Vorticity in the quark-gluon plasma at RHIC

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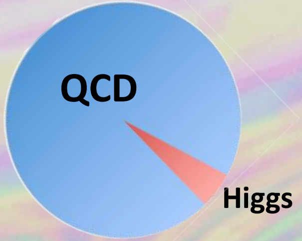
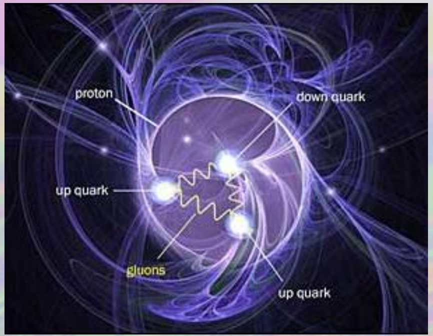
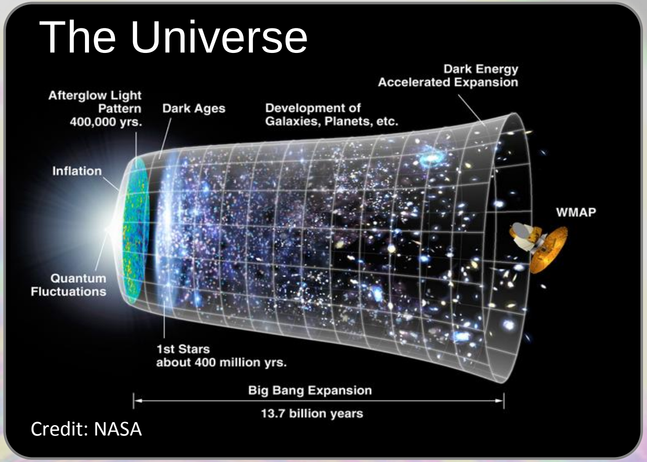
Outline

- Motivation – subjecting our paradigm to scrutiny
- Fluid vorticity and polarization probes
  - Barnett effect / fluid spintronics
- Hyperon polarization in BES-I
- Extraction of ω & B
  - broader context & comparison with predictions
- Outlook & Summary

What we’re after

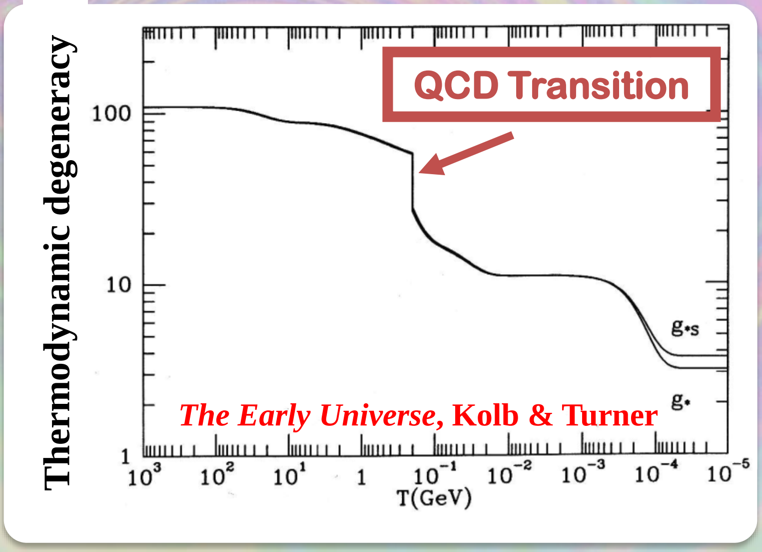






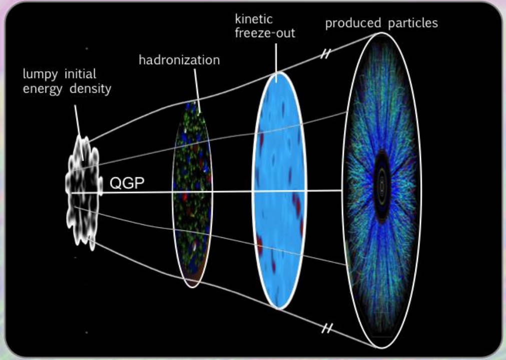
Fundamental understanding of the Strong Interaction

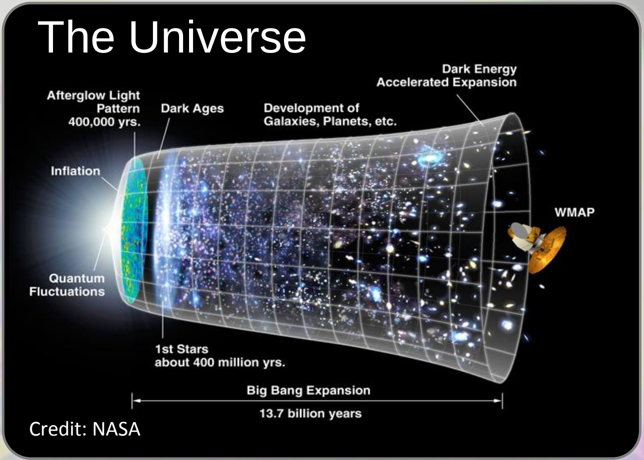
- confines color
- generates ~95% of visible mass

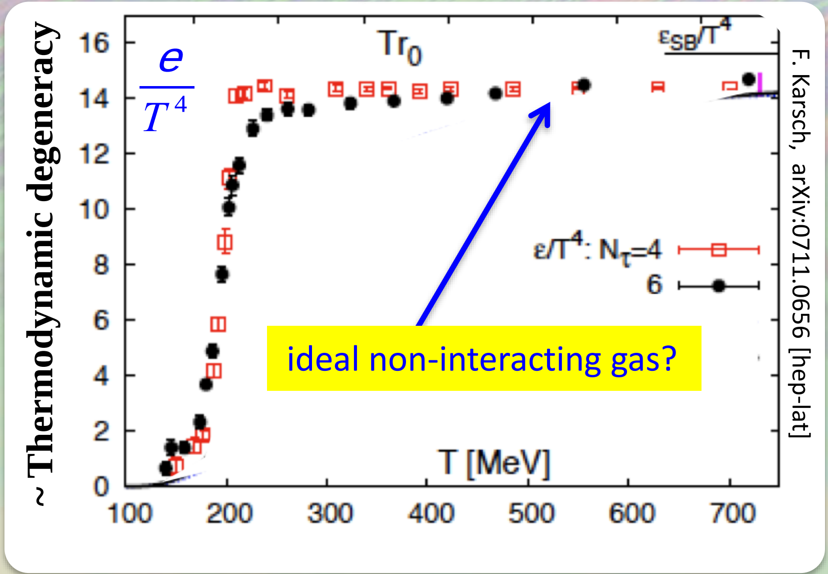


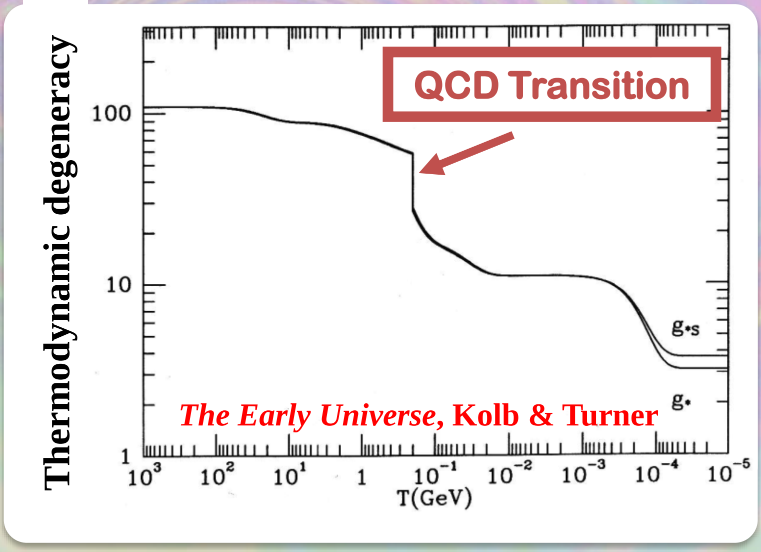
What we expected

Lattice QCD:
weakly-interacting parton gas









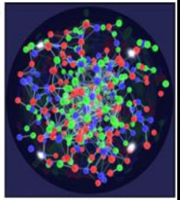
What we found

Lattice QCD:

~~weakly-interacting parton gas~~

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms. BBC NEWS

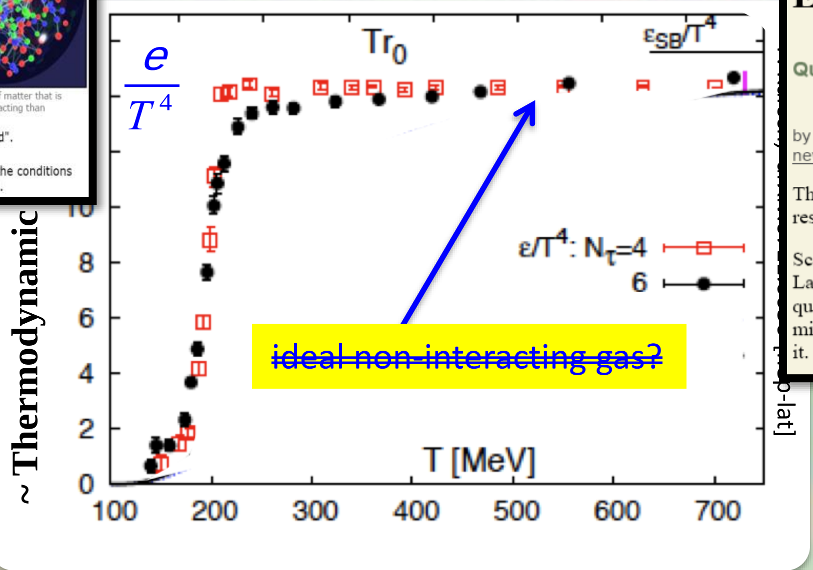


The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.



New State of Matter Is 'Nearly Perfect' Liquid

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society. SCIENTIFIC AMERICAN

Image: BNL

There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

nature

by Mark Peplow
news@nature.com

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strang

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

What we found

Lattice QCD:

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SCIENTIFIC AMERICAN

- The lattice calculations were not wrong. Our physical understanding based on them was wrong (weakly vs strongly coupled).
  - detailed experimental probes dislodged our misconceptions
- Hydro treatment is now a crucial element of the "Standard Model" of RHI collisions
  - Access to Equation of State, transport coefficients, time evolution
- We must continue to subject our new paradigm to detailed experimental scrutiny
- Even assuming hydro: Do we sufficiently understand the fluid structure?

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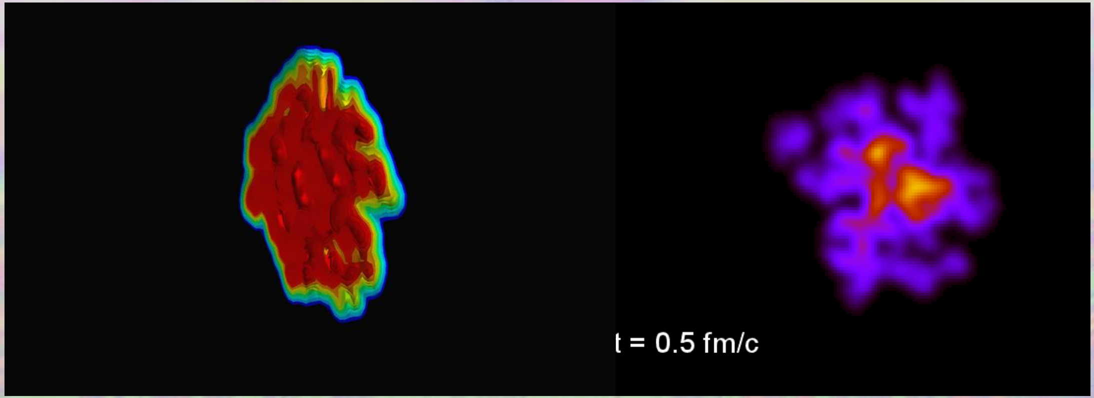
Hydrodynamics –standard paradigm of H.I.C

movies by Bjorn Schenke



From a (lumpy) initial state, solve hydro equations:

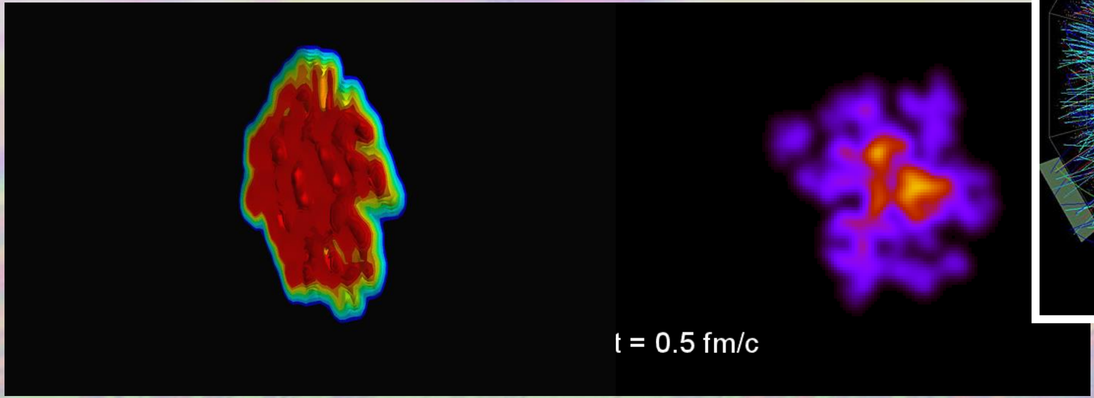
$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = e u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

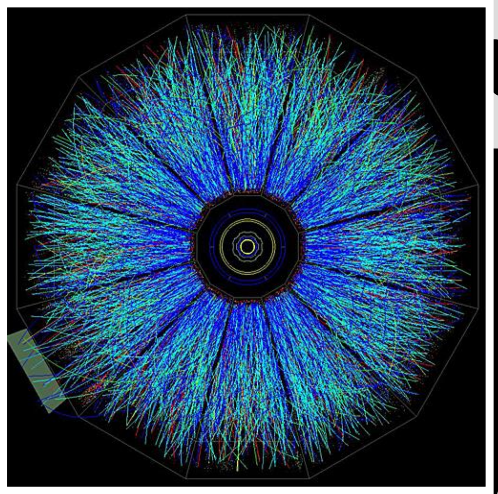
$$u^\mu \partial_\mu \Pi = -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi \frac{\zeta T}{\tau_\Pi} \partial_\lambda \left(\frac{\tau_\Pi}{\zeta T} u^\lambda \right)$$

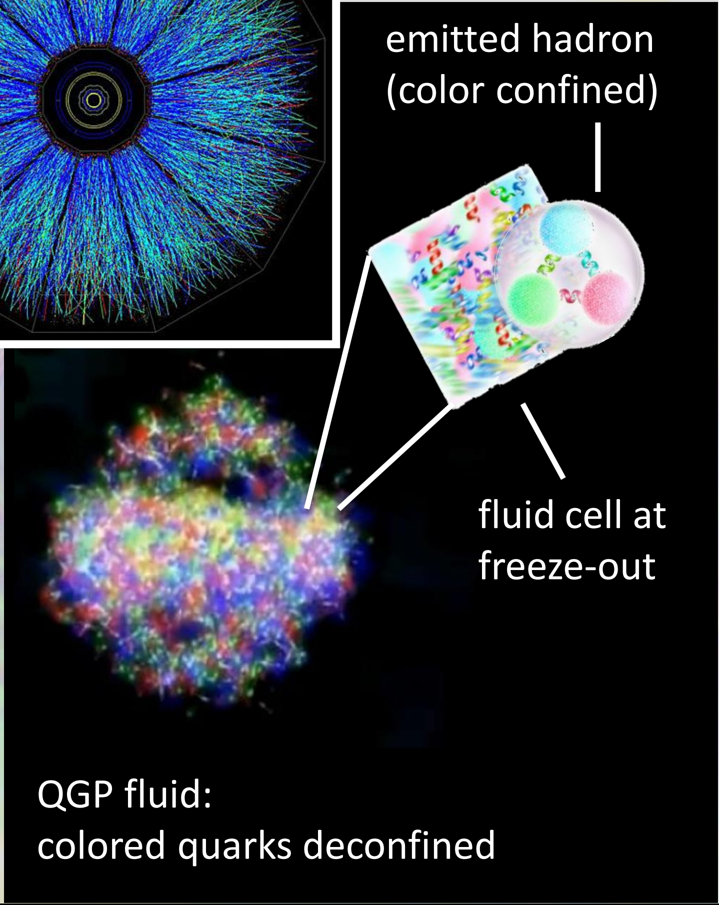
& many more terms...

