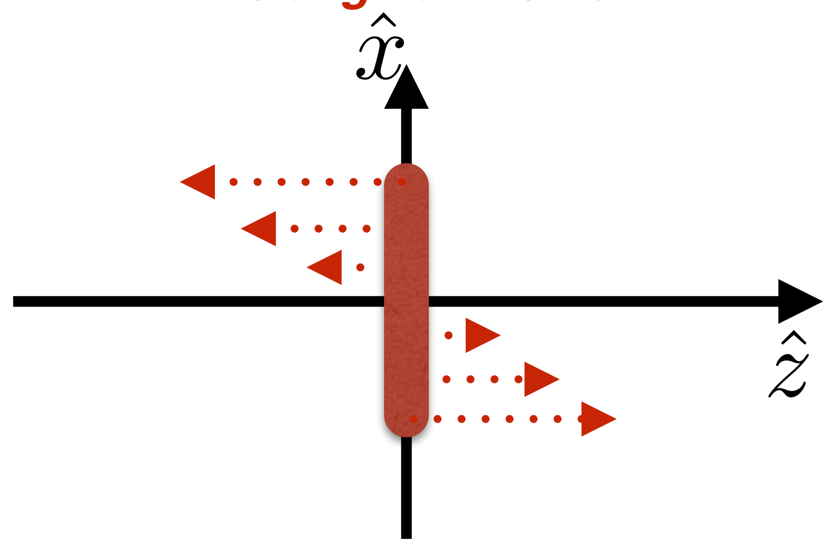
Rotating Quark-Gluon Plasma



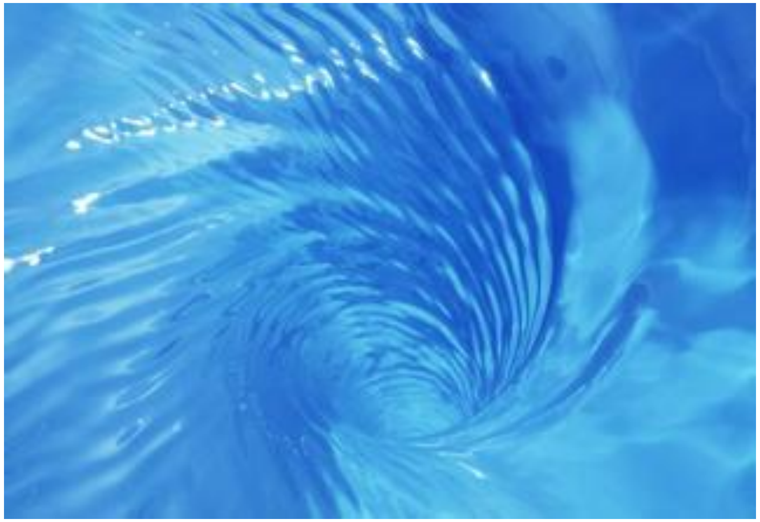
$$L_y = \frac{Ab\sqrt{s}}{2} \sim 10^{4\sim5}\hbar$$



QGP's way of accommodating this angular momentum



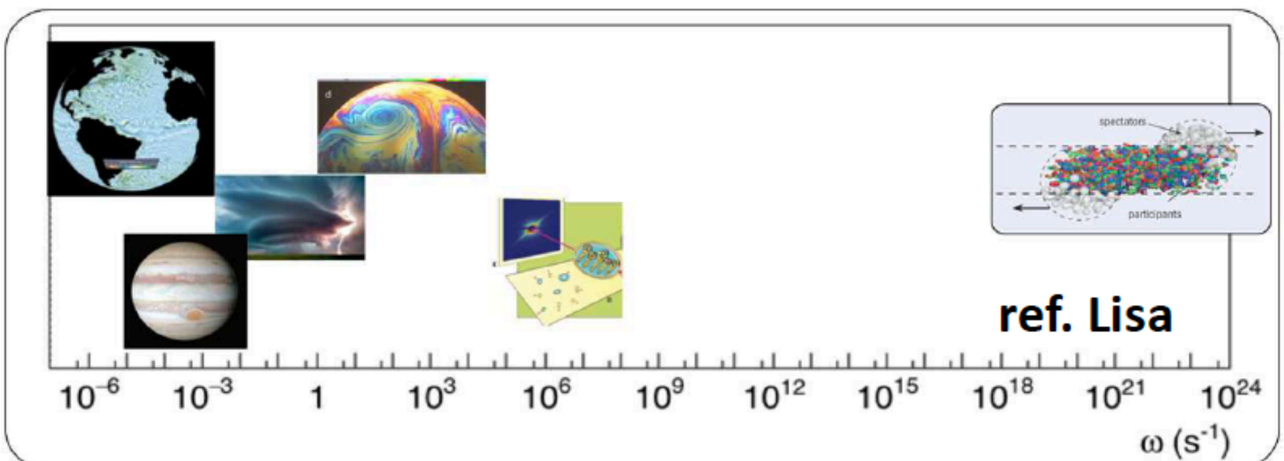
Quantifying Fluid Rotation



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

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

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



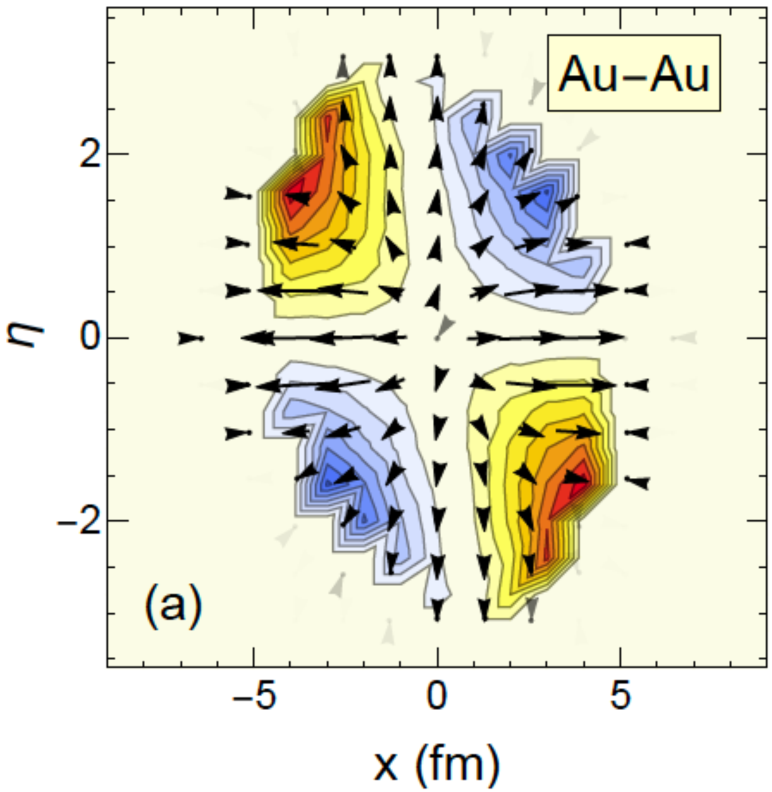
Heavy ion collisions:

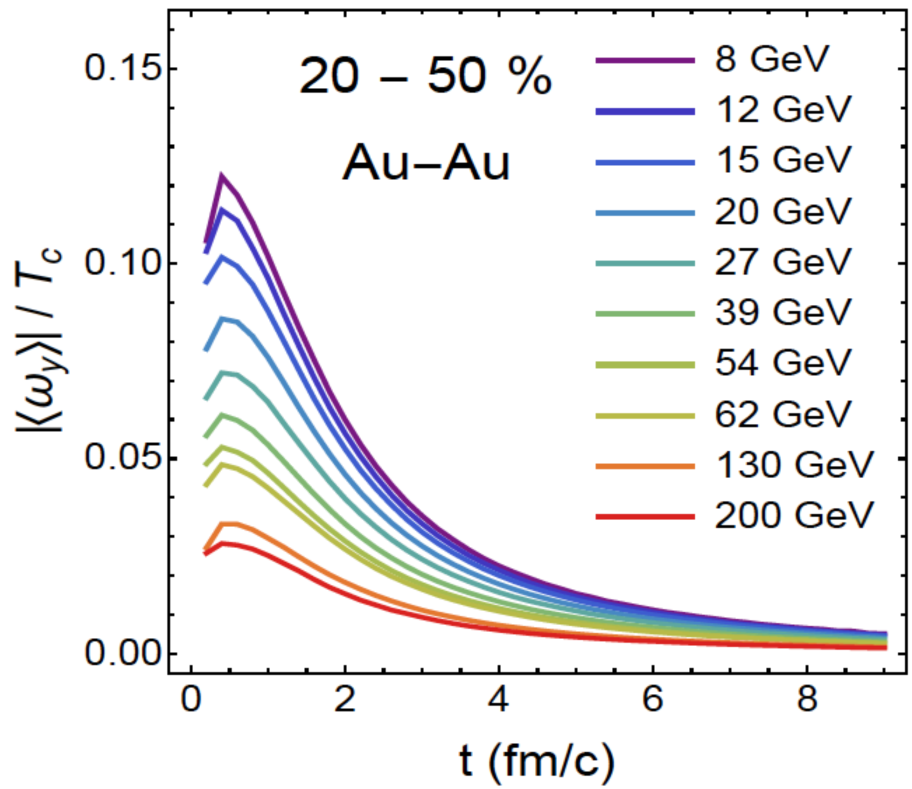
$$v \sim 0.1\, c$$

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

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

Rotating Quark-Gluon Plasma

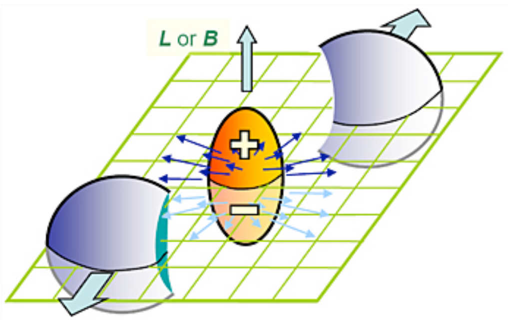


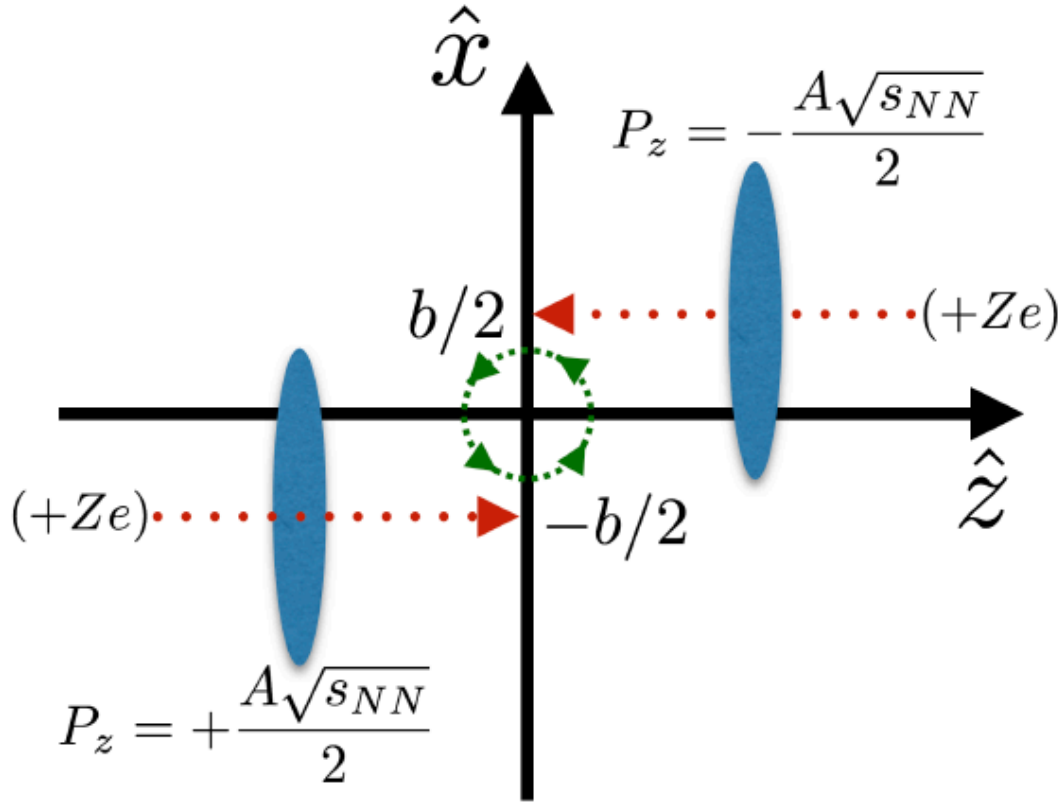


The averaged vorticity strongly increases toward low beam energy!

