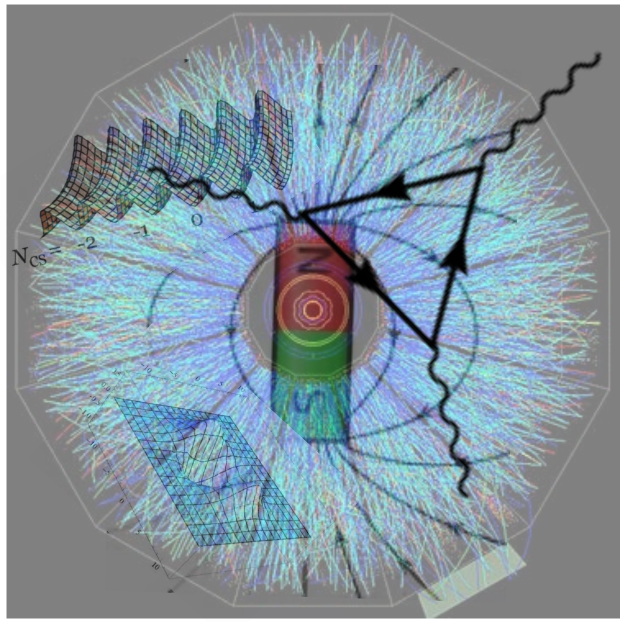
Colloquium @ Physics Department, BNL   Mar 29th

Quark-Gluon Plasma: An Old & New Phase of Quantum Matter



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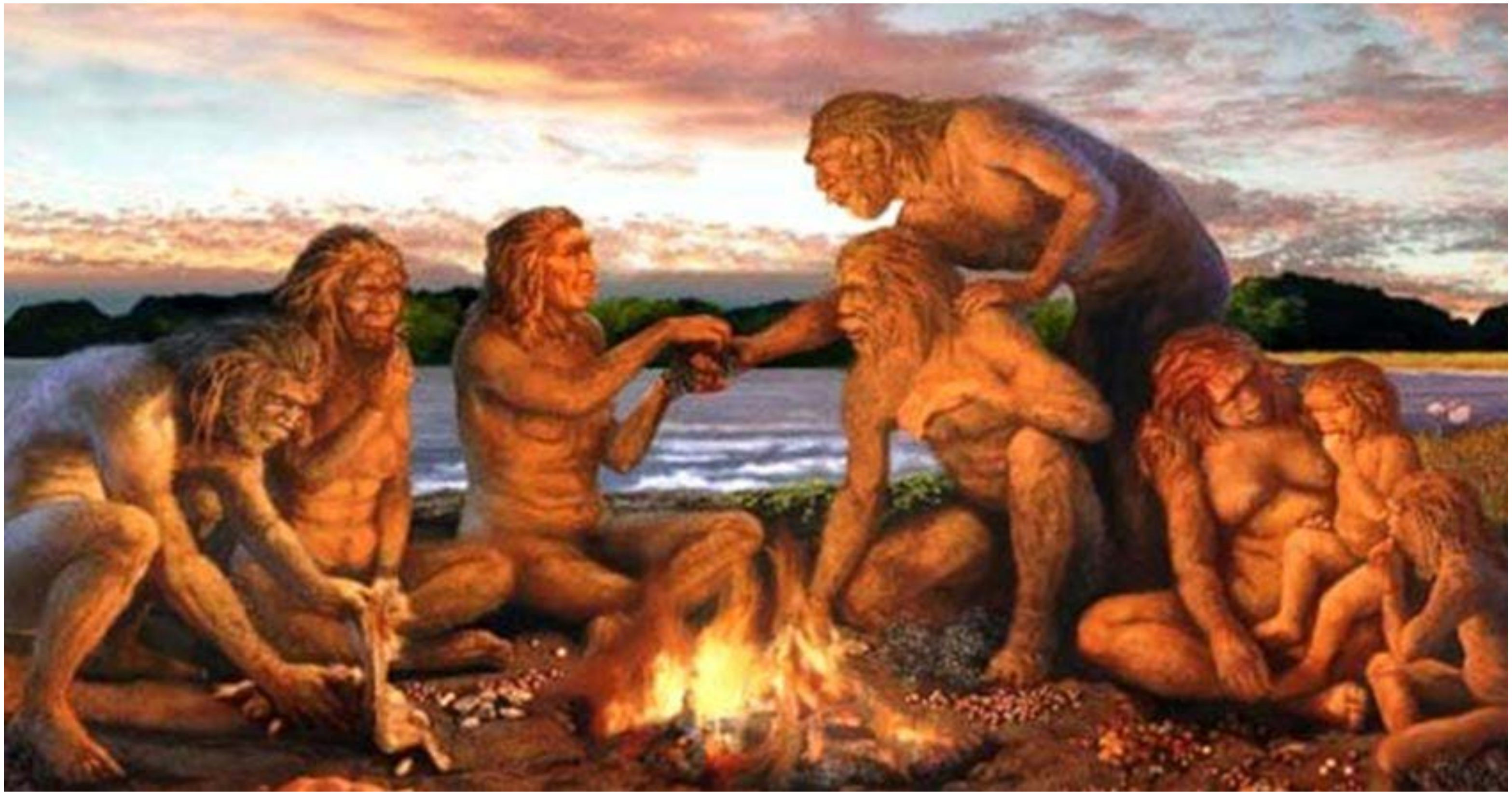
Research Supported by NSF & DOE

Early Use of Fire: Heating Changes Matter



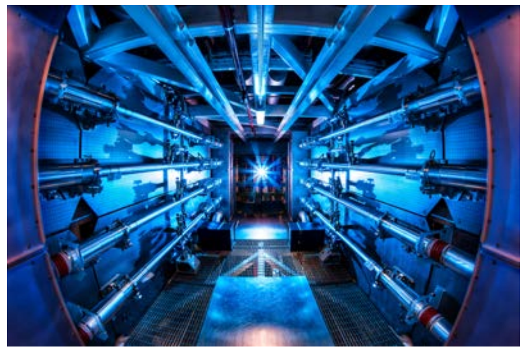
Human use of fire was instrumental for civilization.

Early conception of varied phases of matter & transitions: e.g. boiling water into steam, burning wood into ashes.

Early philosophers (e.g. Empedocles): all matter made of four elements — fire, air, water, earth

From Fire to Extreme Temperature

Our heating capability has since advanced VERY dramatically…



Laser ignition for fusion

Extreme high energy collider

Curiosity questions that even K-12 kids may wonder about:

*** What is the highest temperature ever?**

*** What is the highest man-made temperature?**

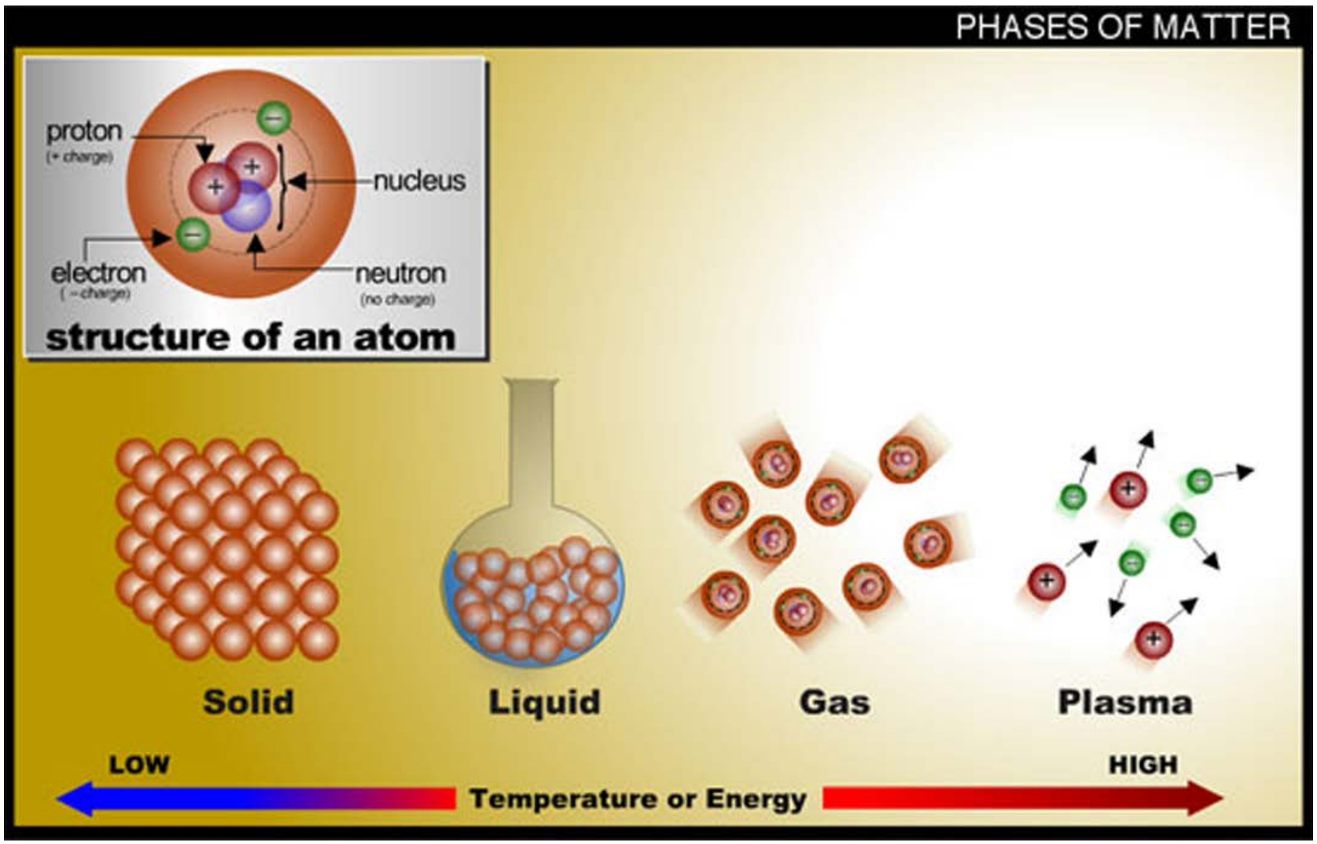
*** What does the matter look like at such extreme temperature?**

——> a scientific frontier of high energy physics

Heating It Up: Energy Scale Matters

Heating increases temperature and enhances the thermal motion of whatever micro. degrees of freedom: a combat of
random thermal motion v.s. ordered structure
(with the latter typically due to dynamical interaction)

From NASA



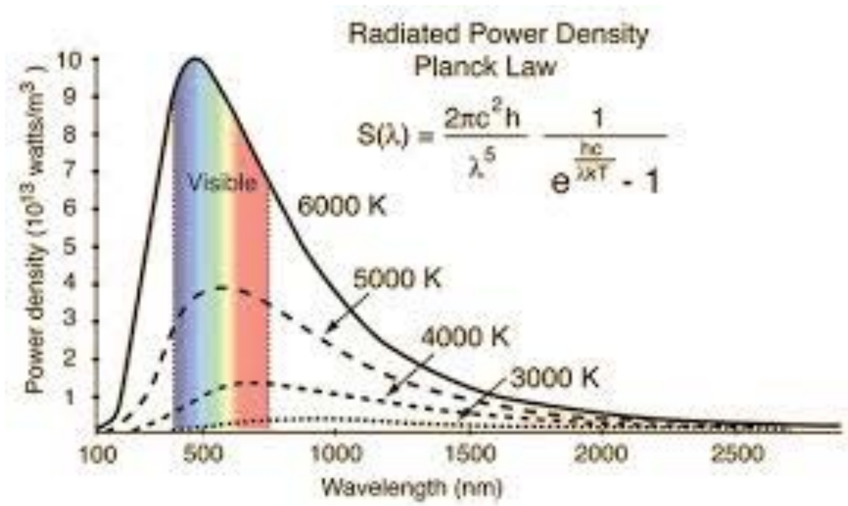
$10^2 \sim 10^3 K$ $\qquad$ $10^4 \sim 10^5 K$

$0.01 \sim 0.1\,\mathrm{eV}$ $\qquad$ $1 \sim 10\,eV$

Inner electrons “peeled off” ~ keV ~ 10^7K

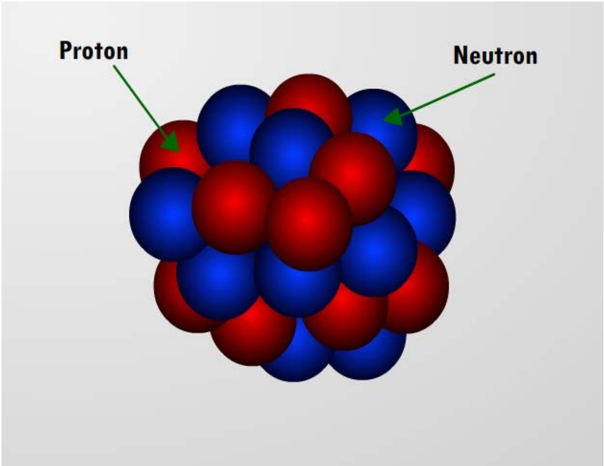
Heating It Up: Energy Scale Matters

What's coming up next upon further heating?



Emissions!!
massless photons — all the time!
What's next?

$e^{-M_e/T}$ $\quad M_e \sim 0.5\text{MeV}$



Ions (nuclei) —
when do they break up?
Nuclear binding energy:

$\sim MeV$

Getting to ~ MeV ~ 10 Million Kelvin

—> Need to know quantum field theory (relativity+QM)

—> Need to know nuclear physics

Heating It Up: Energy Scale Matters

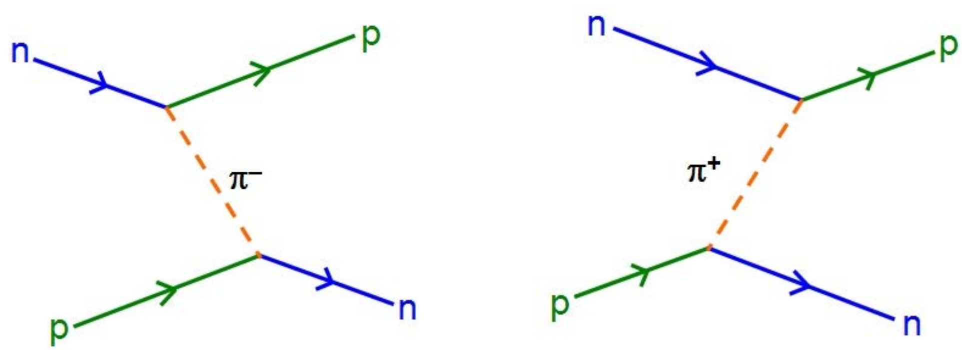
Again, what's coming up next?
— what is the next massive particle?
— what is behind nuclear force?
Hadrons! Specifically, Pions!

$$\pi^{\pm}, \pi^{0}$$

$$M_{\pi} \sim 140\text{MeV} \sim 10^{12} K$$

$$R_{nuc} \sim 1\,\text{fm} \sim 200\text{MeV}$$

Yukawa



What do we expect next?

*** Heating toward T ~ M_pi , many pions are thermally produced.**

*** Repeating the same story of atoms at nuclear level?**

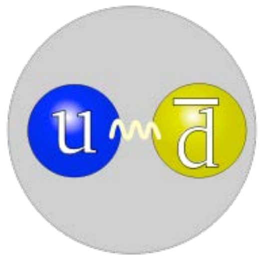
*** Many more hadron types, to be produced sequentially?**

*** Maybe hadrons to be broken up?**

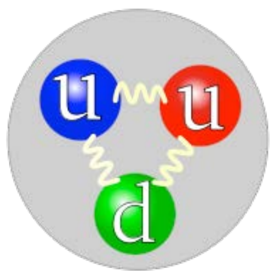
Heating It Up: The "Weird" Hadrons

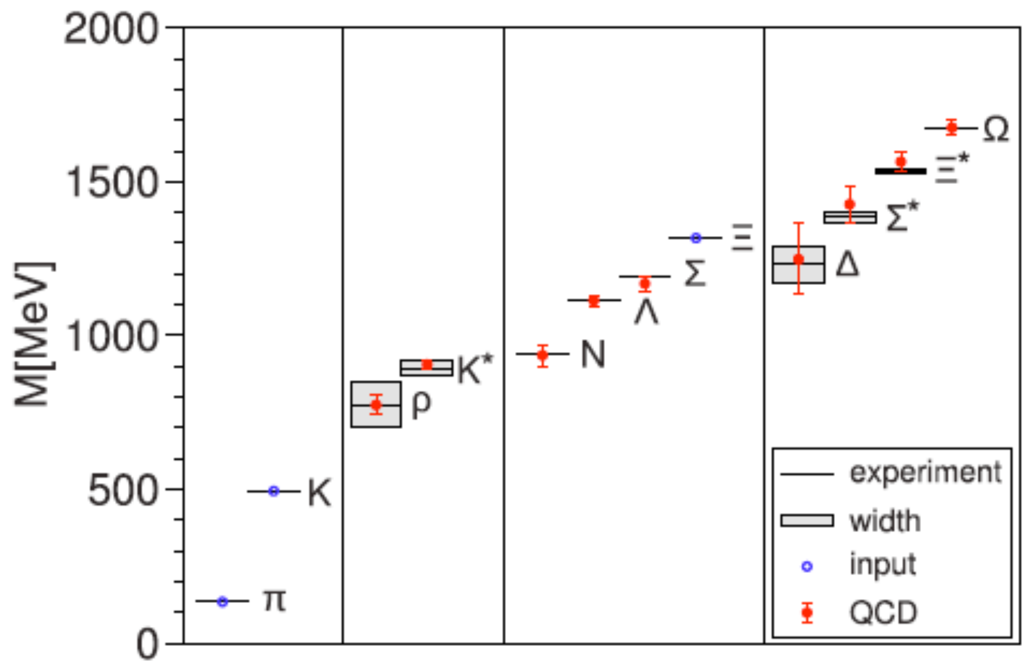
As it turns out, there are thousands different types of hadrons…

Gell-mann



quark model for hadrons

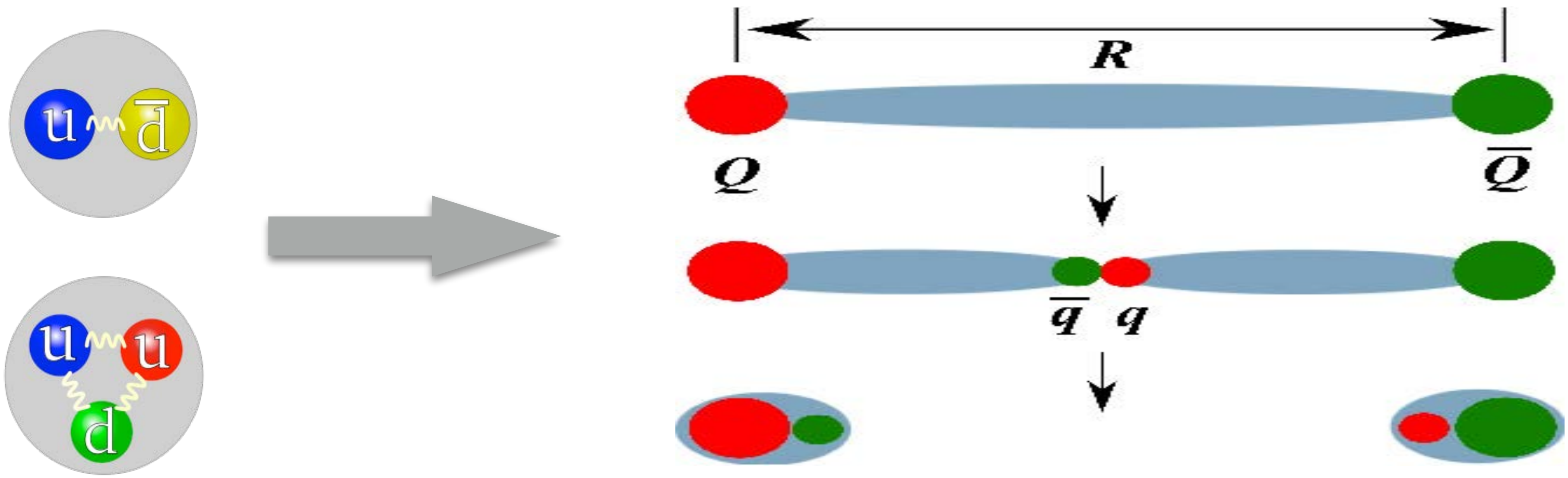




"Atomic physics" for hadrons based on quarks?
If yes, then some binding scale of hadrons?

Heating It Up: The "Weird" Hadrons

Surprisingly, hadrons seem to be unbreakable!



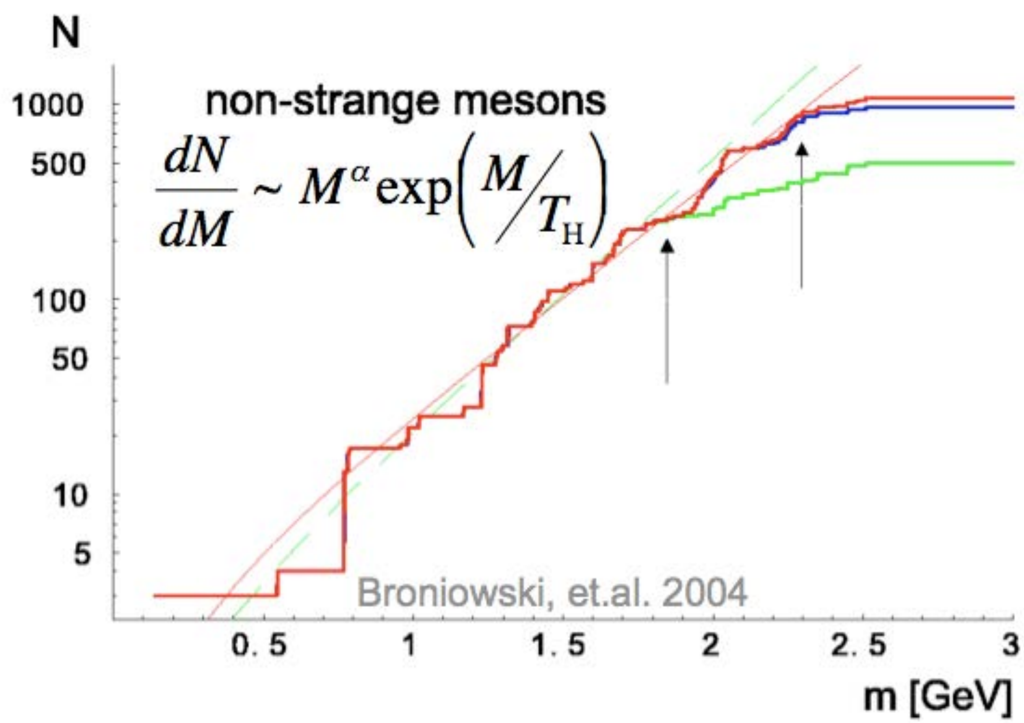
Upon injection of energy, a highly excited hadron becomes STRING like, and eventually breaks into more hadrons (not quarks)!