Connection to experimen… t

movies by Bjorn Schenke





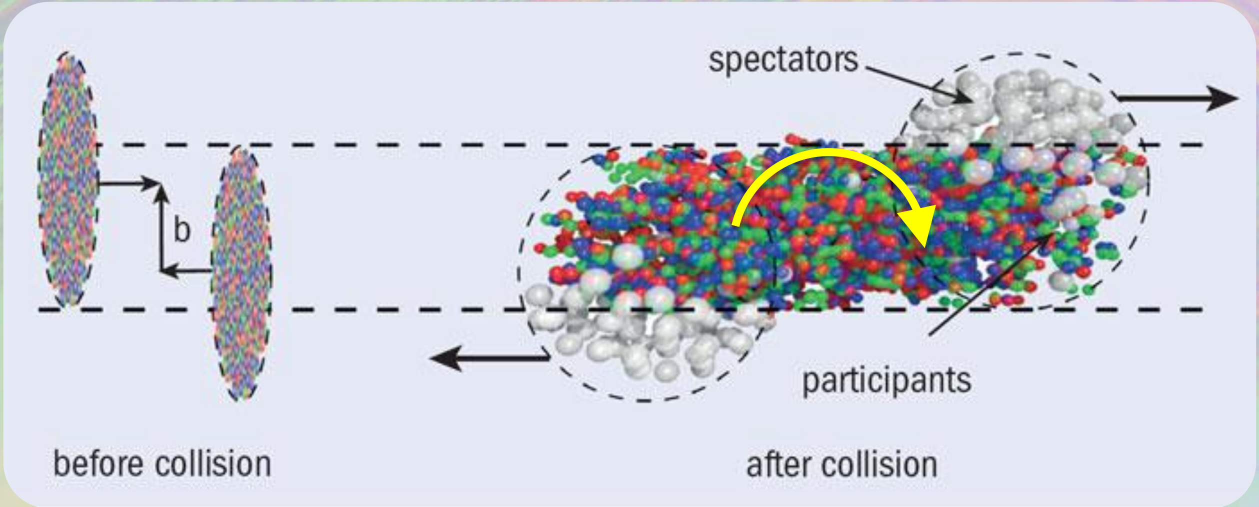


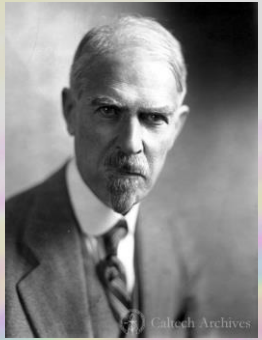
System cools & expands → Freeze-out

- Cooper-Frye prescription – “physics-free”
- emitted hadrons reflect properties of their parent hydro cell (chemical potentials, thermal and collective velocities)

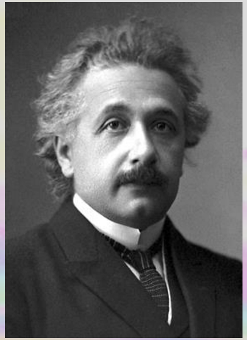
Developing a finer probe/test of hydro

- Non-central heavy ion collisions: $J \sim 10^4\,\hbar$
- Effect on hydrodynamic system?
- What is the experimental probe?



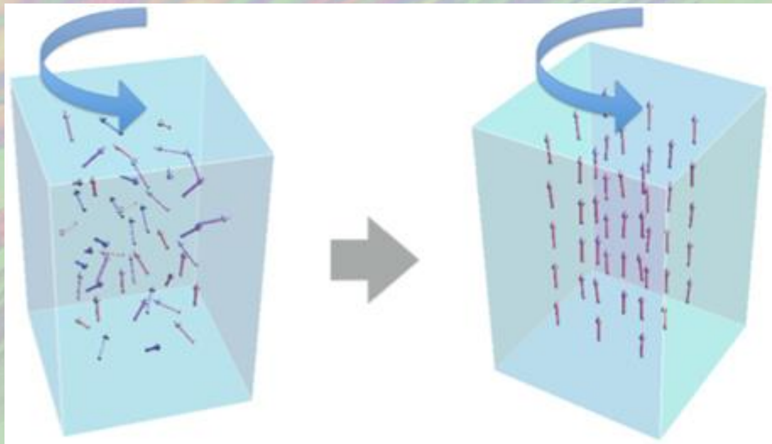


One year , two discoveries



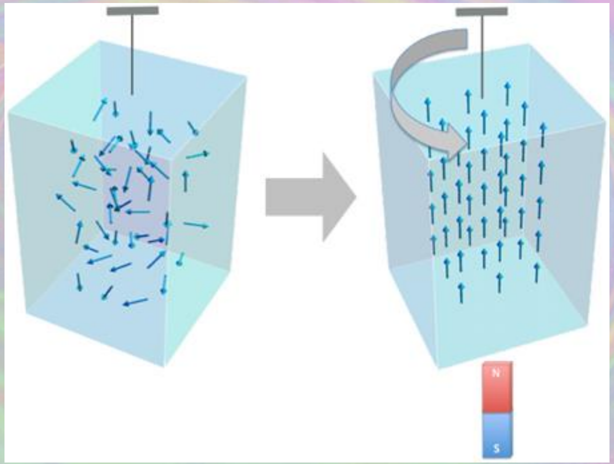
(* N.B. electron spin discovered in 1925)

Barnett Effect (1915)



$$\vec{B} = \vec{\Omega}/\gamma$$

Einstein-de Haas Effect (1915)



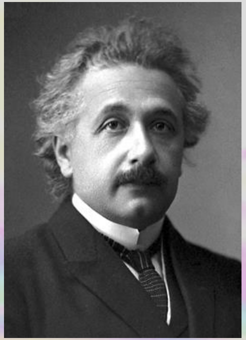
unmagnetized metal object:
mechanical rotation → magnetization

spin alignment

unmagnetized metal object:
introduce B-field → mechanical rotation

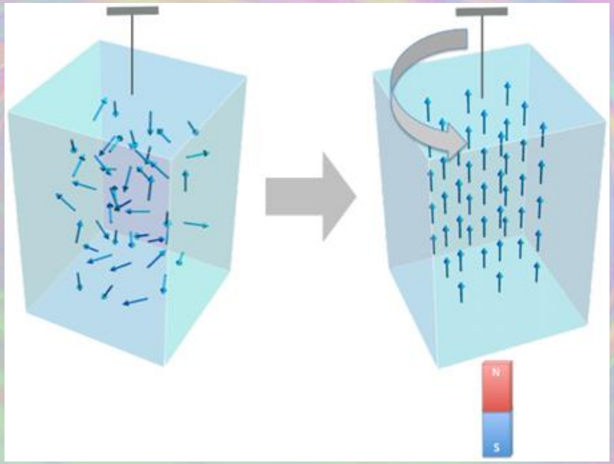
spin alignment

Einstein-de Haas Effect (1915)



This is the only experimental result Einstein published

$$\vec{B} = \vec{\Omega} / \gamma$$

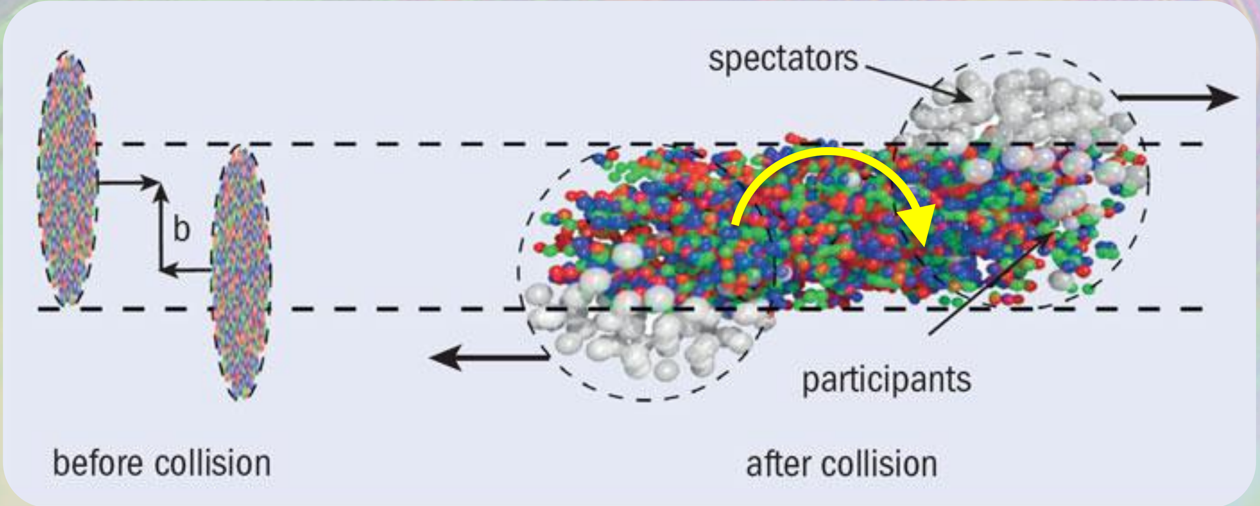


unmagnetized metal object:
introduce B-field → mechanical rotation

spin alignment

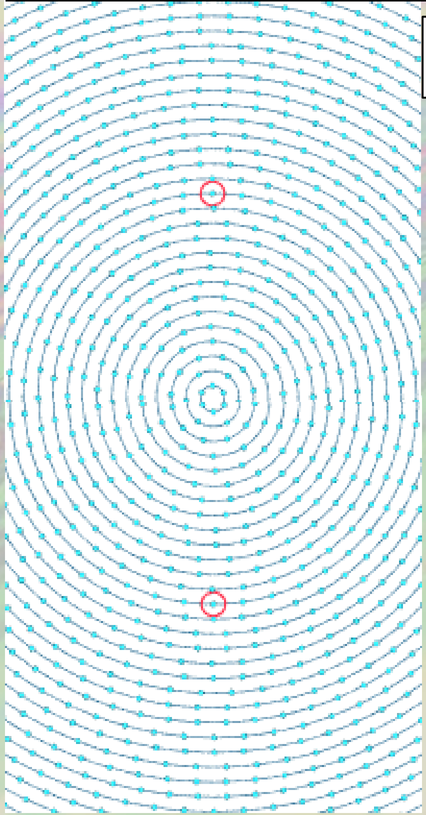
A finer probe?

- Non-central collision: $J \sim 10^4\ \hbar$
- In a hydrodynamic picture, relevant quantity is vorticity $\vec{\omega} = \frac{1}{2}\vec{\nabla} \times \vec{v}$
- How would this manifest experimentally?

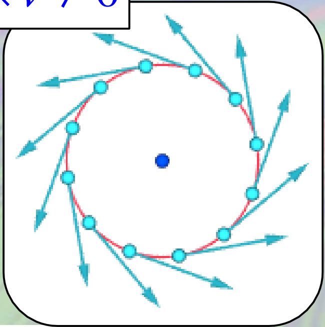


Rotational & irrotational vortices

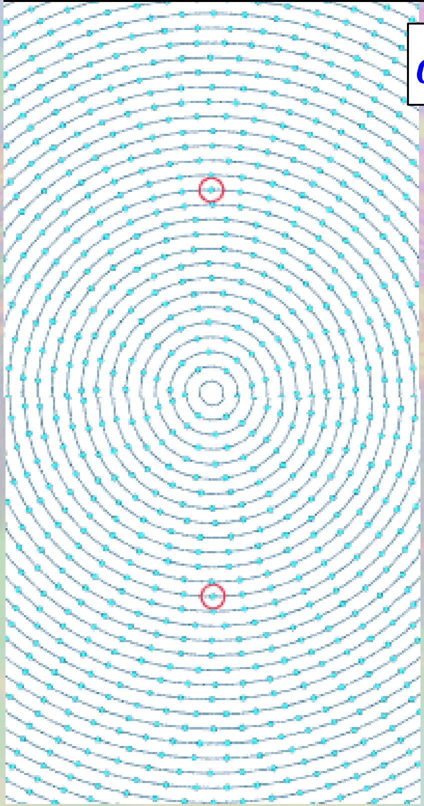
Rotational Vortex (e.g. rigid body): $v \mu r$



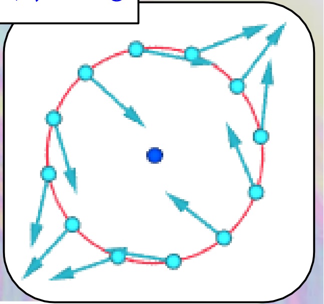
$\vec{\omega} = \frac{1}{2}\vec{\nabla} \times \vec{v} \neq 0$



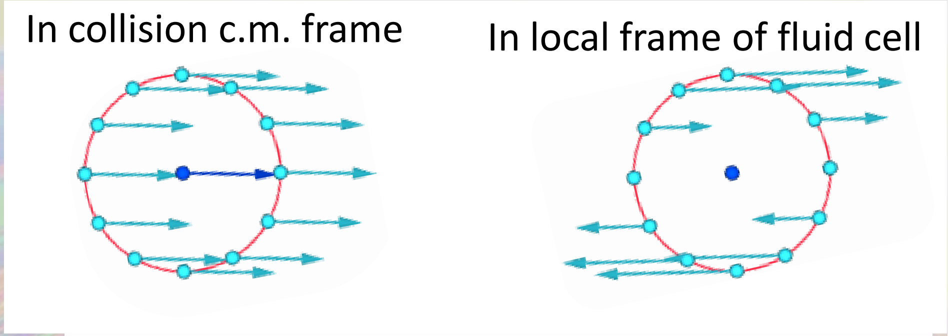
Irrotational Vortex (e.g. tub drain): $v \mu 1/r$



$\vec{\omega} = \frac{1}{2}\vec{\nabla} \times \vec{v} = 0$

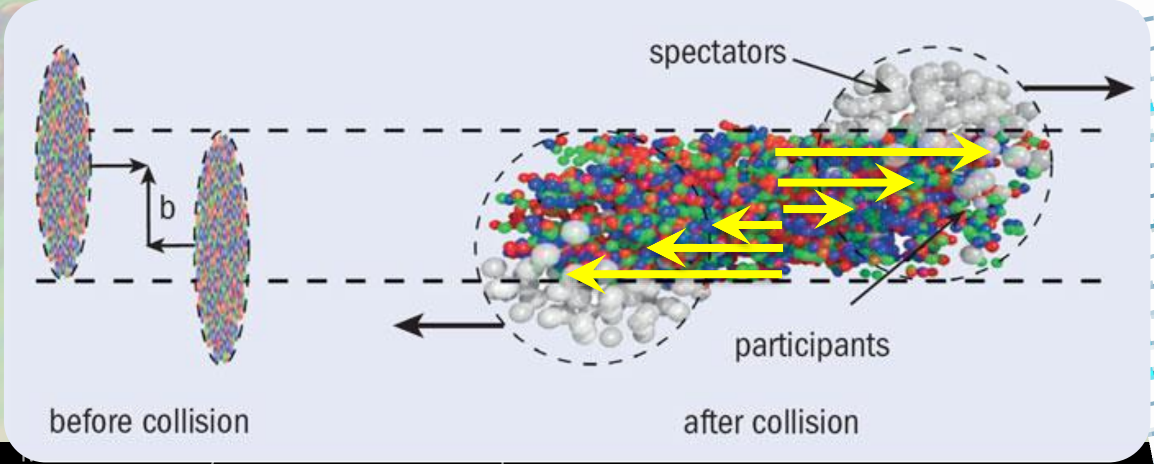


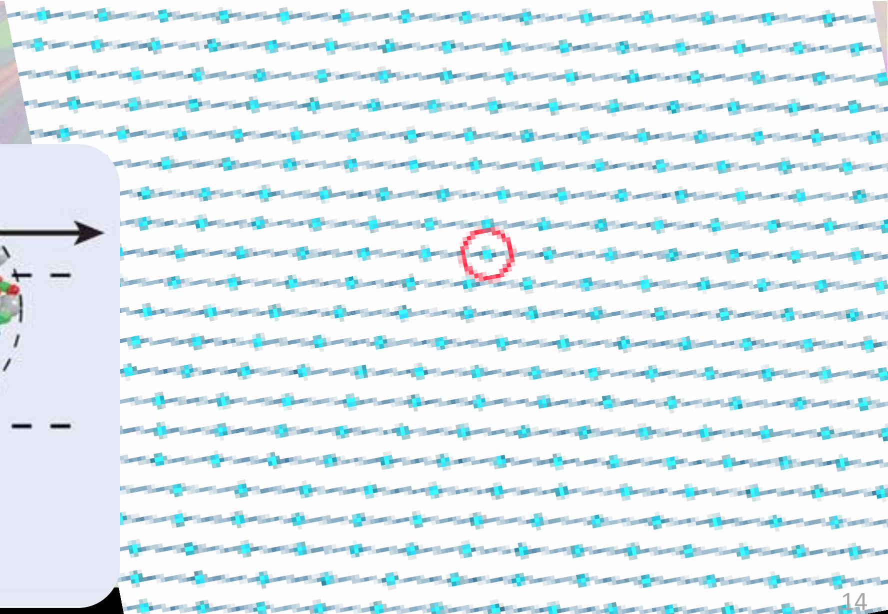
Shear field vorticity



More natural structure for plasma from nuclear collision

$$\omega = \tfrac{1}{2}\nabla \times \vec{v} \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$





