Extreme Matter in Strong External Electromagnetic Fields

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I am talking about…

Homogeneous *B* effects on the chemical freezeout

- □ Finite-T Inverse Magnetic Catalysis
- □ Hadron Resonance Gas → Electric Fluctuations

KF-Hidaka, PRL117, 102301 (2016)

Interplay between *B* and rotation

- □ Finite-μ Inverse Magnetic Catalysis
- □ Quantum Anomaly

Chen-KF-Huang-Mameda, PRD93, 104052 (2016)
Ebihara-KF-Mameda, 1608.00336 [hep-ph]

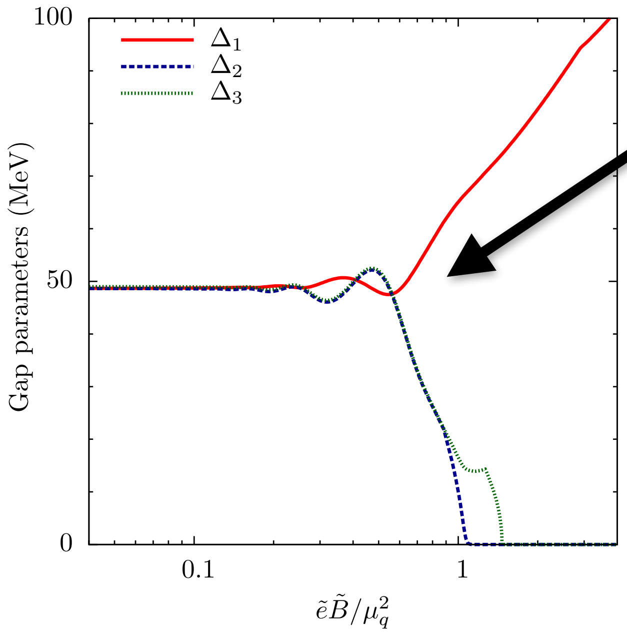
E and inhomogeneous *B* in "worldline formalism"

- □ Dynamically Assisted Schwinger Mechanism
- □ Spatially Assisted Schwinger Mechanism (Magnetic Catalysis)

Copinger-KF, PRL117, 081603 (2016)

B-effects 10 yrs ago (before HIC)

Quark matter (with color-super) in *neutron stars*



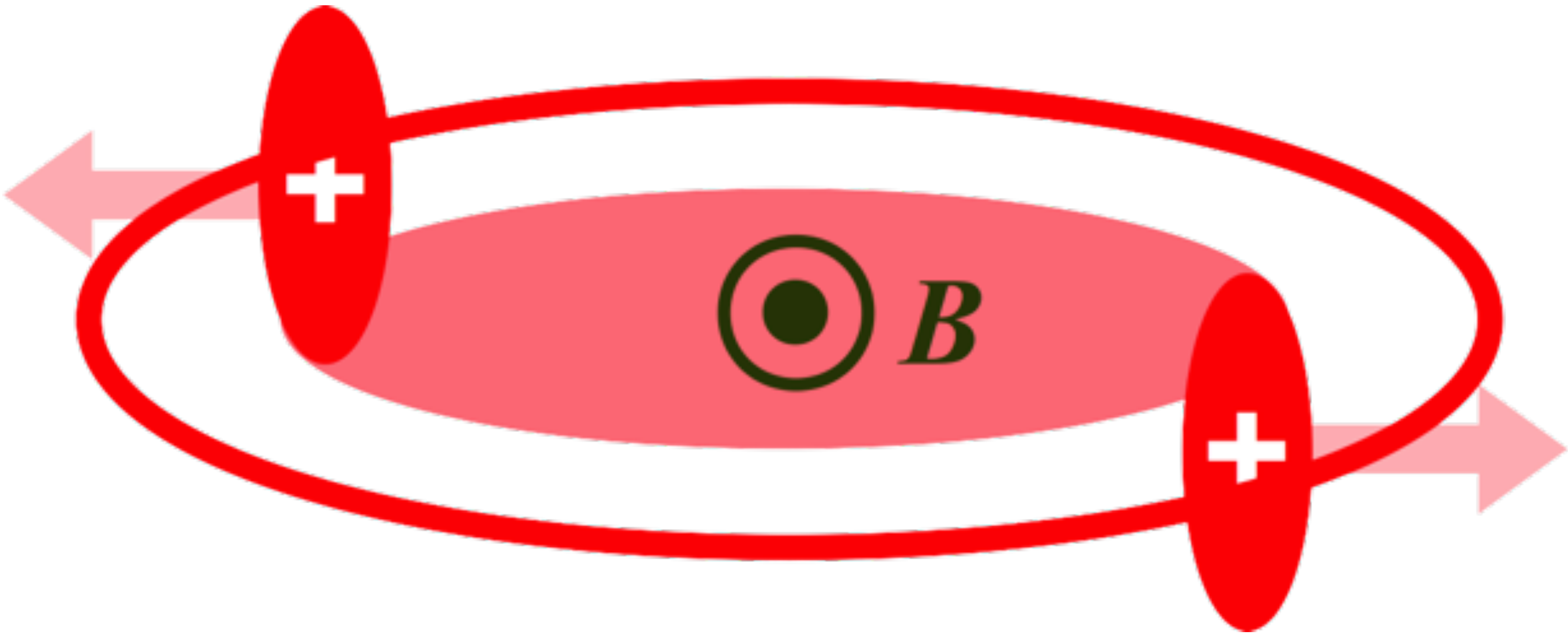
KF-Warringa, PRL100, 032007 (2008)

B*-effects visible only at "unphysically" large *B

eB in Neutron Star
surface: ~ 10^{12} gauss
magnetar: ~ 10^{15} gauss (~10MeV^2)
cores: ~10^{18} gauss (upper bound)

Marginal to affect QCD physics…

B-effects in Heavy-Ion Collisions



Instantaneous, but strongest in the *present* Universe!

GeV-scale (~10^{20} gauss) is a realistic estimate!

Review: X.-G. Huang, 1509.04073 [nucl-th]

***B*-effects must definitely affect QCD physics**

Effects of $eB > (\Lambda_{QCD})^2$ on QCD?