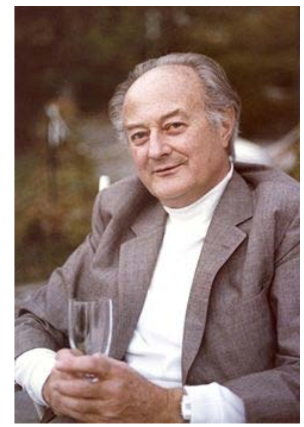
Heating It Up: The "Weird" Hadrons

So… are we going to stay with hadrons despite how hot we heat up matter?

The answer is NO! Surprisingly, there is a predicted limiting temperature for hadrons.

# of hadron types grows exponentially with mass!





Hagedorn

$$\epsilon \sim \int dM\, M^{\beta}\, e^{\frac{M}{T_H}}\, e^{-\frac{M}{T}}$$

This statistical sum diverges for T > T_H ~ 160MeV !

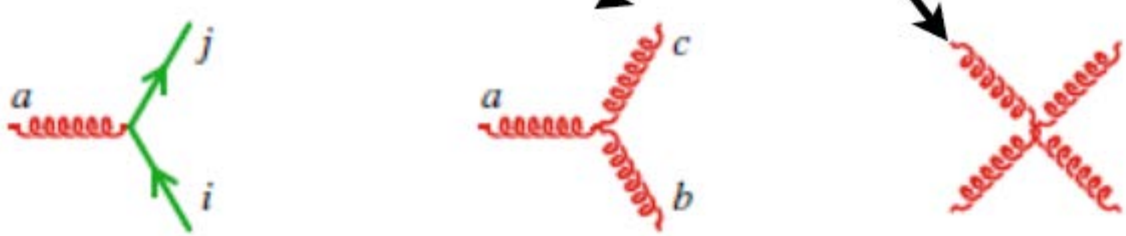
WHAT IS THE MATTER BEYOND THAT?

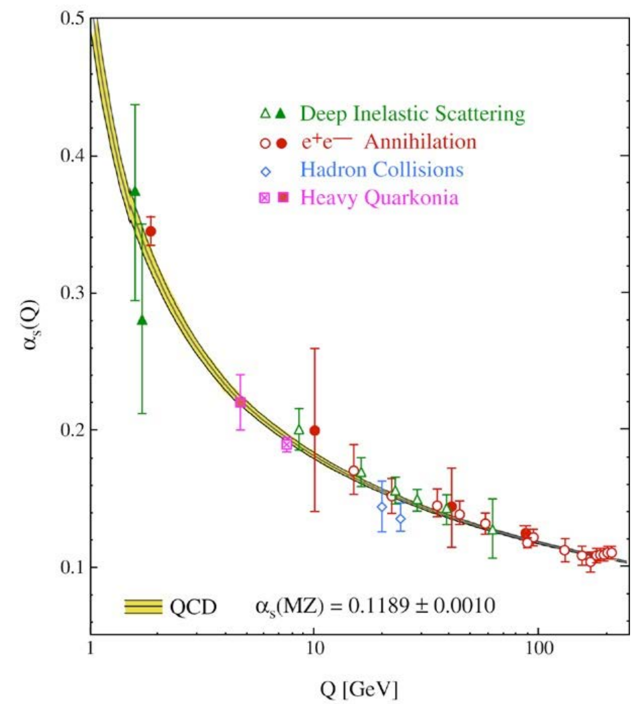
Quantum Chromodynamics (QCD)

To answer the question, we will need to understand better the fundamental theory of strong nuclear force: QCD, a non-Abelian gauge theory of quarks and gluons

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

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



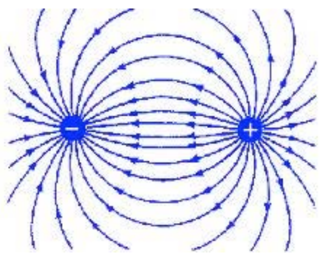


Asymptotic Freedom: coupling becomes large at low energy or long distance scale.

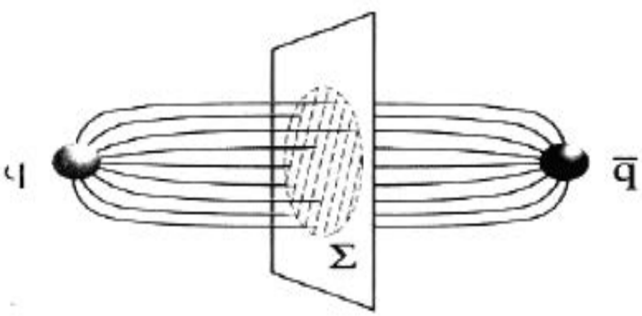
$$\Lambda_{QCD} \sim 200\mathrm{MeV} \qquad R \sim 1\,\mathrm{fm}$$

The QCD Vacuum: Confinement

The missing particles: quarks & gluons (in the QCD lagrangian) are not seen in physically observed states.



QED dipole field

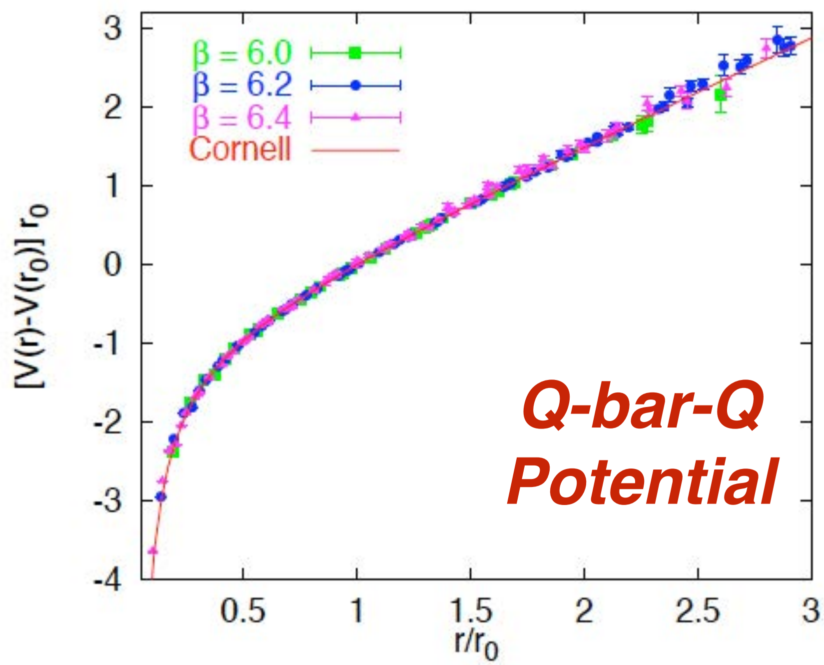


QCD dipole field

Free Quark Searches

from PDG 2014

All searches since 1977 have had negative results.



QCD vacuum as "dual superconductor" with dual Meissner effect

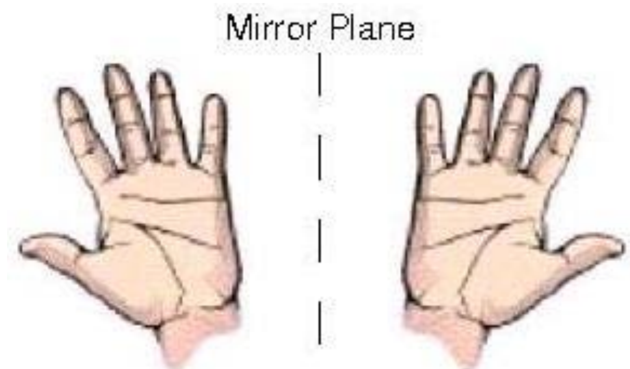
The QCD Vacuum: Chiral Symmetry Breaking

The missing symmetries: while the Lagrangian has (approximate) chiral symmetry, the vacuum and hadron spectrum do not have that.

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

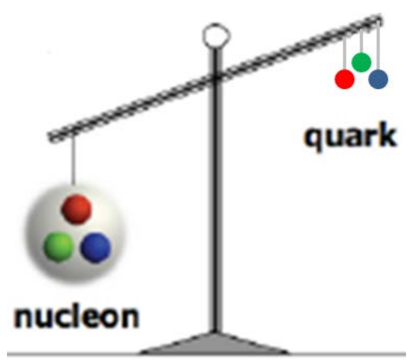
$$\mathcal{L} \rightarrow i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R$$

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



Puzzle #1: why non-degenerate?

$$m_\pi \approx 140MeV \,,\, m_{f0} \approx 600MeV$$
$$m_\rho \approx 770MeV \,,\, m_{a1} \approx 1260MeV$$

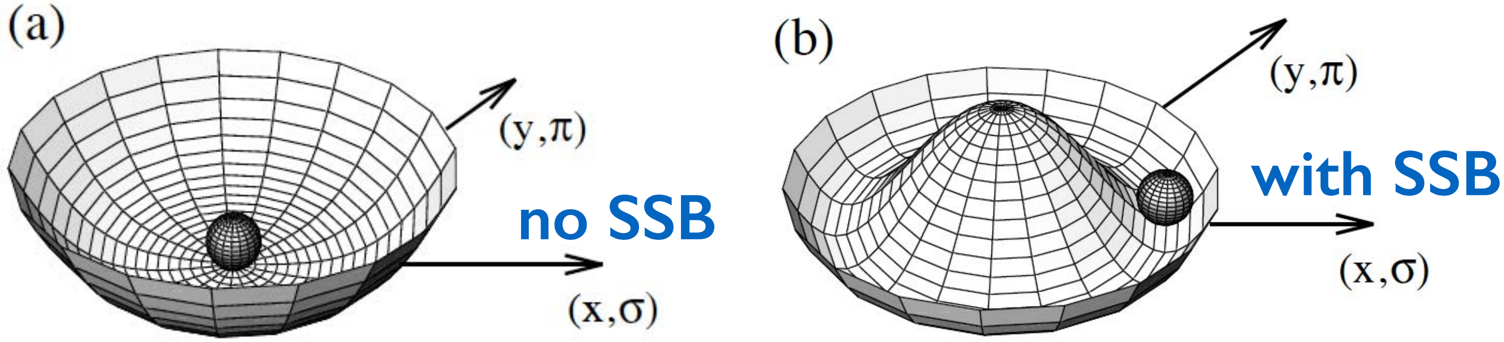


Puzzle #2: why M_n >> 3 M_{u,d}? why M_n /3 >> M_pi /2?*

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

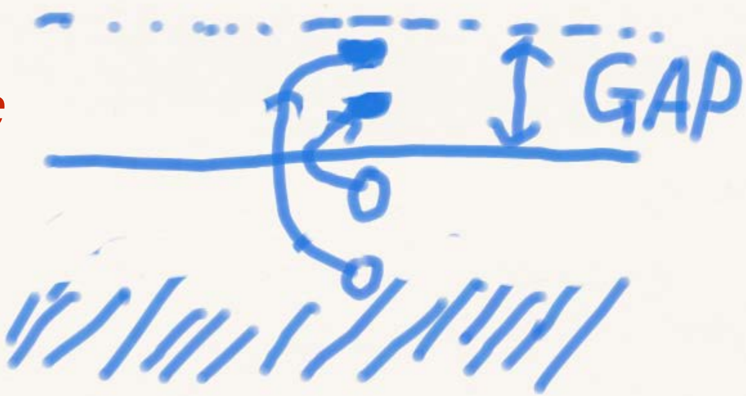
Spontaneous Chiral Symmetry Breaking

Nambu



Quark level picture:

Dirac Sea



Lagrangian (SM) mass:

$$M_{u,d} = 5 \sim 10MeV$$

$$\Delta \sim < \bar{\Psi}\Psi >$$

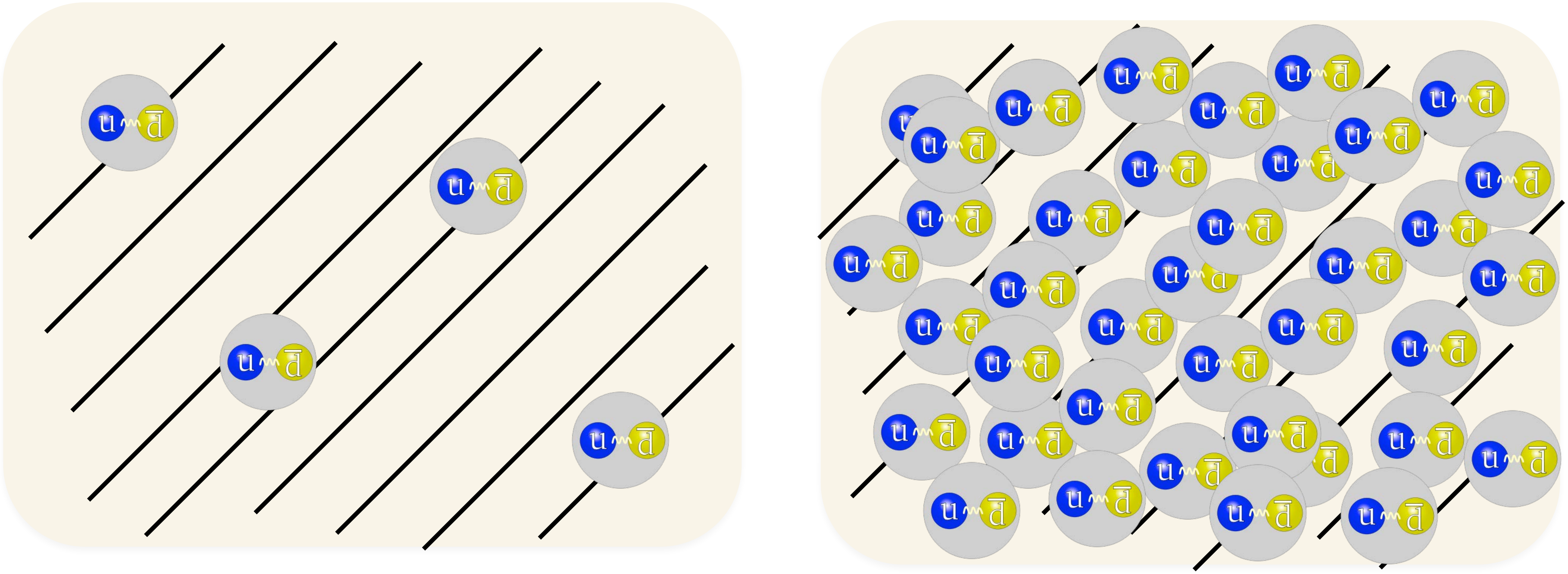
Constituent mass:

$$M_{con.} \sim 300MeV$$

QCD vacuum is not empty, but a complex, nonperturbative form of condensed matter.

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

Heating Nuclear Matter Up (or Compressing It)



It appears most certain that when the system is hot/dense enough:

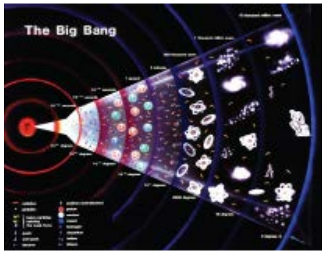
(1) Individual hadrons will lose their identities —> quarks/gluons

(2) The vacuum ordered structure would be destroyed.

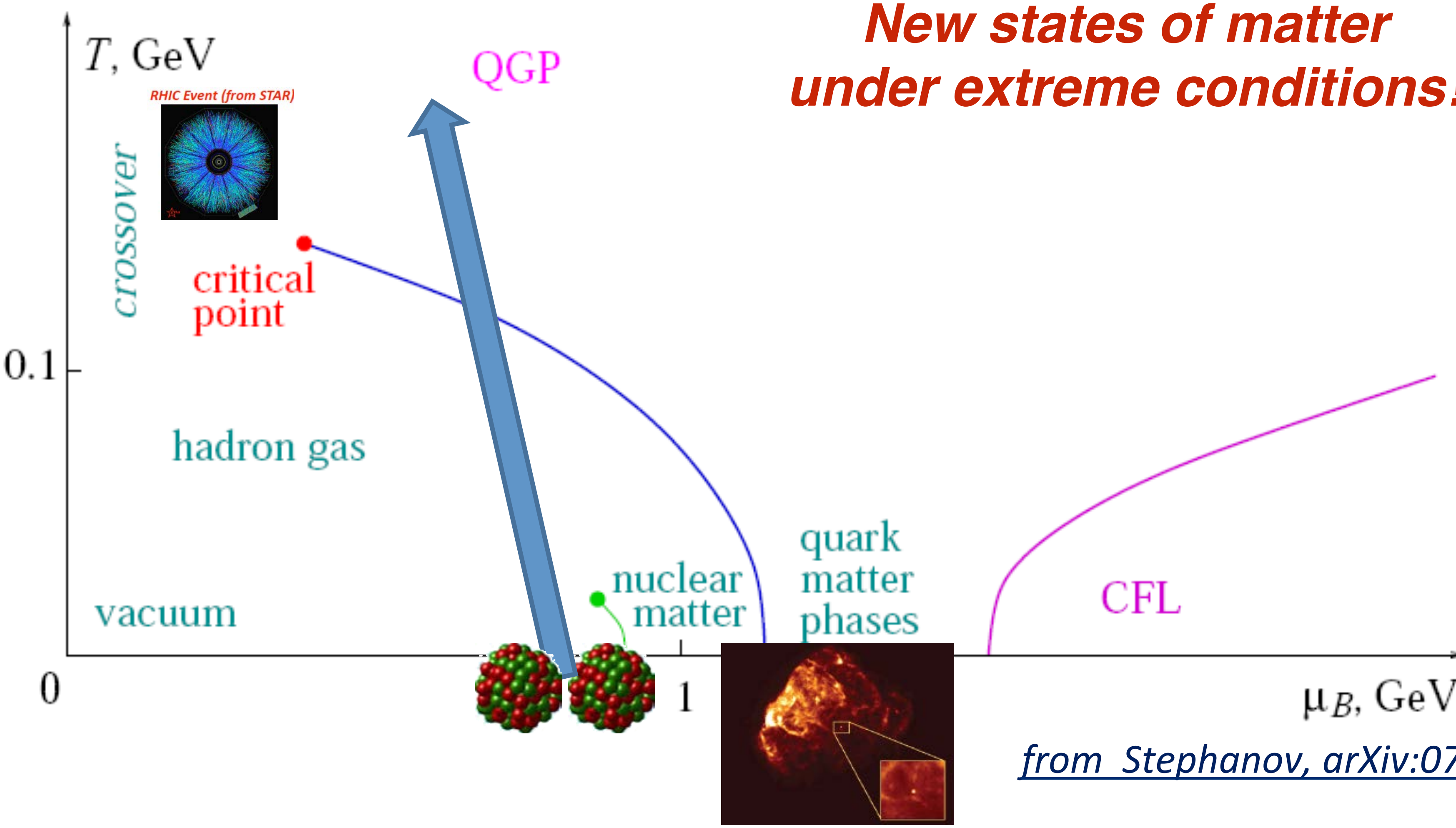
—> Must be a distinctive new phase of nuclear matter !