Local vorticity and polarization

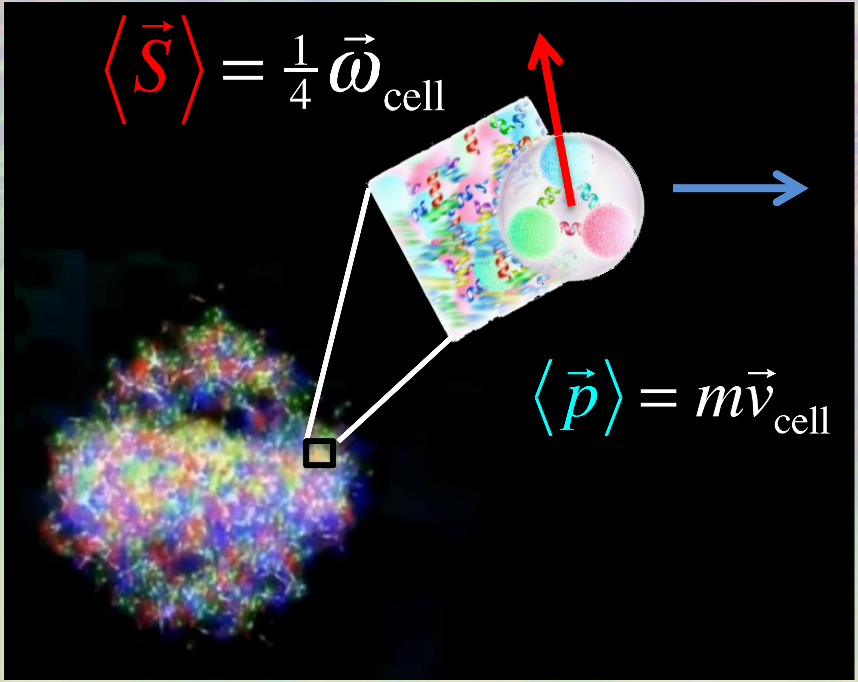
- Fine-scale vorticity *at* the "point" cell reflected in the *spin* of emitted particles

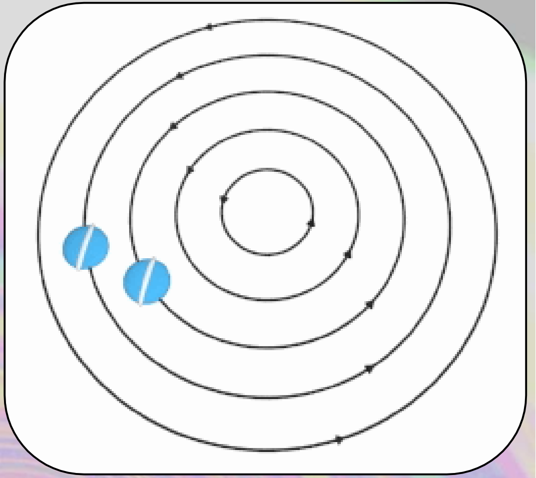
Polarization

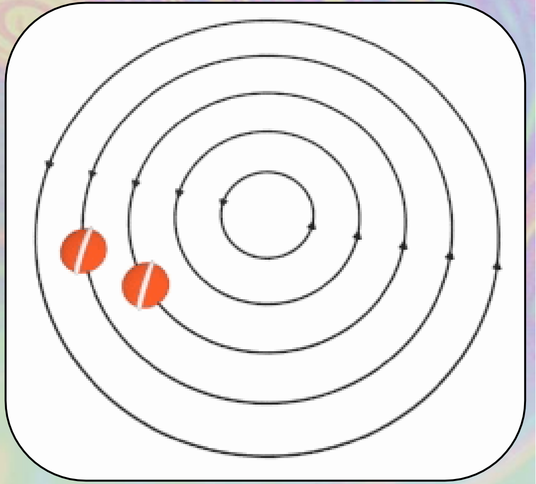
$$\vec{P} \equiv \frac{\langle \vec{S} \rangle}{|\vec{S}|}$$

first suggested by

- Betz et al. (2007)
- Becattini et al. (2008)





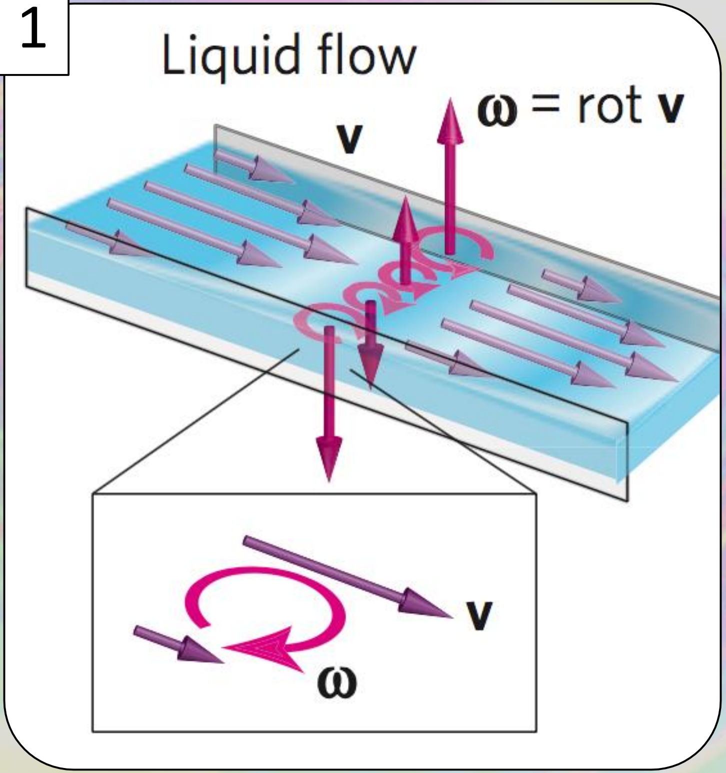


First observation of vorticity-polarization coupling

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

1. Hg flowing down a channel
   - viscous forces with walls → fluid vorticity

1



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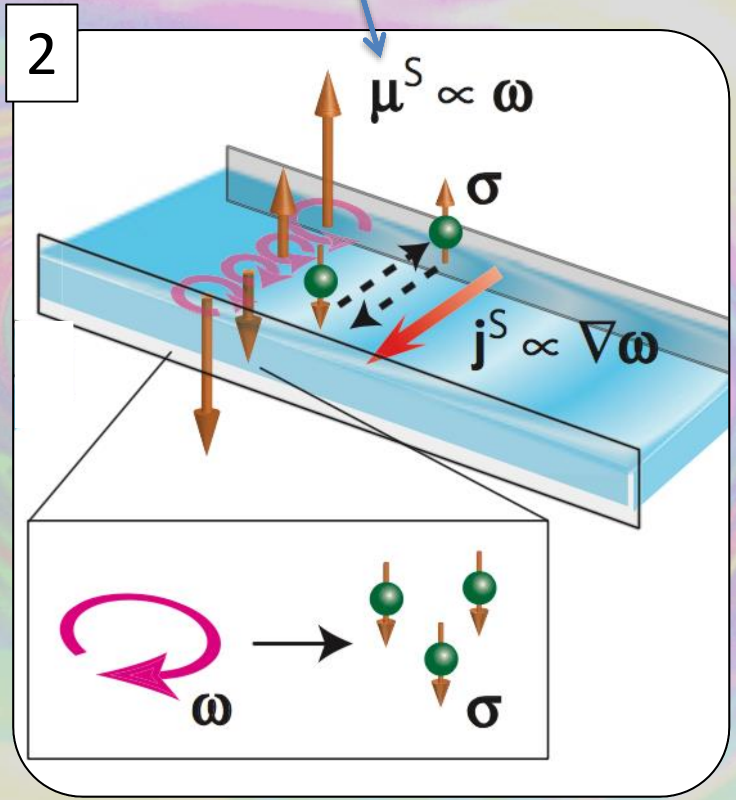
2. mechanical fluid vorticity → e^- polarization

μ^S = spin chemical potential



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1. Hg flowing down a channel
   - viscous forces with walls → fluid vorticity

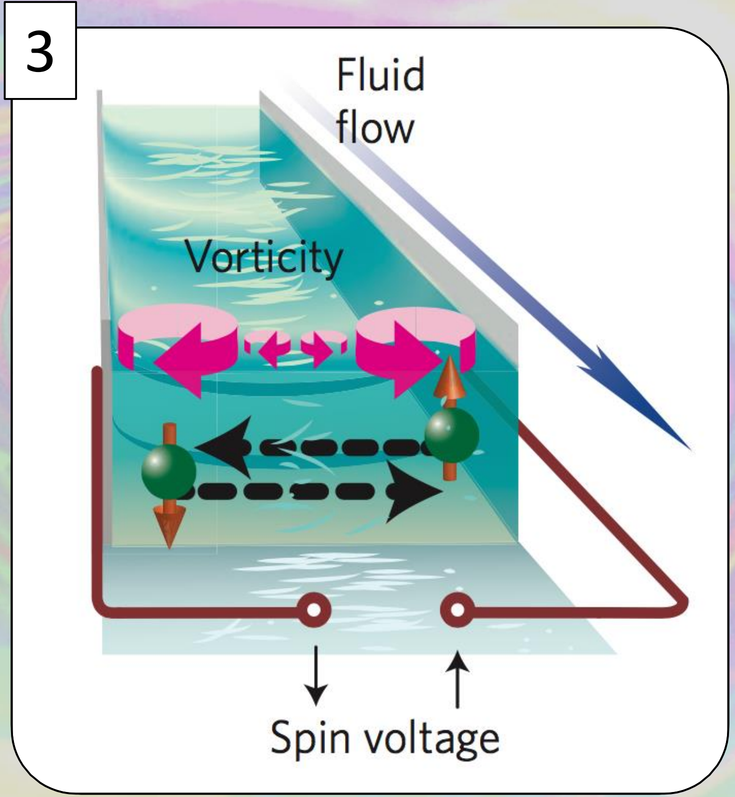
2. mechanical fluid vorticity → e^- polarization

3. Gradient across channel → spin voltage

4. ... can be transformed into electrical voltage, generators, etc. *without magnets*

"This opens a door to the new field of fluid spintronics"

(also an existence proof of $\vec{\omega} \leftrightarrow \vec{P}$ connection)



Subatomic spintronics

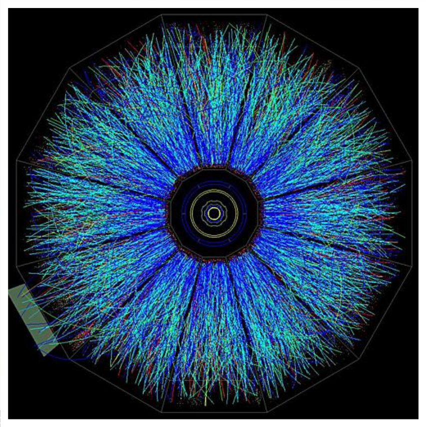
Barnett, Einstein-de Haas, Takahashi $\vec{P} \propto \vec{\omega}$

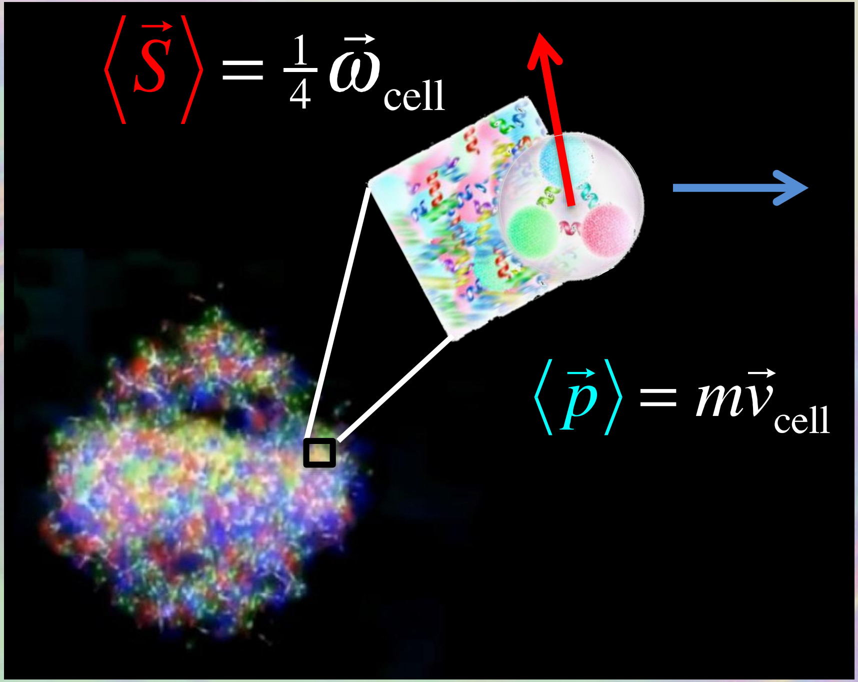
straightforward to measure both

Our experimental situation is a little tougher...

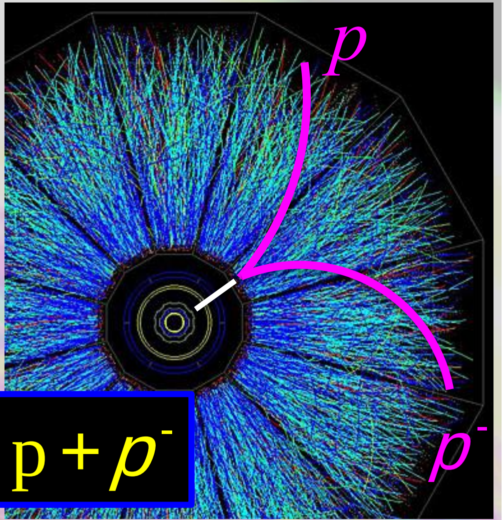
1. how to measure polarization?
2. what is the *direction* of the vorticity?

...but we benefit from their validation of the connection



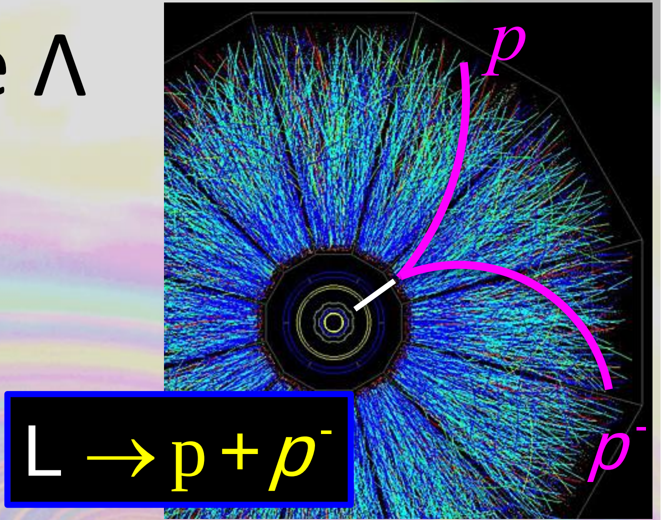


They had the electron, we have Λ



$\Lambda \rightarrow p + \pi^-$

They had the electron, we have Λ



Lambdas are "self-analyzing"

- reveal polarization by preferentially emitting daughter proton in spin direction

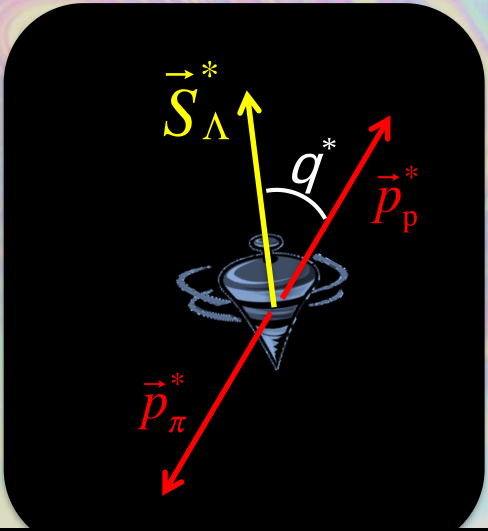
For an ensemble of Λs with polarization $\vec{P}$:

$$\frac{dW}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\vec{P}\cdot\hat{p}_p^*\right) = \frac{1}{4\pi}\left(1+\alpha P\cos\theta^*\right)$$