Magnetic Catalysis

Klimenko, Shovkovy, Miransky, Gusynin, Shushpanov, Smilga, …

***B favors* more chiral symmetry breaking**

Inverse Magnetic Catalysis

Preis, Rebhan, Schmitt, etc…

***B disfavors* chiral sym breaking at high μ_B**

Inverse Magnetic Catalysis (Magnetic Inhibition)

Bali, Endrodi, Bruckmann, Schafer, Fodor, Szabo, etc…

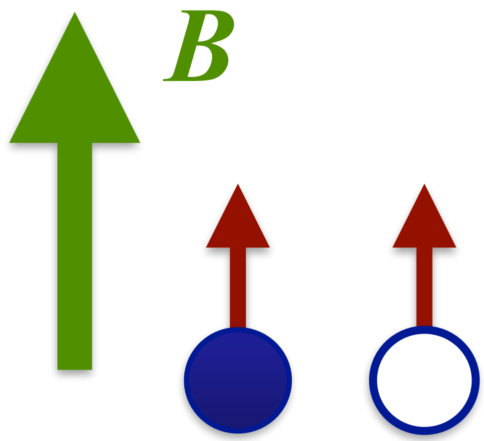
***B disfavors* chiral sym breaking at high T**

Effects of $eB>(\Lambda_{QCD})^2$ *on QCD?*

Magnetic Catalysis

Klimenko, Shovkovy, Miransky, Gusynin, Shushpanov, Smilga, …

B favors **more chiral symmetry breaking**



Scalar condensate : J=0 with S=1 and L=1

NJL / Chiral Perturbation Theory / Lattice

Effects of eB>$(\Lambda_{QCD})^2$ on QCD?

Magnetic Catalysis

Physics understandable in the mean-field level

***B favors* more chiral symmetry breaking**

Inverse Magnetic Catalysis

Physics understandable in the mean-field level

***B disfavors* chiral sym breaking at high μ_B**

Inverse Magnetic Catalysis (Magnetic Inhibition)

Physics *beyond* the mean-field level *Case not closed*

B disfavors* chiral sym breaking at high *T

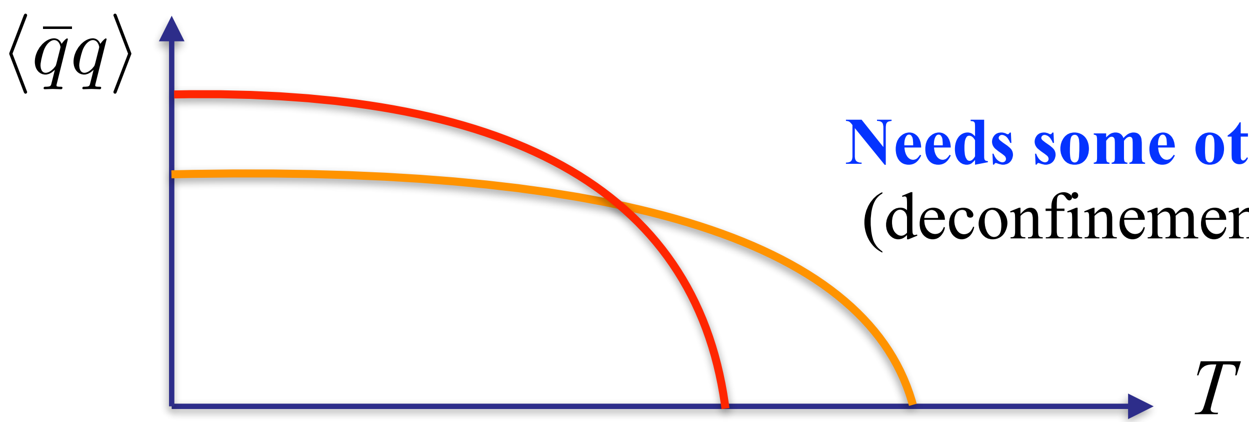
Finite-T Inverse Magnetic Catalysis

Difficulty in understanding the IMC

Critical T in BCS: $T_c \propto \Delta(T=0)$

$\langle \bar{q}q \rangle$ in QCD

Reconcile?
$\langle \bar{q}q \rangle (T=0)$ is increased at finite B
T_c is decreased at finite B



Needs some other dynamics?
(deconfinement / IR meson)

Effects of eB>(Λ_{QCD})^2 on QCD?

Phase Diagram

Klimenko, Shovkovy, Miransky, Gusynin, Shushpanov, Smilga, …

Preis, Rebhan, Schmitt, etc…

Bali, Endrodi, Bruckmann, Schafer, Fodor, Szabo, etc…

Fraga, Noronha, Palhares, Blaizot, Ruggieri, Gatto, etc…

Infinite *B* limit?

Fermions infinitely heavy (quenched limit)
Reduced to anisotropic pure Yang-Mills

1st-order Phase Transition!

Endrodi, Cohen-Yamamoto

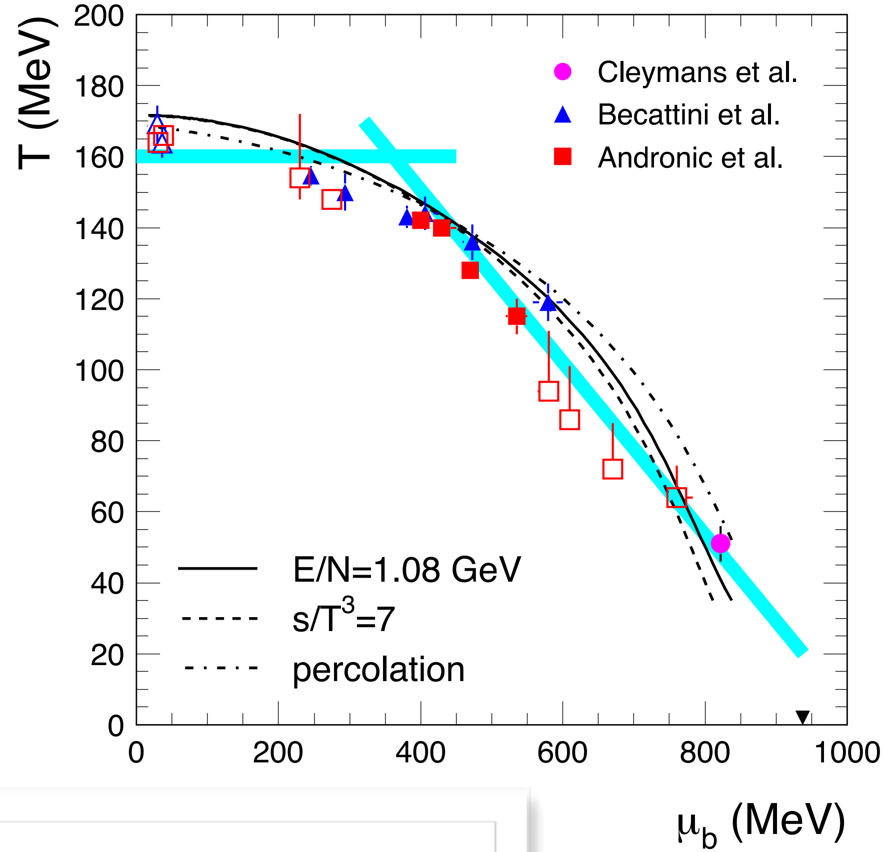
Homogeneous *B* effects on the chemical freezeout