Jiang, Lin, JL, PRC2016; Deng & Huang, PRC2016;
Xia, Li, Wang, et al, PRC; Shi, Li, JL, PLB2018; …

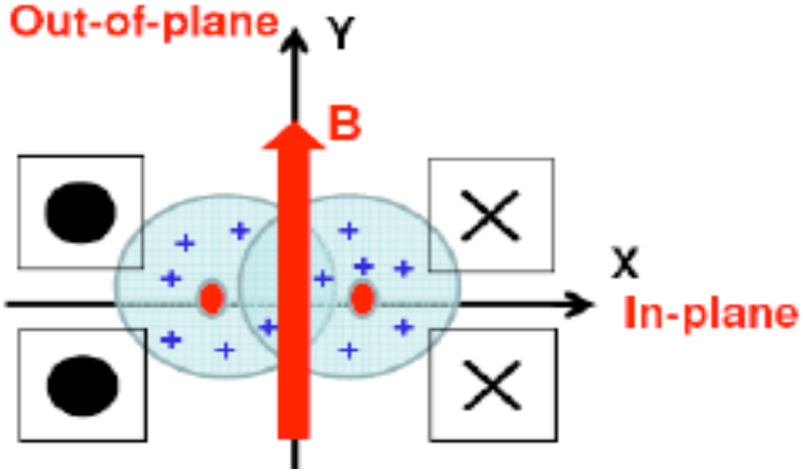
Strong Electromagnetic Fields



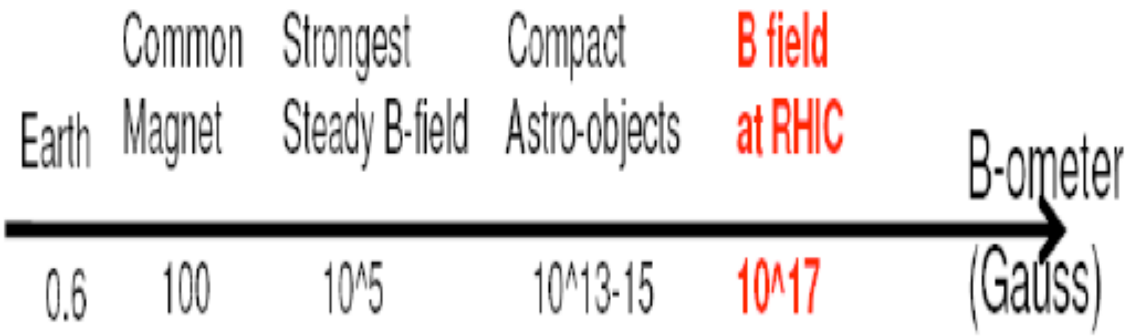


The angular momentum together with large (+Ze) nuclear charge —> strong magnetic field!

Strong Electromagnetic Fields

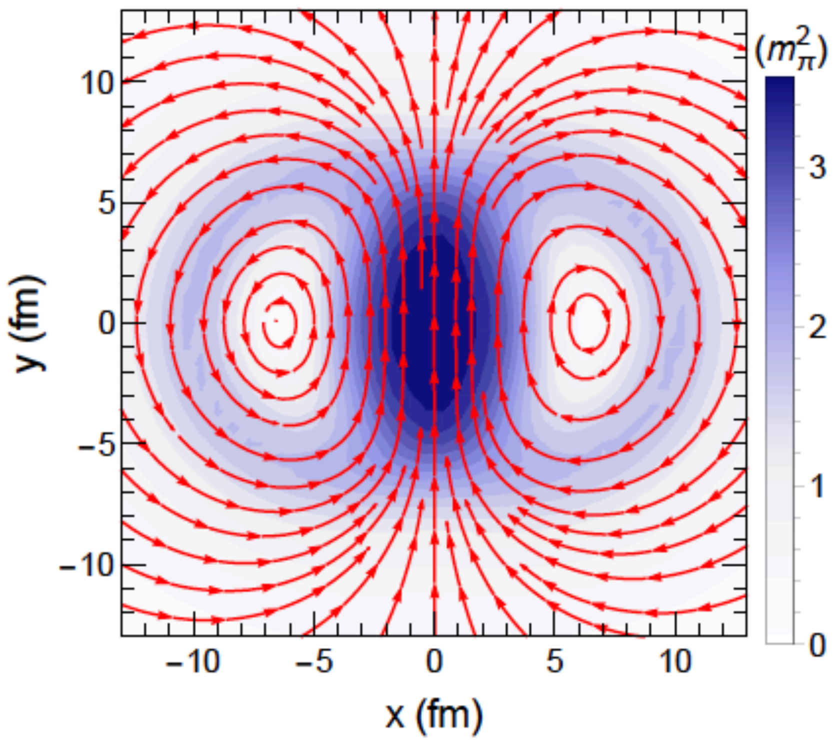


$$E, B \sim \gamma \frac{Z\alpha_{EM}}{R_A^2} \sim 3m_\pi^2$$

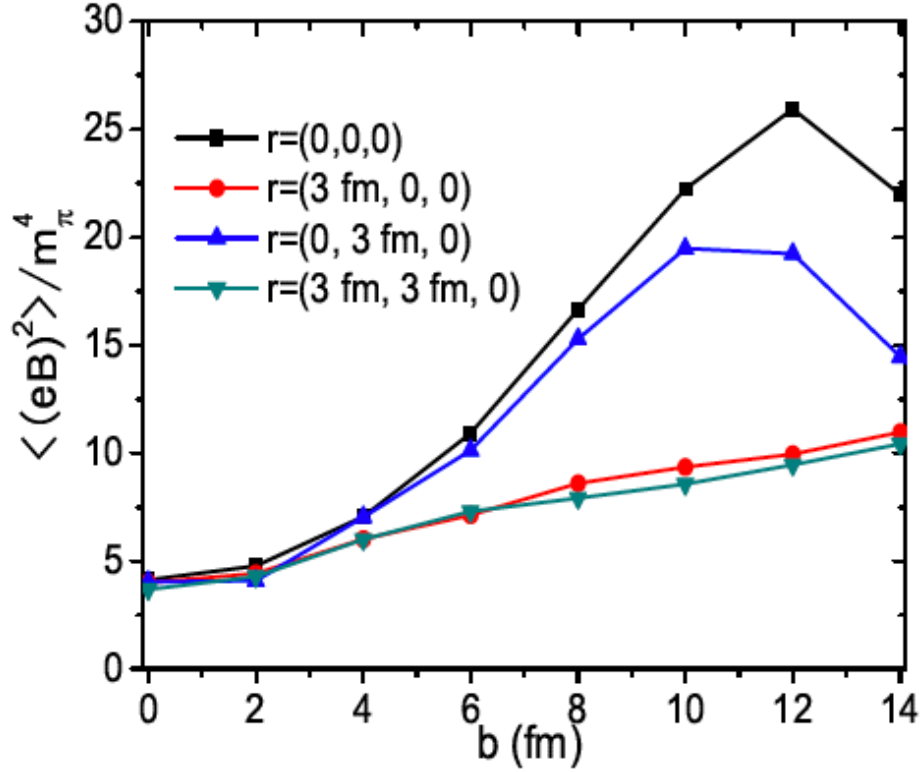


- Strongest B field (and strong E field as well) naturally arises! [Kharzeev,McLerran,Warringa;Skokov,et al; Bzdak-Skokov; **Deng-Huang**; Skokov-McLerran;Tuchin; ...]
- "Out-of-plane" orientation (approximately) **[Bloczynski-Huang-Zhang-Liao]**

Strong Electromagnetic Fields



Huang, Liao, et al PLB2012



Quantitative simulations confirm the existence of such extreme fields!

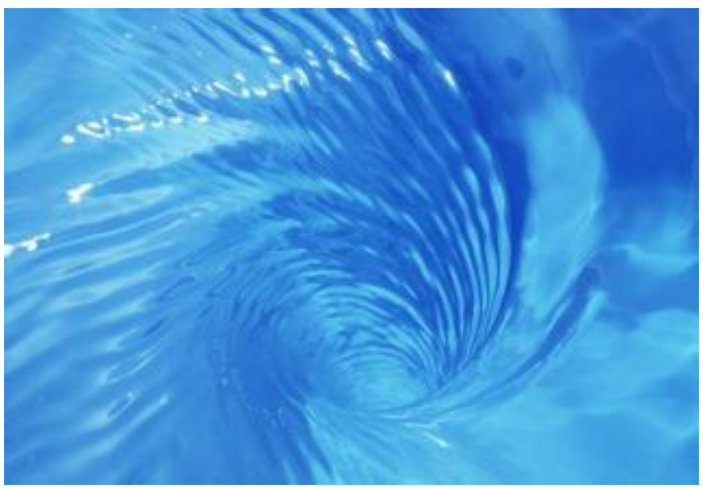
[STAR measurements of dielectron directly from such fields, PRL2018]

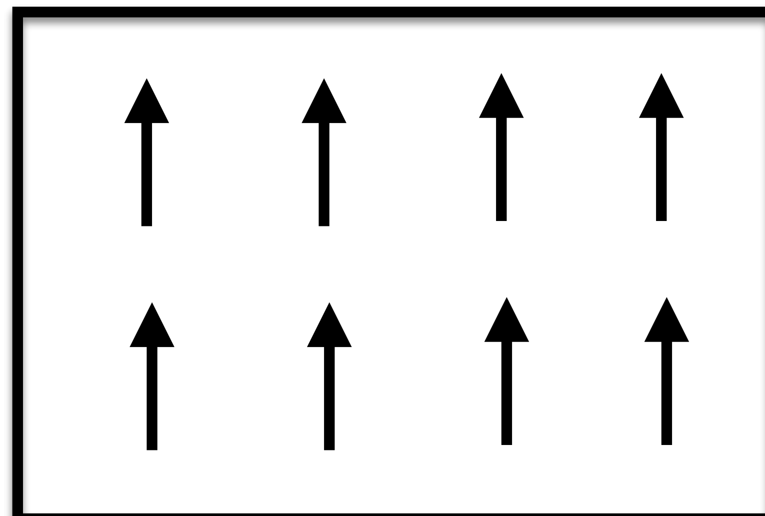
Spin & Rotational Polarization

Spin-Fluid Coupling

How does a many-body system cope with a sizable angular momentum?