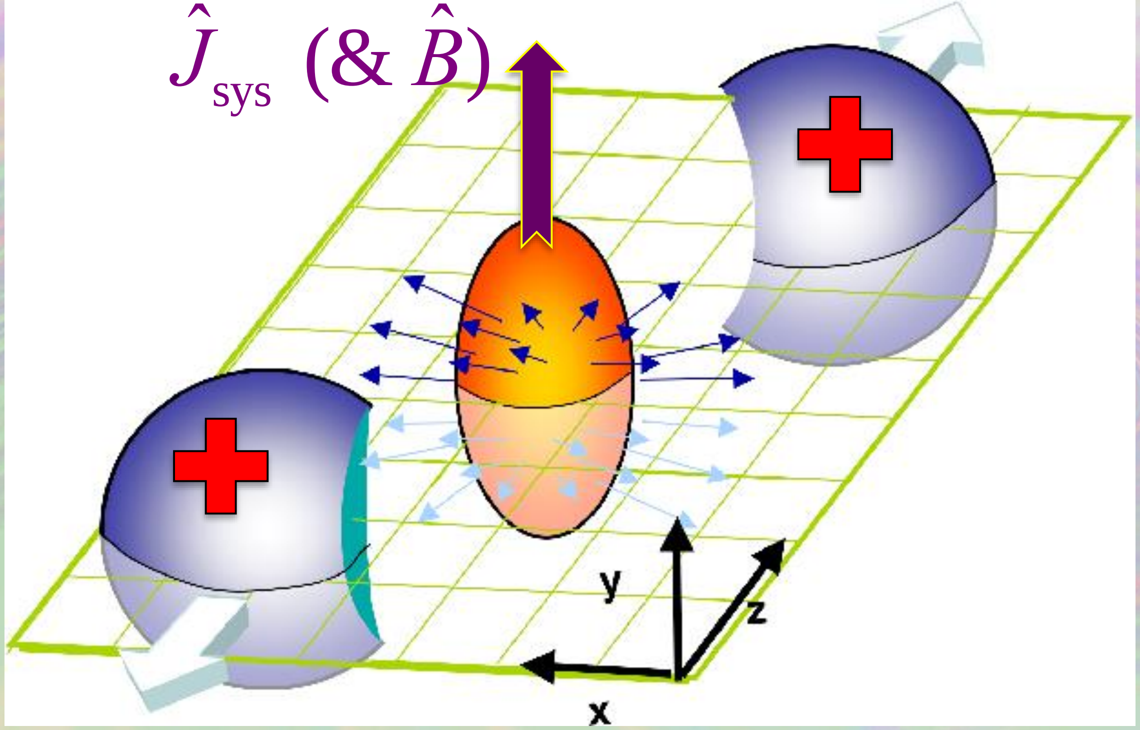
$\alpha = 0.642$ [measured]

$\hat{p}_p^*$ is daughter proton momentum direction *in* Λ *frame*

$0 < |\vec{P}| < 1$: $\quad \vec{P} = \frac{3}{\alpha}\overline{\hat{p}_p^*}$



Global polarization – alignment of $\vec{P}$ with $\hat{J}_{sys}$

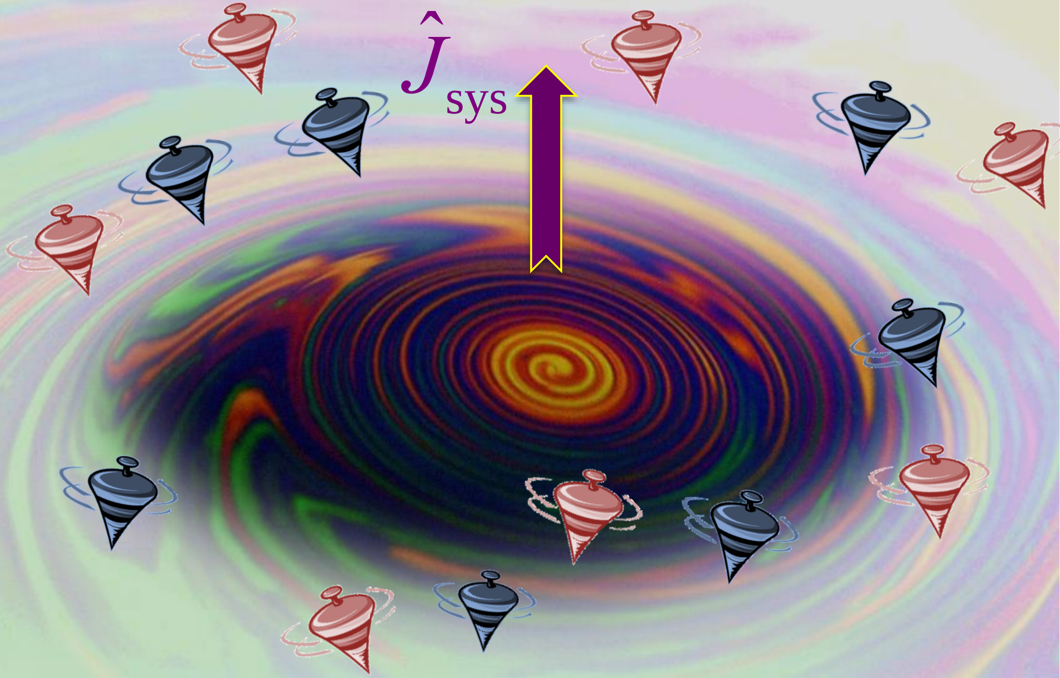


estimated with first-order flow

Global polarization

Vortical coupling: $P \propto \omega$

$\bar{\vec{P}}_{\Lambda} \,||\, +\hat{J}_{sys}$ $\bar{\vec{P}}_{\bar{\Lambda}} \,||\, +\hat{J}_{sys}$



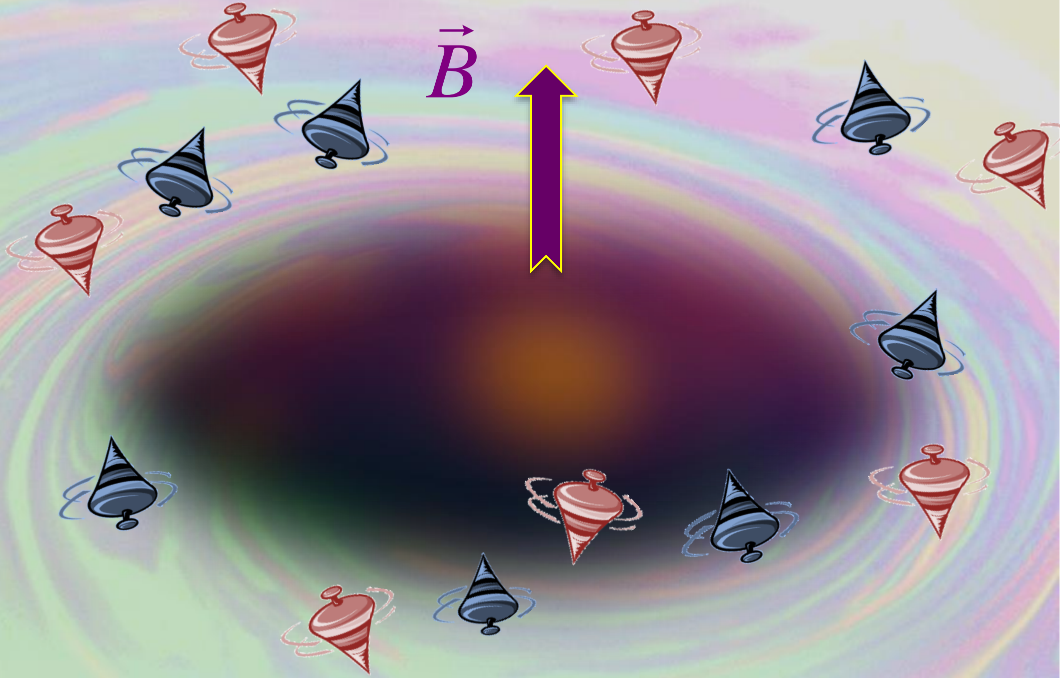
Global polarization

Vortical coupling: $P \propto \omega$

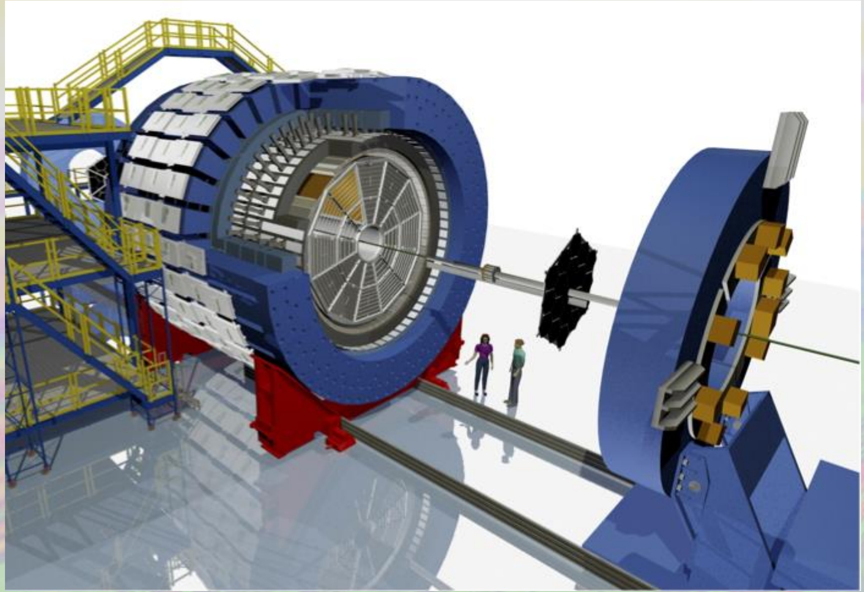
$$\vec{\bar{P}}_{\Lambda} \parallel +\hat{J}_{sys} \qquad \vec{\bar{P}}_{\bar{\Lambda}} \parallel +\hat{J}_{sys}$$

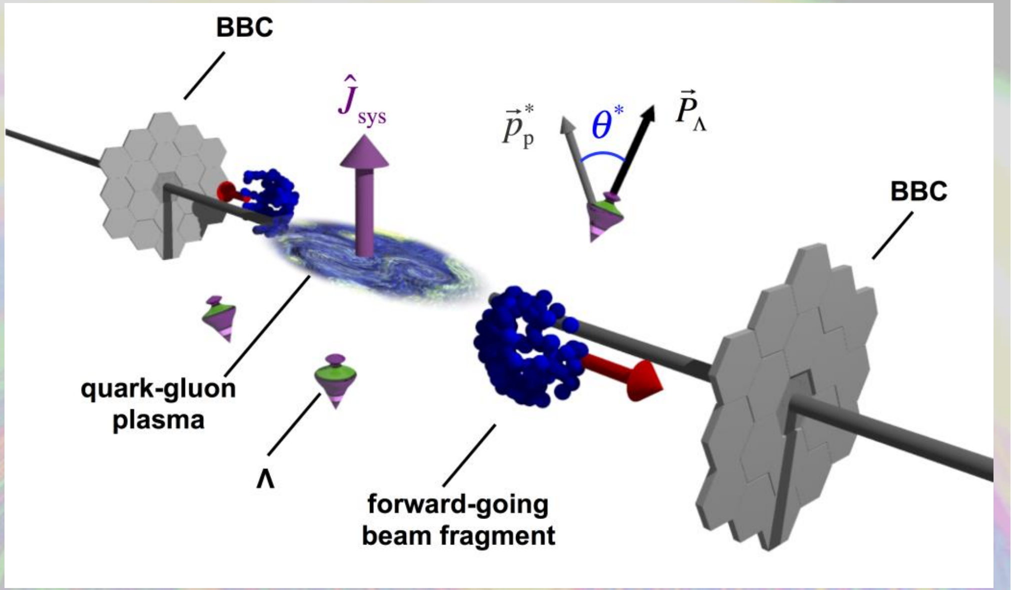
Magnetic coupling: $P \propto \vec{\mu} \cdot \vec{B}$

$$\vec{\bar{P}}_{\Lambda} \parallel -\hat{J}_{sys} \qquad \vec{\bar{P}}_{\bar{\Lambda}} \parallel +\hat{J}_{sys}$$



Both effects may be active

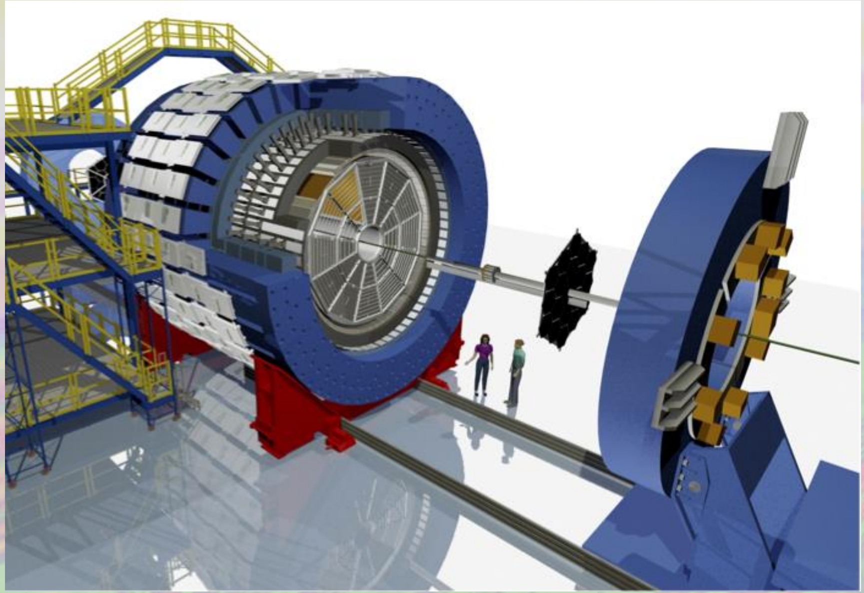


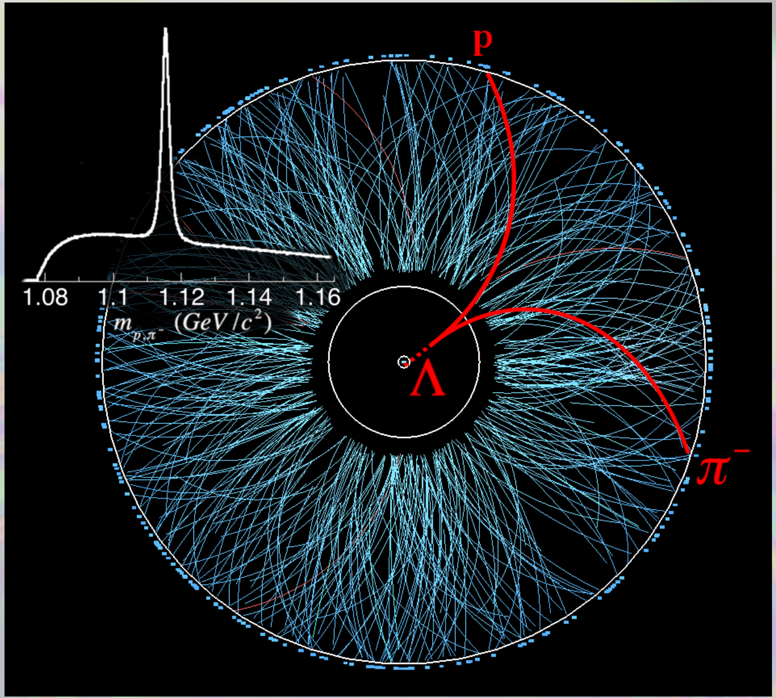


L, $\bar{\mathrm{L}}$ reconstructed in TPC+TOF for $|y|<1$

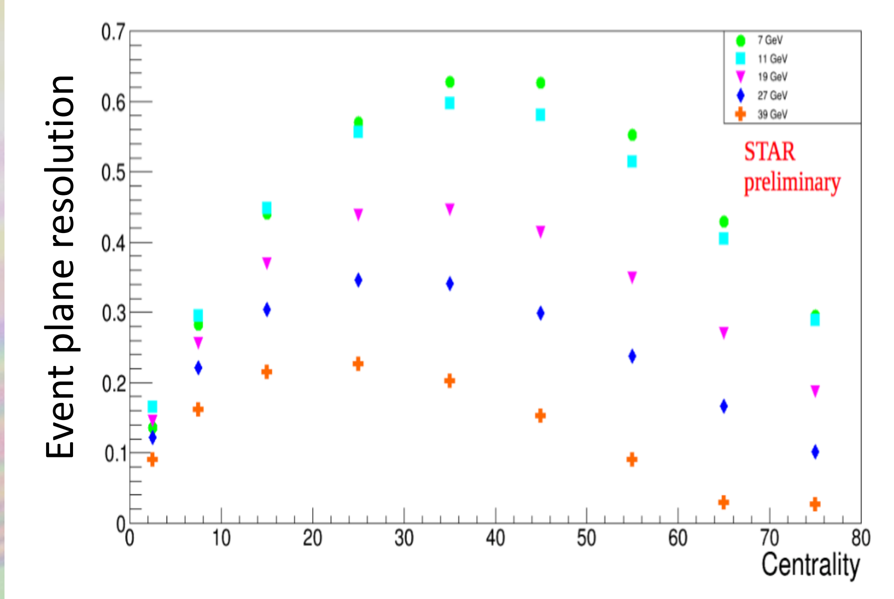
Forward BBCs estimate Reaction Plane: $\vec{B} \parallel \vec{\omega} \parallel \hat{J}_{sys}$