[Early ideas:T.D.Lee, Wick, Collins, Perry, McLerran, Shuryak, Kapusta, …]

Condensed Matter Physics of QCD



"Disturb" the vacuum
by tuning external conditions:
New states of matter
under extreme conditions!



from Stephanov, arXiv:0701002

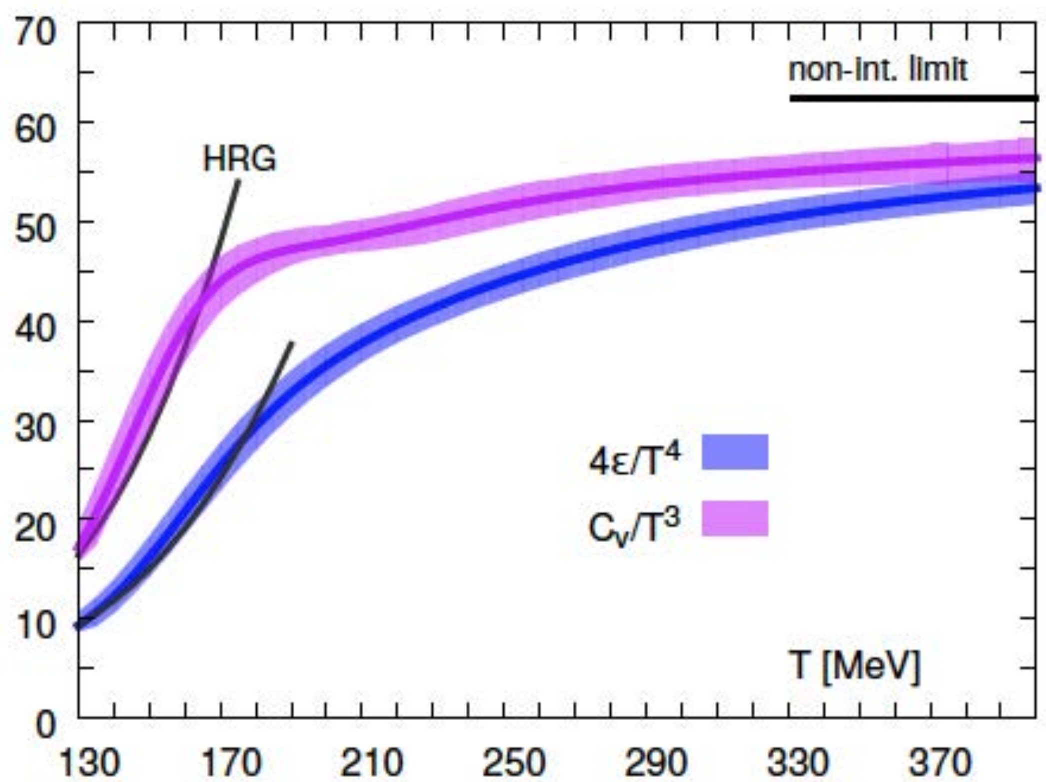
Answer from Lattice QCD

from Lattice QCD (HotQCD)

RHIC LHC

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

free QGP



a relativistic pion gas

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

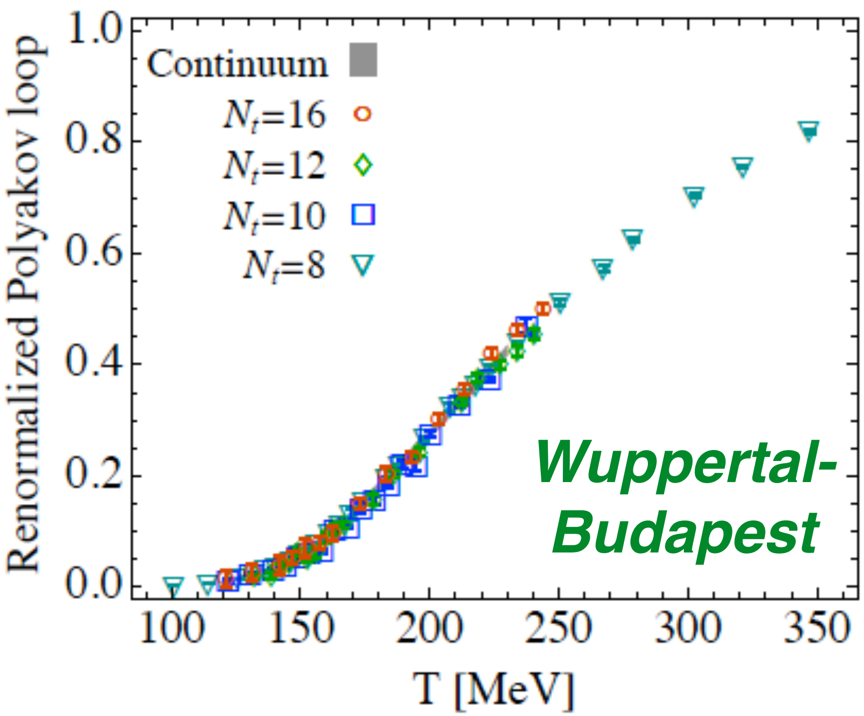
More precisely,
Hadron Resonance Gas

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

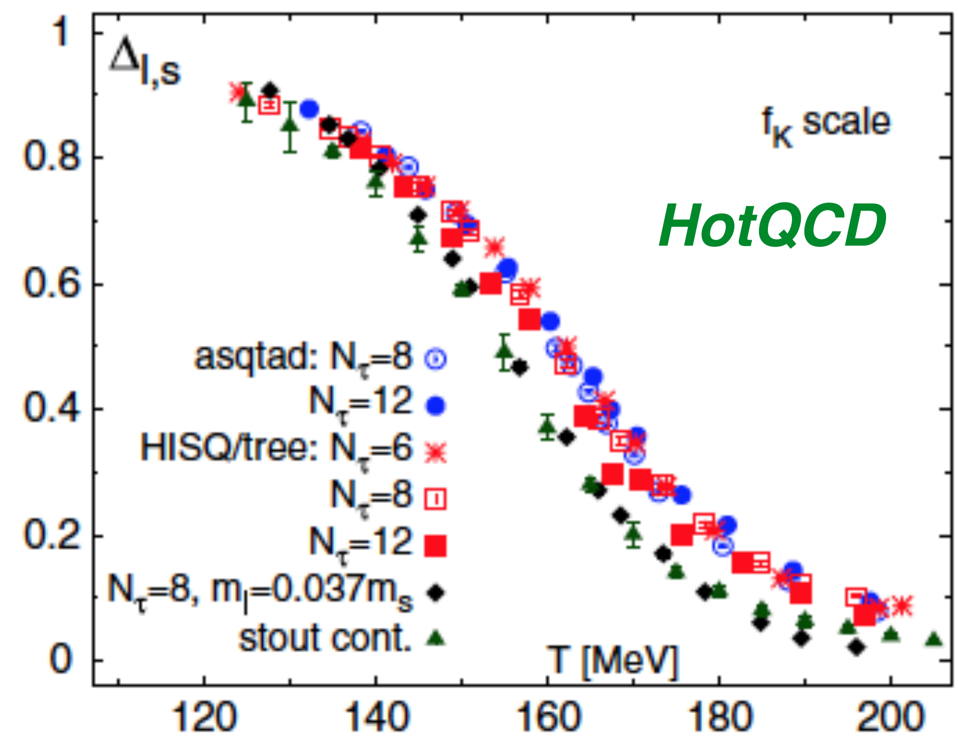
Answer from Lattice QCD

The liberated quarks & gluons

The restored chiral symmetry



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

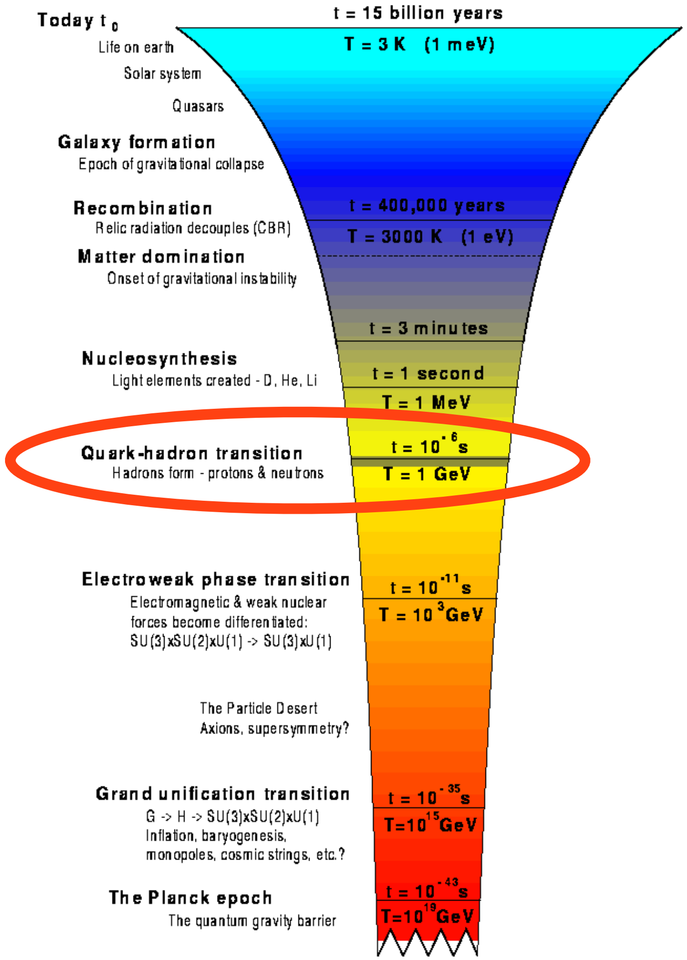


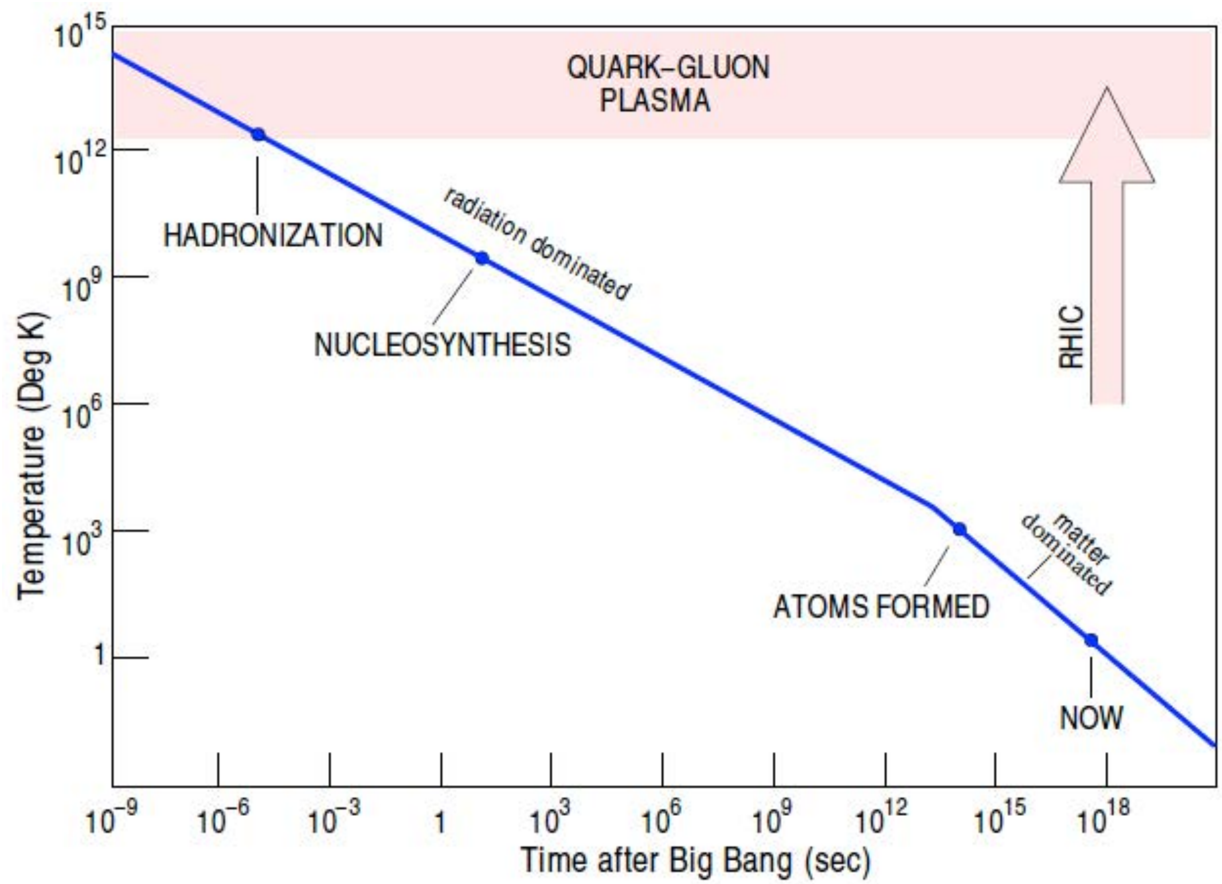
The high T phase of QCD matter (a few hundred MeV & up) is a distinctive quark-gluon plasma (QGP).

Where can we find it?!

Early Universe After Big Bang

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





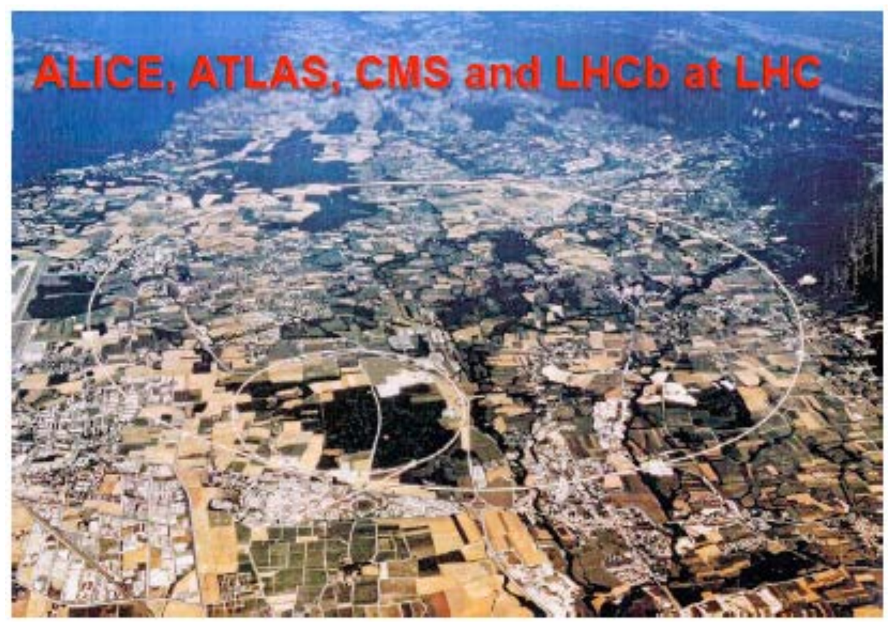
The quark-gluon plasm is an old phase of matter! Can we replicate such epoch state of matter in laboratory?

Little Bang in Heavy Ion Collisions (HIC)

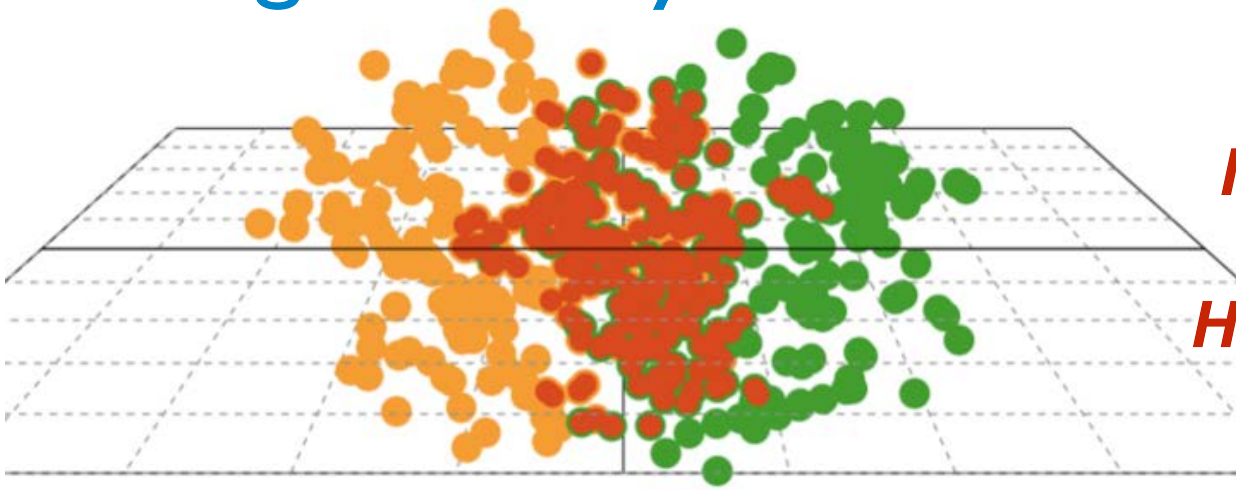
T. D. Lee: "Vacuum Engineering"

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

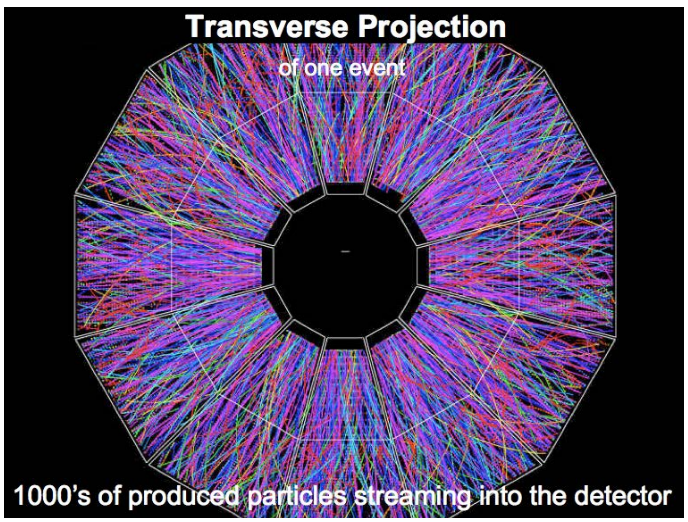
our most powerful heating machine ever

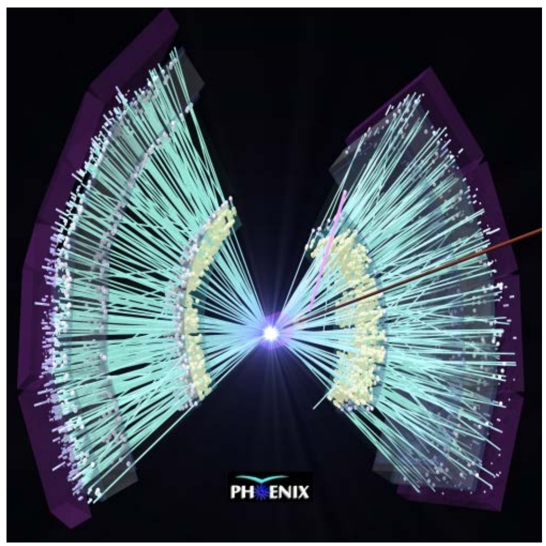


Little Bang in Heavy Ion Collisions (HIC)

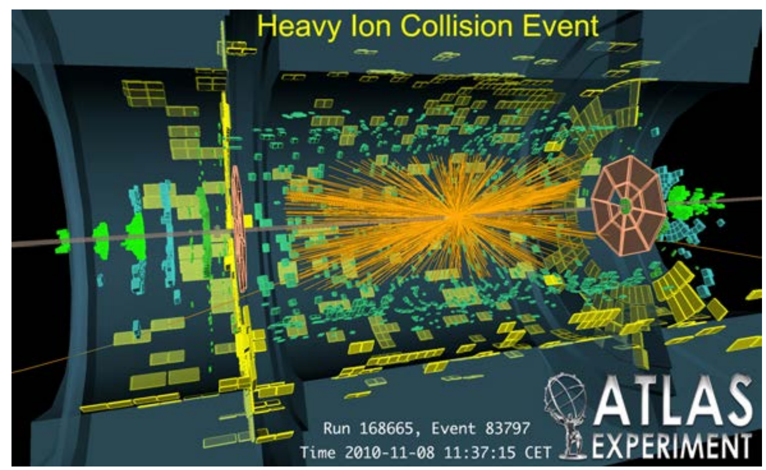


Is QGP created?
Just how hot?
How do we know?



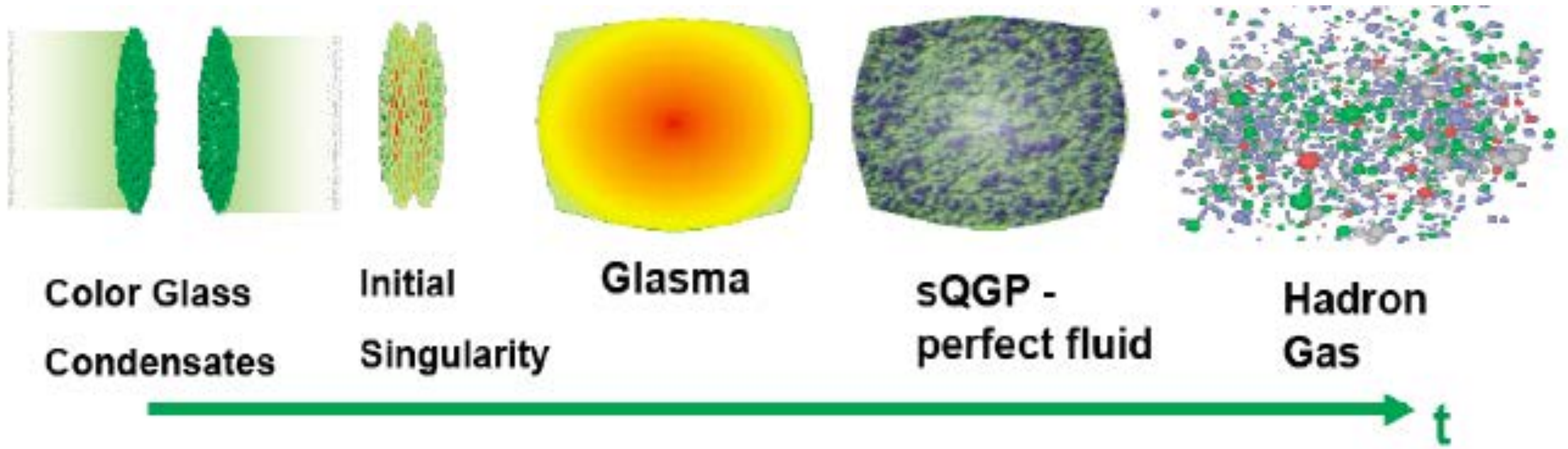


from STAR & PHENIX @ RHIC



from ATLAS @ LHC

Some Basics of Heavy Ion Collisions

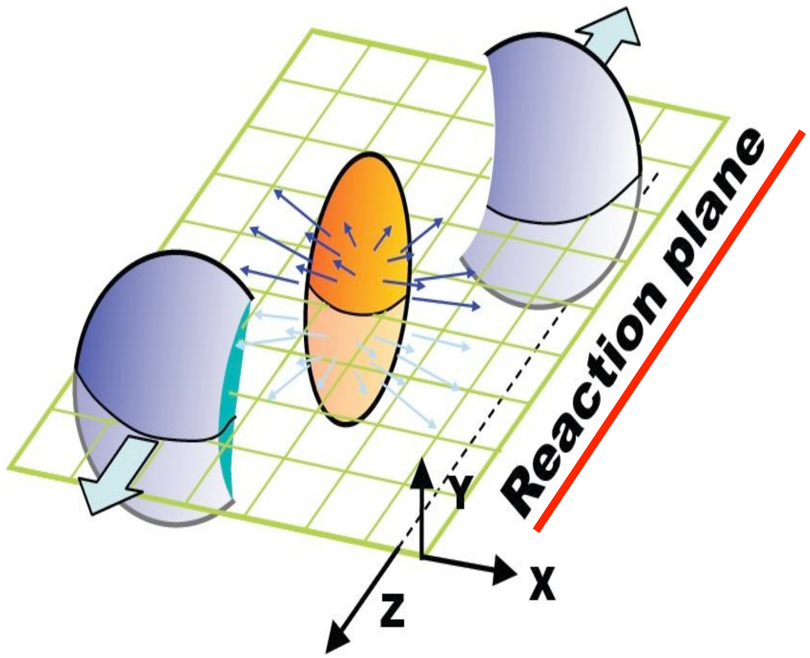


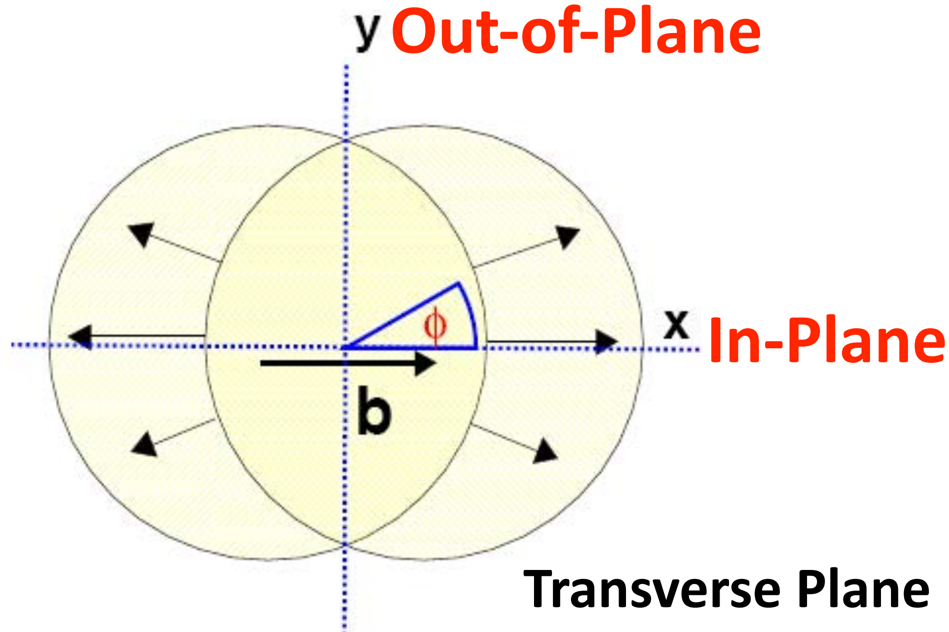
To give some ideas (taking Gold-Gold 200GeV at RHIC as example):