Freezeout ~ Phase Boundaries

Chemical Freezeout

Experimentally seen "Phase Diagram"

Point (T, μ_B, etc) where "inelastic" scattering is turned off (due to changes in inter-particle distance)



Hadron Resonance Gas

$$p_{b/f} = \pm T \sum_{s_z=-s}^{s} \sum_{n=0}^{\infty} \frac{qB}{2\pi} \int \frac{dp_z}{2\pi} \ln(1 \pm e^{-(E-\mu_i Q_i)/T})$$

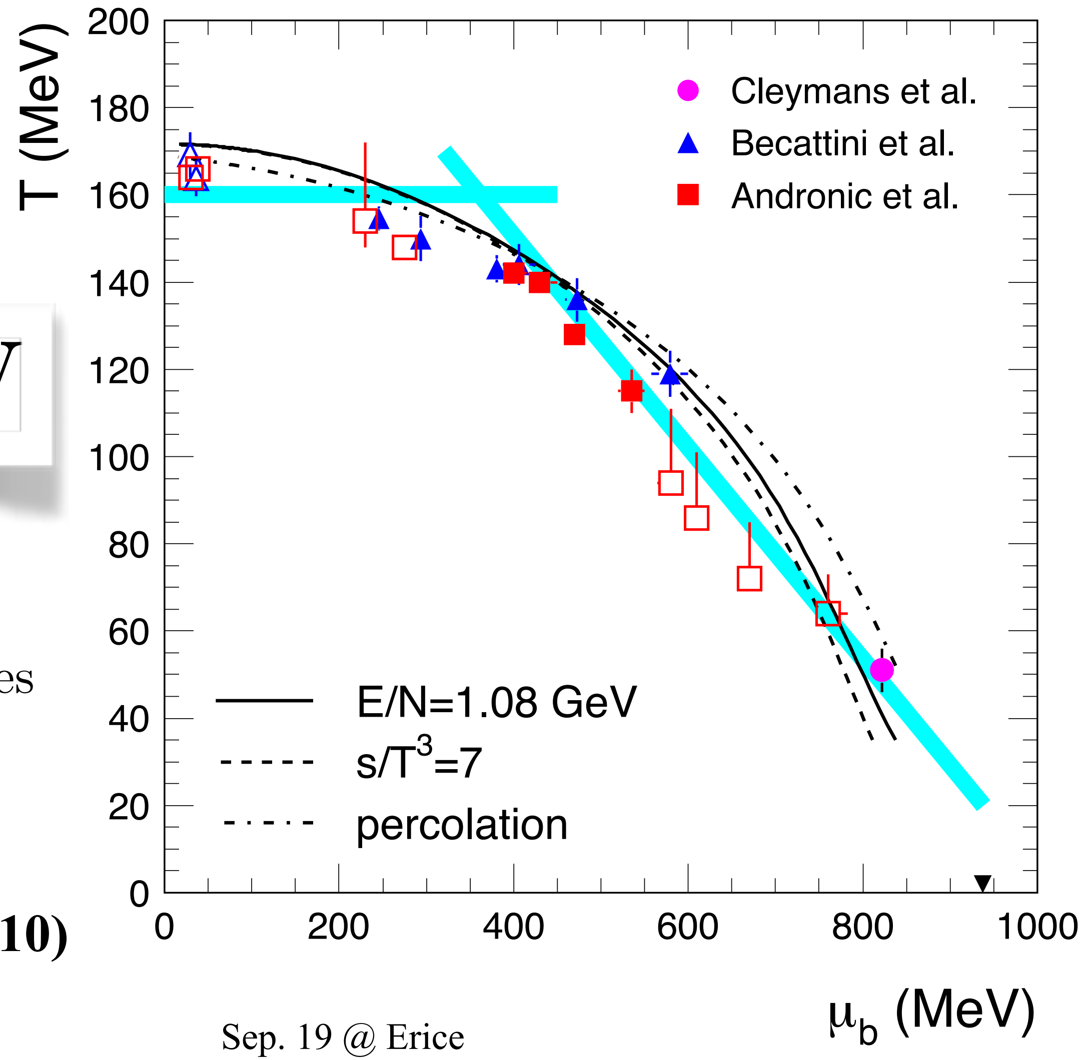
Empirical Freezeout Conditions

Cleymans-Redlich
PRL81, 5284 (1998)