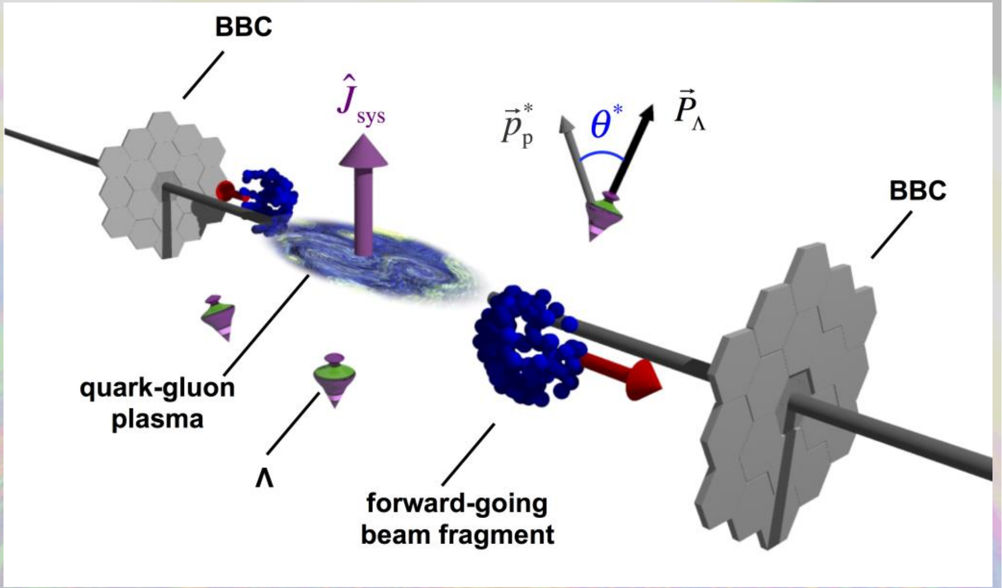
Our job: correlate $\vec{p}_p^{\,*}$ and $\hat{J}_{sys}$





$\Lambda, \bar{\Lambda}$ reconstructed in TPC+TOF for $|y|<1$





Statistics-limited: average polarization, $\bar{P}_{\mathrm{H}} \equiv \int d\vec{\beta}_\Lambda \frac{dN}{d\vec{\beta}_\Lambda} \vec{P}\left(\vec{\beta}_\Lambda\right) \cdot \hat{J}_{\mathrm{sys}}$

$\bar{P}_{\mathrm{H}} = \frac{8}{\pi\alpha} \frac{\langle \sin(\phi_{\mathrm{p}}^{*} - \Psi_{\mathrm{EP}}^{(1)}) \rangle}{R_{\mathrm{EP}}^{(1)}}$ where average is over events & Λs

$\Psi_{\mathrm{EP}}^{(1)}$ is the first-order event plane (from BBCs)

$R_{\mathrm{EP}}^{(1)}$ is the first-order event plane resolution

Event-plane resolution

- best for mid-central collisions
- significantly worse at higher energy
- errorbars $d\bar{P}_{\mathrm{H}} \; \mu \left(R_{\mathrm{EP}}^{(1)} \sqrt{\# \mathrm{L}} \right)^{-1}$

First global polarization signal

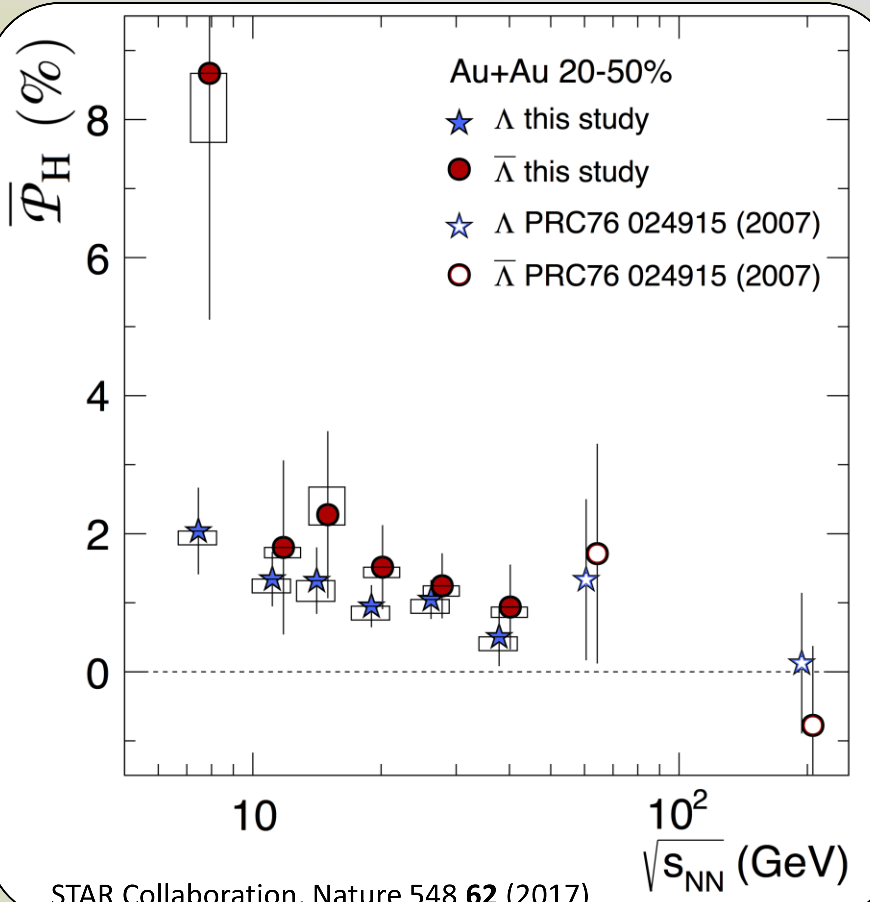
- Systematic uncertainty (dominated by combinatoric background) small relative to statistical uncertainty
- vortical coupling dominant

$$\bar{P}_{\Lambda} \gg \bar{P}_{\bar{\Lambda}} > 0$$

- tantalizing suggestion (but no claim!) of additional magnetic coupling

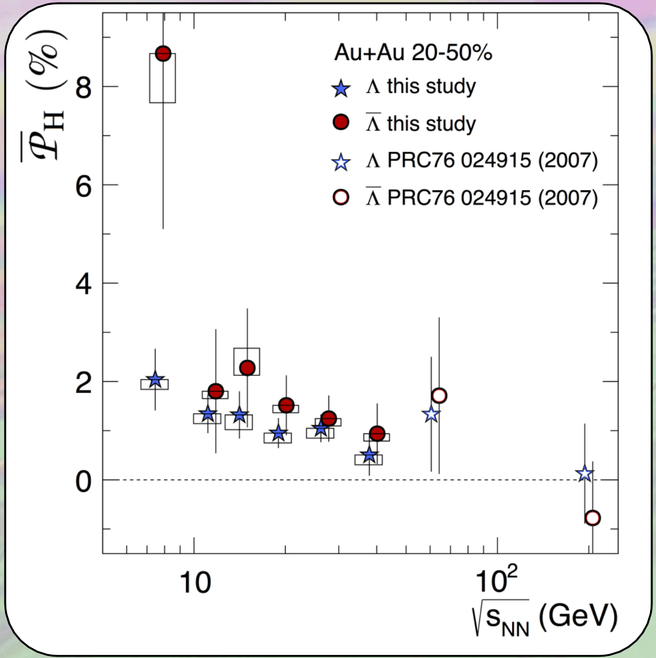
$$\bar{P}_{\bar{\Lambda}} > \bar{P}_{\Lambda} \quad ???$$

- Signal falls with energy (large errorbars...)
  - previous “null” result in line with trend



STAR Collaboration, Nature 548 **62** (2017)

Extracting vorticity and magnetic field



Magneto-hydro equilibrium interpretation

$$\text{Prob} \sim \exp\left(-E/T + \mu_B B/T + \vec{\omega}\cdot\vec{S}/T + \vec{\mu}\cdot\vec{B}/T\right)$$

for small polarization: $P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$ $\quad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$

vorticity from sum: $\frac{\omega}{T} = P_\Lambda + P_{\bar{\Lambda}}$

B-field from difference: $\frac{B}{T} = \frac{1}{2\mu_\Lambda}\left(P_{\bar{\Lambda}} - P_\Lambda\right)$

(here $\mu_\Lambda = |\mu_\Lambda|$)

Becattini, Karpenko, ML, Upsal, Voloshin PRC95 (2017) 054902

Feed-down complication

- Most of our Lambdas are not emitted directly from the plasma.
- Significant feed-down from (polarized) parents complicates the picture
- Still a linear relationship (for small polarization)

Becattini, Karpenko, ML, Upsal, Voloshin PRC95 (2017) 054902

$$\begin{pmatrix} \frac{\omega}{T} \\ \frac{B}{T} \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R}C_{\Sigma^0 R}\right) S_R\left(S_R+1\right) & \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3} f_{\Sigma^0 R}C_{\Sigma^0 R}\right)\left(S_R+1\right)\mu_R \\ \frac{2}{3}\sum_{\bar{R}} \left(f_{\bar{\Lambda}\bar{R}}C_{\bar{\Lambda}\bar{R}} - \frac{1}{3} f_{\bar{\Sigma}^0 \bar{R}}C_{\bar{\Sigma}^0 \bar{R}}\right) S_{\bar{R}}\left(S_{\bar{R}}+1\right) & \frac{2}{3}\sum_{\bar{R}} \left(f_{\bar{\Lambda}\bar{R}}C_{\bar{\Lambda}\bar{R}} - \frac{1}{3} f_{\bar{\Sigma}^0 \bar{R}}C_{\bar{\Sigma}^0 \bar{R}}\right)\left(S_{\bar{R}}+1\right)\mu_{\bar{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_{\Lambda}^{\text{meas}} \\ P_{\bar{\Lambda}}^{\text{meas}} \end{pmatrix}$$

overall, ~15% effect

$f_{\Lambda R}$ = fraction of Λs that originate from parent $R \to \Lambda$

$C_{\Lambda R}$ = coefficient of spin transfer from parent R to daughter Λ

$f_{\Sigma^0 R}$ = fraction of Λs that originate from parent $R \to \Sigma^0 \to \Lambda$

$C_{\Sigma^0 R}$ = coefficient of spin transfer from parent R to daughter Σ^0

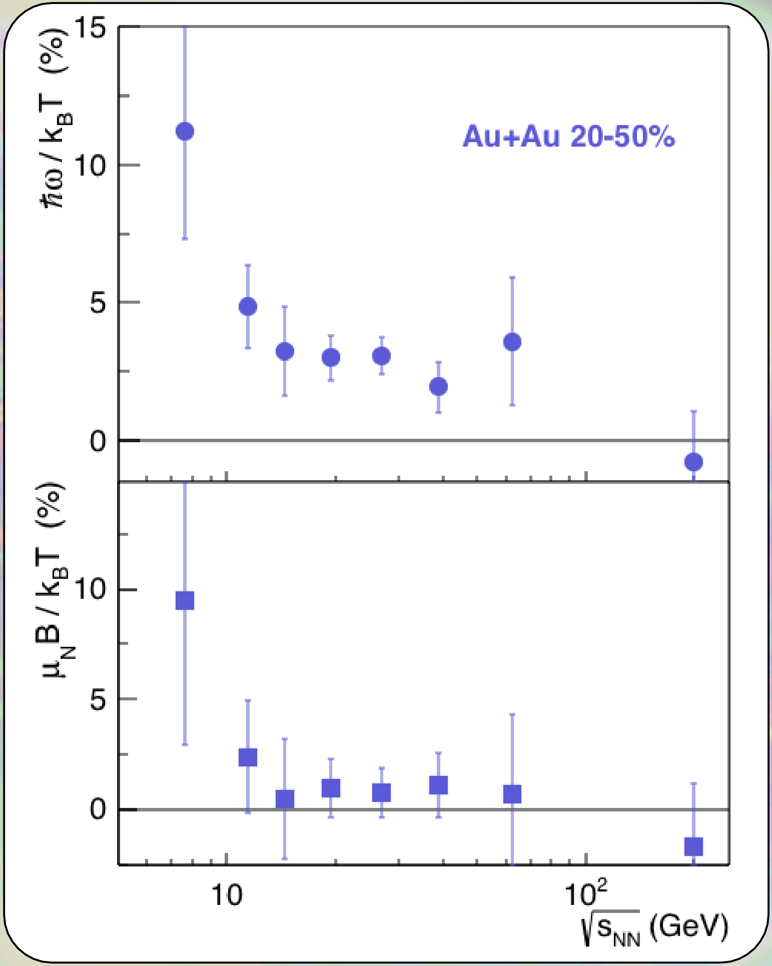
Extracted Physical Parameters

Significant vorticity signal

- $P_{\Lambda_{\text{primary}}} = \frac{w}{2T} \gg 5\%$
- (probably) falling with collision energy, despite increasing J_{sys}

Magnetic field

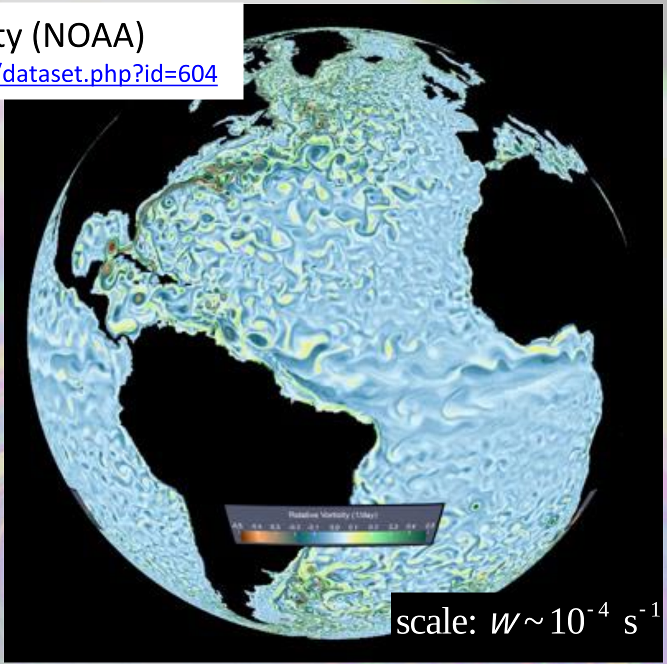
- positive value would be expected
- 2σ above zero, *averaged* over BES energies
- Higher statistics dataset for 27 GeV in run 2018 → hope for 5σ measurement

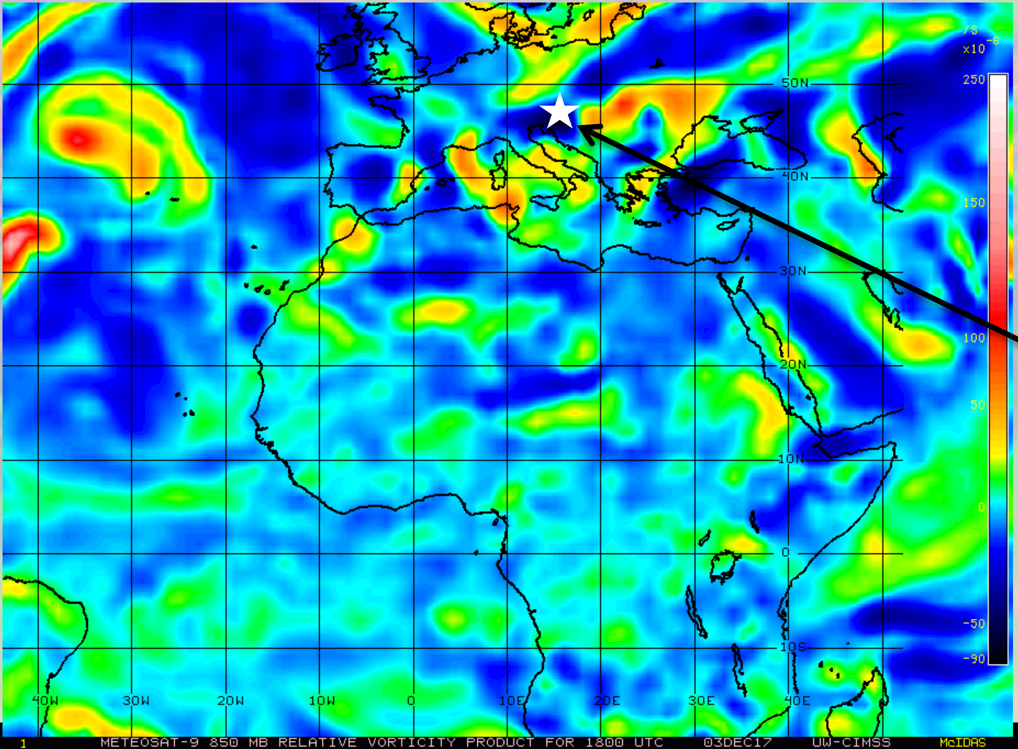


Perspective

- ocean flows: ω ~ 10^{-5} s^{-1}
- terrestrial atmosphere: ω ~ 10^{-4} s^{-1}

Ocean surface vorticity (NOAA)
http://sos.noaa.gov/Datasets/dataset.php?id=604





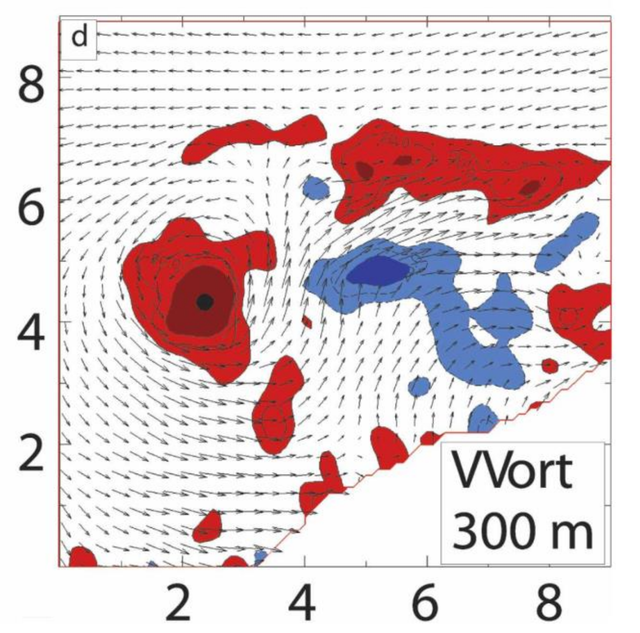
Budapest

zero

vorticity as of 21:00 yesterday (3 Nov 2017)
http://tropic.ssec.wisc.edu/real-time/europe/winds/wm7vor.GIF