- 197 (79p+118n) nucleons colliding with 197 nucleons
  (Nuclei A as a handle)
- 100GeV/nucleon, 200GeV N-N C.M. energy, 42mb x-section
  (Collision Energy as a handle)
- 39TeV in, about 28TeV left in the middle → creating ~7500 particles
- **We observe the final state hadrons' identity and 3-momentum**
- Estimated initial temperature ~300MeV **(Trillion Kelvin)** > Tc ~170MeV
- Estimated initial energy density 5-10GeV/fm^3 > H.G. threshold 1GeV/fm^3

HIC Systematics

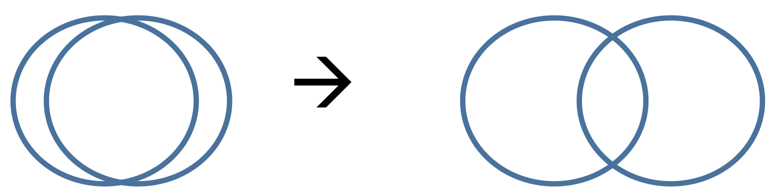
◆ **Centrality:**



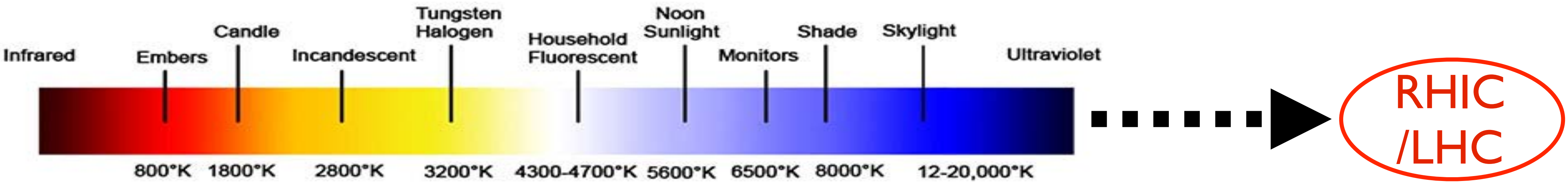


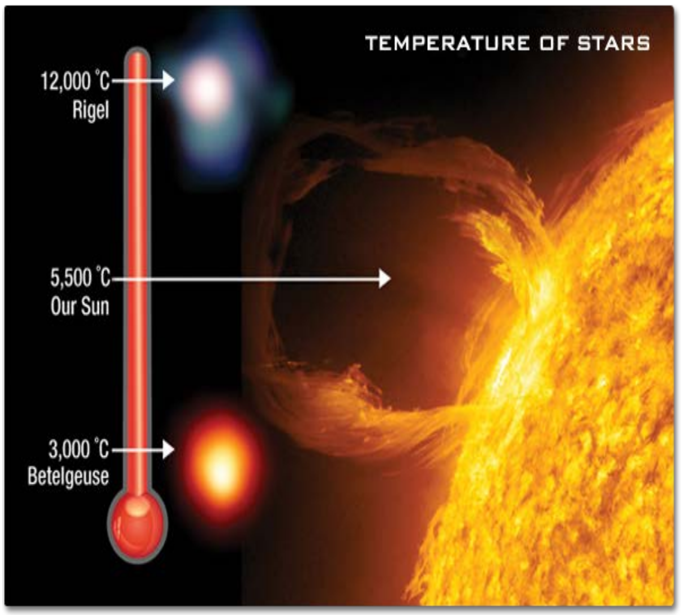
Centrality:	*(most) central →*	*(most) peripheral*	
Impact parameter b:	*(very) small →*	*(very) large*	
Initial geo. anisotropy:	*(very) small →*	*(very) large*	
Final hadron multiplicity:	*high →*	*low*	*(exp. classification)*

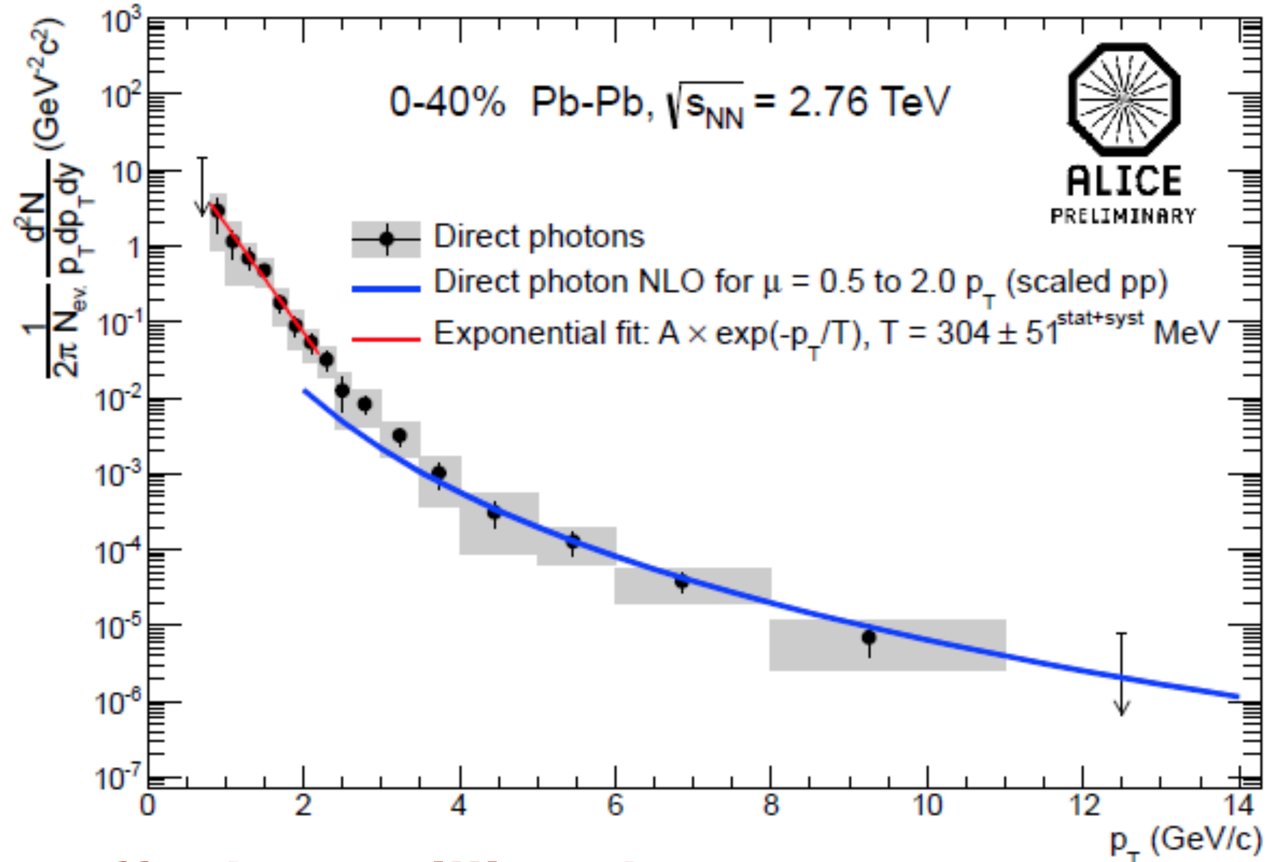
Fireball geometry from initial overlap: crucial !



QGP Shining Bright!

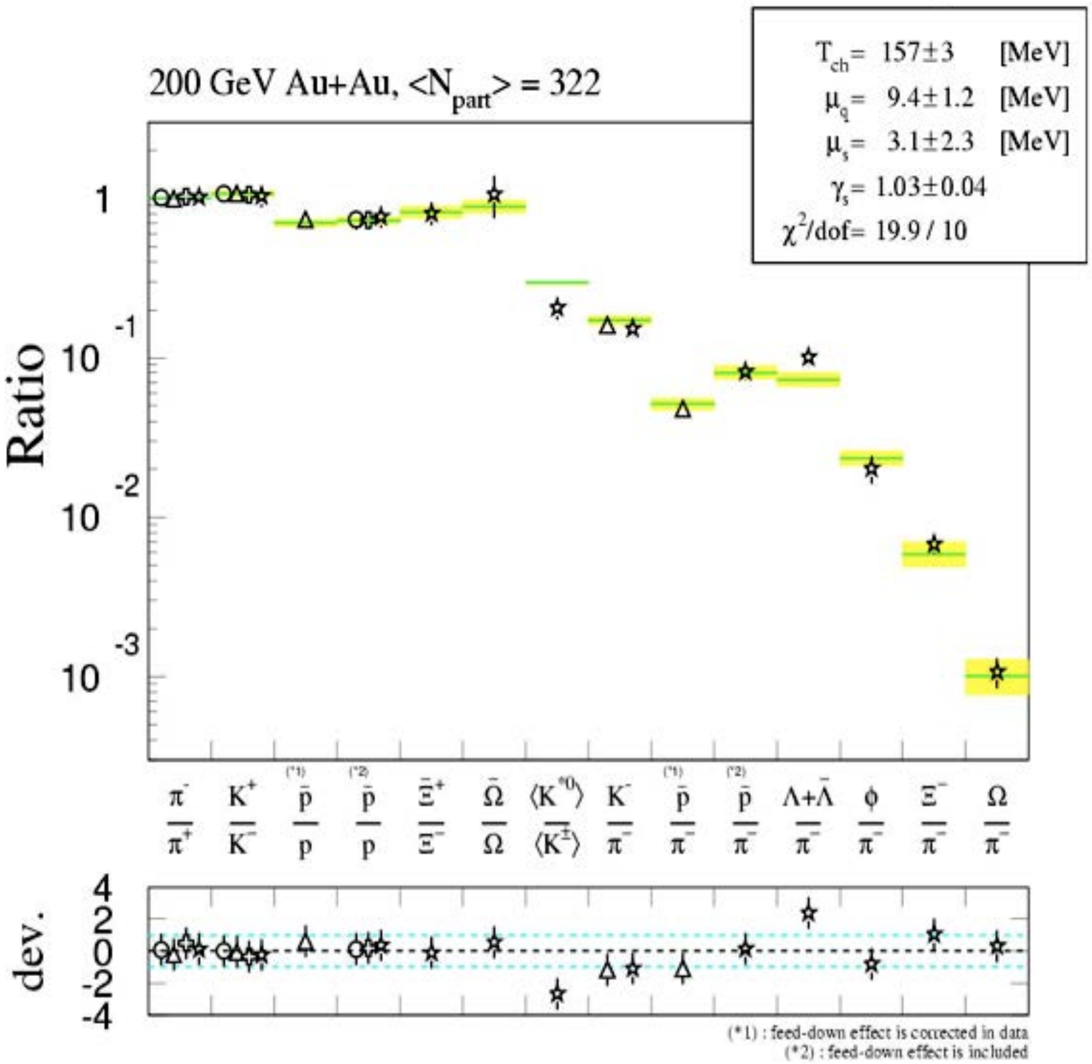




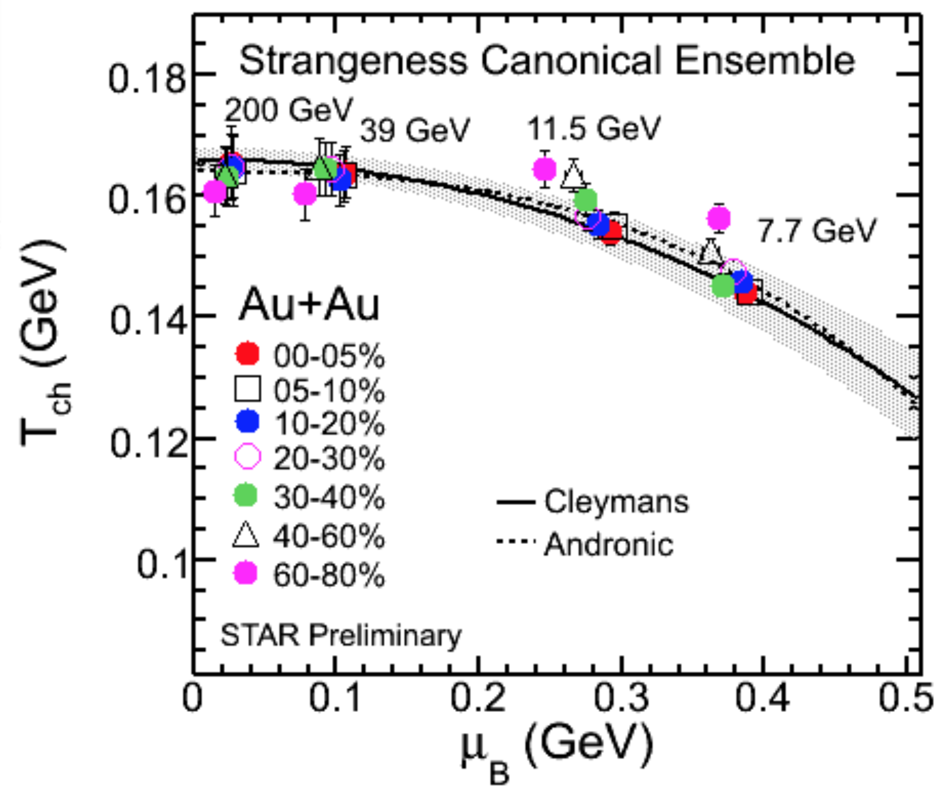


QGP is hot stuff: about trillion degrees !
Official Guinness World Record:
the highest man-made temperature!

QGP Thermally Produces Hadrons

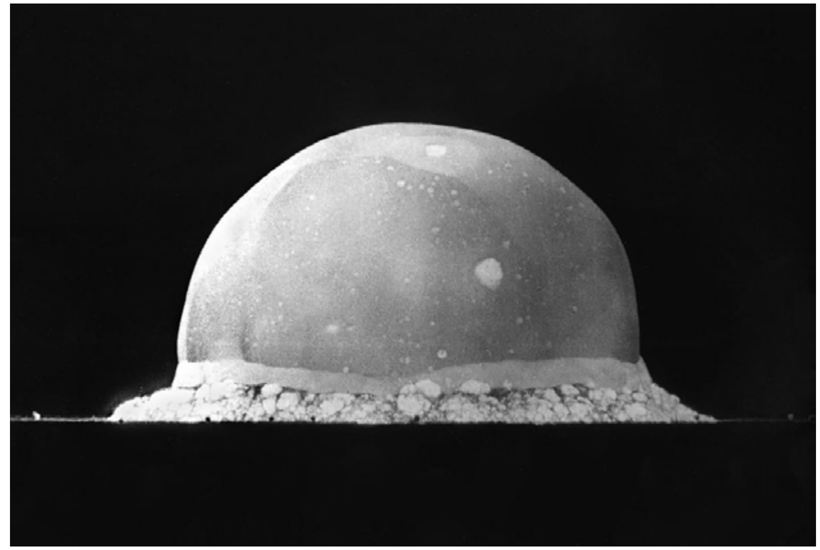


From STAR



QGP is hot stuff!

Being Explosive!



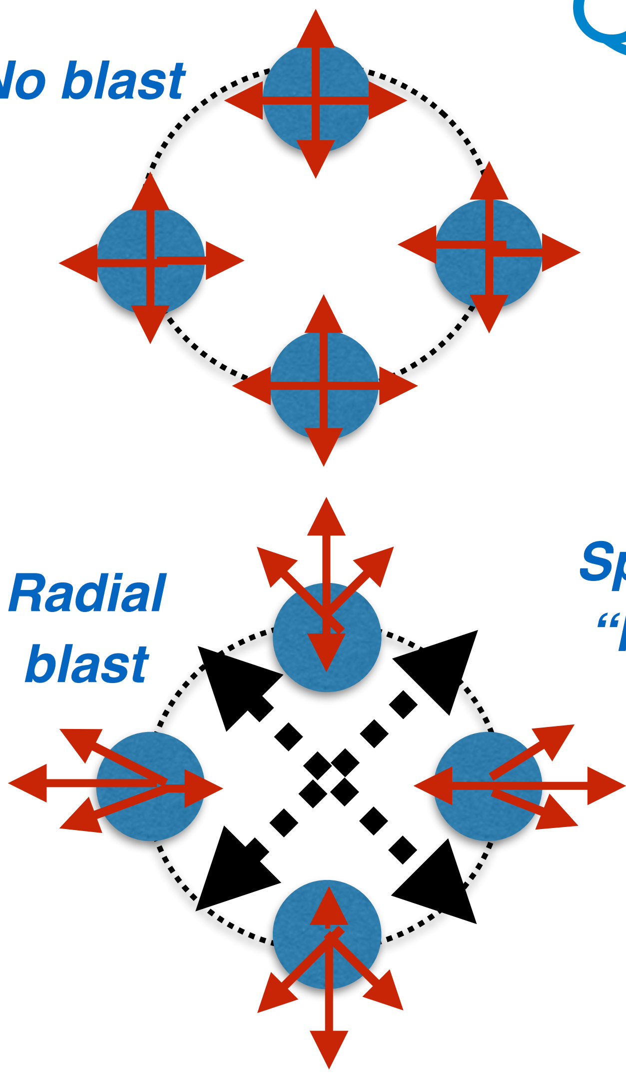
From Wikipedia about Trinity Bomb:

Fifty beryllium-copper diaphragm microphones were also used to record the pressure of the blast wave. These were supplemented by mechanical pressure gauges.[104] These indicated a blast energy of 9.9 kilotons of TNT (41 TJ) ± 0.1 kilotons of TNT (0.42 TJ). With only one of the mechanical pressure gauges working correctly that indicated 10 kilotons of TNT (42 TJ). [105]

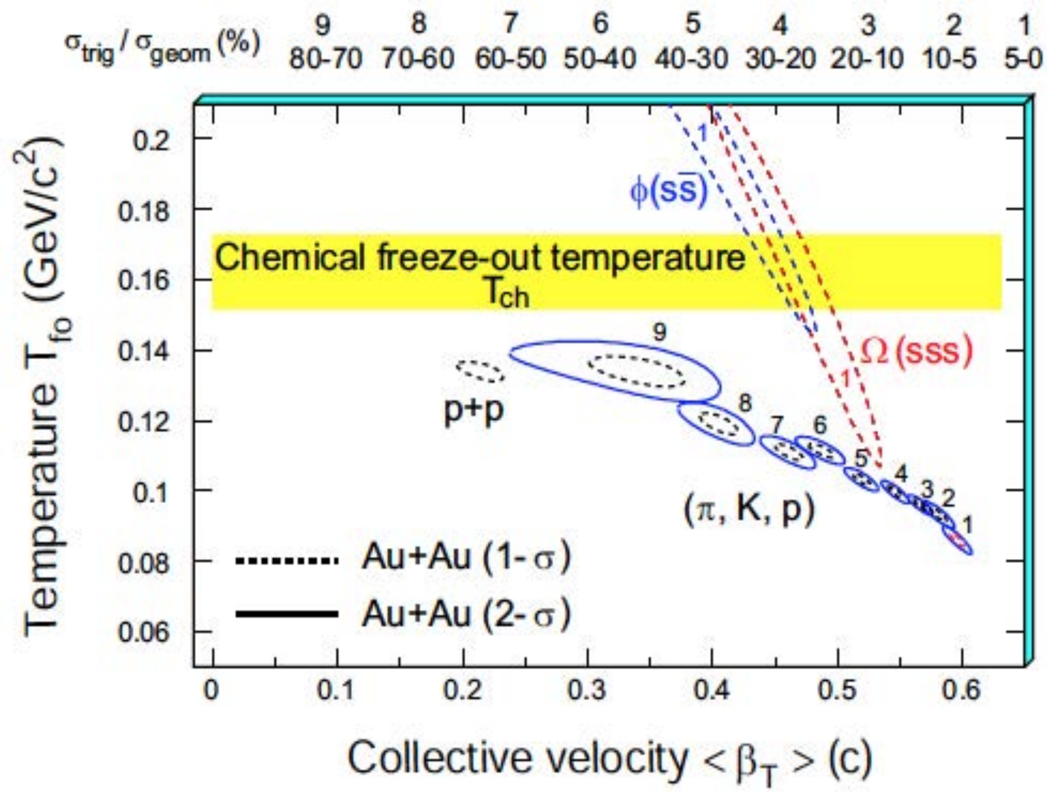
Fermi prepared his own experiment to measure the energy that was released as blast. He later recalled that:

About 40 seconds after the explosion the air blast reached me. I tried to estimate its strength by dropping from about six feet small pieces of paper before, during, and after the passage of the blast wave. Since, at the time, there was no wind I could observe very distinctly and actually measure the displacement of the pieces of paper that were in the process of falling while the blast was passing. The shift was about 2 1/2 meters, which, at the time, I estimated to correspond to the blast that would be produced by ten thousand tons of T.N.T.[106]

QGP Blasting Out!