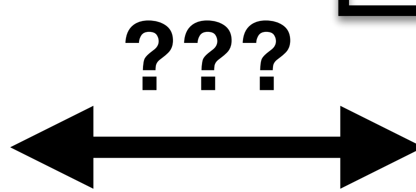
Orbital motion (vorticity);
Spin alignment (polarization).





Fluid vorticity

Macroscopic



Individual spin

Microscopic, quantum

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!

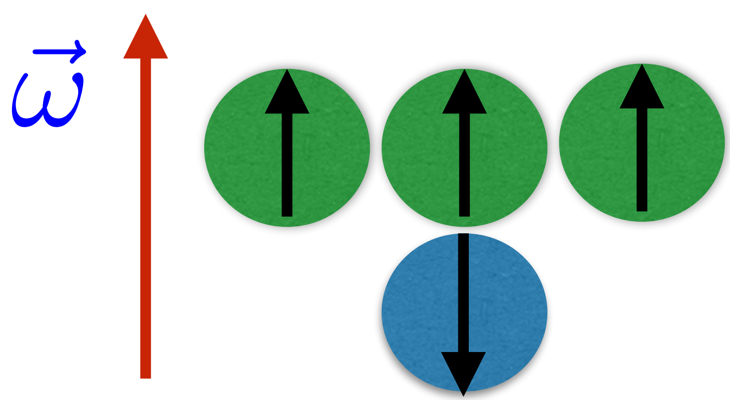
Rotational Polarization

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

Rotational polarization effect!

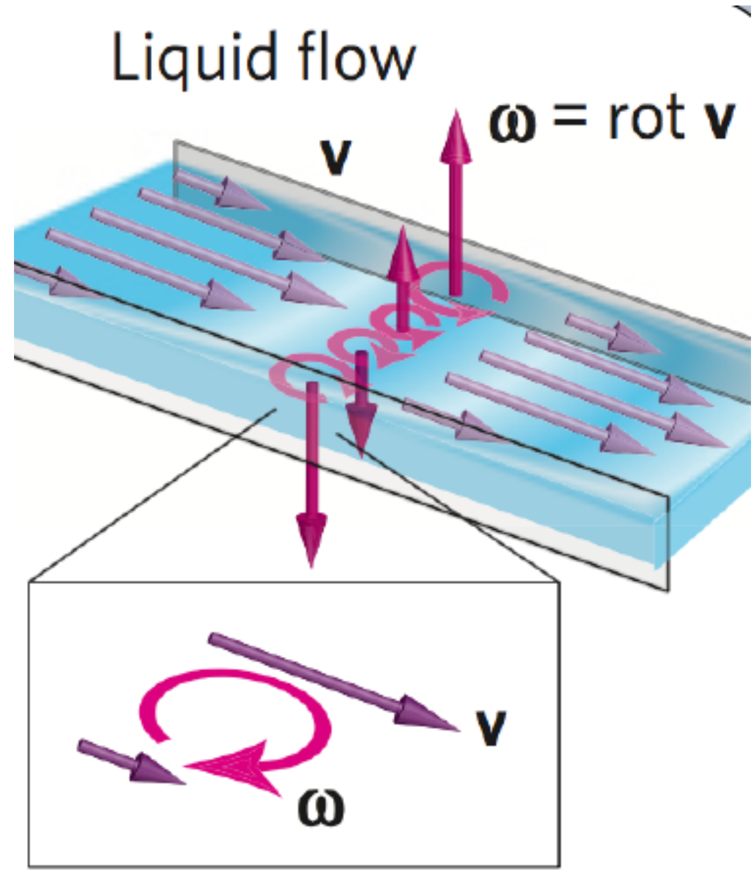
For thermally produced particles: "equal-partition" of angular momentum

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



From Vorticity to Spin Polarization

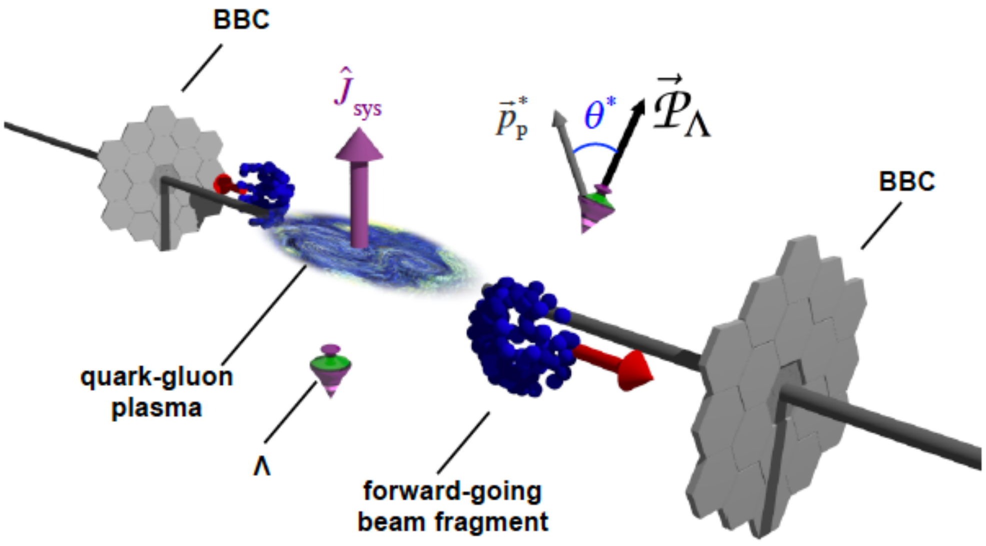
"Spin hydrodynamic generation"
Takahashi, *et al*. Nat. Phys. (2016)

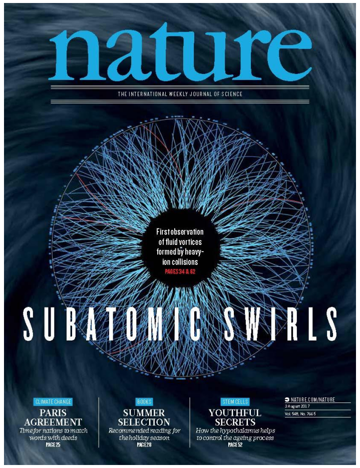


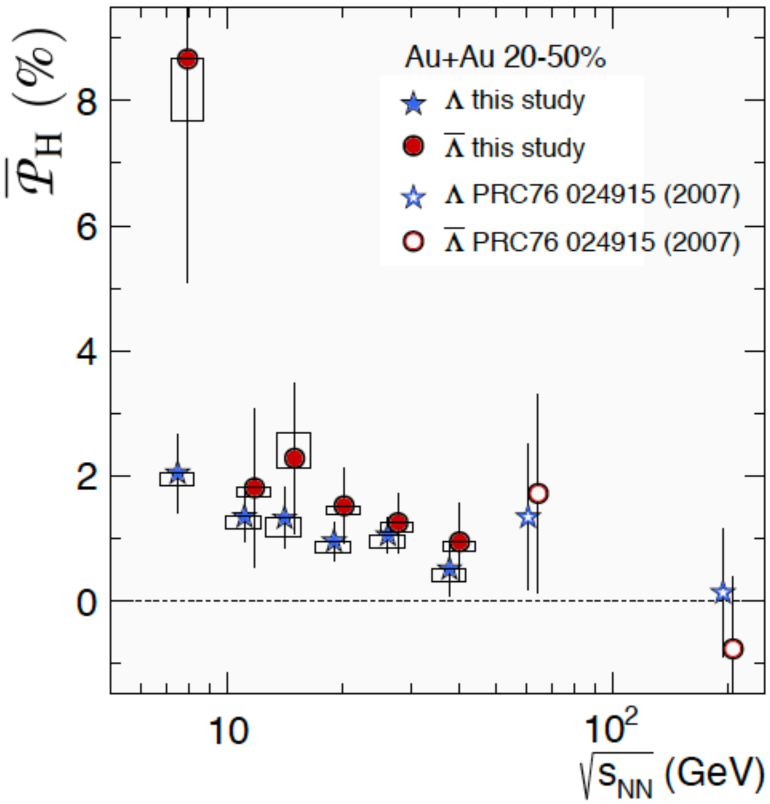
Viscous fluid flow
—> vorticity
—> spin polarization

"Fluid Spintronics"

Fluid Spintronics in the Subatomic Swirls

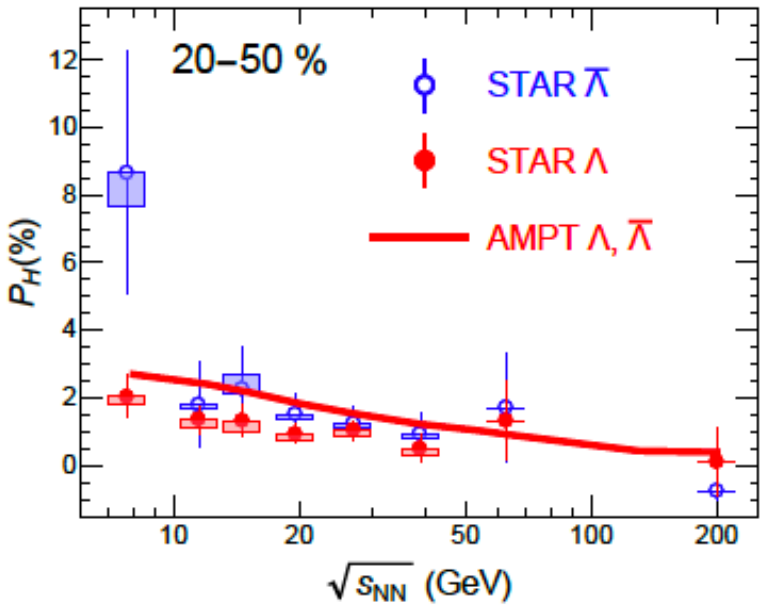




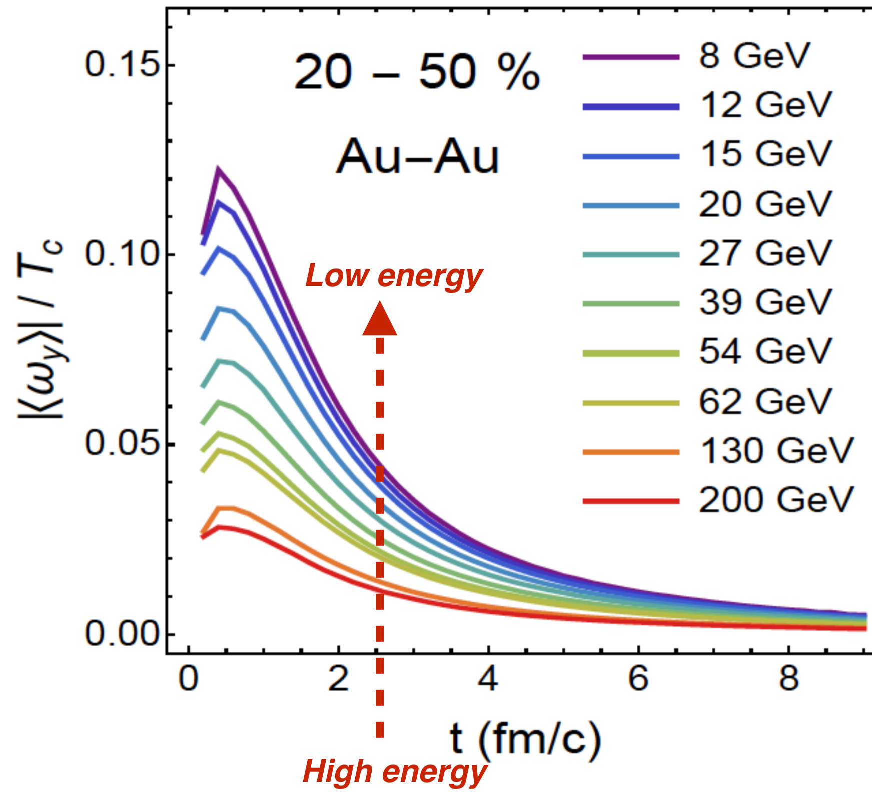


STAR Collaboration, Nature 2017

Fluid Spintronics in the Subatomic Swirls



Jiang, Lin, JL, PRC2016



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

The most vortical fluid!