Perspective

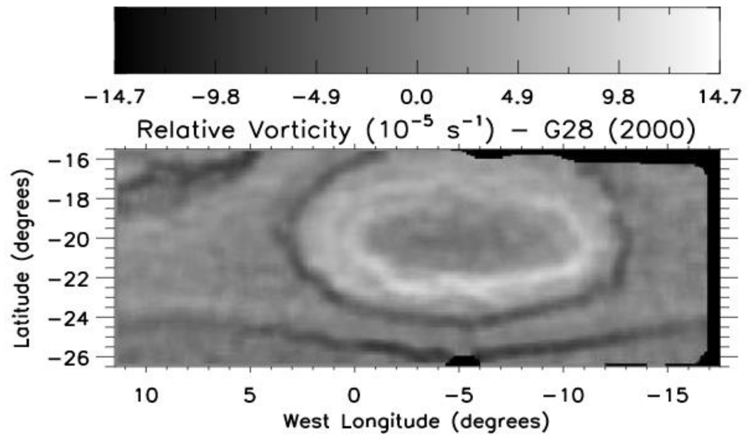
- ocean flows: $\omega \sim 10^{-5}\ s^{-1}$
- terrestrial atmosphere: $\omega \sim 10^{-4}\ s^{-1}$
- core of supercell tornado: $\omega \sim 10^{-1}\ s^{-1}$



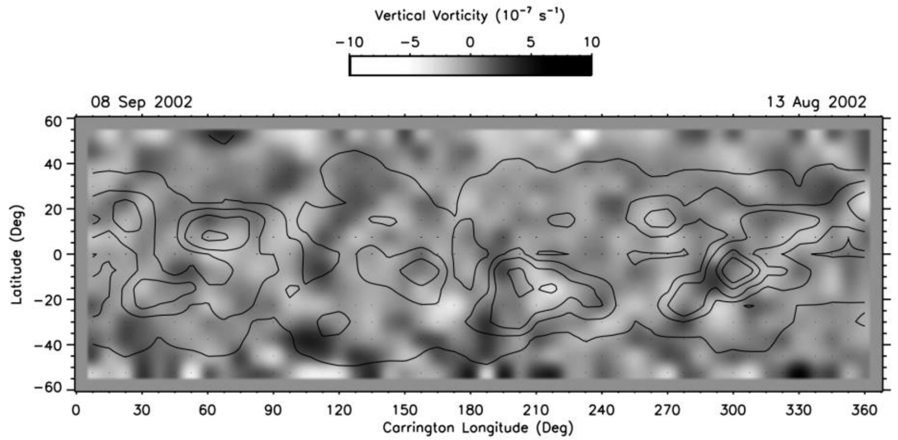
Dopper measurement of supercell tornado system tornado, 21 May 1998, Bridgeport, Nebraska
J. Wurman *et al.*, Mon. Weather Rev. 135, 2392 (2007)

Perspective

- ocean flows: $\omega \sim 10^{-5}\ s^{-1}$
- terrestrial atmosphere: $\omega \sim 10^{-4}\ s^{-1}$
- core of supercell tornado: $\omega \sim 10^{-1}\ s^{-1}$
- solar subsurface flow: $\omega \sim 10^{-6}\ s^{-1}$
- "Collar" of Jupiter's Great Red Spot: $\omega \sim 10^{-4}\ s^{-1}$



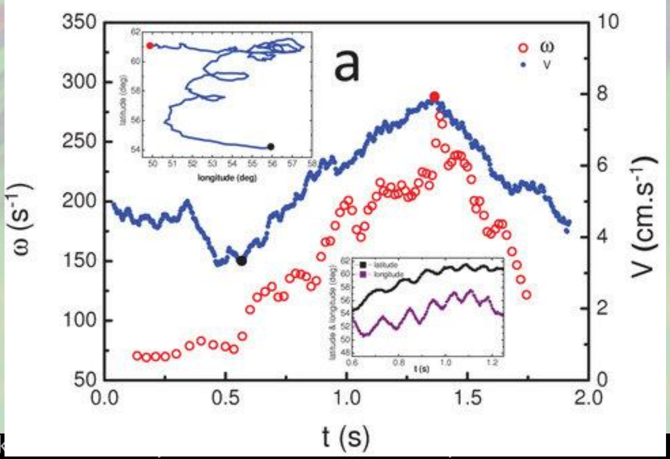
D. Choi et al, Icarus 188 (2007) 35

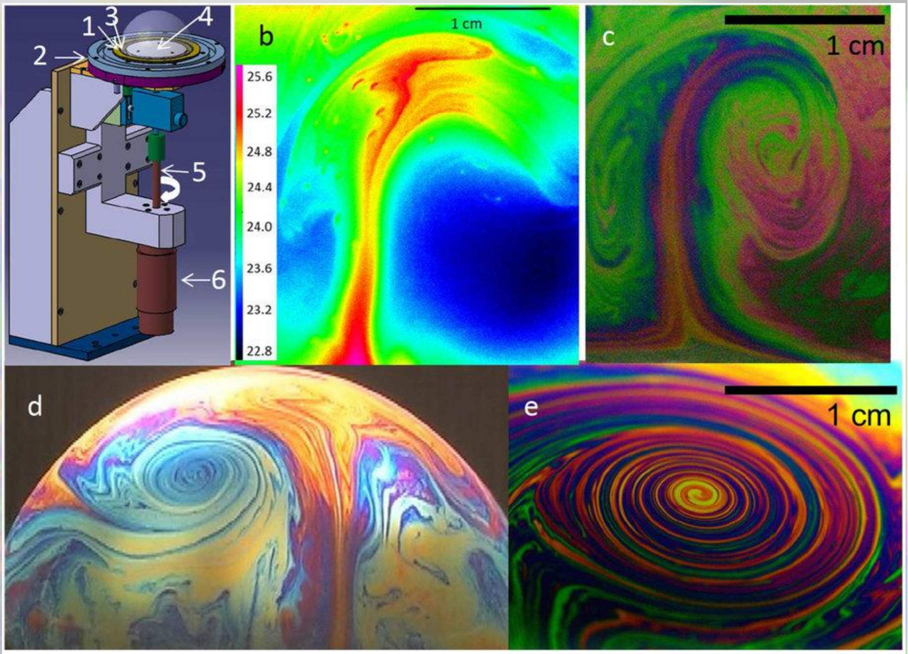


solar subsurface vorticity, 2002 R. Komm *et al.*, Astrophys. J. 667, 571 (2007)

Perspective

- ocean flows: ω ~ 10^{-5} s^{-1}
- terrestrial atmosphere: ω ~ 10^{-4} s^{-1}
- core of supercell tornado: ω ~ 10^{-1} s^{-1}
- solar subsurface flow: ω ~ 10^{-6} s^{-1}
- “Collar” of Jupiter’s Great Red Spot: ω ~ 10^{-4} s^{-1}
- Heated, rotating soap bubbles: ω ~ 10^{2} s^{-1}

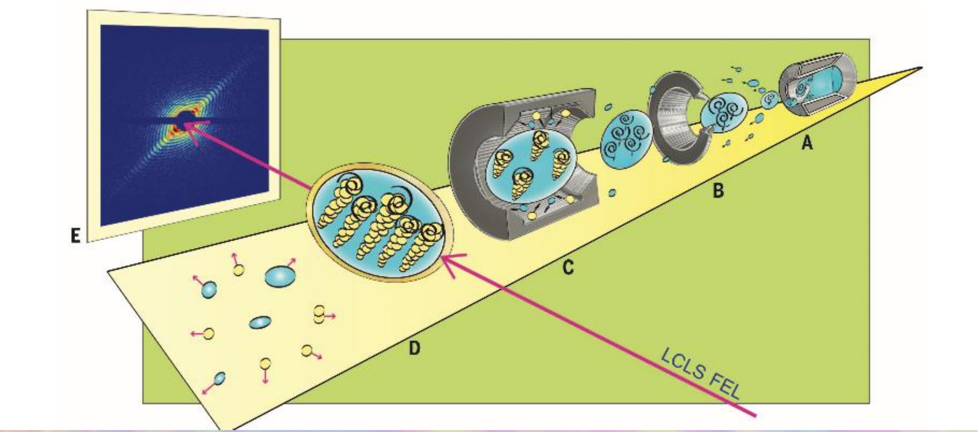


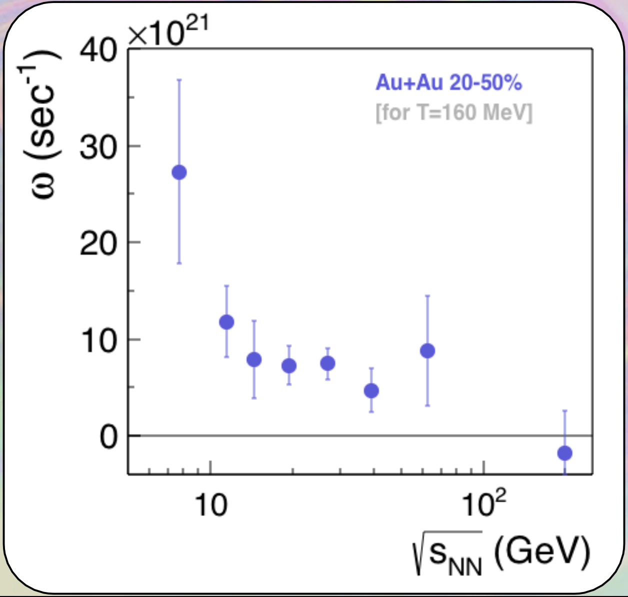


Intensity of vortices: from soap bubbles to hurricanes
T. Meuel, *et al*, (Nature) Scientific Reports **3** 3455 (2013)

World’s record

- ocean flows: ω ~ 10^{-5} s^{-1}
- terrestrial atmosphere: ω ~ 10^{-4} s^{-1}
- core of supercell tornado: ω ~ 10^{-1} s^{-1}
- solar subsurface flow: ω ~ 10^{-6} s^{-1}
- “Collar” of Jupiter’s Great Red Spot: ω ~ 10^{-4} s^{-1}
- Heated, rotating soap bubbles: ω ~ 10^{2} s^{-1}
- Max vorticity in bulk superfluid He-II: ω ~ 150 s^{-1}
  R. Donnelly, Ann. Rev. Fluid Mech. 25, 325 (1993)
- Max vorticity in nanodroplets of superfluid He-II: 10^{6} s^{-1}
  Gomez et al, Science 345 (2014) 903





Perfect for a jetlagged speaker...

- RHIC serves the perfect fluid

Perfect for a jetlagged speaker...

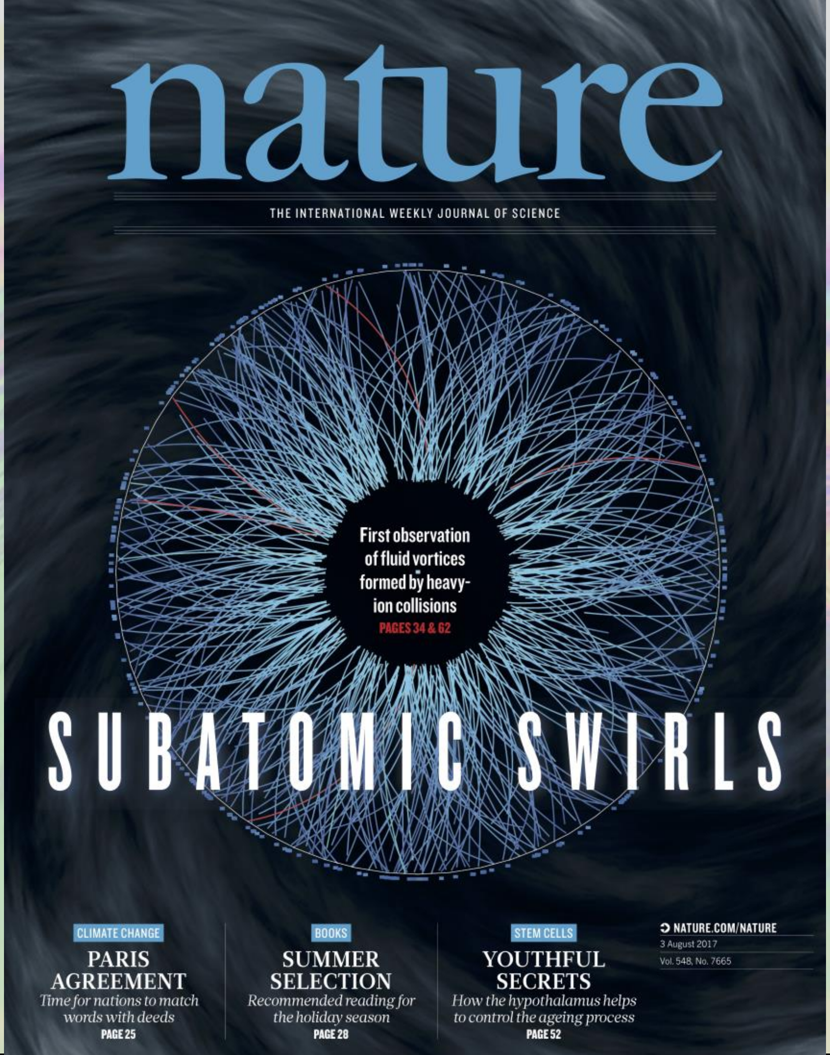
- RHIC serves the perfect fluid
- The hottest fluid in the universe

Perfect for a jetlagged speaker...

- RHIC serves the perfect fluid
- The hottest fluid in the universe
- The easiest-flowing fluid

Perfect for a jetlagged speaker...

- RHIC serves the perfect fluid
- The hottest fluid in the universe
- The easiest-flowing fluid
- The most vortical fluid


nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
First observation of fluid vortices formed by heavy-ion collisions
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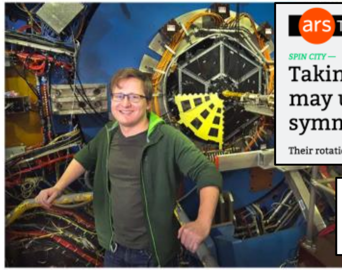
NATURE.COM/NATURE
3 August 2017
Vol. 548, No. 7665

Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174

'Perfect Liquid' Quark-Gluon Plasma is the Most Vortical Fluid

Swirling soup of matter's fundamental building blocks spins ten billion trillion times faster than the most powerful tornado, setting new record for "vorticity"

August 2, 2017



Ohio State University graduate student Isaac Upsal helped lead the analysis of results from the STAR detector that revealed a "vorticity" record for the quark-gluon plasma created in collisions at the Relativistic Heavy Ion Collider (RHIC).

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World's Fastest-Swirling Vortex Simulates the Big Bang

ars TECHNICA

SPIN CITY —

Taking quark-gluon plasma for a spin may un-break a fundamental symmetry

Their rotations may tell us fundamental things about quantum chromodynamics.

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PUBLIC RELEASE: 2-AUG-2017

'Perfect liquid' quark-gluon plas[ma …] most vortical fluid

Futurity

Science and Technology

Fluid spins trillions of times faster than

The Telegraph India

Wednesday , August 9 , 2017

PHYS ORG

Home » Physics » Plasma Physics » August 2, 2017

'Perfect liquid' quark-gluon plasma is the most vortical fluid

August 2, 2017

INSIDE SCIENCE — Reliable news for an expanding universe

CREATURE CULTURE EARTH HUMAN PHYSICS SPACE SPORTS TECHNOLOGY

Primordial particle soup smashes spin-speed record

Physicists discover the universe's most violent vortices inside the exotic state of matter.