Spectra with "blue shift"



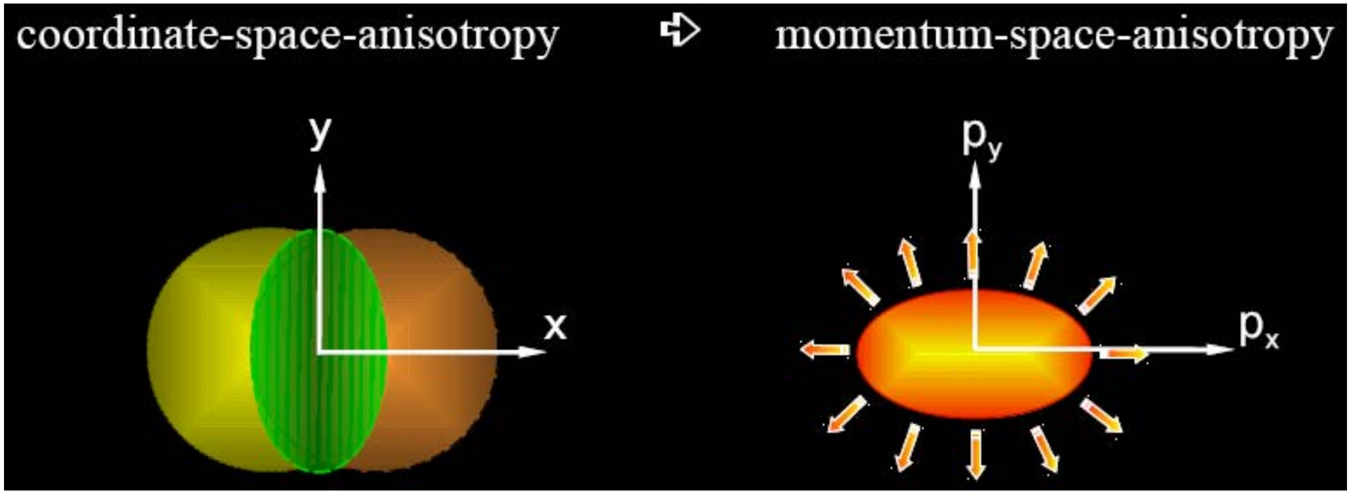
Strong blast wave seen in final hadrons distributions

—> highly explosive

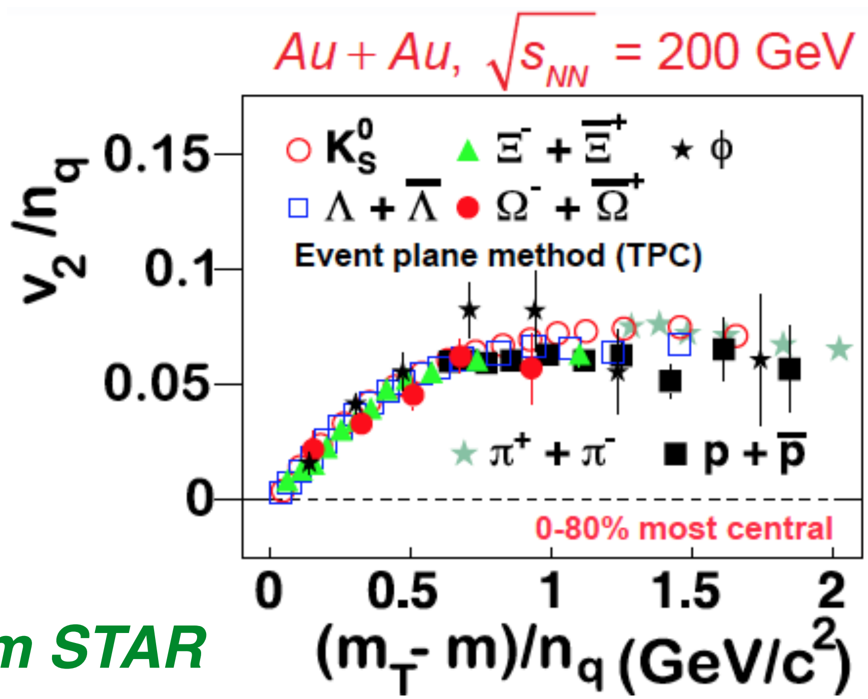
—> high initial energy density & pressure gradient!

$$\epsilon_{in} \sim 20GeV/fm^3 \gg 1 \sim 2GeV/fm^3$$

Anisotropic Blast: Elliptic Flow



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



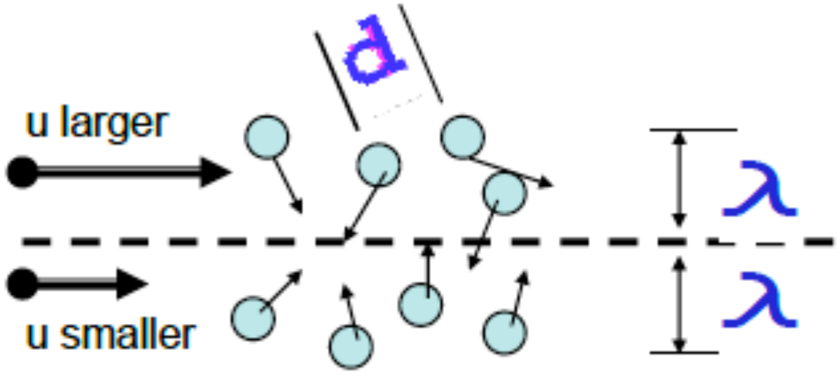
from STAR

relativistic hydrodynamics @ 1~ 10 fm scale.

This response is very sensitive to fluid dissipation

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

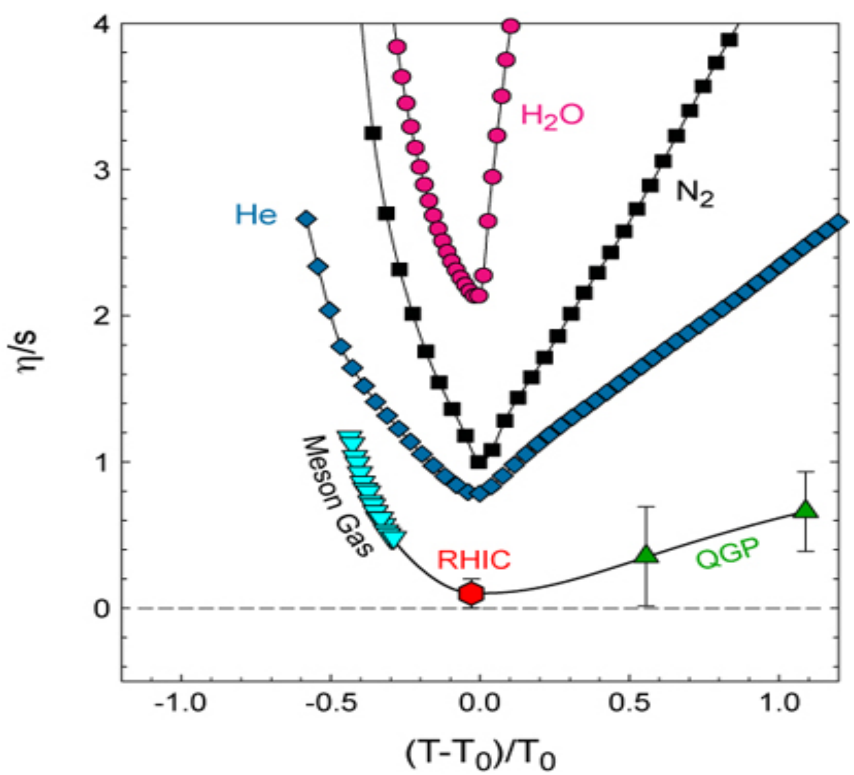
QGP: Nearly Perfect Quantum Liquid



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

$$s \sim n$$

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



QGP is a quantum liquid:

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

[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.

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!

[Perhaps one good place to get to know it all:
Quark Matter Conference Proceedings]

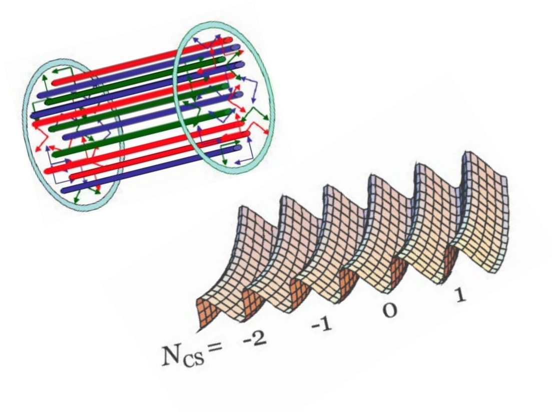
The (Creative) Use of QGP & HIC

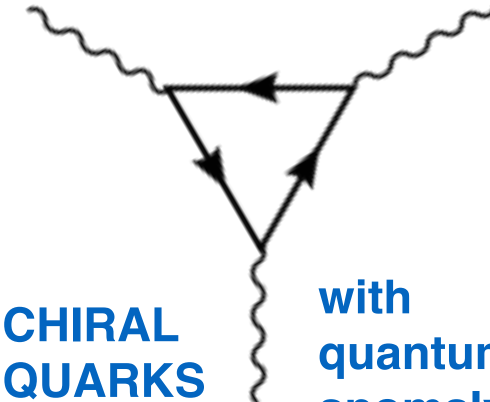
The QGP (new material) & HIC (new laboratory) provide exciting opportunities for many interesting new physics

** Learning about initial nuclear wave functions*
** Relativistic viscous hydrodynamics (on its edge)*
** Predicting new hadrons (strangeness fluctuations)*
** Far from equilibrium physics (BEC in the very hot)*
** Understanding confinement from deconfined QGP*
** Producing rare particles (anti-hyper-triton, anti-alpha,…)*
** Constraining nuclear structure (C12 ~ 3 alpha cluster?)*
** Universal critical phenomenon for QCD*
** Applied string theory (aka gauge/gravity duality)*
** Cosmology & early universe,*
** ……*

I will have time to tell you only one recent interesting story.

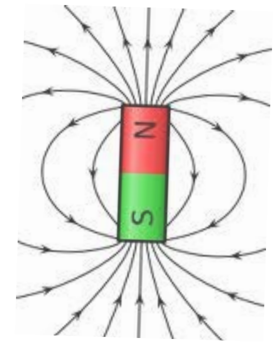
Anomalous Transport in Chiral & Quantum QGP





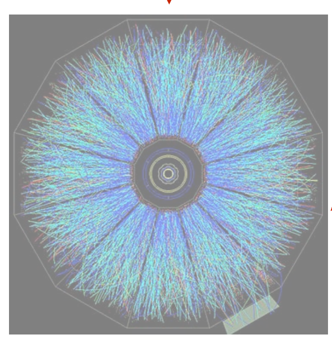
CHIRAL QUARKS

with quantum anomaly



nontrival gluonic configurations

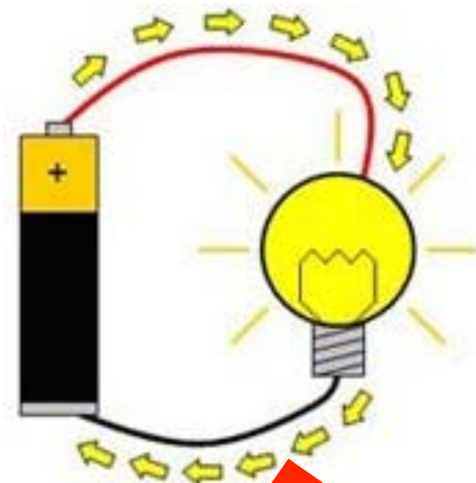
strongest magnetic fields



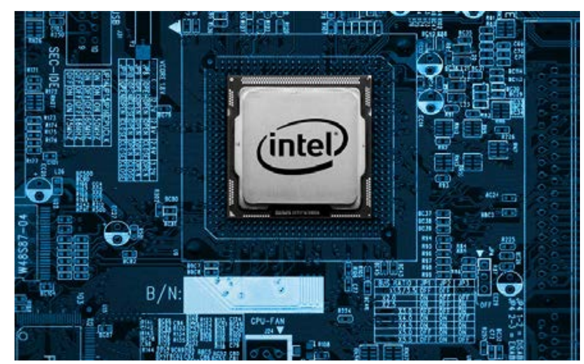
All available in one UNIQUE LABORATORY: Heavy Ion Collisions

Electricity

We owe a lot to foundation builders of ELECTRICITY, which people and society today heavily rely upon.



In just a few hundred years

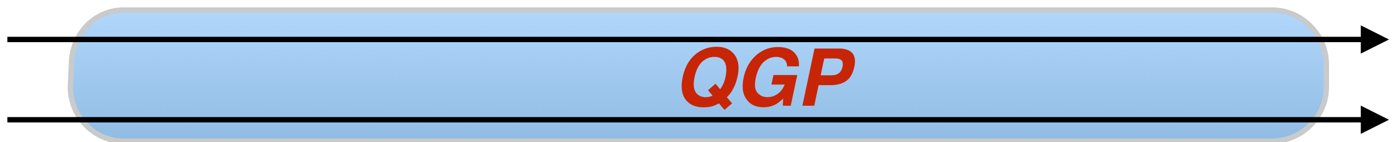


Ohm's Law

$$jv = \sigma E,$$

Hundreds of Years from Now: Quarkicity?

How about hot QCD matter, the quark-gluon plasma, when probed with E & B fields?



$\vec{E}\ or\ \vec{B}$

Unleashed imagination: QGP put into a thin wire

Maybe we shall consider file for a patent of *<u>quarkical devices</u>*

Of course we still have the good old Ohm's Law $j_V = \sigma E,$

But what else?

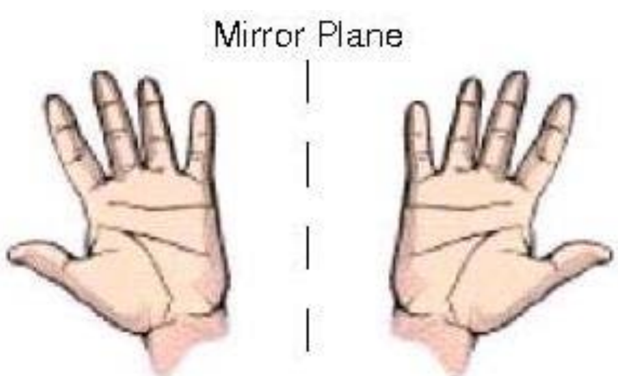
QGP with Restored Chiral Symmetry

**** The quark-gluon plasma at high temperature has restored chiral symmetry for light flavors of quarks.***

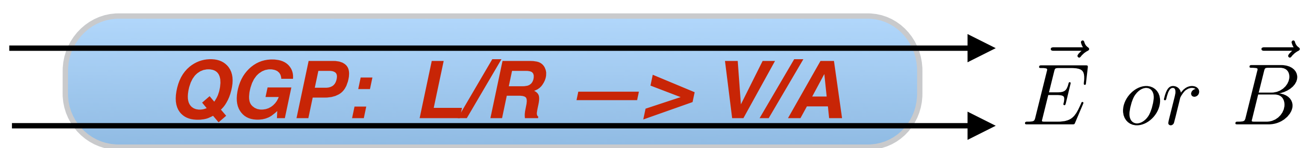
Restored chiral symmetry in QGP allows us to "see" more: we can separately look at right- and left-handed quarks!

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

$$J^\mu = J^\mu_R + J^\mu_L \ , \ \ J^\mu_5 = J^\mu_R - J^\mu_L$$



The R/L sectors respond to E/B fields independently, and differently!



Generalized "Ohm Table" for QGP

$$\begin{pmatrix} \vec{\mathbf{J}} \\ \vec{\mathbf{J}}_5 \end{pmatrix} = \begin{pmatrix} \sigma & \sigma_5 \mu_5 \\ \sigma_{\chi e} \mu \mu_5 & \sigma_5 \mu \end{pmatrix} \begin{pmatrix} \vec{\mathbf{E}} \\ \vec{\mathbf{B}} \end{pmatrix}$$

*** Chiral Magnetic Effect (CME)**
[Vilenkin, 1980; Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

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

*** Chiral Separation Effect (CSE)**
[Son, Zhitnitsky,2004; Metlitski,Zhitnitsky,2004;…]

$$\vec{\mathbf{J}}_5 = \sigma_5 \mu \vec{\mathbf{B}}$$

*** Chiral Electric Separation Effect (CESE)**
[Huang, JL, 2013; Jiang, Huang, JL, 2014;…]

$$\vec{\mathbf{J}}_5 = \sigma_{\chi e} \mu \mu_5 \vec{\mathbf{E}}$$

A Chiral QGP?!

* **The Chiral Magnetic (CME) is an anomalous transport**

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

P odd
CP even

P even
CP odd

A Chiral QGP?!

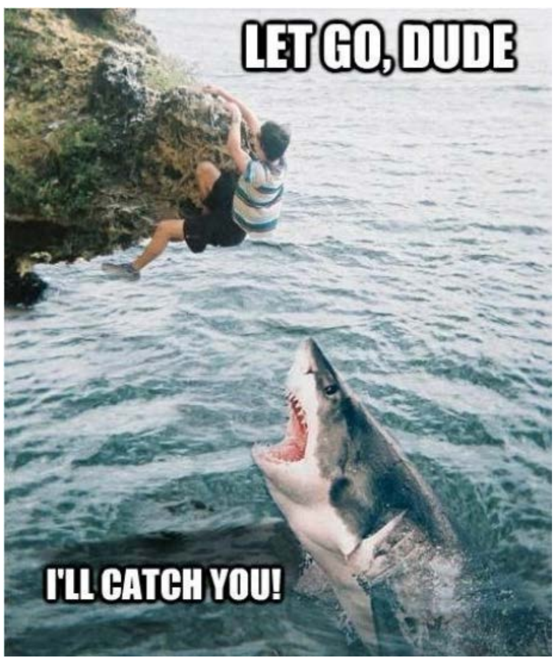
*** The Chiral Magnetic (CME) is an anomalous transport**

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

P odd
CP even

P even
CP odd

In NORMAL environment, this will NOT happen.



A Chiral QGP?!

* The Chiral Magnetic (CME) is an anomalous transport

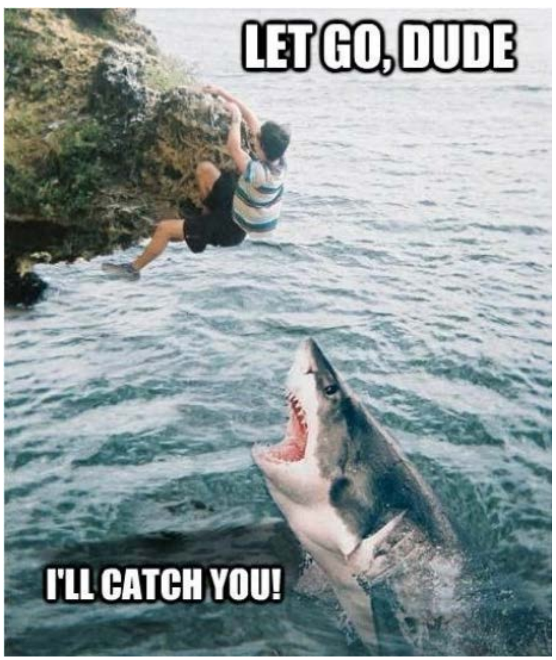
$$\vec{J} = \sigma_5 \mu_5 \vec{B}$$

P odd
CP even

P even
CP odd

In NORMAL environment, this will NOT happen.

For this to occur: need a P- and CP-Odd environment!



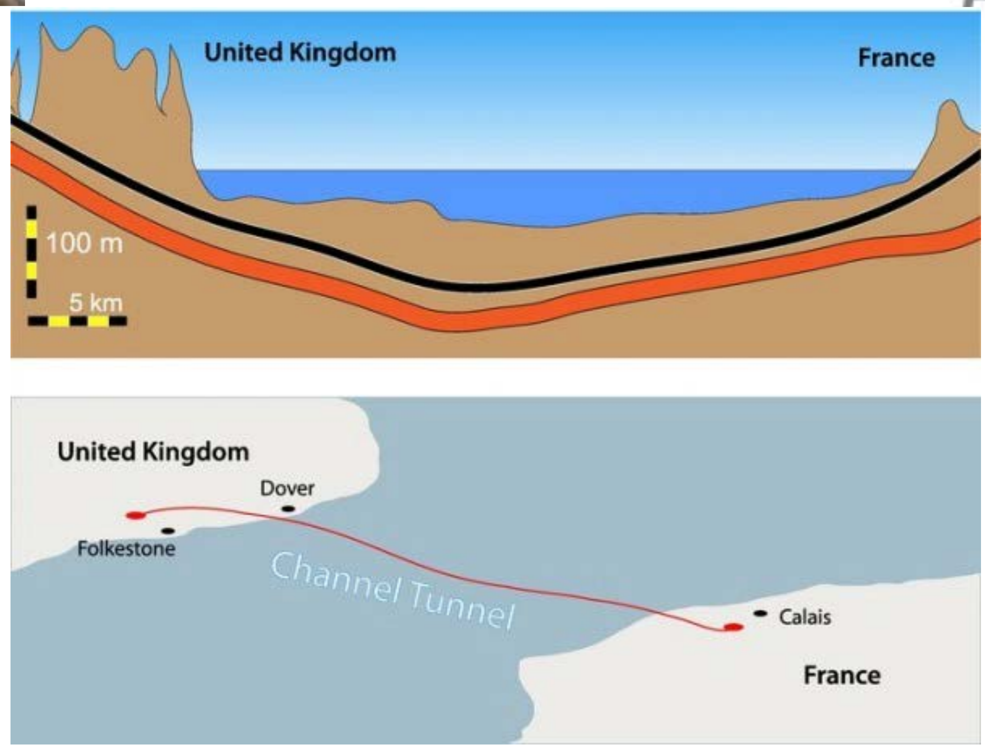
μ_5

A (convenient) way to quantify
IMBALANCE
in the numbers of
LH vs RH chiral fermions
—>
A CHIRAL QGP!

But how to get that in the 1st place?

Between RH & LH World…

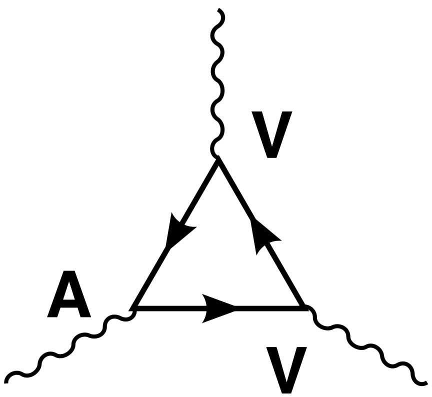
Between RH & LH World…



Leaping between RH & LH Worlds, you only need a TUNNEL!

All You Need is E-dot-B!

**** The "TUNNEL" we need, is provided by <u>E-dot-B</u>,***
thanks to <u>CHIRAL ANOMALY</u> , another fundamental property!