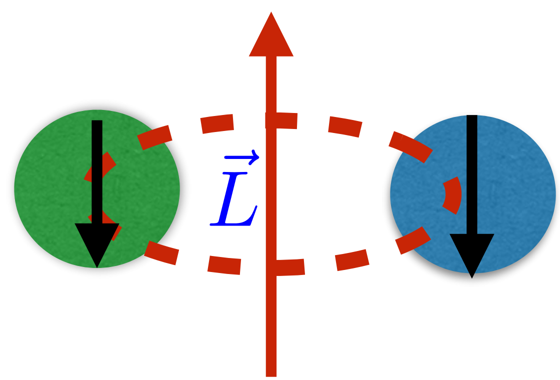
STAR Collaboration, Nature 2017

Rotational Suppression of Fermion Pairing

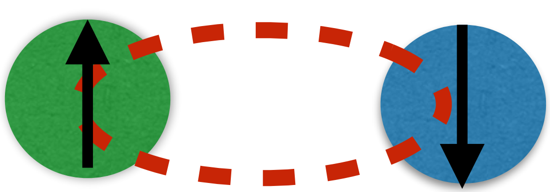
Let us consider pairing phenomenon in fermion systems.
There are many examples:
superconductivity, superfluidity, chiral condensate, diquark, …

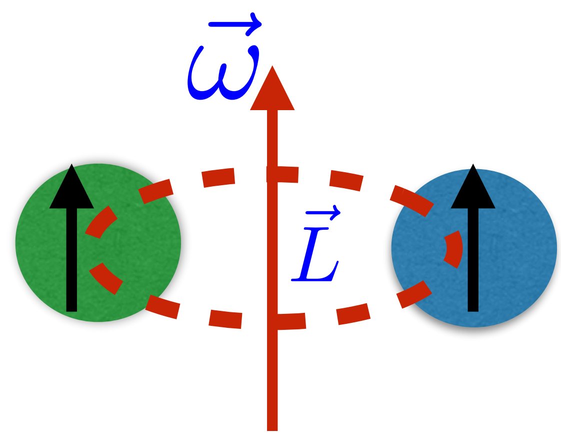
We consider scalar pairing state, with J=0.

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



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





[Yin Jiang, JL, PRL2016]
[Rotational Inhabitation: Chen, Fukushima, Huang, Mameda, PRD2016]

Chiral Magnetic Effect in the Subatomic Chiral Matter

Exciting Progress: See Recent Reviews

Progress in Particle and Nuclear Physics 88 (2016) 1–28

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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Review

Chiral magnetic and vortical effects in high-energy nuclear collisions—A status report

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[f] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

Prog. Part. Nucl. Phys. 88, 1 (2016)[arXiv:1511.04050 [hep-ph]].

J. Liao, Pramana 84, no. 5, 901 (2015) [arXiv:1401.2500 [hep-ph]].

X.G. Huang, ROPP2016; Hattori, Huang, 2017.

Chiral Anomaly

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

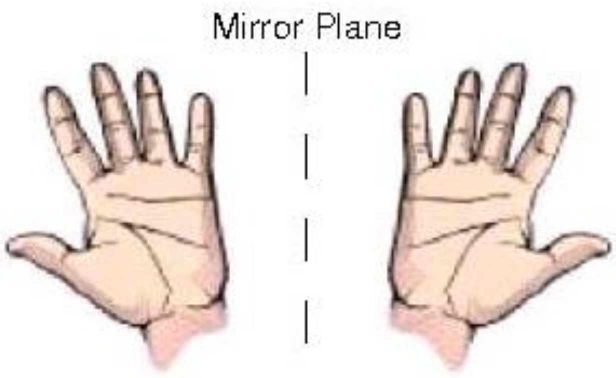
Classical symmetry:

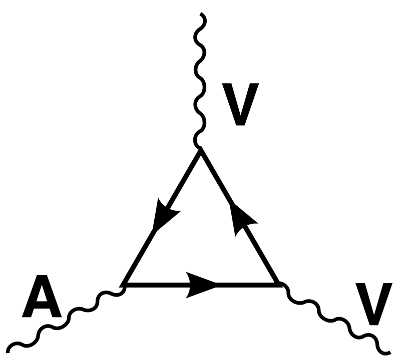
$$\mathcal{L} = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi$$

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

$$\Lambda_A : \Psi \to e^{i\gamma_5\theta}\Psi$$

$$\partial_\mu J_5^\mu = 0$$





[e.g. pi0—> 2 gamma]

Broken at QM level:

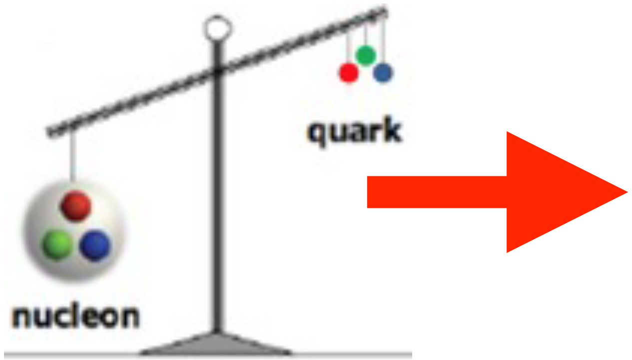
$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

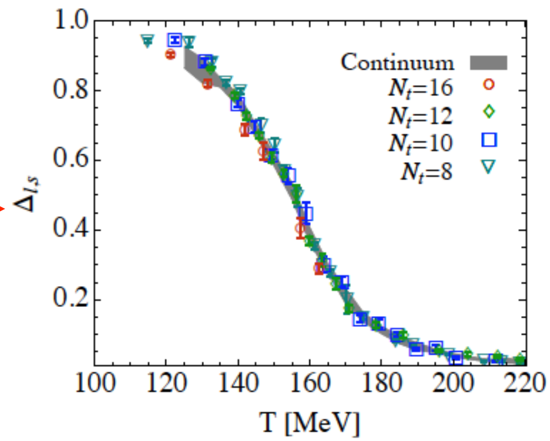
$$dQ_5/dt = \int_{\vec{\mathbf{x}}} C_A \vec{\mathbf{E}} \cdot \vec{\mathbf{B}}$$

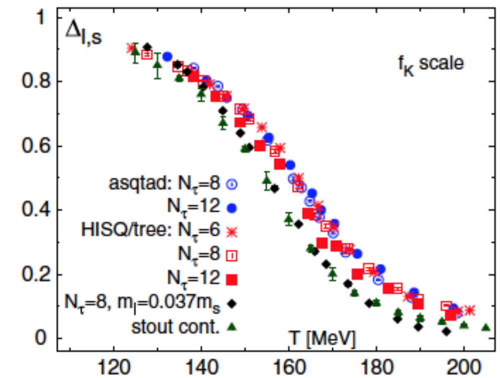
* C_A is universal anomaly coefficient
* Anomaly is intrinsically QUANTUM effect

Chiral Restoration in QGP

**** Spontaneously broken chiral symmetry in the vacuum is a fundamental property of QCD.***





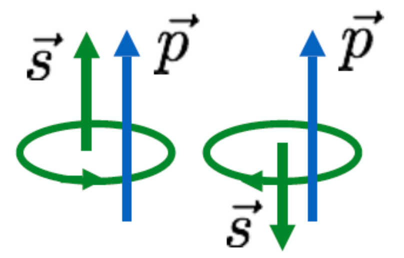


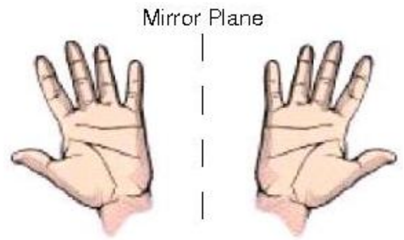
**** A chirally symmetric quark-gluon plasma at high temperature is also a fundamental property of QCD!***

Can we see direct experimental evidence for that?

Chiral Restoration via Chiral Anomaly

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





$$\partial_\mu J_5^\mu = 2iM\bar{\Psi}\gamma^5\Psi + C_A \vec{E}\cdot\vec{B}$$

Low T

Strong spon. breaking

High T

Quantum Anomaly

Look for pure quantum anomaly effect in hot QGP with chiral symmetry restoration!

The Chiral Magnetic Effect (CME)

Chirality & Anomaly & Topology

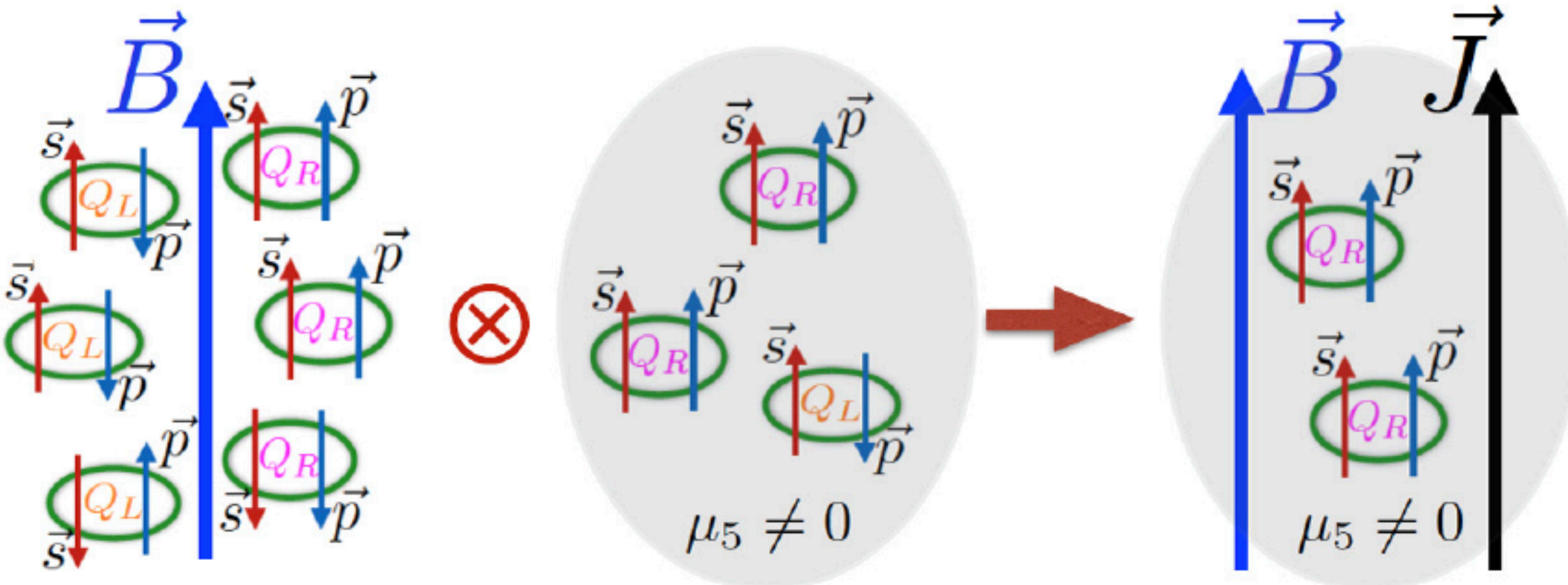
$$\vec{J} = \frac{Q^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Electric Current

Magnetic Field

Q.M. Transport

Intuitive Picture of CME



Intuitive understanding of CME:

Magnetic polarization —> correlation between micro. SPIN & EXTERNAL FORCE ⊗ **Chiral imbalance —> correlation between directions of SPIN & MOMENTUM**

→ ***Transport current along magnetic field***

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

From Micro. Laws To Macro. Phenomena

Micro. Laws:		Macro. Phenomena:
Symmetry; Lagrangian; Conservation laws;	⟷	Thermodynamics; Transport; Fluid Dynamics; ......