下一篇4　2017年08月04日　星期五　放大　缩小

夸克胶子等离子体"整体极化"理论获证

最新发现与创新

科技日报济南8月3日电　（记者王延斌　通讯员车慧卿）宇宙在最初诞生[的…]万分之几秒内以"夸克胶子等离子体"的形式存在，这种类似"电浆"的状态[被认]为是固体、液体、气体之后的第四种物质形态。近日，我国科学家首次提出的

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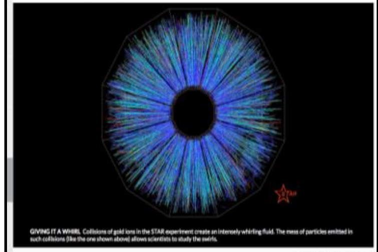
Smashing gold ions creates most swirly fluid ever

Record-making vorticity found in quark-gluon plasma

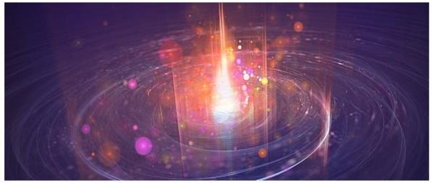


Spektrum.de

Der schnellste Wirbel des Universums?

Den schnellsten bisher gemessenen Wirbel erzeugten Physiker in einem Teilchenbeschleuniger. Die Flüssigkeit ist dabei ein Plasma aus fundamentalen Teilchen: Quarks und Gluonen.

von Manon Bischoff



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INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 57 NUMBER 9 NOVEMBER 2017

HEAVY IONS

Fastest spinning fluid clocked by RHIC

Experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory have found that droplets of quark–gluon plasma (QGP) can spin faster than any other fluid. The immensely hot and fast-expanding QGP is already known to behave as a near "perfect" liquid, exhibiting a viscosity lower than any other. Now, researchers on RHIC's STAR experiment report that the vorticity (or curl) of the fluid produced in RHIC's relativistic heavy-ion collisions is about $9\times10^{21}\,s^{-1}$. That exceeds

Edition: India

newsR

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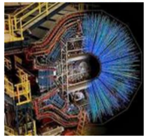
Science Technology Computer Industry

Perfect liquid quark-gluon plasma is the most vortical fluid

ENERGY DAILY — the power of earth and beyond

Friday, 4 August 2017 (22 days ago)

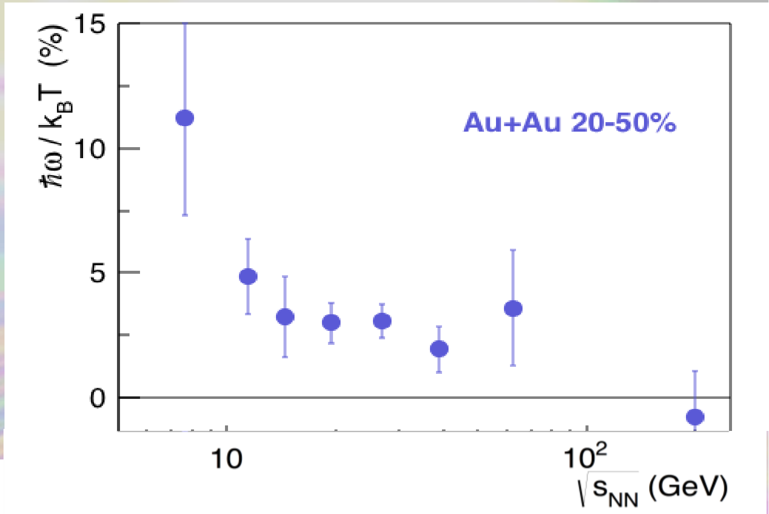


Upton, NY (SPX) Aug 03, 2017

Particle collisions recreating the quark-gluon plasma (QGP) that filled the early universe reveal that droplets of this primordial soup swirl far faster than any other fluid. The new analysis of data from the Relativistic Heavy Ion Collider (RHIC) - a U.S. Department of Energy Office of Science User Facility for nuclear physics research at Brookhaven National Laboratory -

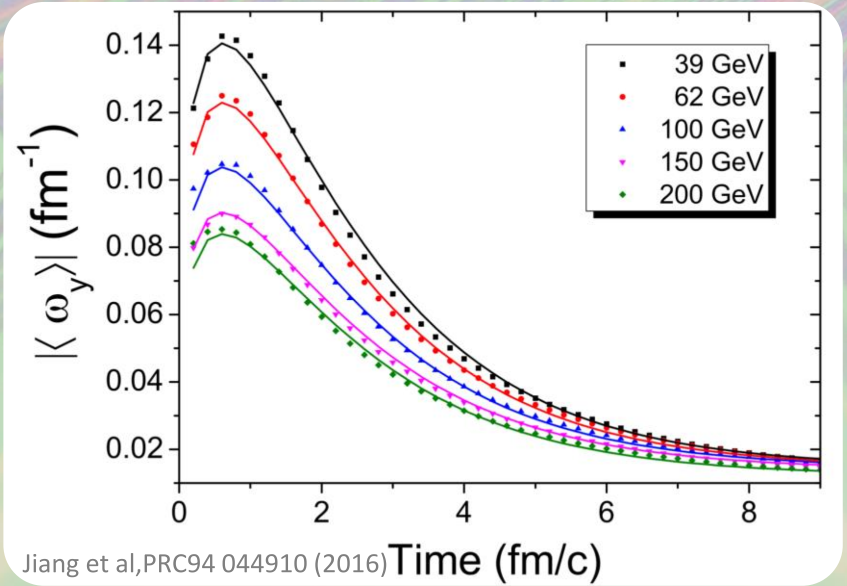
BUT SERIOUSLY

Vorticity ~ theory expectation



Thermal vorticity ω/T = 2-10%
→ ω = 0.02-0.09 fm^{-1} (T_{assume}=160 MeV)

Magnitude, √s-dep in range of transport &
3D viscous hydro calculations with rotation



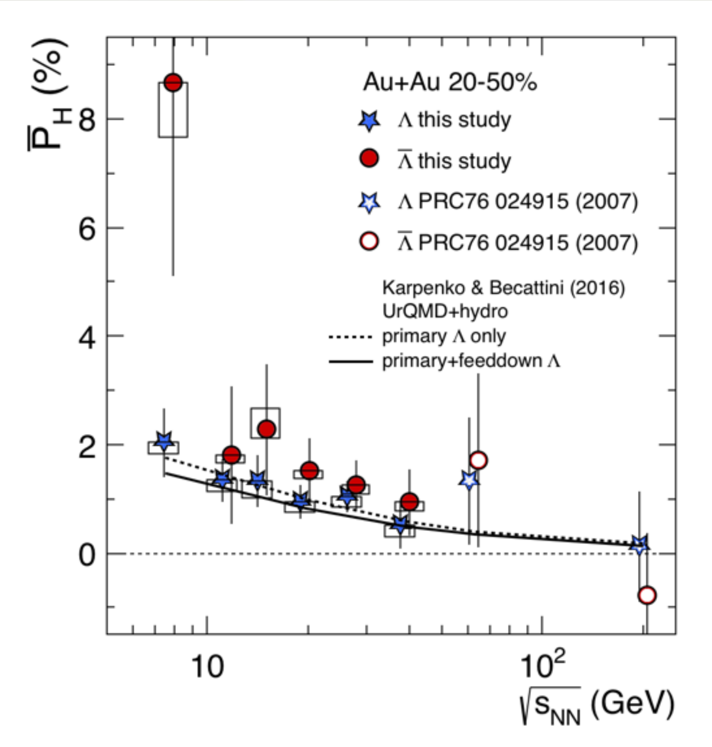
Jiang et al,PRC94 044910 (2016)

TABLE I. Time dependence of average vorticity projected to the reaction plane for heavy-ion reactions at the NICA energy of $\sqrt{s_{NN}} = 4.65 + 4.65$ GeV.

t (fm/c)	Vorticity (classical) (c/fm)	Thermal vorticity (relativistic) (1)
0.17	0.1345	0.0847
1.02	0.1238	0.0975
1.86	0.1079	0.0846
2.71	0.0924	0.0886
3.56	0.0773	0.0739

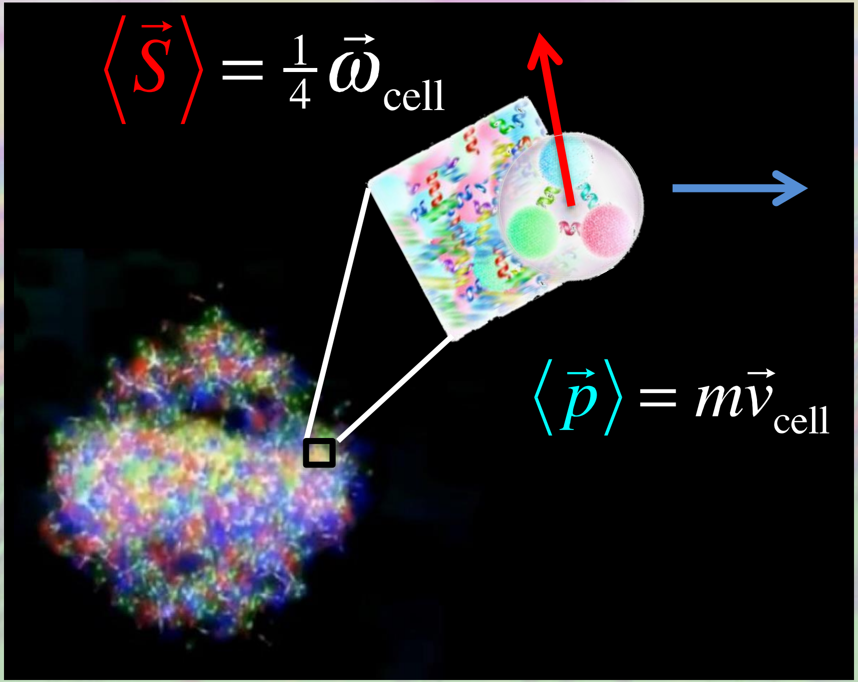
Direct comparison with 3D calculation

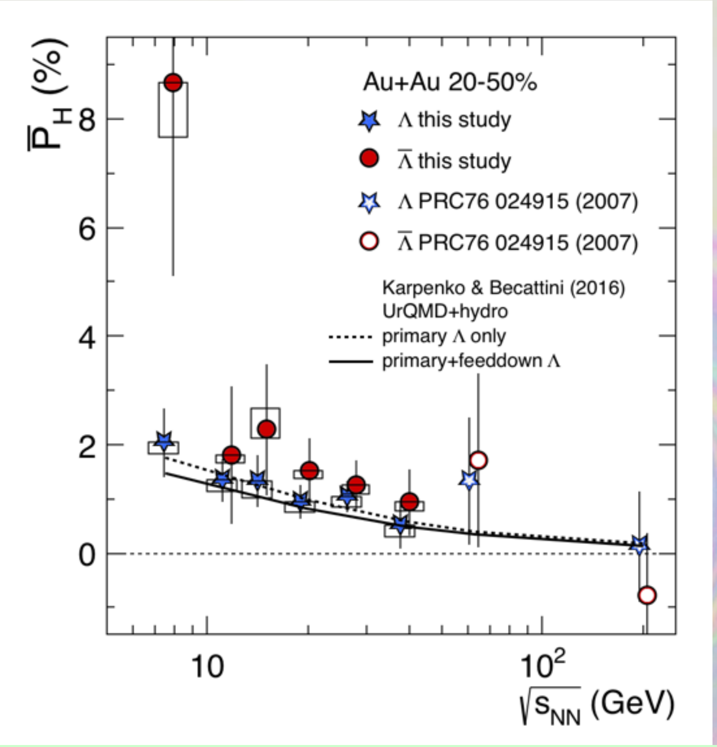
- UrQMD (lumpy conditions) + hydro
- matching & evolution parameters tuned to reproduce dN/dη, dN/p_T, v_2 (*not* ω)
- strong dependence on lumpiness of initial conditions given by UrQMD



Theory: Karpenko & Becattini, EPJ C77 (2017) 213; 1610.04717

A key take-away





This is a stunning success and validation of the hydro paradigm underlying our understanding of heavy ion collisions. The substructure of the prediction is being tested at a much finer level than "just" anisotropy of the momentum distribution

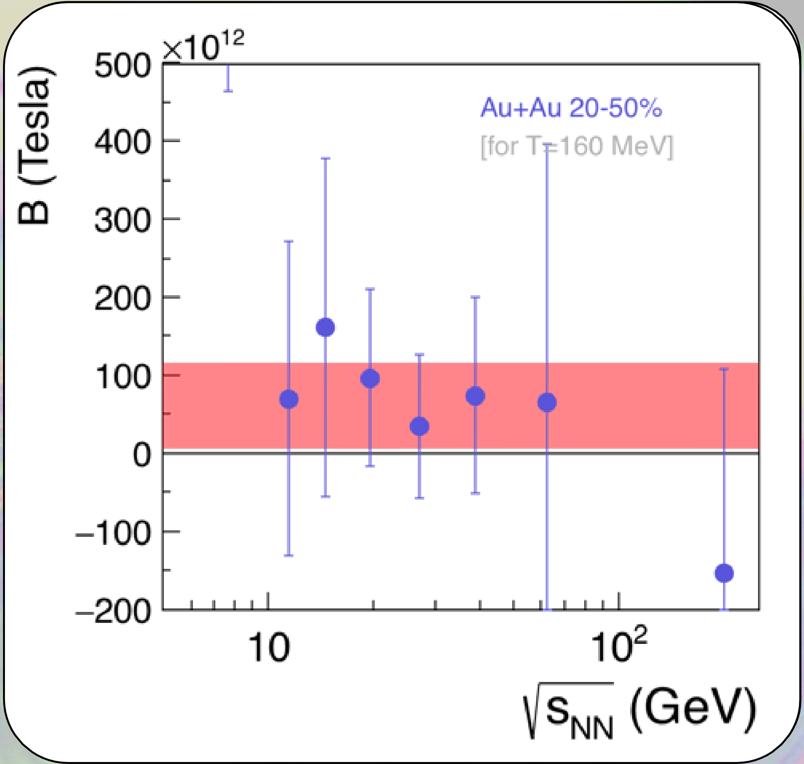
Magnetic field?

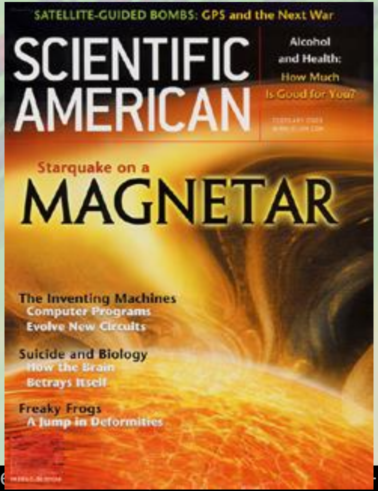
- Statistical uncertainties preclude claim
- B should change with energy, but...