$$E/N \sim 1\text{GeV}$$

E : internal energy

N : particles + antiparticles

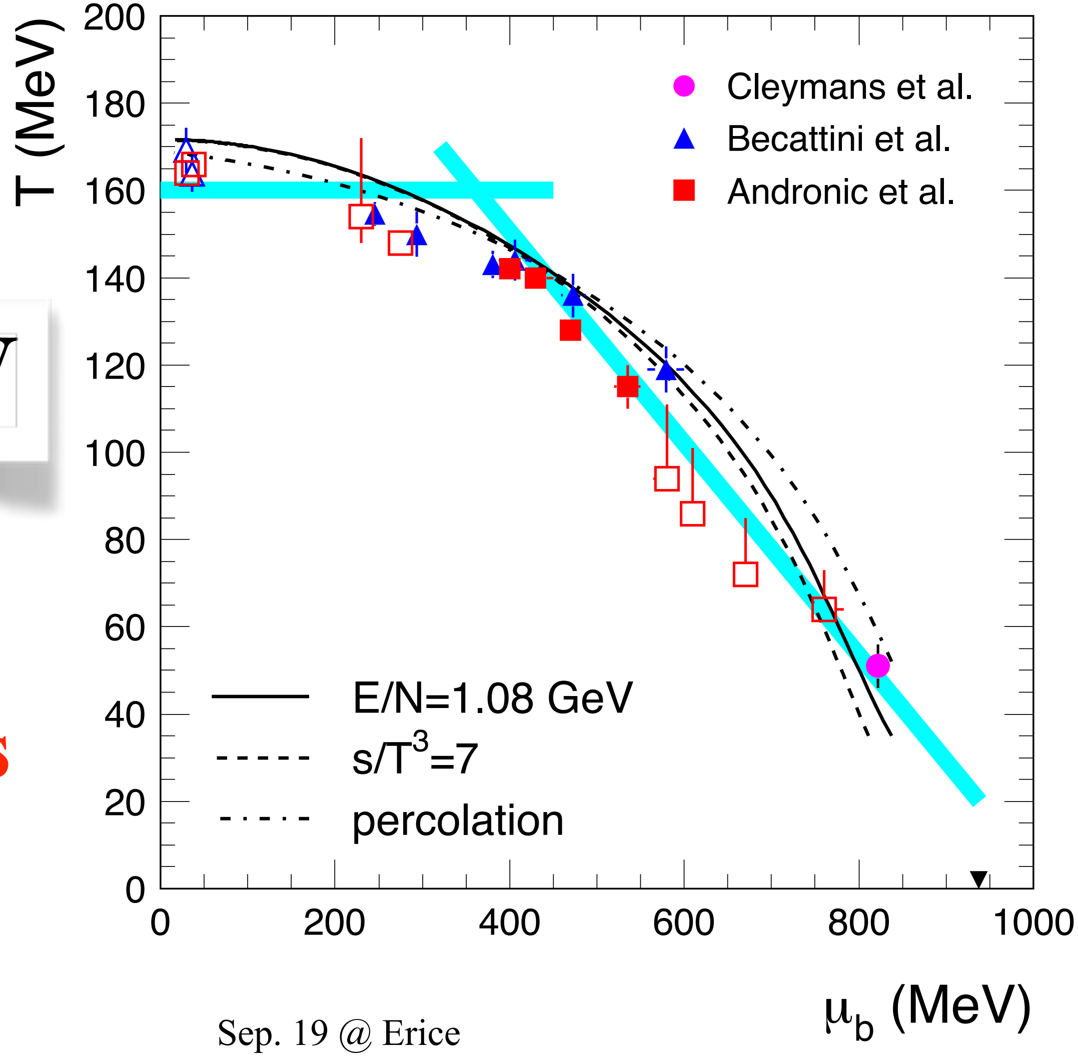


Andronic et al. (2010)

Empirical Freezeout Conditions

Assume:
empirical condition not changed by *B*

$$E/N \sim 1\text{GeV}$$



How these curves modified by *B*?

Landau Quantization

$$\epsilon^2 = p_z^2 + 2|eB|(n+1/2) + m^2 - 2s\,eB$$

Dominated by *n*=0 (Lowest Landau Level)

$$m_{\text{eff}}^2 = m^2 + |eB| - 2s\,eB$$

Effective masses of large spin resonances pushed down significantly — more hadrons

Phase space (Landau degeneracy) enhanced proportional to *eB* — even more hadrons

Things are not so simple

It is not obvious whether the chemical freezeout curves are shifted down in accord to the inverse MC.

With increasing *B* :

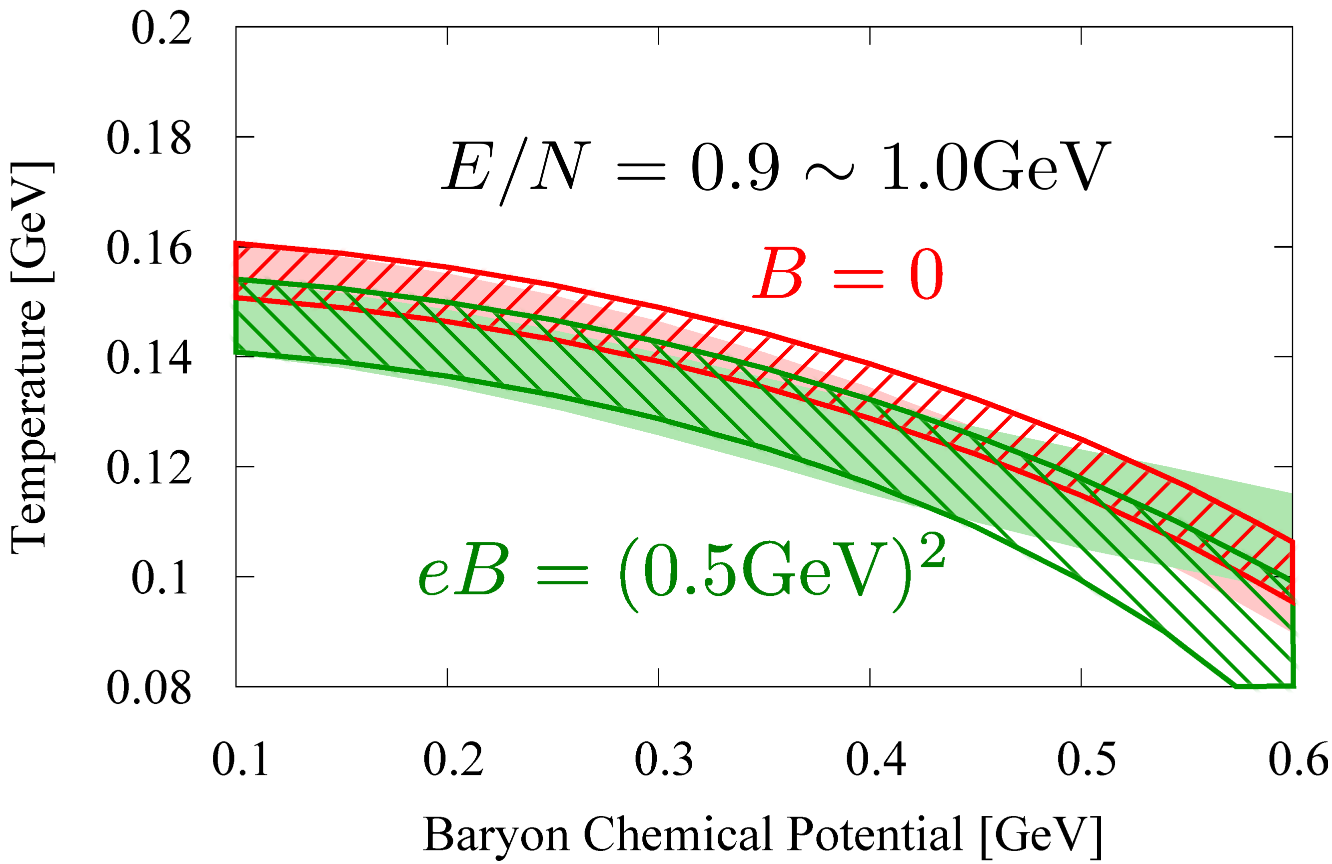
Which is earlier???