Quantum Field Theory → *Weakly Interacting* → **Kinetic Theory** → *Strongly Interacting* → **Fluid Dynamics**

WHAT ABOU the "SEMI"-SYMMETRY???
i..e ANOMALY?!
— classical symmetry that is broken in quantum theory

CME = Macroscopic Chiral Anomaly

Anomaly --> $\partial^\mu j_\mu^5 = \frac{q^2}{2\pi^2} E \cdot B$ $\frac{dN_5}{dt d^3x} = \frac{q^2}{2\pi^2} E \cdot B$

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

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

*** 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.)

CME is a quantum/anomalous transport current as macroscopic manifestation of microscopic quantum anomaly.

Fluid Dynamics That Knows Left & Right

conservation law: $\partial_\mu J^\mu = 0$ → $\partial_\mu J^\mu = C E^\mu B_\mu$

constituent relation: $J^\mu = n u^\mu + \nu^\mu$

$\partial_\mu s^\mu \geq 0$

$$\nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left(\frac{\mu}{T}\right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu$$

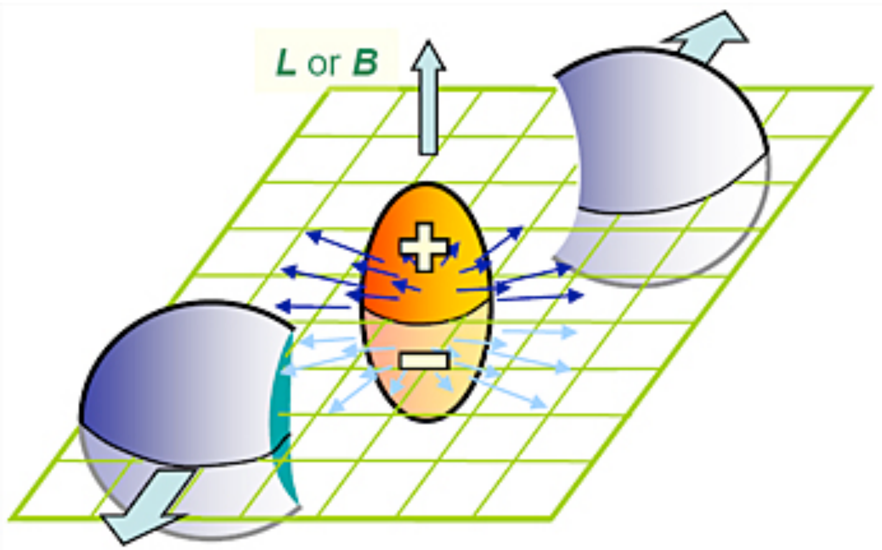
[Son, Surowka, 2009;…]

CVE CME

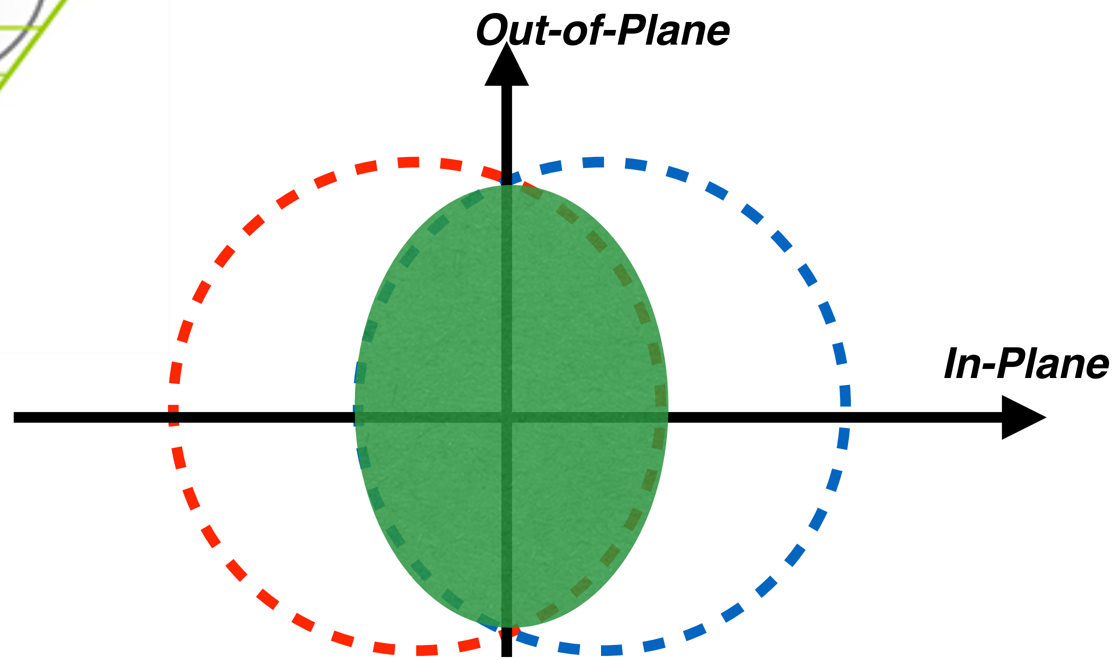
Microscopic quantum anomaly emerges as macroscopic anomalous hydrodynamic currents!

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

Looking for CME in Heavy Ion Collisions



The quark-gluon plasma is a subatomic CHIRAL MATTER.

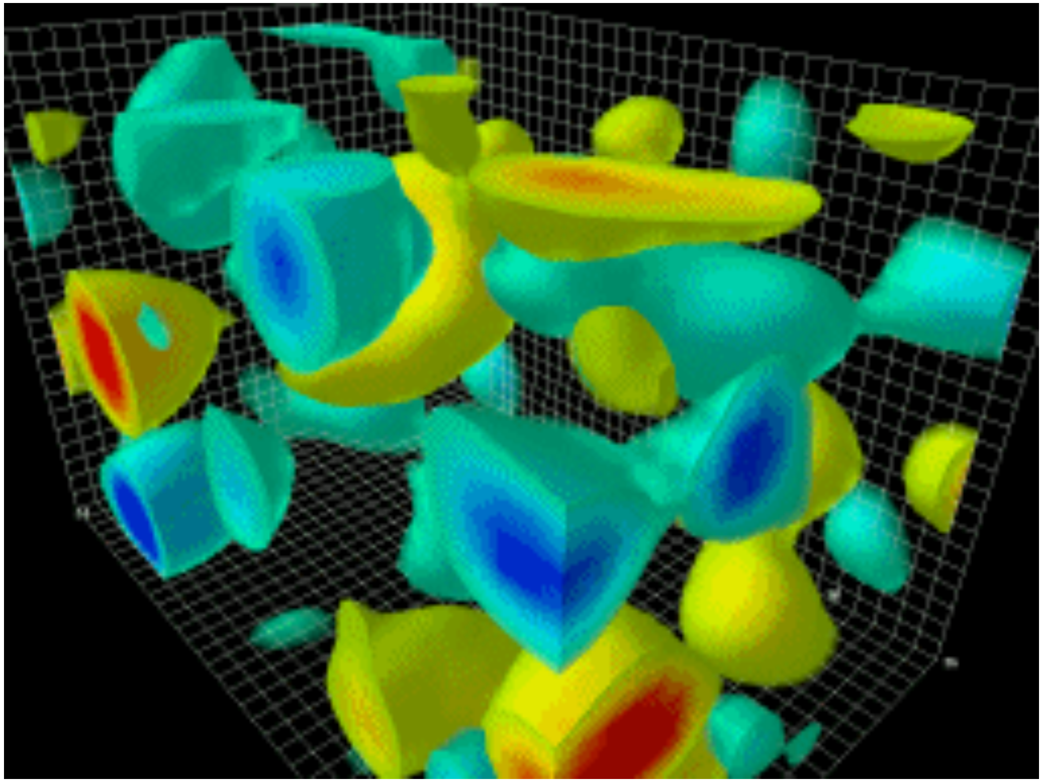


Can we observe CME in heavy ion collisions??

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

1) *(nearly) chiral quarks*
2) *chirality imbalance*
3) *strong magnetic field*

From Gluon Topology to Quark Chirality



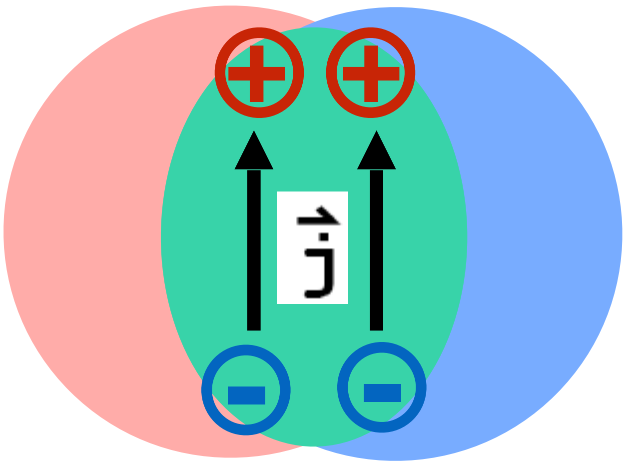
$$Q_w = \frac{1}{32\pi^2} \int d^4x \, (gG_a^{\mu\nu}) \cdot (g\tilde{G}_{\mu\nu}^a)$$

$$N_5(t \to +\infty) - N_5(t \to -\infty) = \frac{g^2}{16\pi^2} \int dt d^3\mathbf{r} \, G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