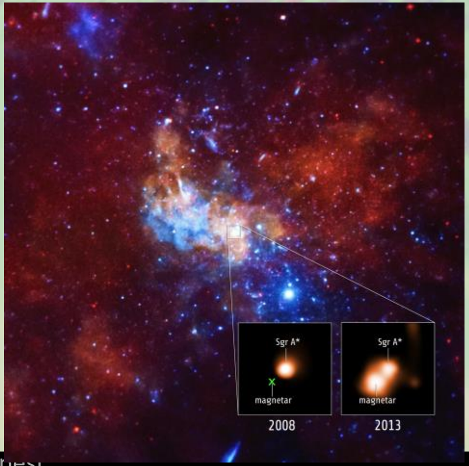
$$\langle B \rangle_{\sqrt{s}} = 6.0 \pm 5.5 \times 10^{13}\ \mathrm{T}$$

- Highest fields in the known universe:

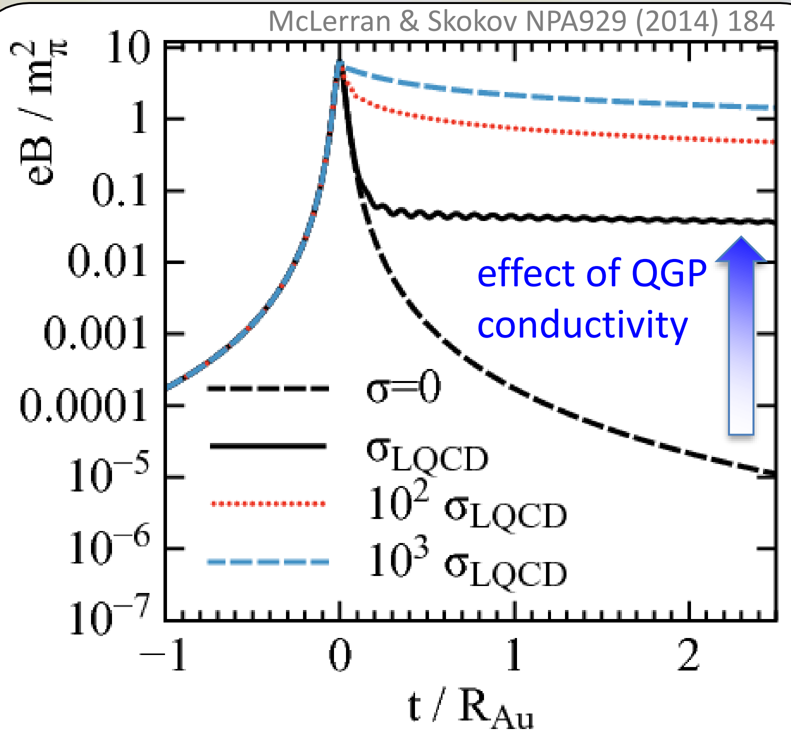
  Magnetars ~ 10^{10}-10^{11} T



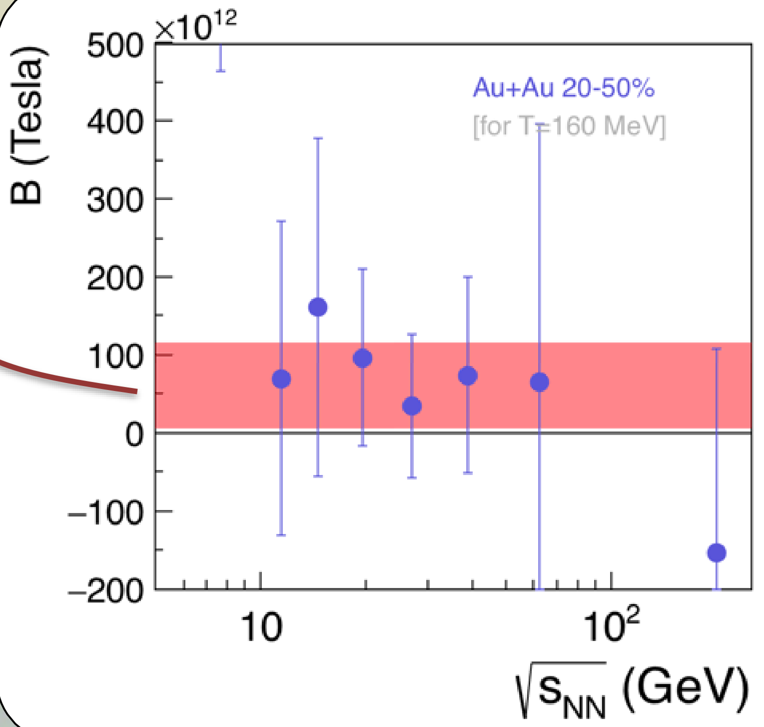




McGill Online Magnetar Catalog: ApJS 212 (2014)
http://www.physics.mcgill.ca/~pulsar/magnetar/main.html



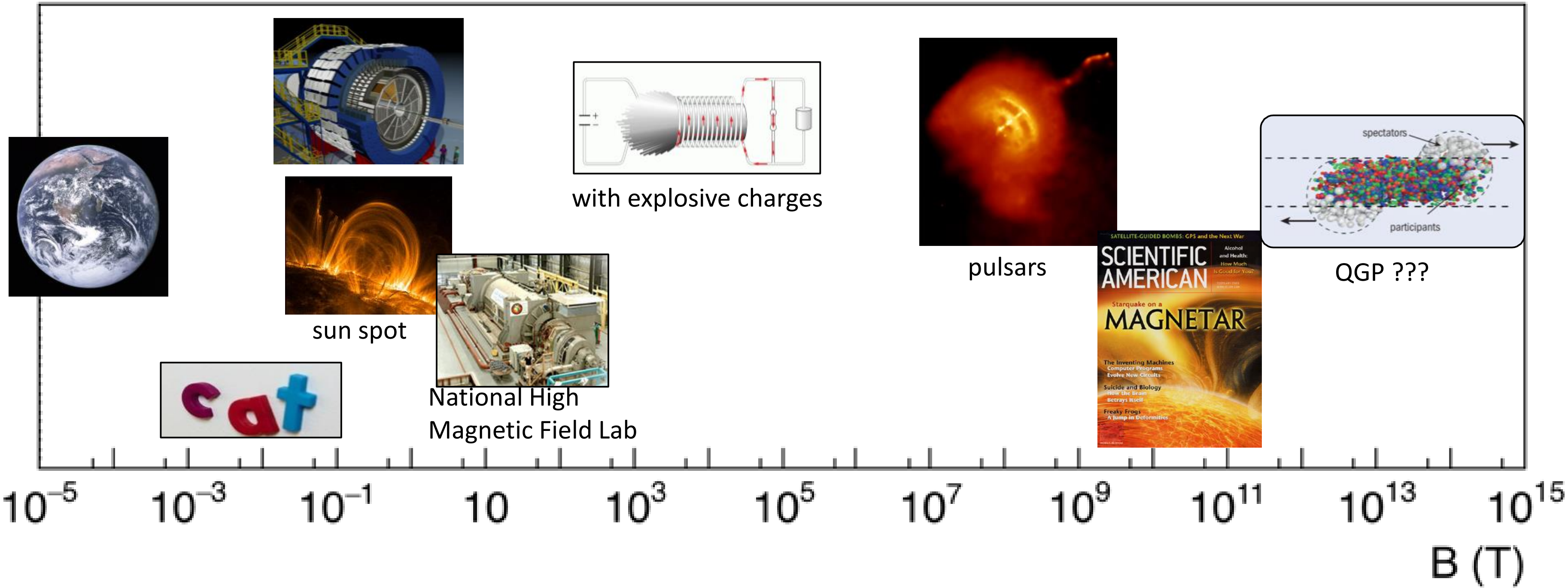
Predicted time-dependent B-field



- Lifetime of extreme magnetic fields may be greatly enhanced by QGP conductivity (Lenz's Law)
- (High-stats) polarization measurements may provide a unique probe

$m_p^2 / e \approx 10^{14}$ T

Magnetic Fields

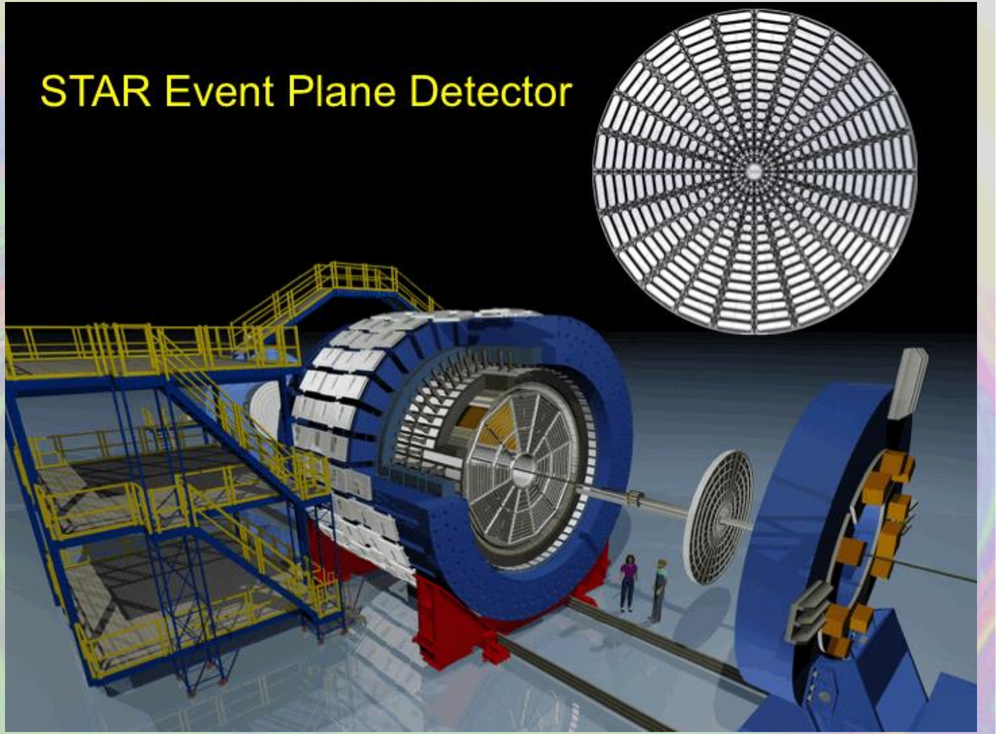


Coming up

- ω & B : of very high interest to the field
    - model substructure
    - dedicated workshops
    - novel QCD effects (CME, CVE)

- Based on this discovery, BNL approved 2 weeks dedicated running in 2018
    - further exploration in 2019+

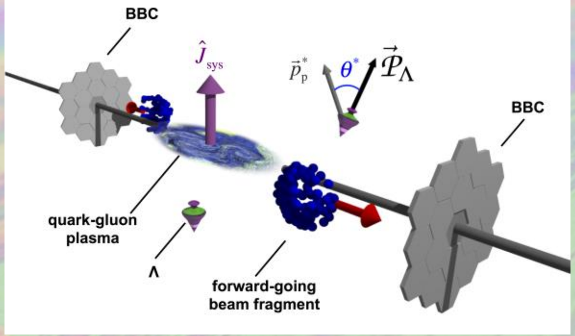
- STAR upgrade detector – EPD
    - project led & built by Ohio State
    - significant improvement on $\hat{J}$ resolution

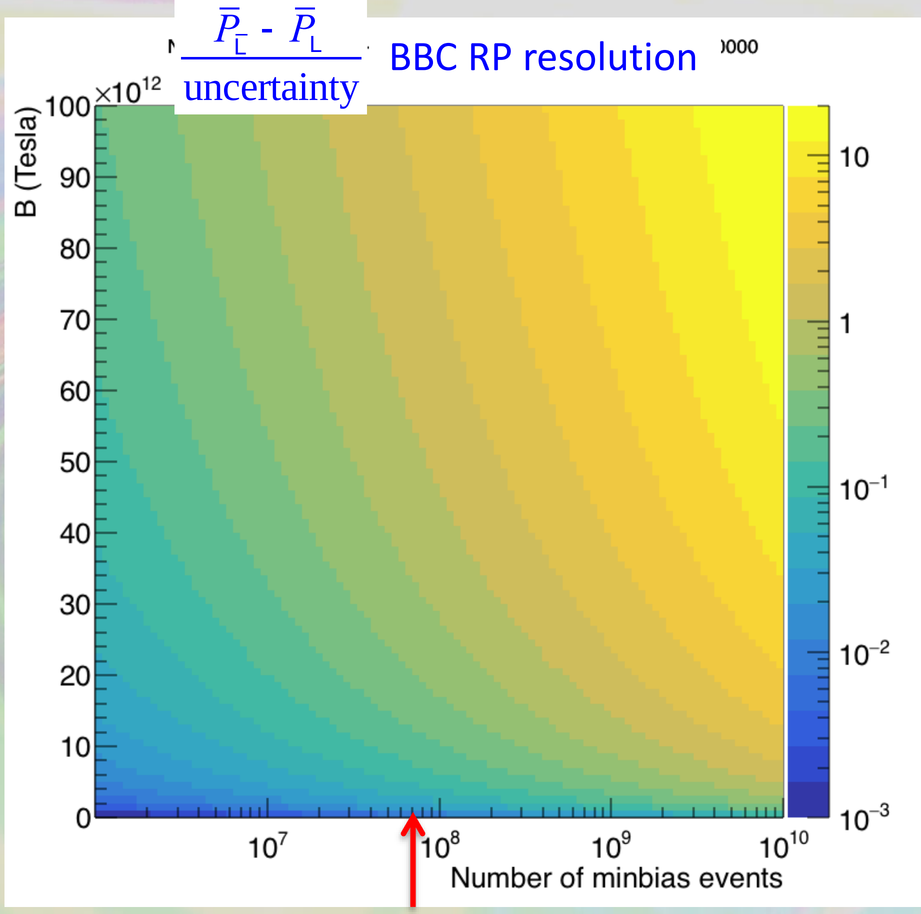


Magnetic splitting? 2018 run at 27 GeV

Expect fields ~ 5x10^{13} T (for how long?)

BES-I: 67x10^{6} min. bias events with BBC





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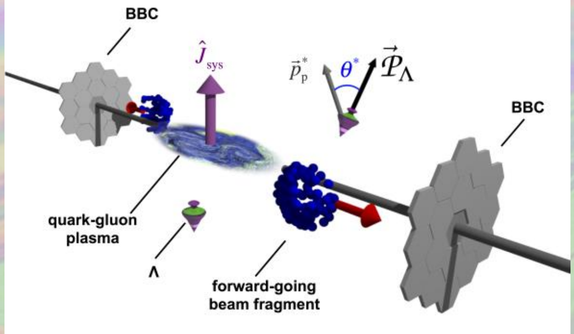
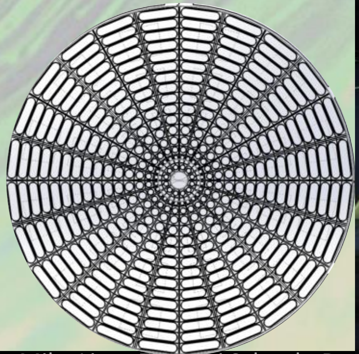
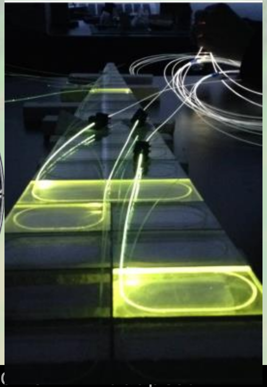
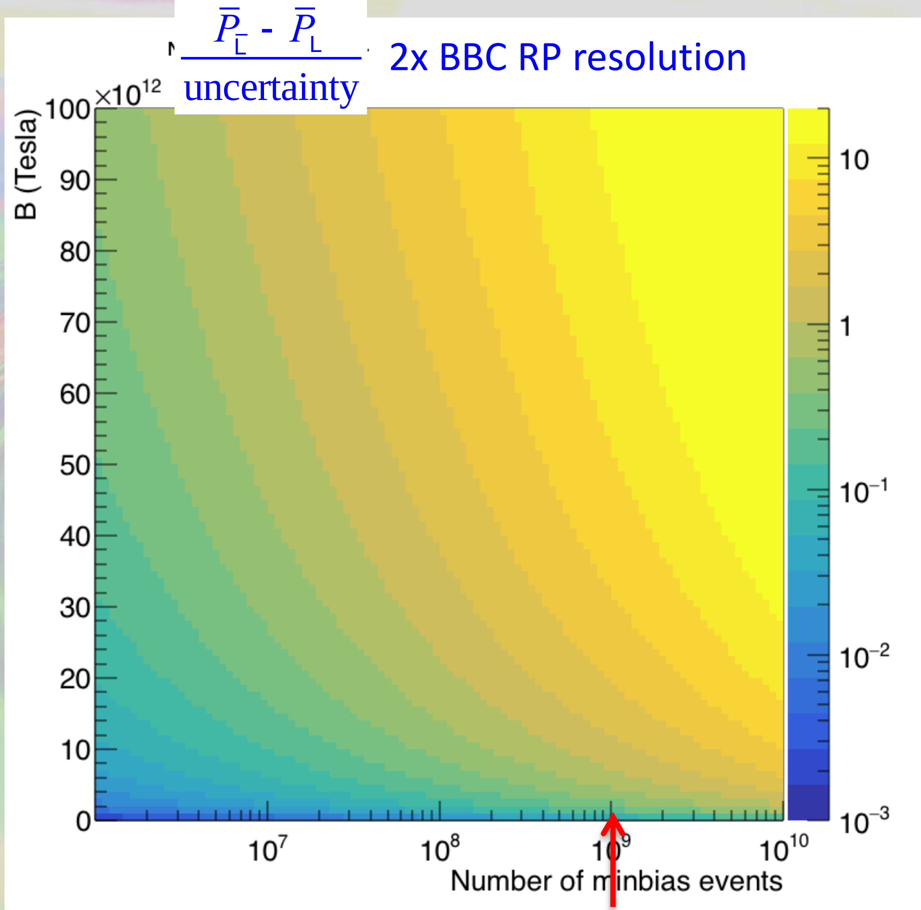


2018 : 10^{9} events & detector upgrade







Summary

- First observation of global polarization by STAR@RHIC
- Interpretation in magnetic-vortical model:
  - clear vortical component of expected sign & magnitude for BES energies
  - magnetic component consistent with zero, but tantalizing hint that STAR pursues in 2018 & BES-II
- stunning success/validation of hydro picture
  - subjected to unique probe of substructure considerably finer than previously achieved
  - much more can be done to probe substructure of the substructure
- non-central H.I. collisions create most vortical fluid observed to date
  - generated by early shear viscosity, persists through low viscosity

- Vorticity & B-field crucial elements to validate/calibrate high-profile CME & CVE measurements @ RHIC

THANKS FOR YOUR ATTENTION