- ***E* increases**
- ***N* increases**

$$E/N \sim 1\mathrm{GeV}$$

realized earlier or later?

Shifted Freezeout Curves



Slanted lines

With conservation of S and Q

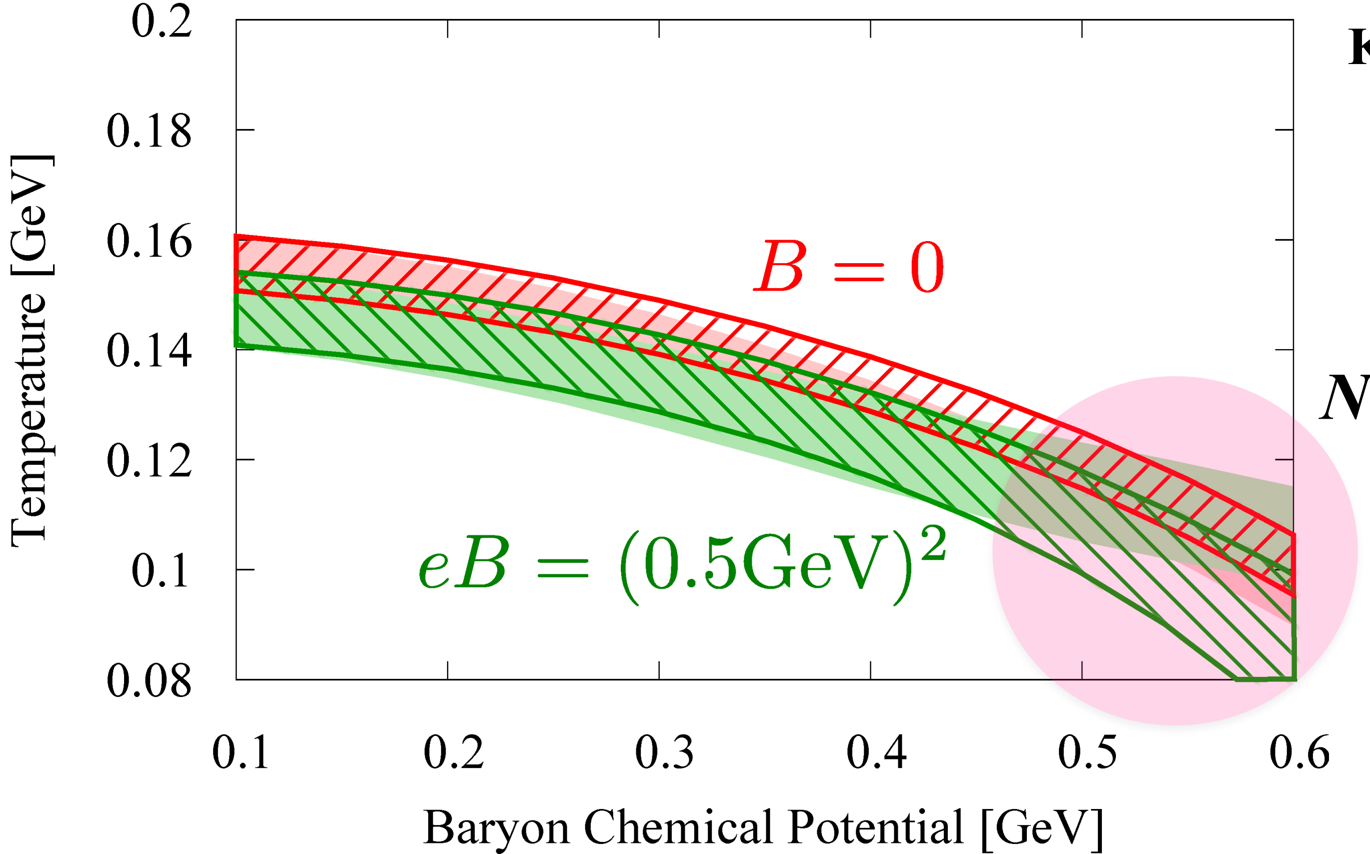
Shaded lines

Without conserv. of S and Q

KF-Hidaka (2016)

NO Puzzle of Inverse Magnetic Catalysis!!!

Shifted Freezeout Curves



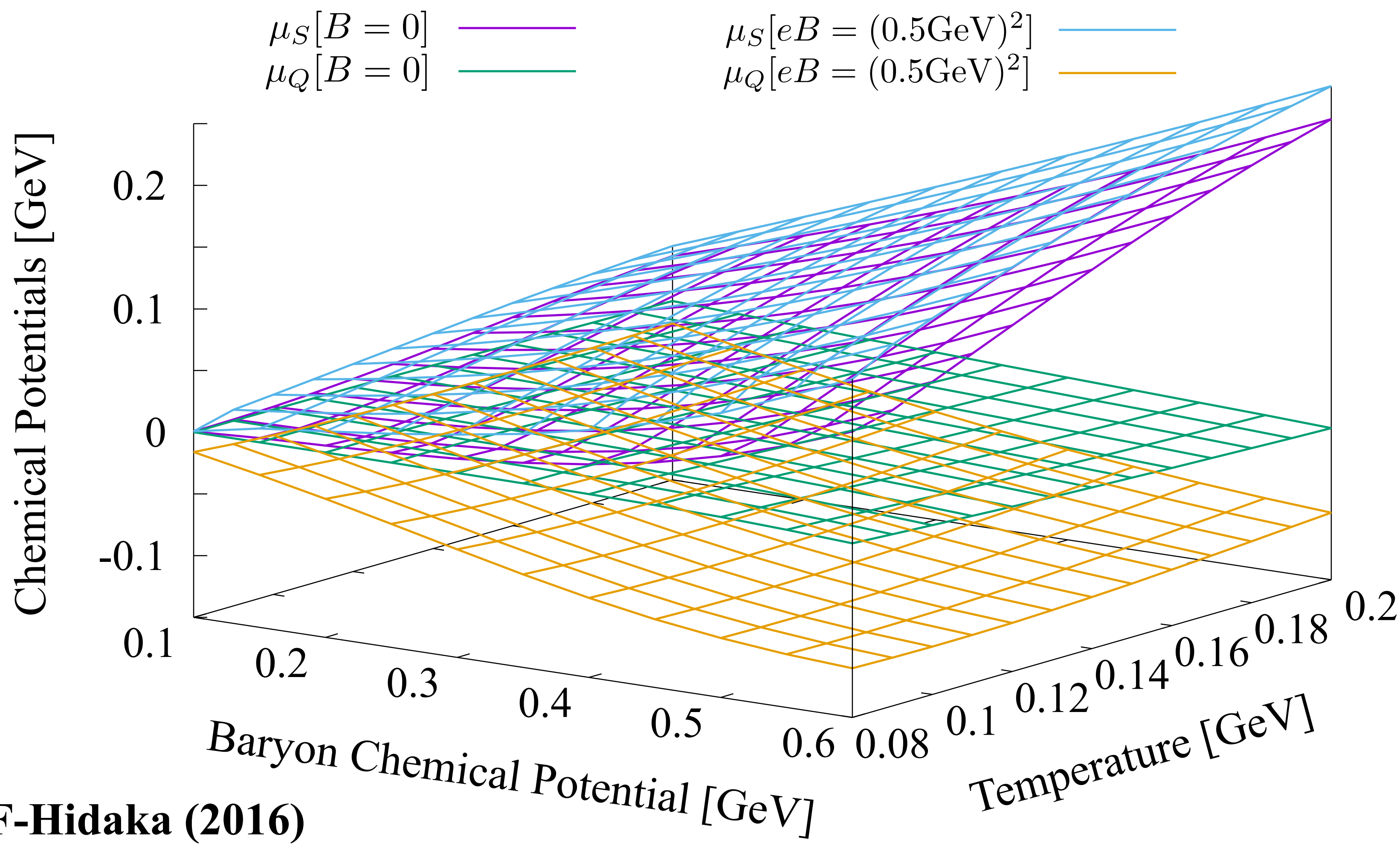
KF-Hidaka (2016)