QCD anomaly: gluon topology —> chirality imbalance

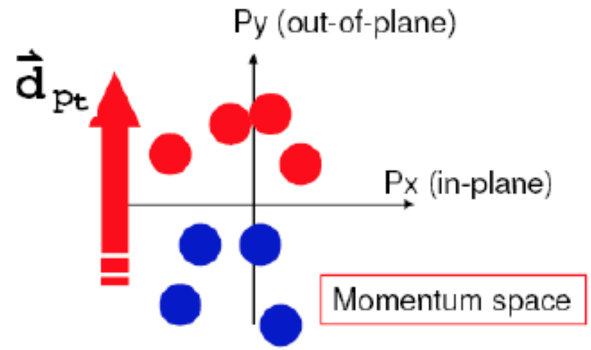
$$N_R - N_L = N_5 = 2Q_w$$

From CME Current to Charge Separation



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

strong radial blast: position —> momentum



Charge Separation *or*
Electric Dipole in Pt Space
(along ***out-of-plane****)*

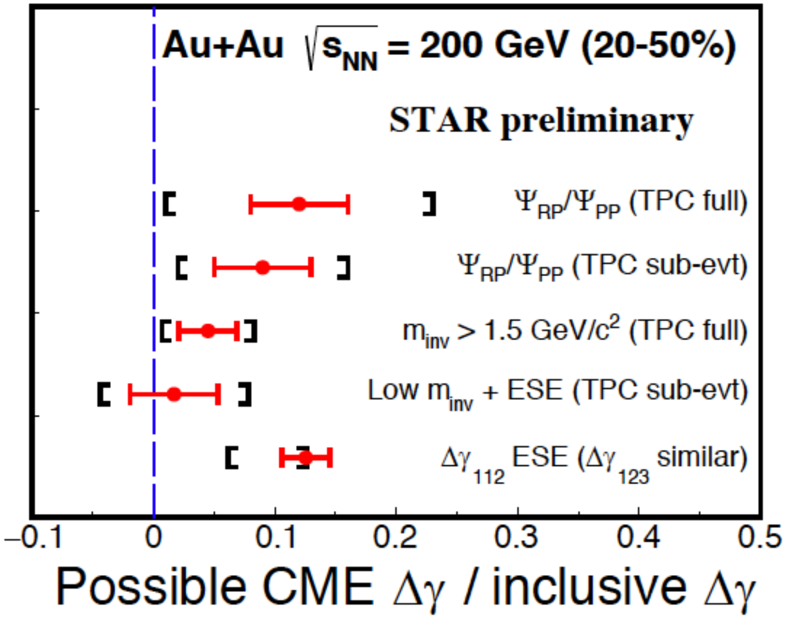
[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

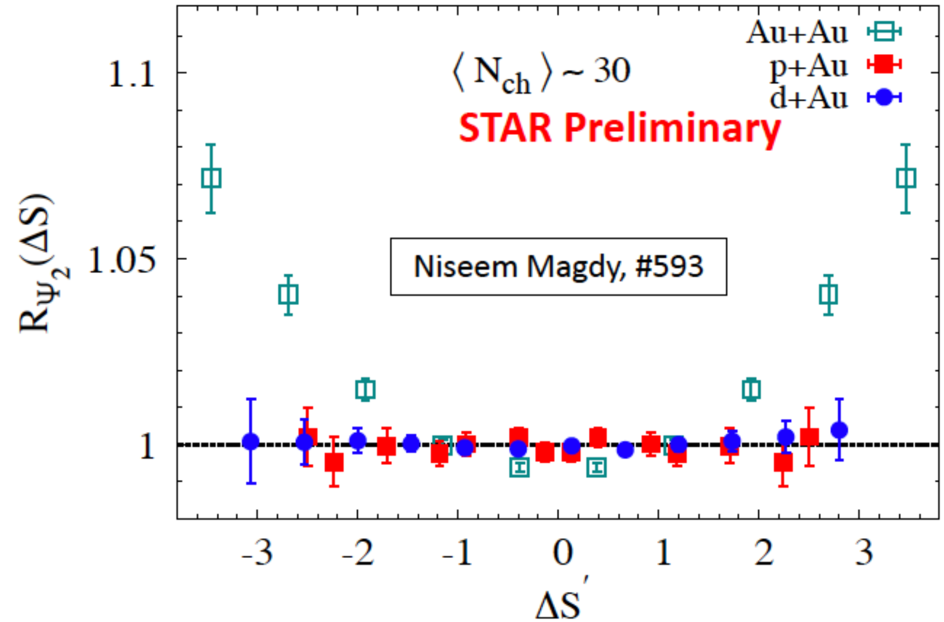
$$\frac{dN_\pm}{d\phi} \propto ... + a_\pm \sin(\phi - \Psi_{RP})$$

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

Very difficult measurement:
- ***Zero average, only nonzero variance;***
- ***Correlation measurement with significant backgrounds;***
- ***Signal likely small***

Latest Exp. Search Status





[From Z. Ye, STAR Summary Talk @ QM2018]

STAR @ RHIC 200GeV: " naive" statistical interpretation: (8.5 +/- 1.2) %

ALICE @ LHC 2.76TeV: signal level possibly about 8~10% (upper limit ~30%)

CMS @ LHC 5.02TeV: signal level no more than 7%

The trend with beam energy seems in line with expectation!

Chinese Physics C Vol. 42, No. 1 (2018) 011001

arXiv:1611.04586

Quantifying the chiral magnetic effect from anomalous-viscous fluid dynamics*

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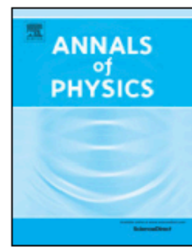


Anomalous chiral transport in heavy ion collisions from Anomalous-Viscous Fluid Dynamics

Check for updates

Shuzhe Shi [a,*], Yin Jiang [b,c], Elias Lilleskov [d,a], Jinfeng Liao [a,e,*]

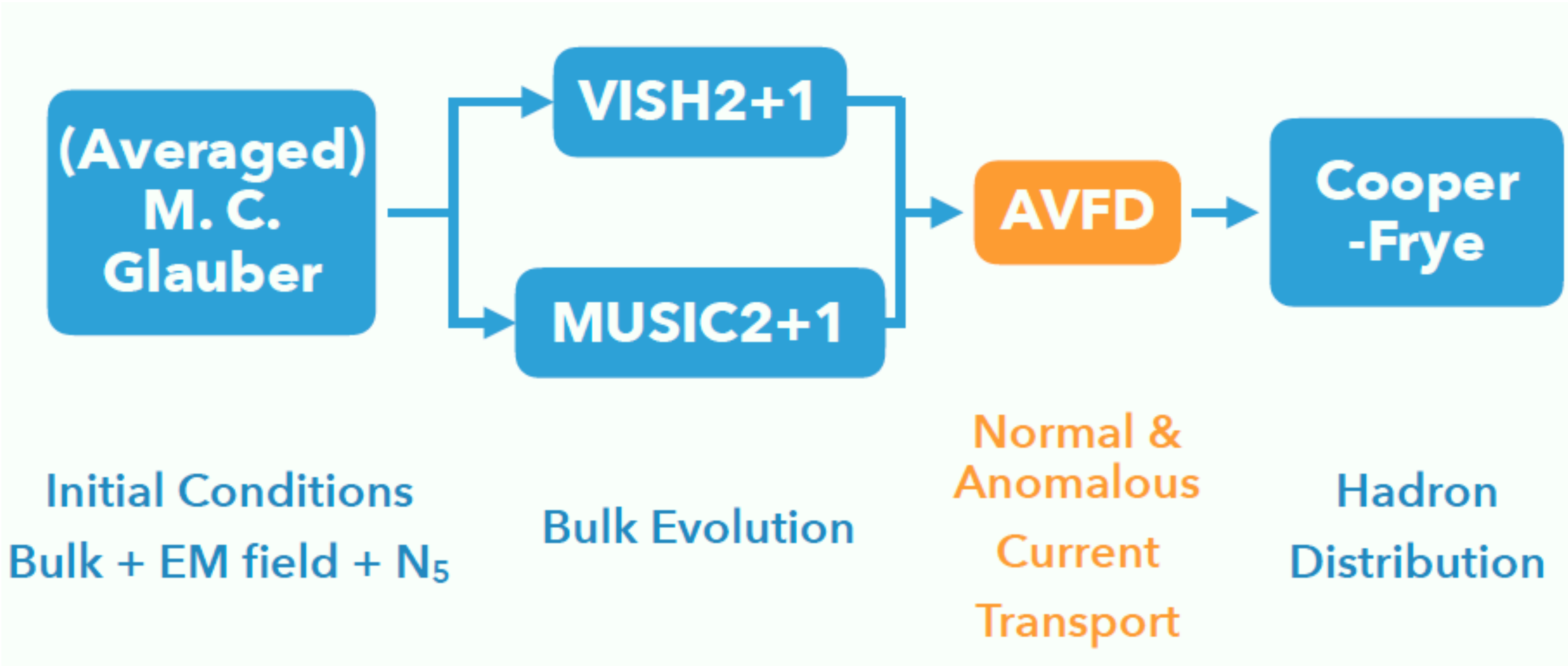
arXiv:1711.02496

Badly needed: Quantitative predictions for CME signal in heavy ion collisions!

Anomalous Viscous Fluid Dynamics (AVFD)

AVFD:
Anomalous-Viscous Fluid Dynamics

The AVFD Framework



We now have a versatile tool to quantitatively understand and answer many important questions about CME in heavy ion collisions!

arXiv:1611.04586 ***arXiv:1711.02496***

The AVFD Framework

Anomalous-Viscous Fluid Dynamics

$$D_\mu J_R^\mu = + \frac{N_c q^2}{4\pi^2} E_\mu B^\mu \qquad D_\mu J_L^\mu = - \frac{N_c q^2}{4\pi^2} E_\mu B^\mu$$

$$J_R^\mu = n_R u^\mu + \nu_R^\mu + \frac{N_c q}{4\pi^2} \mu_R B^\mu$$

$$J_L^\mu = n_L u^\mu + \nu_L^\mu - \frac{N_c q}{4\pi^2} \mu_L B^\mu$$

CME

Viscous Effect

$$\Delta^\mu{}_\nu \, d\, \nu_{R,L}^\nu = - \frac{1}{\tau_{rlx}} (\nu_{R,L}^\mu - \nu_{NS}^\mu)$$