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

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

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

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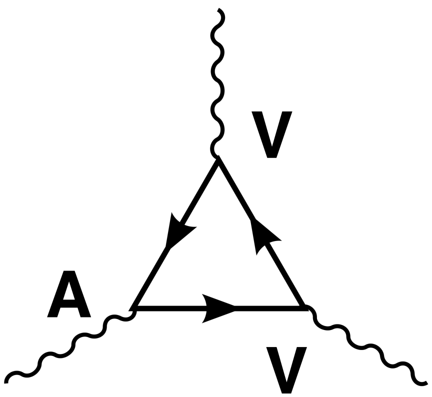

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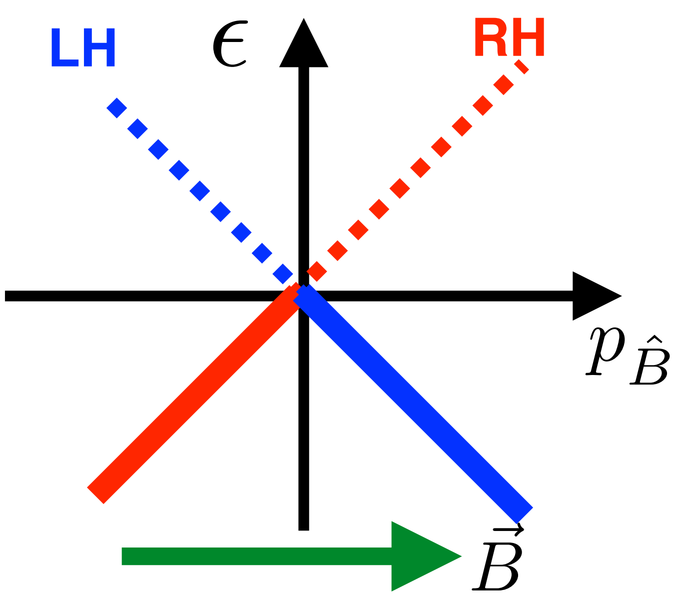

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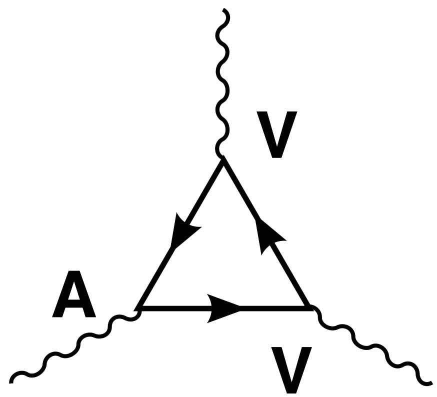

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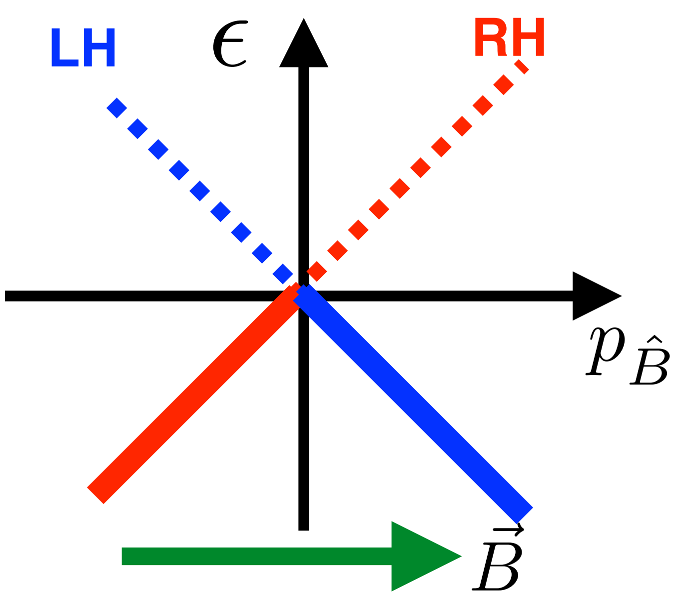
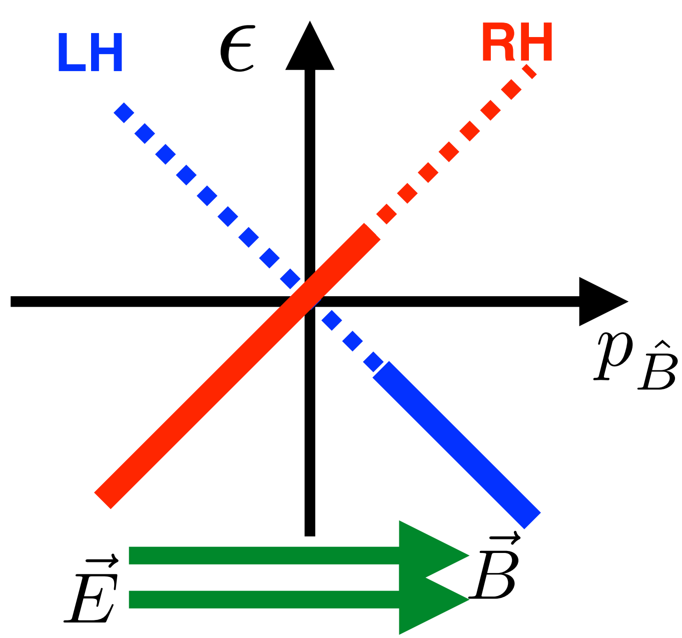
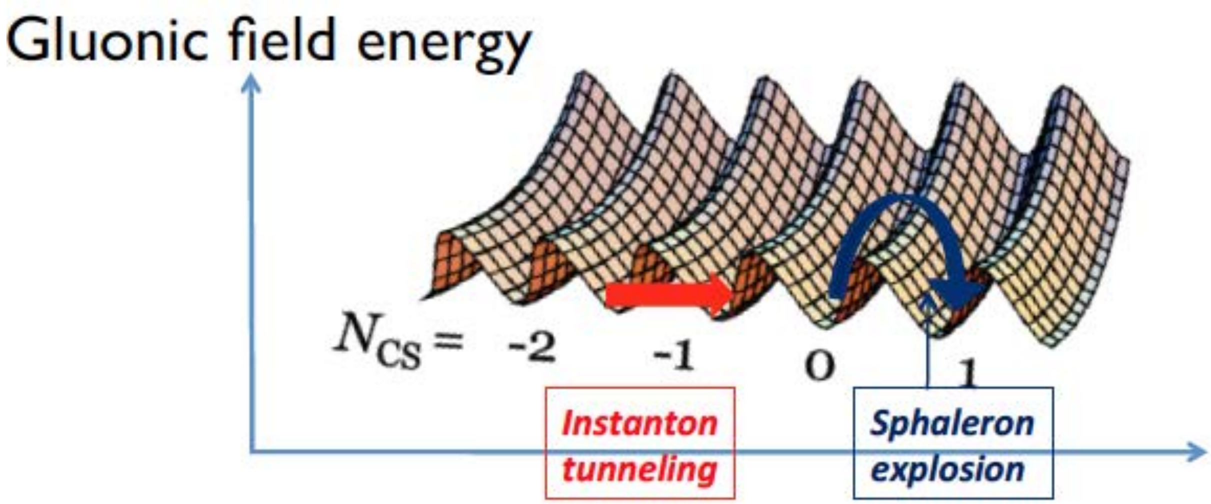


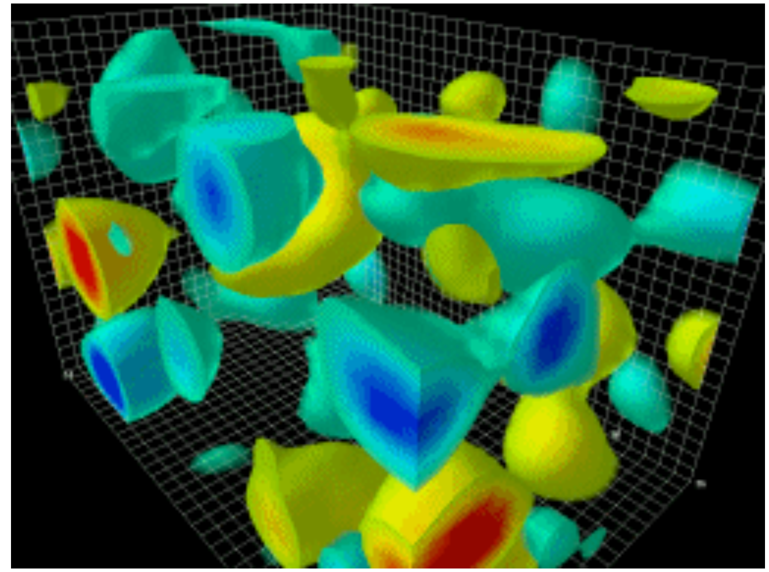


Topological Objects Provide E-dot-B

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



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

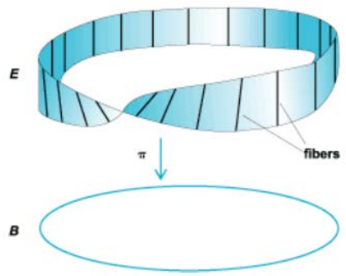


Lattice QCD Visualization

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

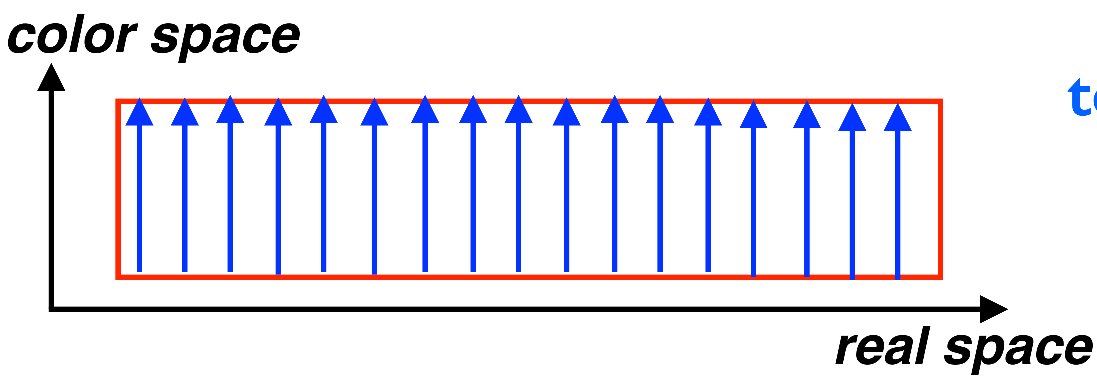
P & CP ODD

Topological Objects Provide E-dot-B



Möbius strip, the simplest nontrivial example of a fiber bundle

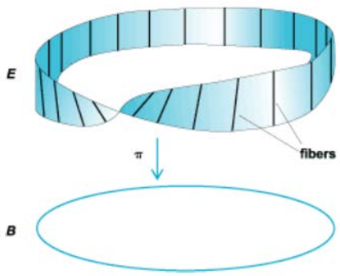
The Mobius Strip is a neat example to illustrate the gauge field topology.



# 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



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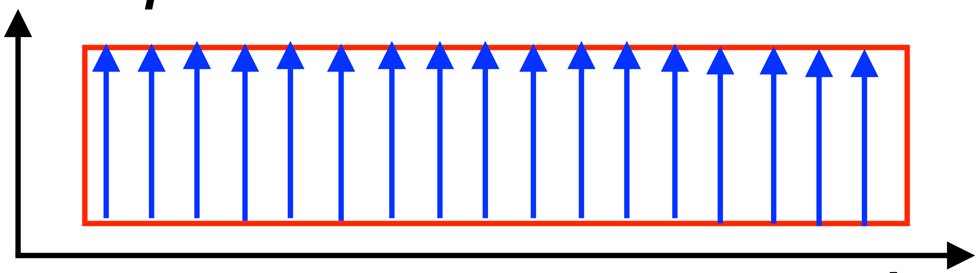

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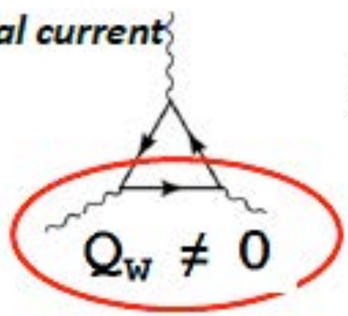


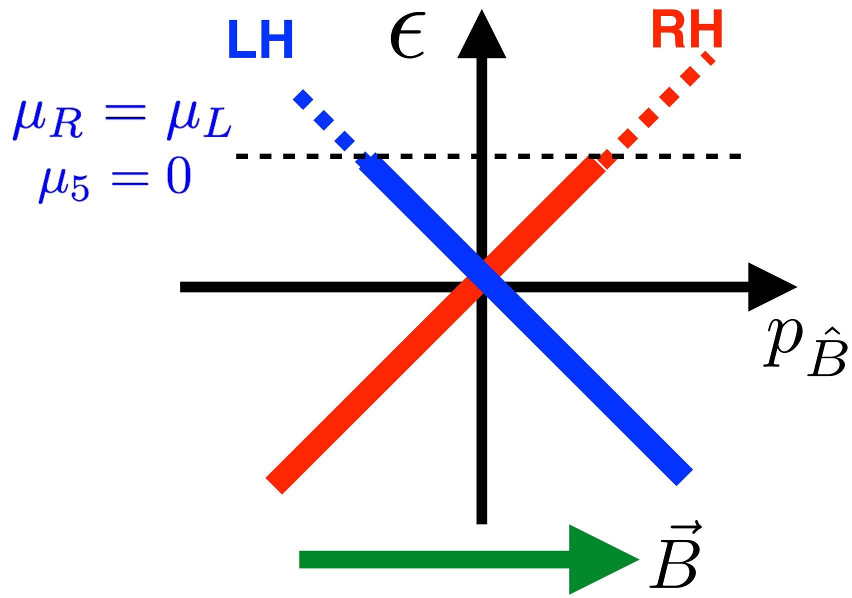
$$\partial^\mu j_\mu^5 = 2\sum_f m_f \langle \bar{\psi}_f i\gamma_5 \psi_f \rangle_A - \frac{N_f g^2}{16\pi^2} F_{\mu\nu}^a \tilde{F}_a^{\mu\nu}$$

$$\boxed{(N_L^f - N_R^f) = 2Q_w}$$

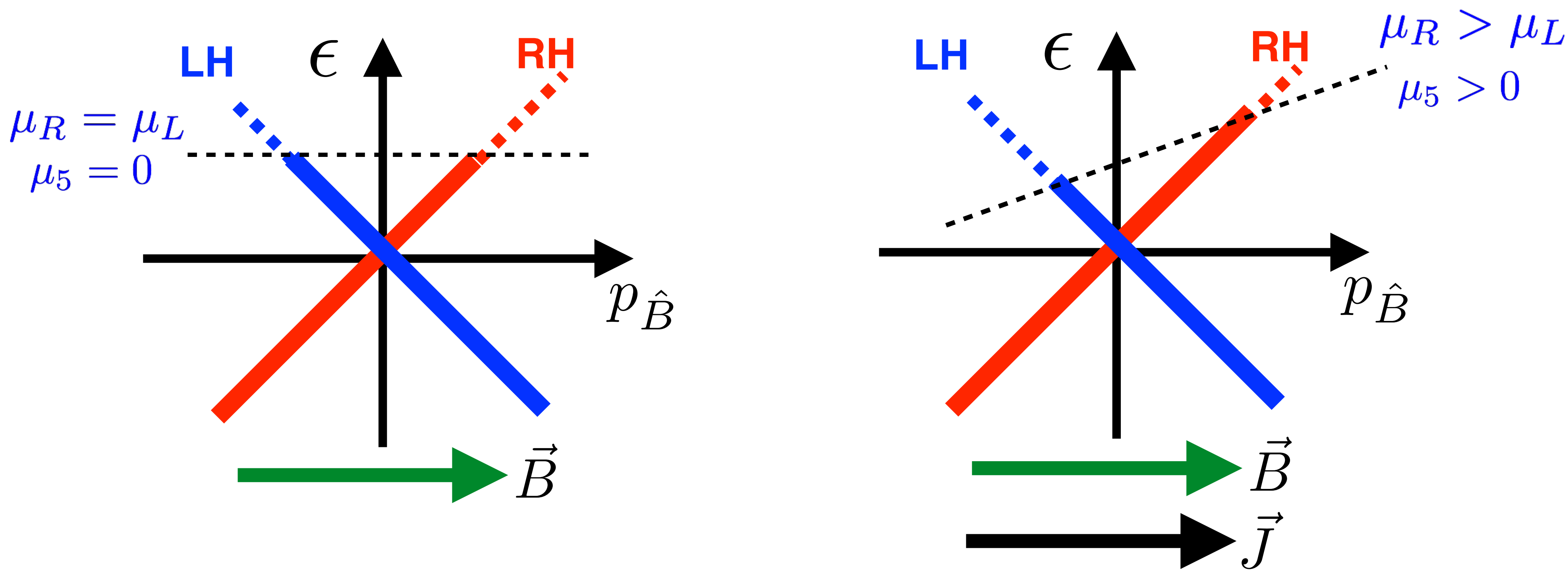
Nonzero topological charge generates chirality change

Chirality imbalance <——> QCD topological fluctuations!

So How Does CME Work?

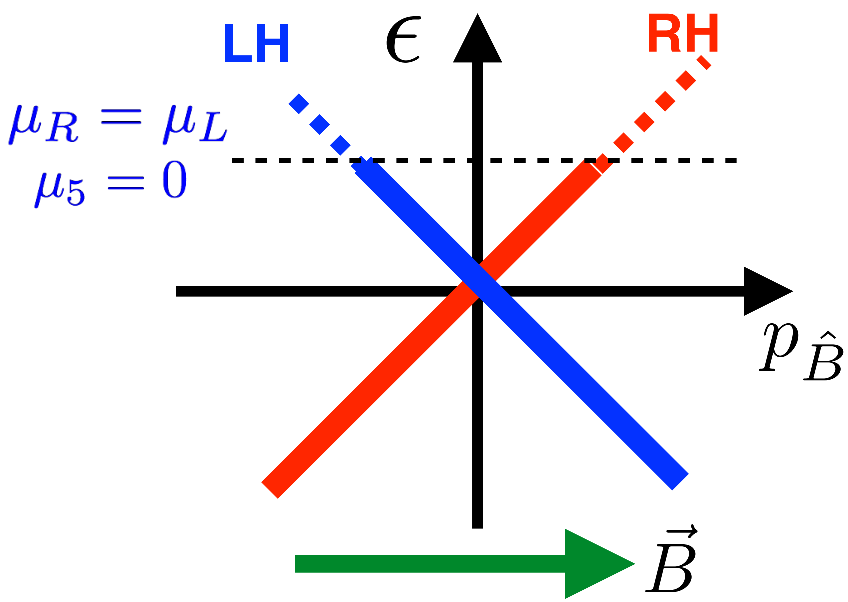


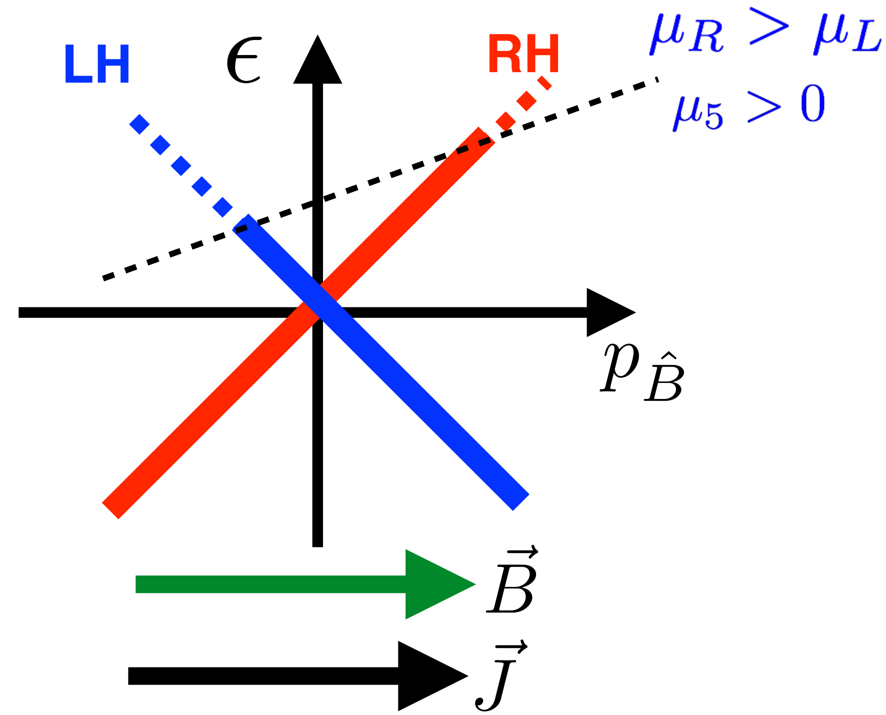
So How Does CME Work?



One may recognize strong similarity between CME & anomaly.

So How Does CME Work?





One may recognize strong similarity between CME & anomaly.

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

$$\updownarrow$$

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

The CME conductivity is

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

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

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

Macro Transport from Micro Quantum Anomaly

Theoretical challenge: how to understand and formulate the macroscopic manifestations of chiral anomaly in many-body system?

**** How to modify kinetic theory?***

**** How to modify hydrodynamics?***

Experimental challenge: can we observe anomaly driven transport in real many-body systems?

**** Quark-gluon plasma in heavy ion collisions***

**** Dirac & Weyl semi-metals***

Chiral Kinetic Theory

Chiral fermions out-of-equilibrium: how anomaly shows up?

[Son, Yamamoto; Stephanov, Yin; Chen, Son, Stephanov, Yee, Yin; Gao, Liang, Pu, Wang, Wang;…: 2012~2015]

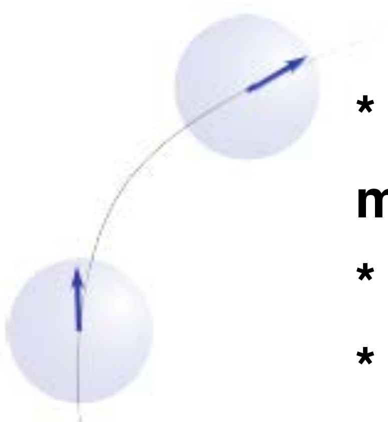
$$\frac{df}{dt} \equiv \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \boldsymbol{x}}\dot{\boldsymbol{x}} + \frac{\partial f}{\partial \boldsymbol{p}}\dot{\boldsymbol{p}} = C[f]$$

$$\dot{\boldsymbol{x}} - \boldsymbol{v} - \overbrace{\dot{\boldsymbol{p}} \times \boldsymbol{b}}^{\text{anom. velocity}} = 0;$$

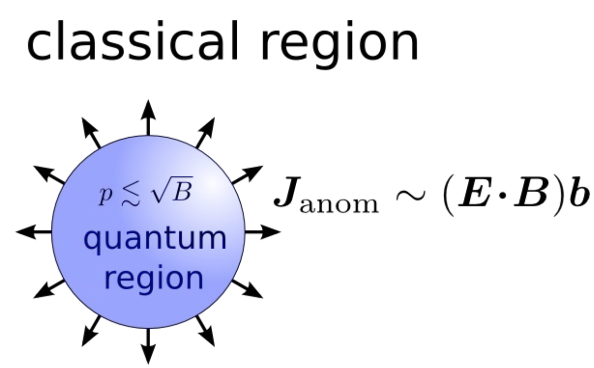
$$\dot{\boldsymbol{p}} - \boldsymbol{E} - \dot{\boldsymbol{x}} \times \boldsymbol{B} = 0;$$

$$\boldsymbol{b} = \frac{\hat{\boldsymbol{p}}}{2|\boldsymbol{p}|^2}$$

Berry curvature



* **Definite chirality: Spin "rotates" with momentum —> Berry Phase**
* **CKT: Introducing O(h-bar) quantum effect**
* **Correctly accounting for anomaly effects**



The Chiral Kinetic Theory framework is under rapid development, and will provide the framework for quantitative modeling of anomaly effects for early stage of heavy ion collisions!