***N* increases faster**

***p* gets lighter**
***n* remains intact**

Electric charge conserv.

Charge Conservations



KF-Hidaka (2016)

Charge Conservations

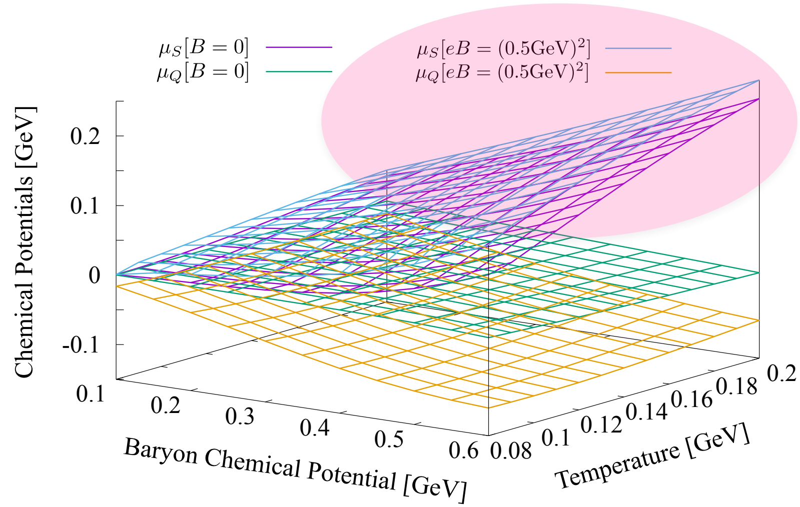
At high *T*

$$\mu_S \sim \mu_B/3$$

The chemical potential felt by free strange quarks is

$$\mu_B/3 - \mu_S \sim 0 \text{ if } \mu_S \sim \mu_B/3$$

This signals for realization of "**quark deconfinement**" even in HRG without quark d.o.f.

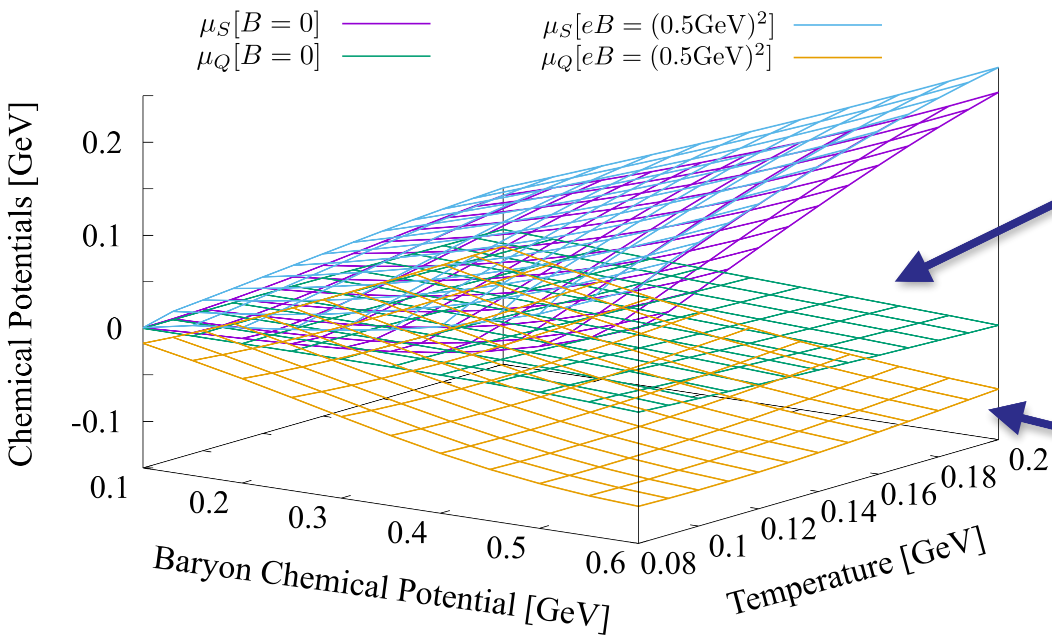


Charge Conservations

μ_Q is fixed to meet $B/(2Q) = 1.2683$

In (heavy) nuclei there are **a bit** more neutrons than protons.

Isospin sym. breaking is minor → μ_Q is nonzero but small.