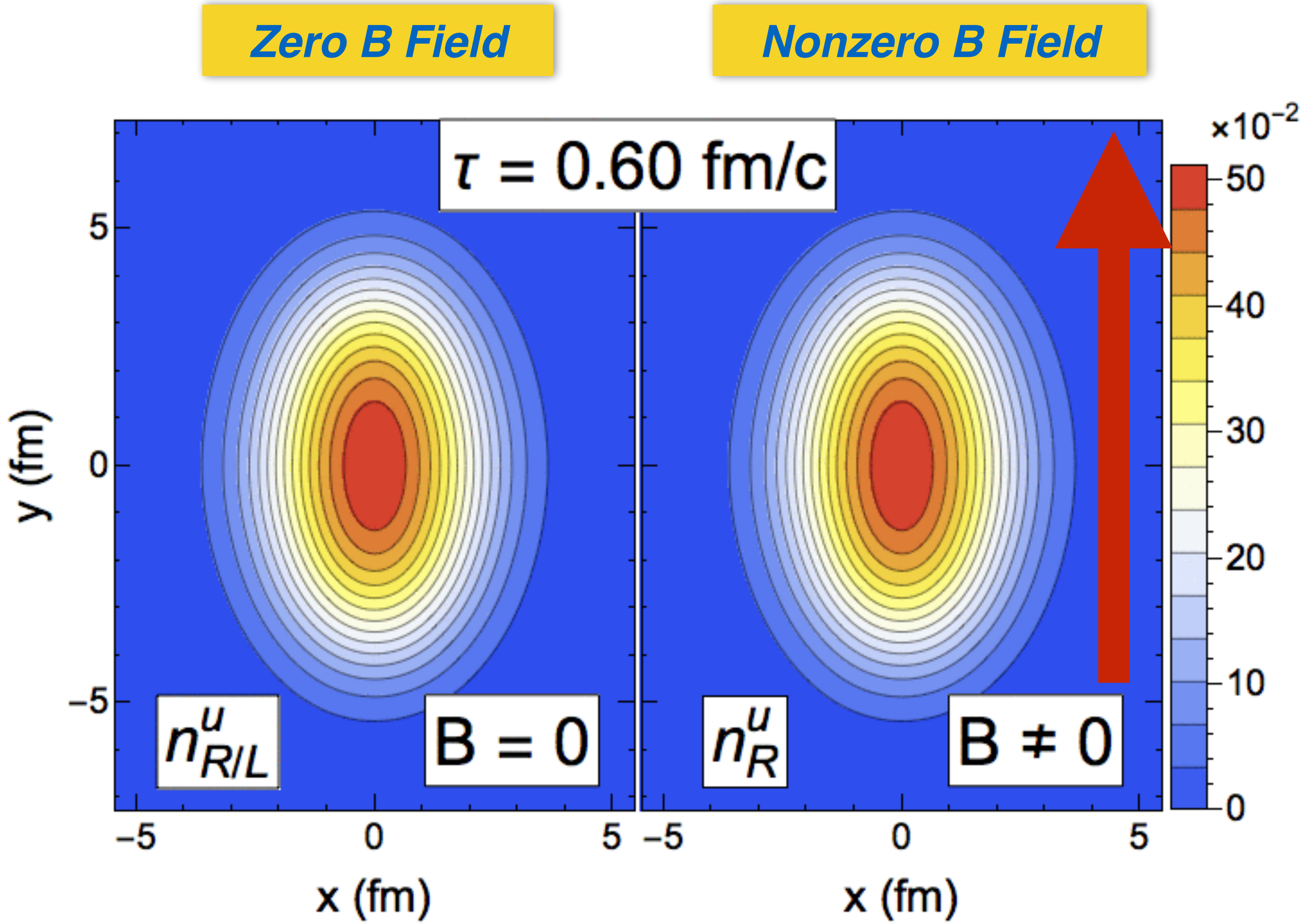
$$\nu_{NS}^\mu = \frac{\sigma}{2} T \Delta^{\mu\nu} \partial_\nu \frac{\mu}{T} + \frac{\sigma}{2} q E^\mu$$

on top of VISH2+1D —— OSU Group

[We now also have MUSIC-AVFD!]

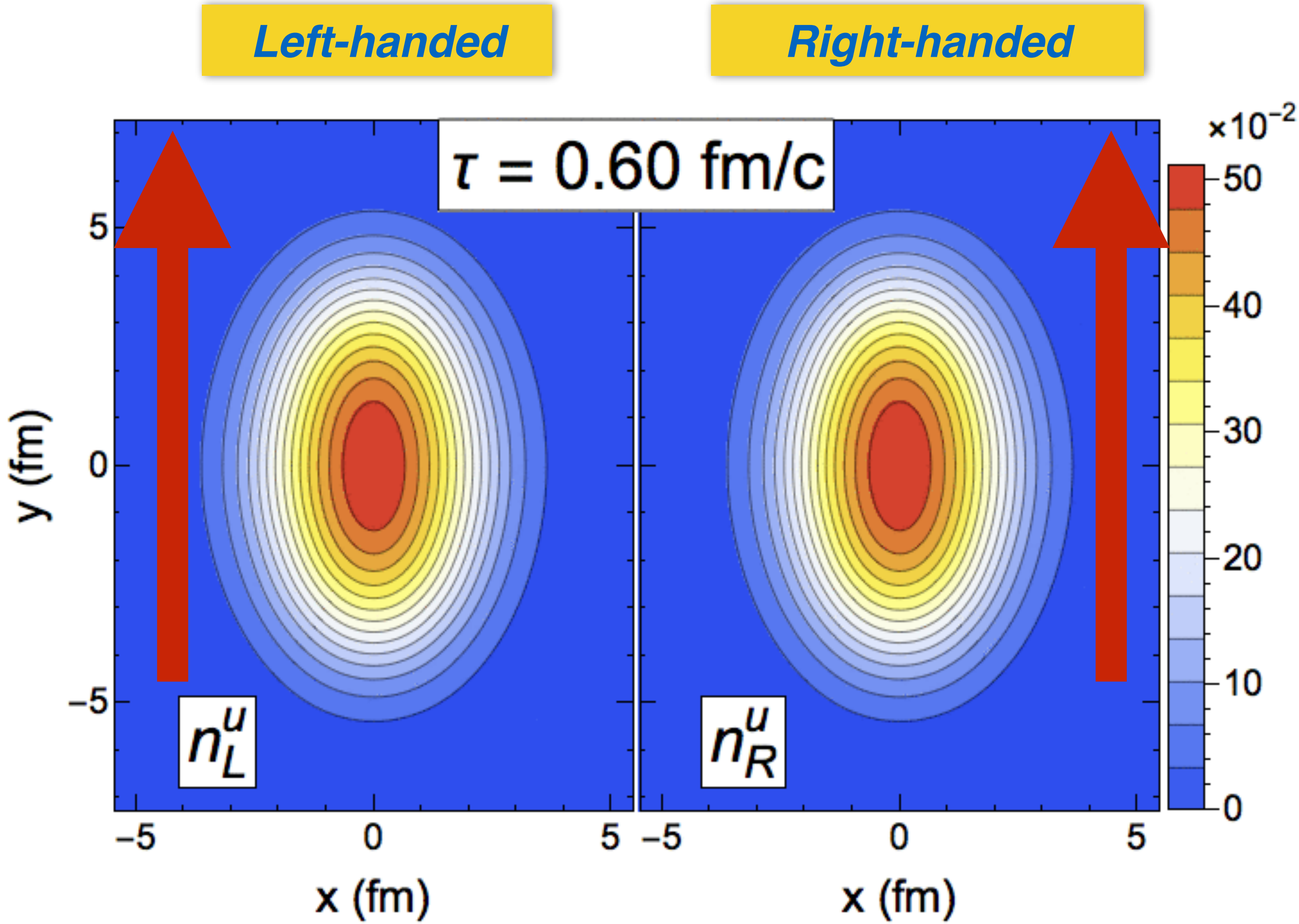
The AVFD At Work

[arXiv:1611.04586; arXiv:1711.02496]

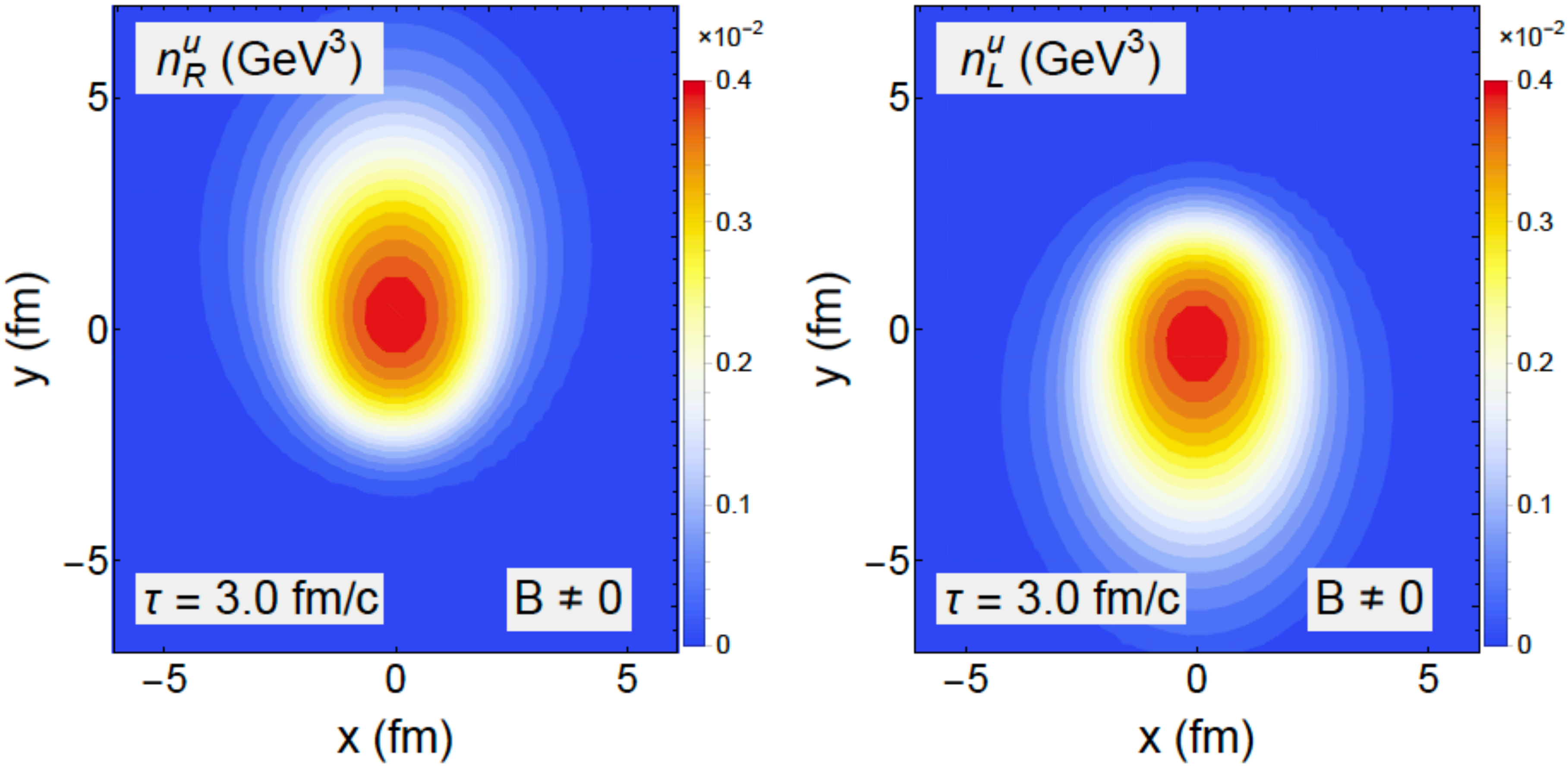


The AVFD At Work

[arXiv:1611.04586; arXiv:1711.02496]