Hydrodynamics with Chiral Anomaly

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

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;…]

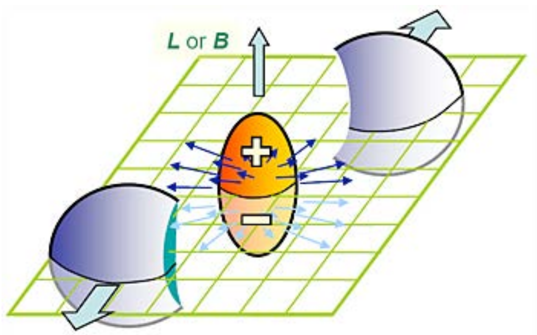
CVE CME

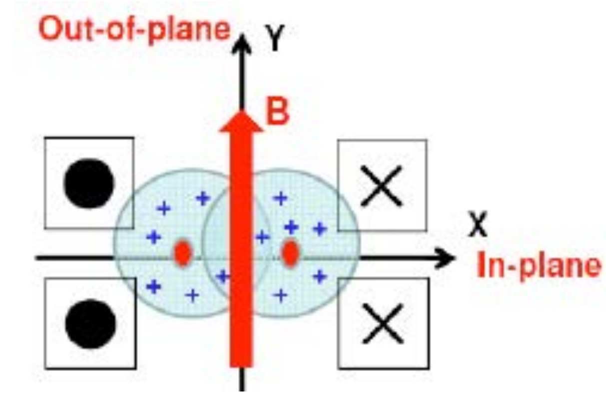
Chiral Fluid: Microscopic Quantum Anomaly manifests itself as macroscopic hydrodynamic currents!

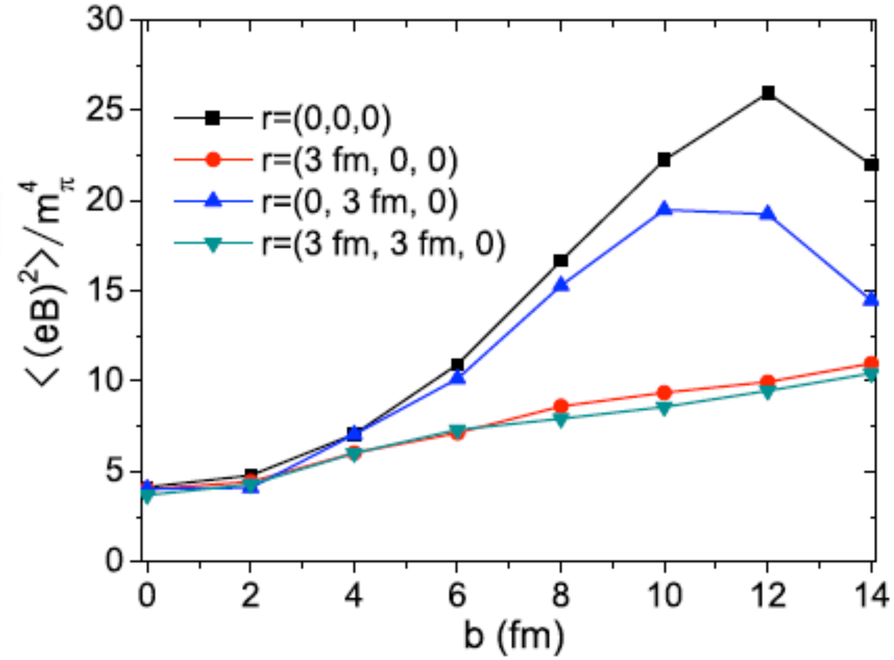
It provides a hydro framework for simulating anomaly effects.
Initial attempts of applying Chiral-Hydro to heavy ion were made.
[Hirano, Hirono; Yin, Yee; Hirono, Hirano, Kharzeev; Yin, Liao;…]

[In passing: fluid rotation induces similar effects as magnetic field]

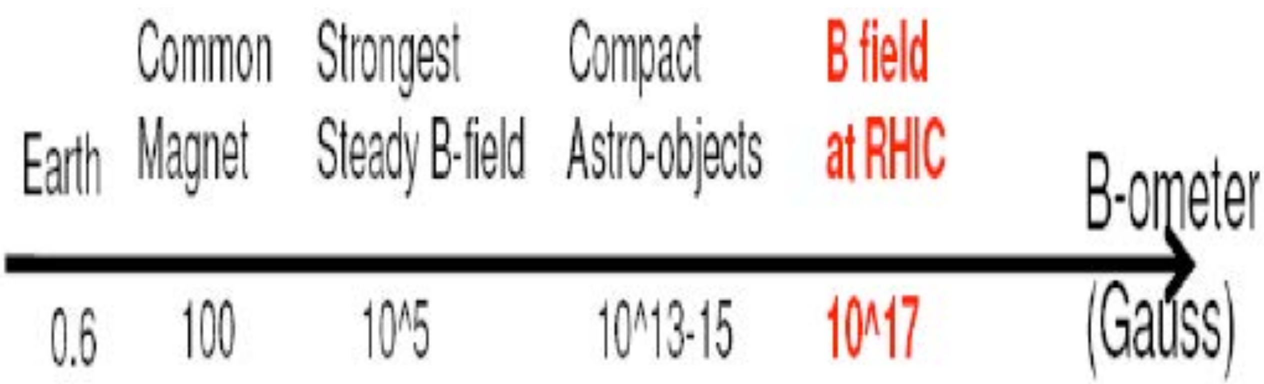
Strong EM Fields in Heavy Ion Collisions







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

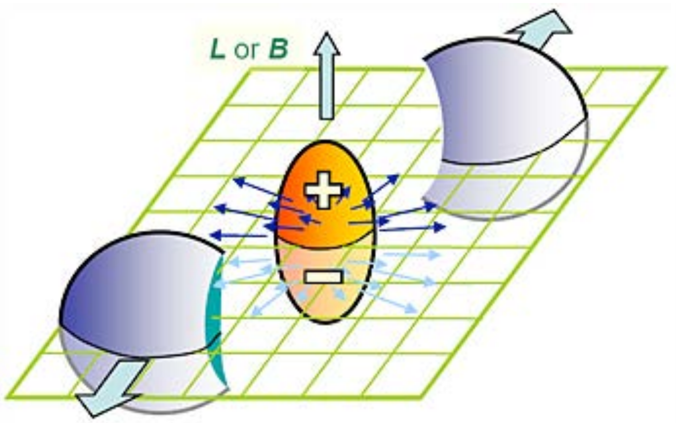


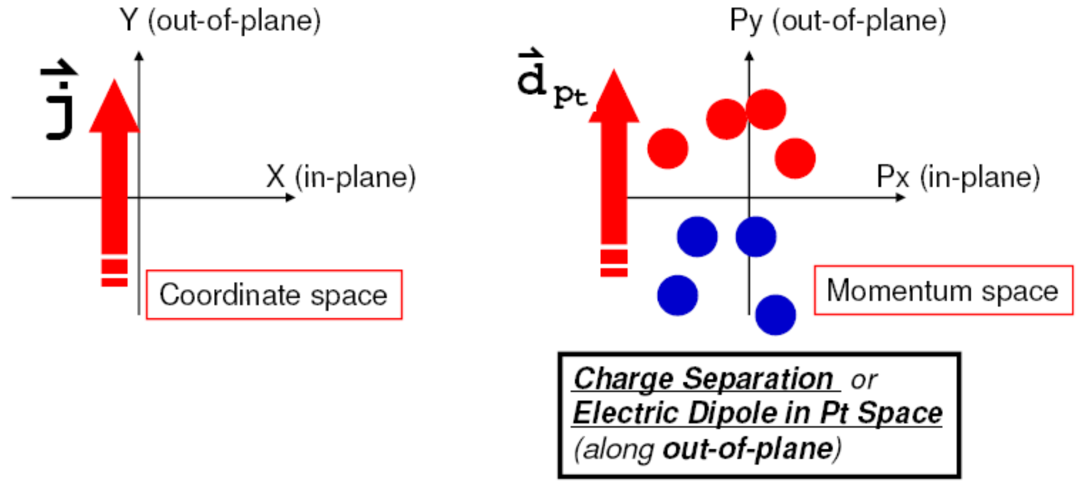
- Strongest B field (and strong E field as well) naturally arises!

[Kharzeev, McLerran, Warringa; Skokov, et al; Bzdak-Skokov; Deng-Huang; Bloczynski-Huang-Zhang-Liao; Skokov-McLerran; Tuchin; ...]

- "Out-of-plane" orientation (approximately)

From CME Current to Charge Separation





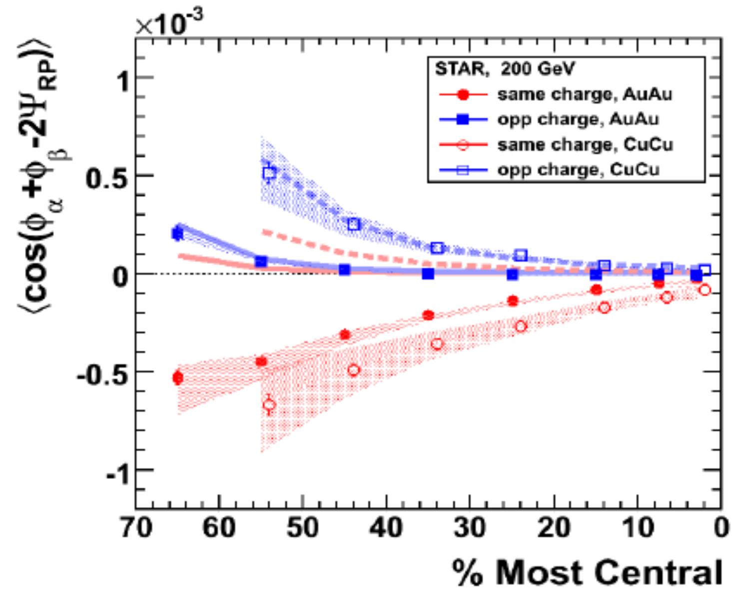
[Kharzeev 2004; Kharzeev, McLerran, Warringa,2008;…]

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

The dipole flips e-by-e

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

[Voloshin, 2004]

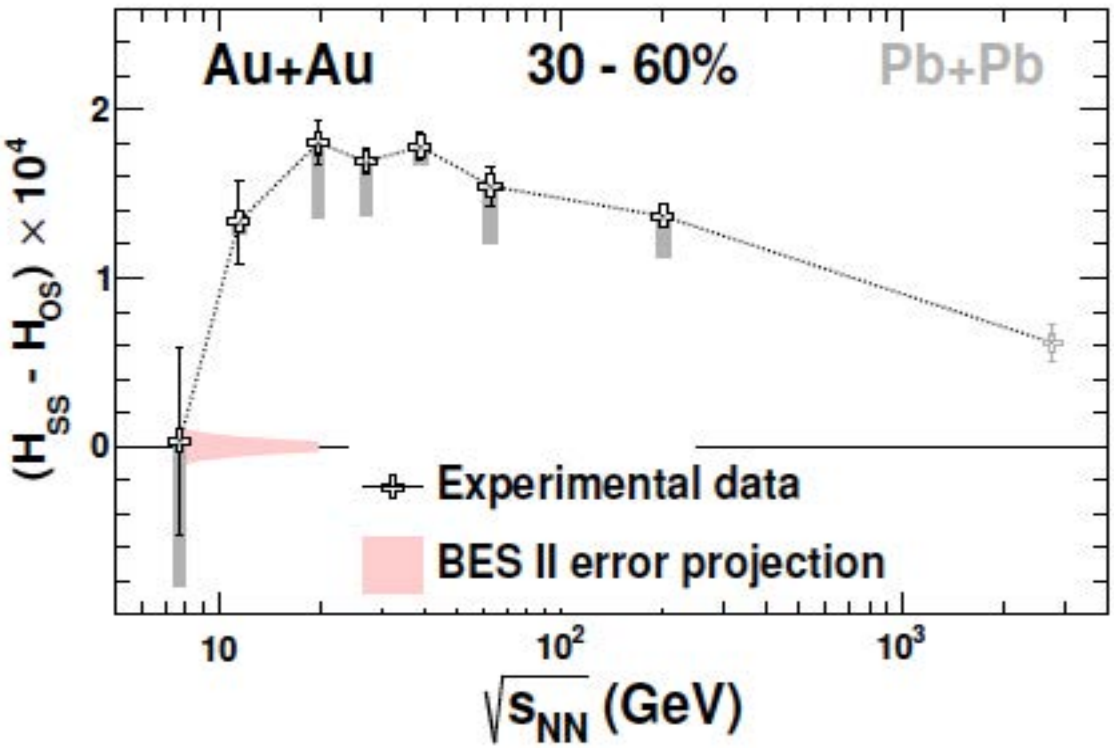


[STAR 2009] ***Data triggered wide initial enthusiasm***

Separation of CME & Flow-Driven Background

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

$$[B_{in} - B_{out}] \sim v_2 \sim \gamma$$



[STAR]

Could one make some sense of data by two-component picture?

$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2)\rangle = F + H,$$

H: "CME Signal"
F: "Flow Driven Background"

[Bzdak, Koch, JL, 2012; Blocynski, Huang, Zhang, JL, 2013]

Toward Quantitative CME

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Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

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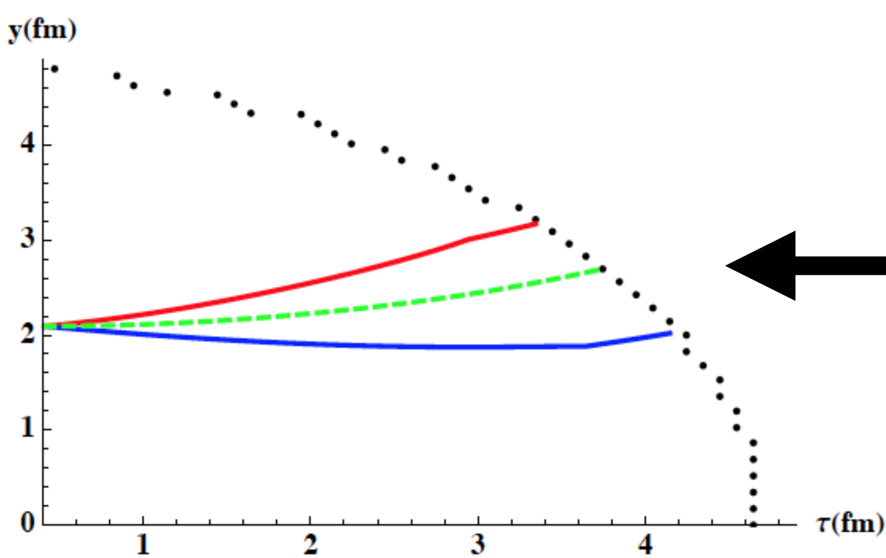
[c] RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA

[Yi Yin, JL, PLB arXiv:1504.06906]



$$\partial_\mu J^\mu = \partial_\mu \left(n u^\mu + Q_f C_A \mu_A B^\mu\right) = 0$$

$$\partial_\mu J^\mu_A = \partial_\mu \left(n_A u^\mu + Q_f C_A \mu_V B^\mu\right) = -Q_f^2 e C_A E_\mu B^\mu$$

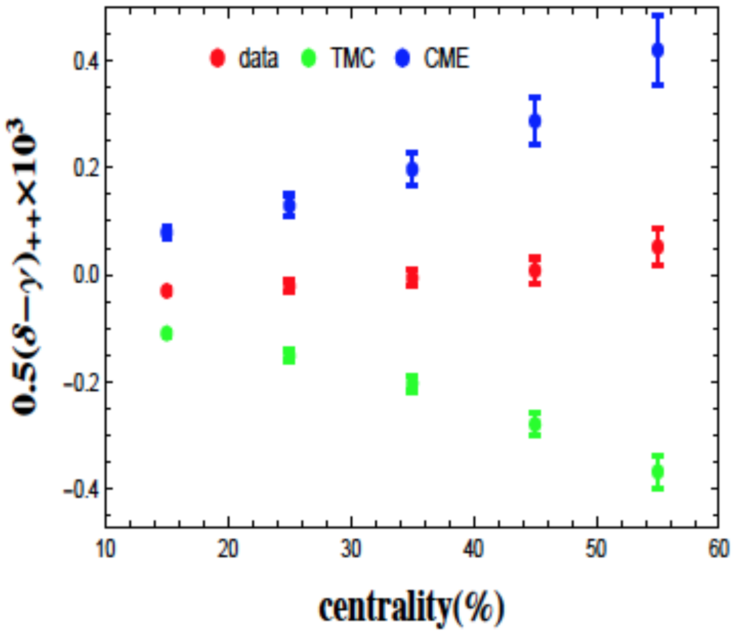
Charge separation!

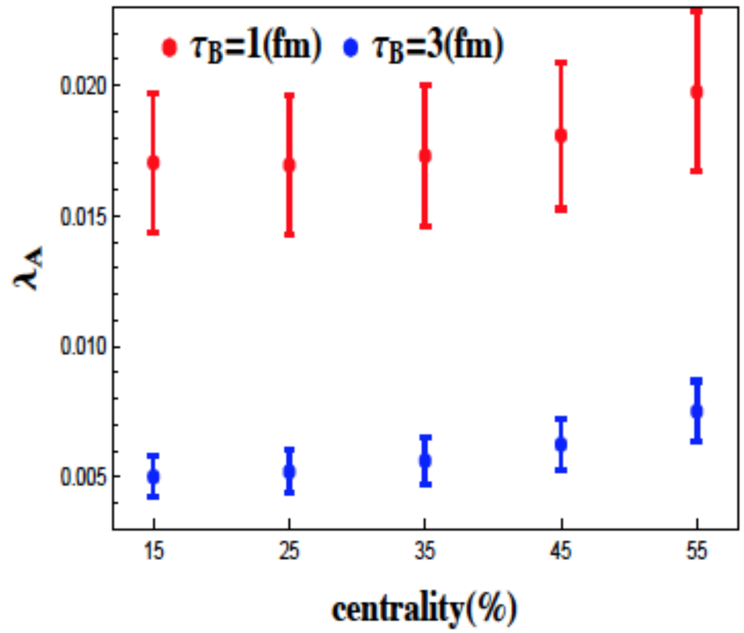
$$\left[\frac{dN^H}{d\phi}\right]_{\rm CME} \propto \left[1 + 2Q^H a_1^H \sin(\phi) + \ldots\right]$$

Toward Quantitative CME

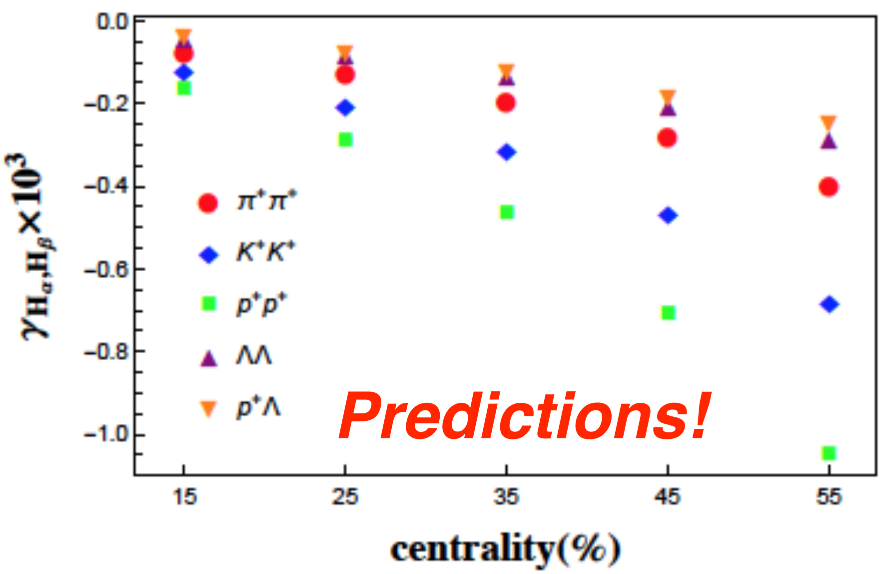
$$\gamma^{\text{data}}_{\alpha,\beta} \simeq \gamma^{CME}_{\alpha,\beta} + \gamma^{TMC}_{\alpha,\beta} \ , \ \delta^{\text{data}}_{\alpha,\beta} \simeq \delta^{CME}_{\alpha,\beta} + \delta^{TMC}_{\alpha,\beta}$$

[Yi Yin, JL, PLB arXiv:1504.06906]





~ percent of initial entropy density, or ~ (0.2GeV)^3 !



Predictions!