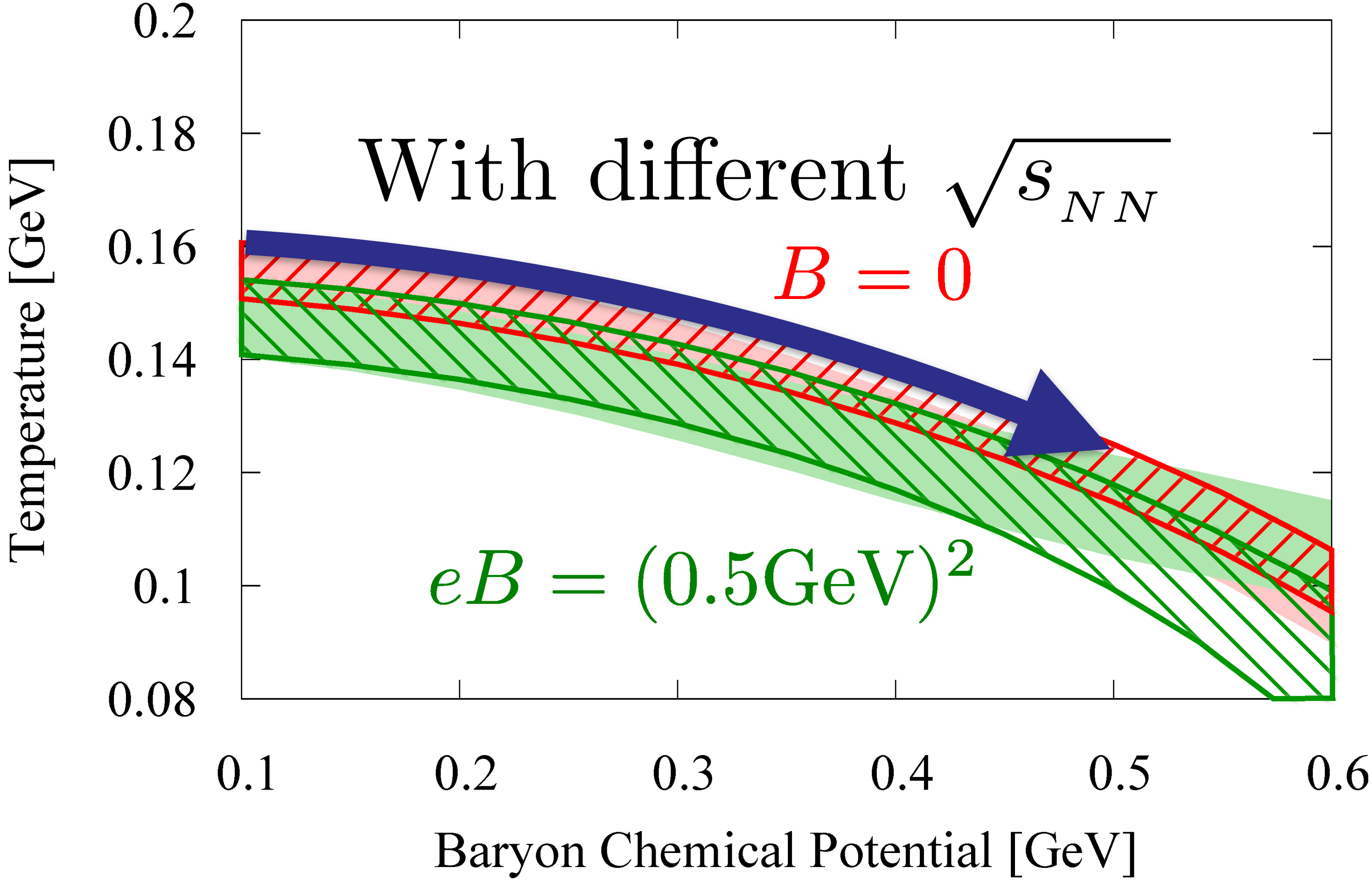


$\mu_Q \sim 10^{-2}\text{GeV}$

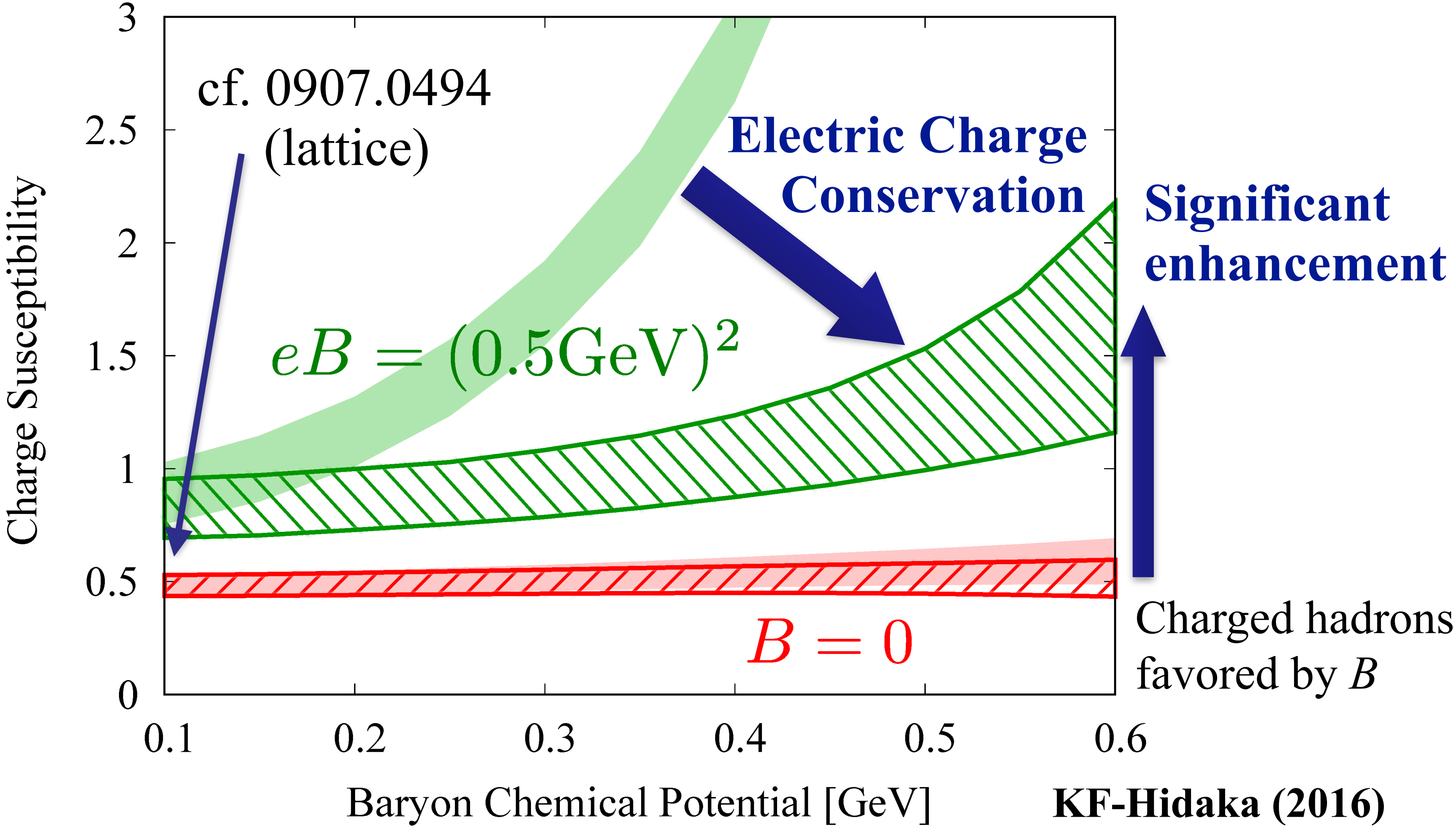
***B* breaks isospin sym.**

$\mu_Q \sim 10^{-1}\text{GeV}$

Observables on Freezeout Lines



Electric Charge Fluctuations

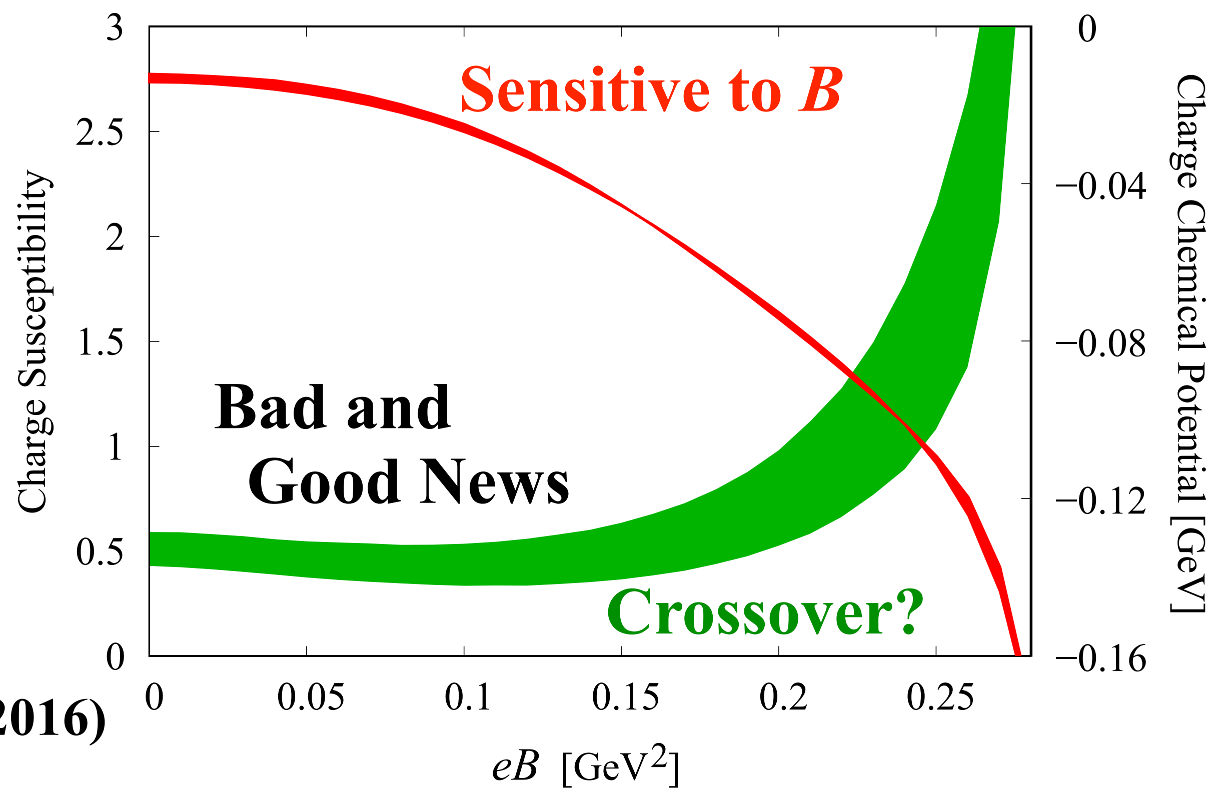


KF-Hidaka (2016)

Sensitivity to B

Chemical potential fixed at 0.6GeV

Temperature fixed by the condition E/N=0.9~1GeV



KF-Hidaka (2016)

Conjecture

Enhanced fluctuations imply
enhanced electric conductivity

High Density: proton + neutron
Strong *B*: proton (lightened)

Dense and magnetized nuclear matter dominated by protons

Easy to sustain the decaying *B* (Lenz's law)