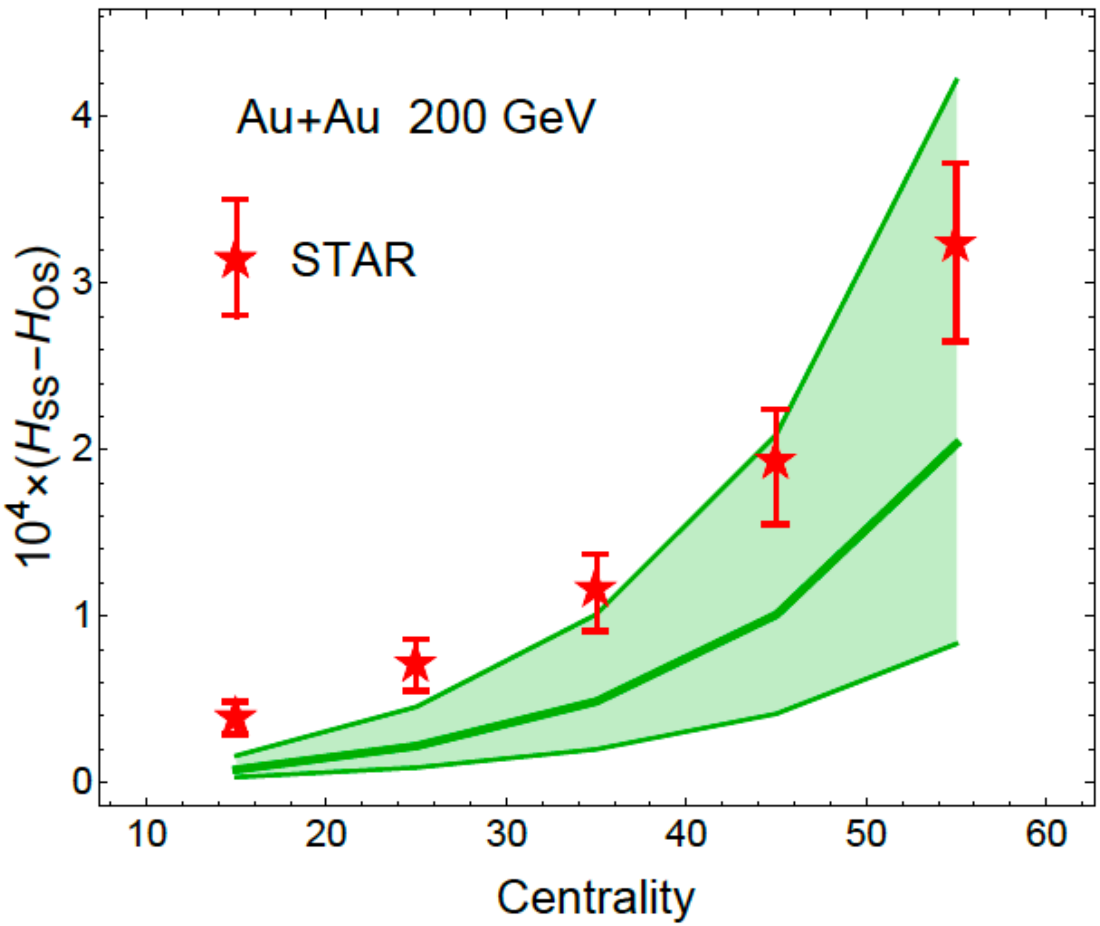
The Charge Separation from AVFD



B field ⊗ μ_5 ⇒ current ⇒ dipole (charge separation)

$dN_{\pm}/d\phi \propto 1 + 2\, a_{1\pm} \sin(\phi - \psi_{RP}) + \ldots$

AVFD Predictions v.s Experimental Data



$$B(\tau) = \frac{B_0}{1 + (\tau/\tau_B)^2}$$

$$\tau_B = 0.6\mathrm{fm/c}$$

$$\sqrt{\langle n_5^2 \rangle} \simeq \frac{Q_s^4\,(\pi \rho_{tube}^2 \tau_0)\,\sqrt{N_{coll.}}}{16\pi^2\,A_{overlap}}$$

Excellent agreement!

Shi, Jiang, JL, et al: arXiv:1611.04586 [CPC]; arXiv:1711.02496 [Annals of Physics]

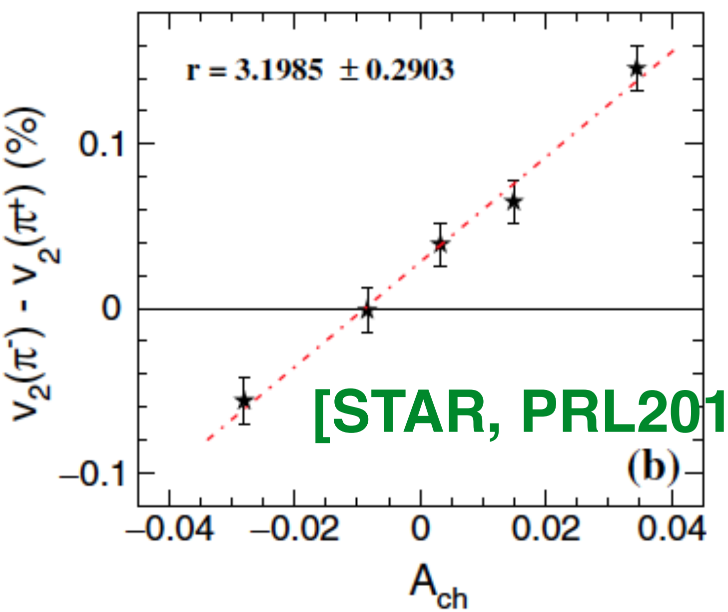
Chiral Magnetic Wave (CMW)

CMW: gapless collective excitation in chiral fluid
—> charge quadrupole of QGP —> elliptic flow splitting

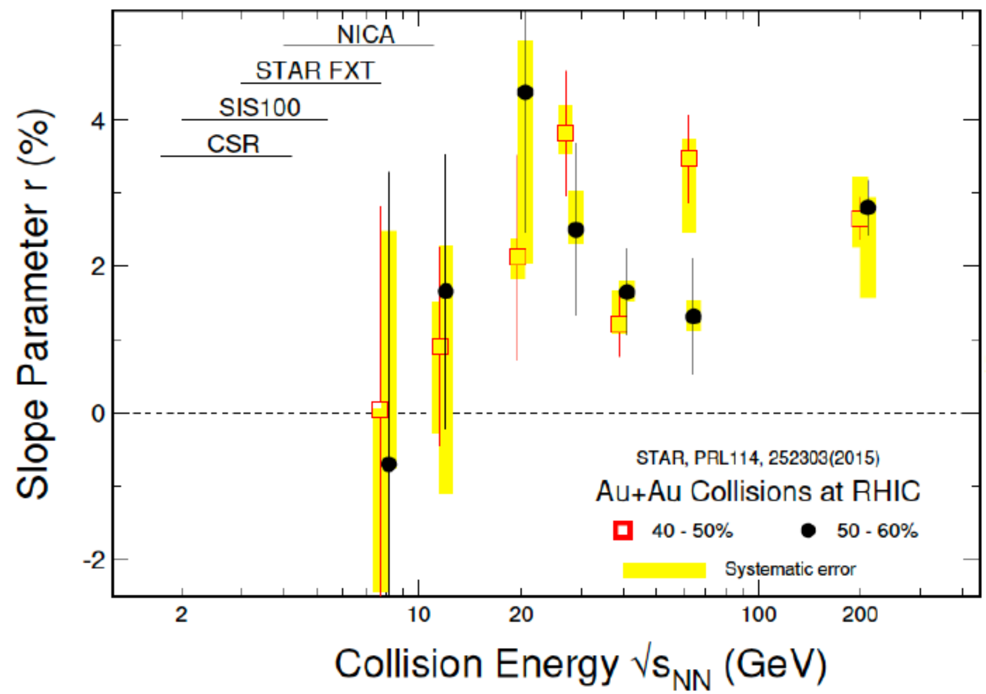
[Burnier, Kharzeev, JL, Yee, PRL2011; & arXiv: 1208.2537]

$$v_2^- - v_2^+ = r_e\, A$$

charge quadrupole due to CMW transport



[STAR, PRL2015]



[STAR@RHIC]
[Also seen by ALICE@LHC]

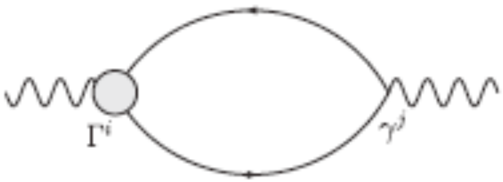
There Are Electric Fields Too!

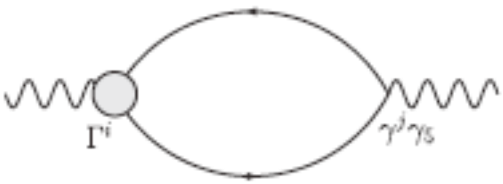
Chiral matter in strong electric field:

Chiral Electric Separation Effect (CESE)

[Huang, JL, PRL2013; Jiang, Huang, Liao, PRD2014]

$$j_A = \chi_e \mu_V \mu_A \boldsymbol{E},$$





$$\sigma_e = \chi_e \mu_V \mu_A$$

QED plasma

$$\sigma_e \approx \frac{T}{e^4 ln(1/e)} \left(20.5 \frac{\mu_V \mu_A}{T^2}\right)$$

QCD plasma

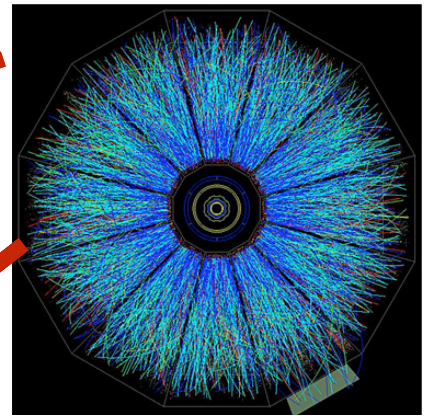
$$\sigma_e \approx \frac{N_c N_f T}{g^4 ln(1/g)} \left(4.83 \frac{\mu_V \mu_A}{T^2}\right)$$

Summary & Outlook

Summary: the Subatomic Swirls

Quark-Gluon Plasma:
A Subatomic Chiral Fluid

The new, 5th state of matter

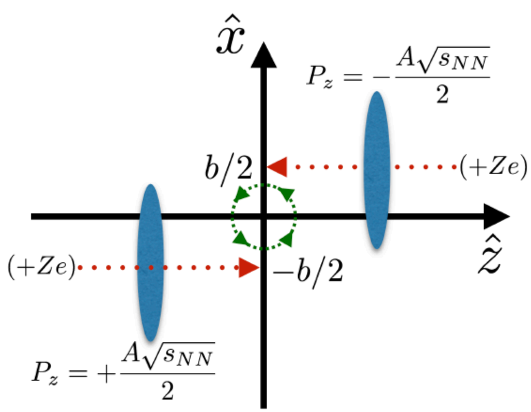


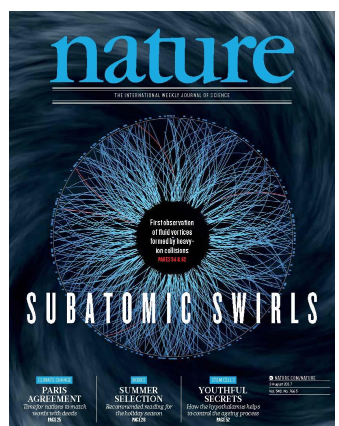
The oldest state of matter: early cosmos

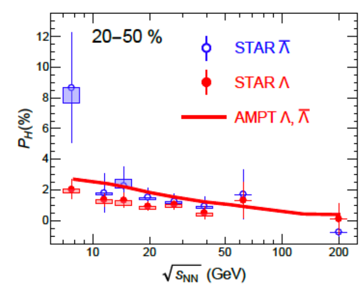
The hottest material

The most perfect fluid

Subatomic swirls as the most vortical fluid with the strongest B field







Spin Polarization

CME