The messages:

*** B field lifetime ~ 1fm is OK!**

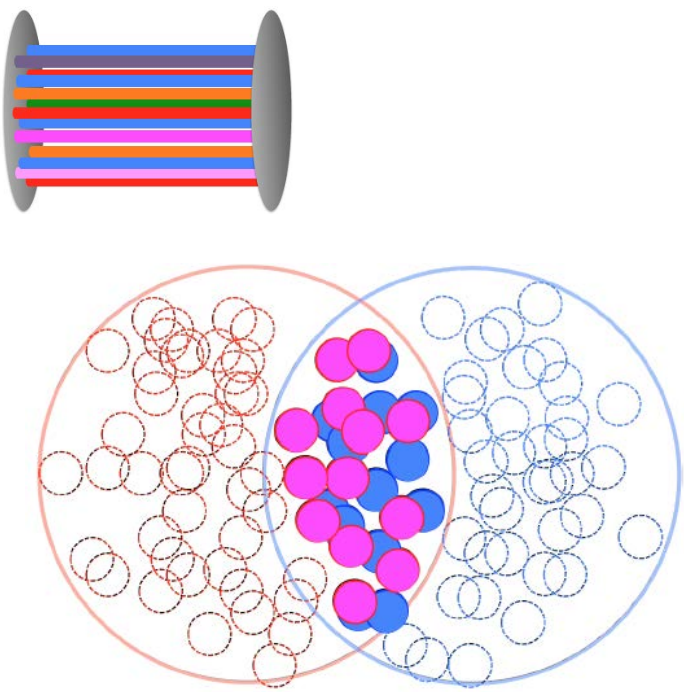
*** Needed axial charge realistic!**

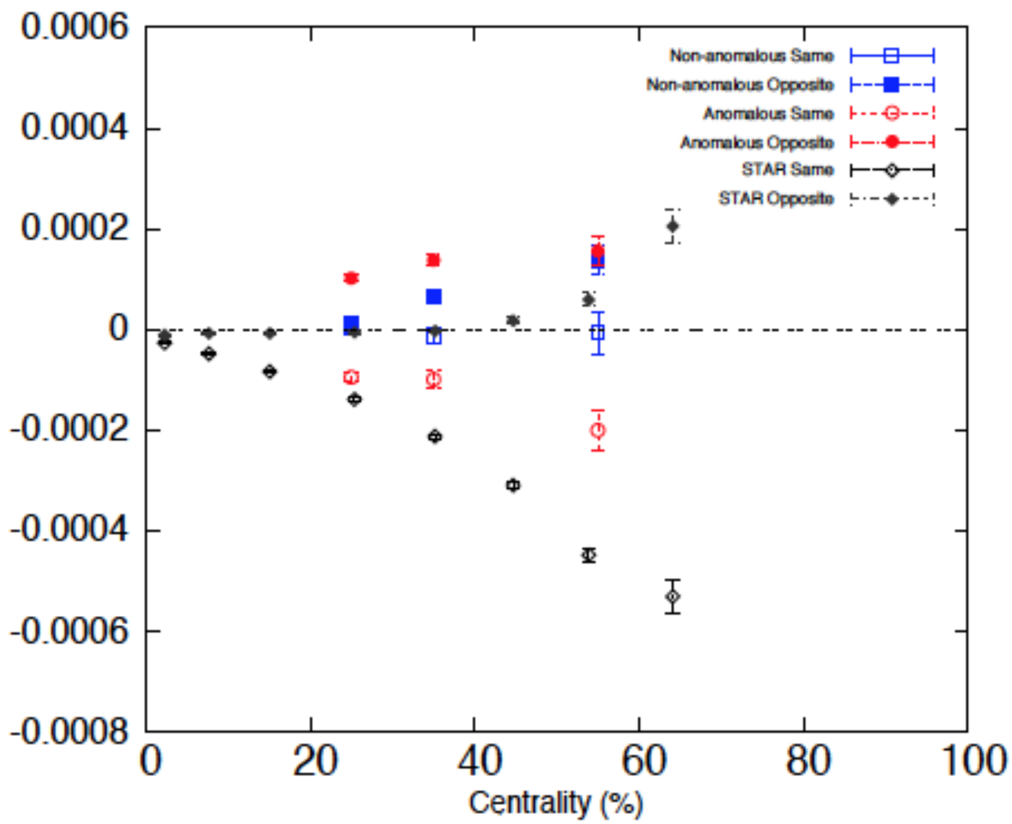
*** Data consistent with CME!**

Toward Quantitative CME

The first event-by-event anomalous hydro simulations with glasma initial conditions for axial charges

[Hirono, Hirano, Kharzeev, arXiv:1412.0311]



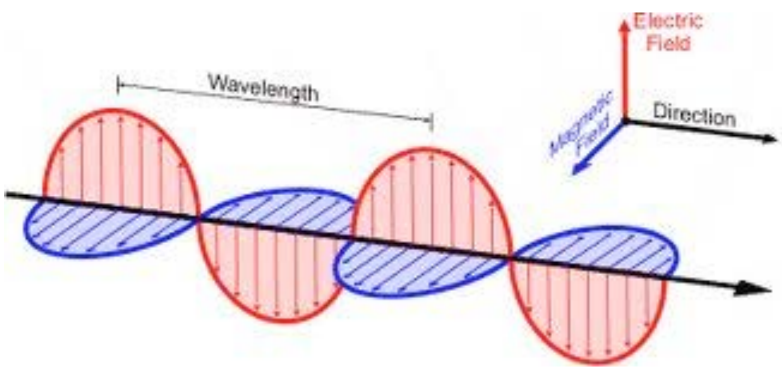


**** The correlations are sensitive to the CME contributions***

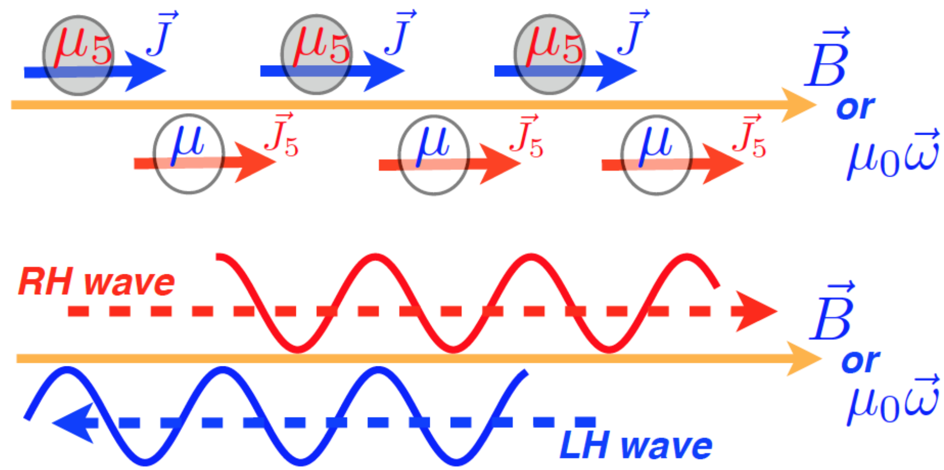
**** Comparison with data suggests "room" for backgrounds.***

Chiral Magnetic Wave (CMW)

Wave: propagating "oscillations" of two coupled quantities
e.g. sound wave (pressure & density); EM wave (E & B fields)



EM wave



Chiral Magnetic Wave

CME + CSE —> gapless collective excitations, the CMW

$$\vec{\mathrm{J}} = \sigma_5 \mu_5 \vec{\mathrm{B}}$$
$$\vec{\mathrm{J}}_5 = \sigma_5 \mu \vec{\mathrm{B}}$$

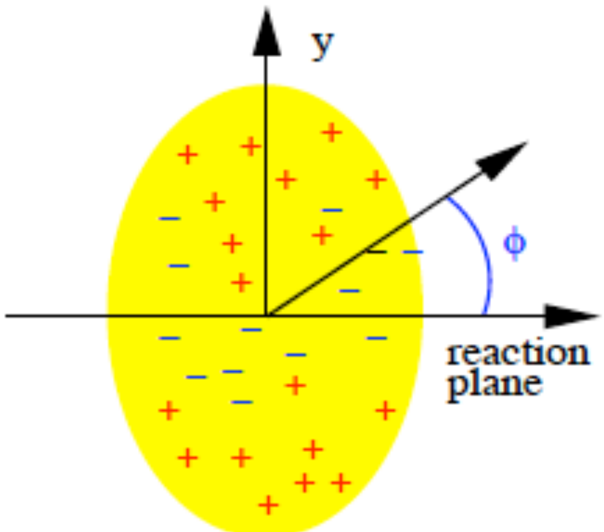
$$\left(\partial_0 \pm \frac{(Qe)}{(4\pi^2)\chi}\vec{\mathrm{B}} \cdot \nabla\right) \delta J^0_{R/L} = \left(\partial_0 \pm v_B \partial_{\hat{\mathrm{B}}}\right) \delta J^0_{R/L} = 0.$$

[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, 2011]

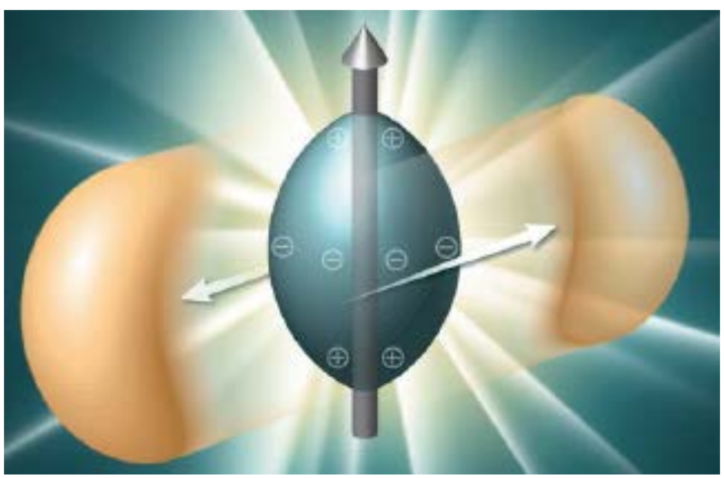
CMW Induced Flow Splitting

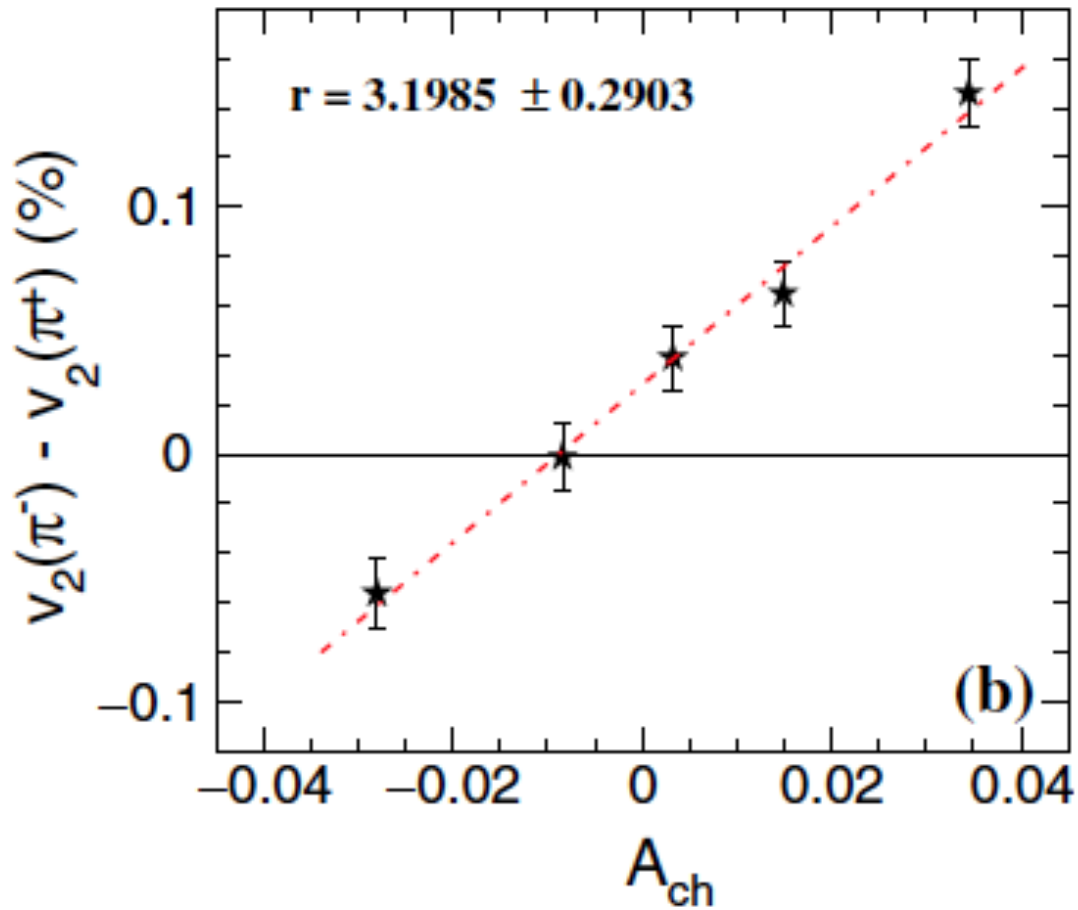
CMW —> charge quadrupole of QGP —> flow splitting

[Kharzeev, Yee, 2010; Burnier, Kharzeev, JL, Yee, PRL2011]



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



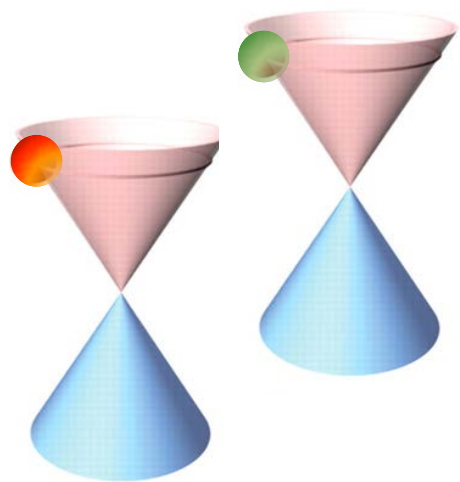


[STAR, PRL2015]

New Territory of CME Search: Table-Top Exp.

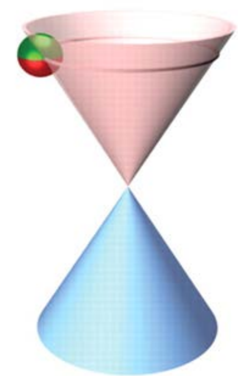
The anomalous transport phenomena are universal phenomena across boundaries of disciplines, encompassing a wide range of chiral systems!

Weyl semimetal
(non-degenerated bands)



TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2

Massless fermion dispersion: $\hat{H}=\hbar v_{\mathrm{F}}\begin{pmatrix} 0 & k_x-ik_y \\ k_x+ik_y & 0 \end{pmatrix}=\hbar v_{\mathrm{F}}\,\boldsymbol{\sigma}\cdot\mathbf{k}$,

These quasiparticles also exhibit chiral anomaly!

New Territory of CME Search: Table-Top Exp.

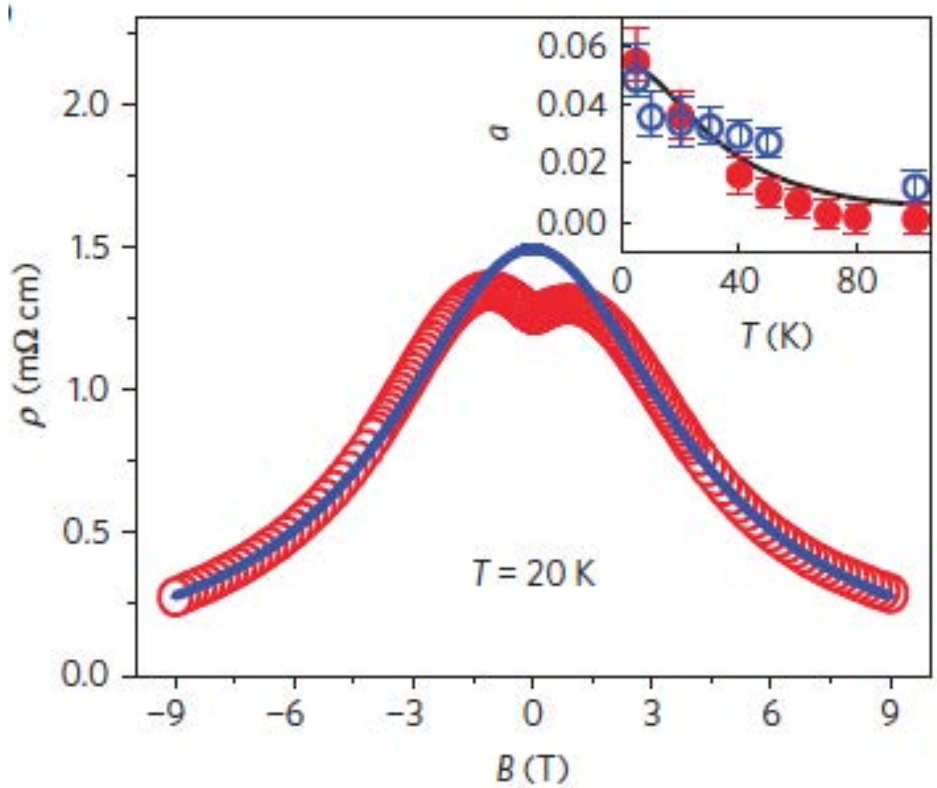
$$N_{L,R} \approx \frac{e^2}{4\pi^2\hbar^2 c}\vec{E}\cdot\vec{B}\tau_v$$

$$\mu \equiv \mu_L - \mu_R \sim \vec{E}\cdot\vec{B}\tau_v$$

$$\vec{J}_{CME} = \frac{e^2}{2\pi^2}\mu\vec{B}$$

$$J^i_{CME} = \sigma^{ik}_{CME}E^k; \quad \sigma^{zz}_{CME} \sim B^2$$

$$\sigma = \sigma_0 + \sigma_{CME} = + \sigma_0 + a(T)B^2$$



nature physics

LETTERS

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Chiral magnetic effect in $ZrTe_5$

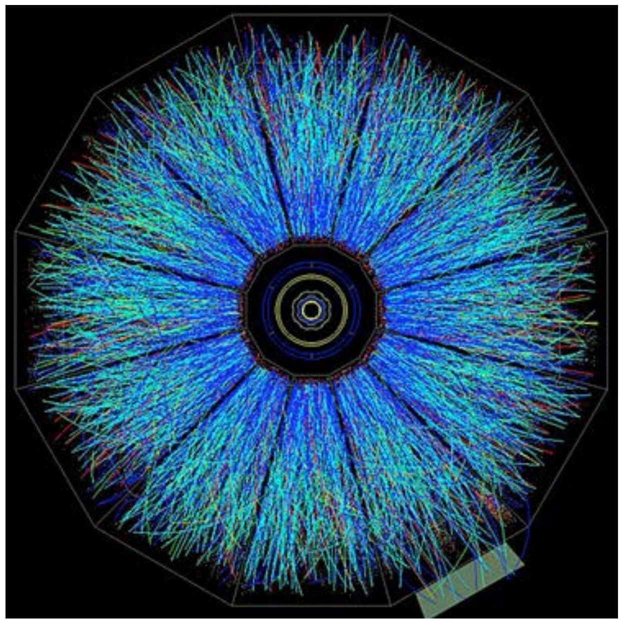
Qiang Li[1★], Dmitri E. Kharzeev[2,3★], Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1★]

arXiv:1412.6543 [cond-mat.str-el]

Summary

An old and new phase of quantum matter:
quark-gluon plasma.

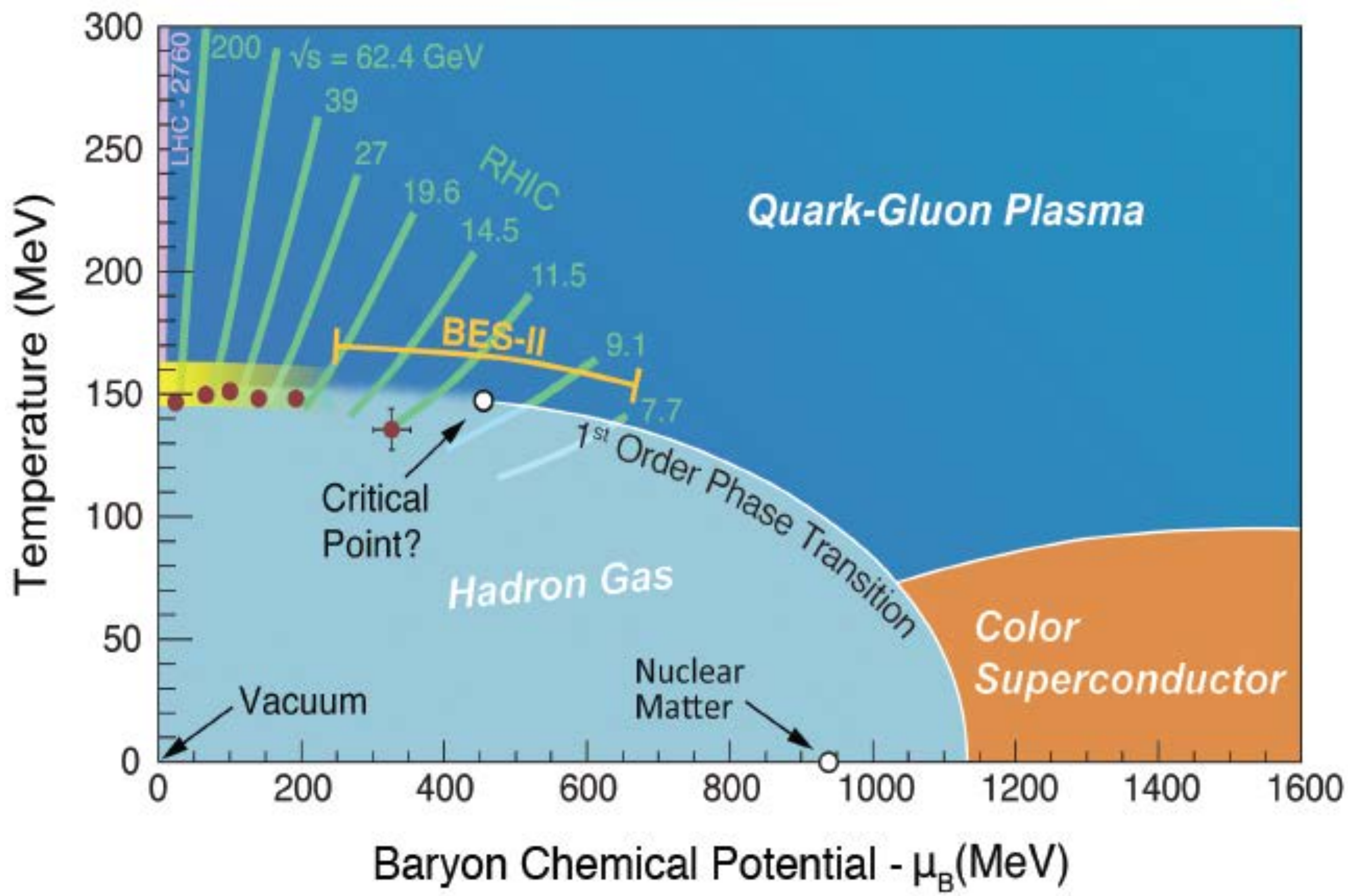
Heavy ion collisions create such QGP
with unprecedented high temperature ~ trillion K.



Microscopic chiral anomaly manifests as
anomalous transport effects in a chiral QGP:
Chiral Magnetic Effect, Chiral Magnetic Wave, …

Toward Physics of Beam Energy Scan

**** Establishing a chiral QGP at higher energy***
**** Searching for chiral critical point or 1st-order transition at lower energy***



Beam Energy Scan Theory (BEST) Collaboration:
BNL, IU, LBNL, McGill U, Michigan State U, MIT, NCSU, OSU, Stony Brook U, U Chicago, U Conn, U Huston, UIC