cf. B changes transport coefficients:
see KF-Hattori-Yee-Yin, PRD93, 074028 (2016) for heavy-quark diffusion coefficients

Possible signatures for B

Centrality differentiated thermal parameter analysis

- **Magnetic shift of the chemical freezeout points with different centralities.**

  Freezeout *T* decreases in accord to the IMC.

- **Enhancement of μ_Q with different centralities.**

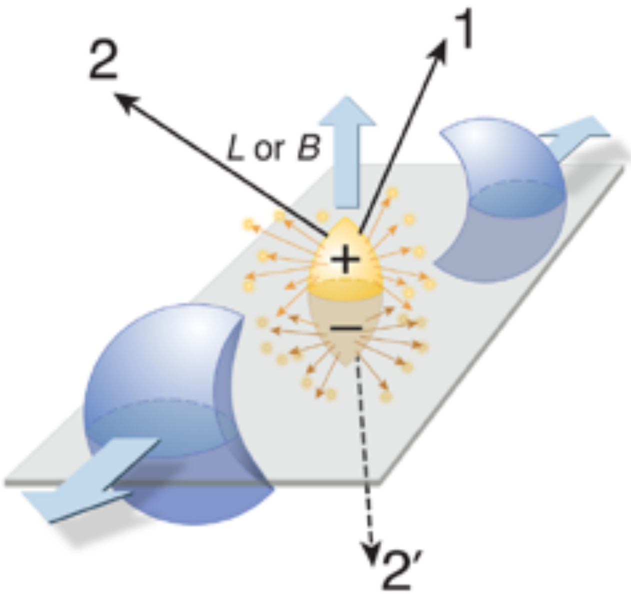
  Easily accessible information from HIC experiment.

- **Enhancement of χ_Q with different centralities.**

  A bit challenging but possible experimental signature.

Interplay between *B* and Rotation

Large J in Heavy-Ion Collisions



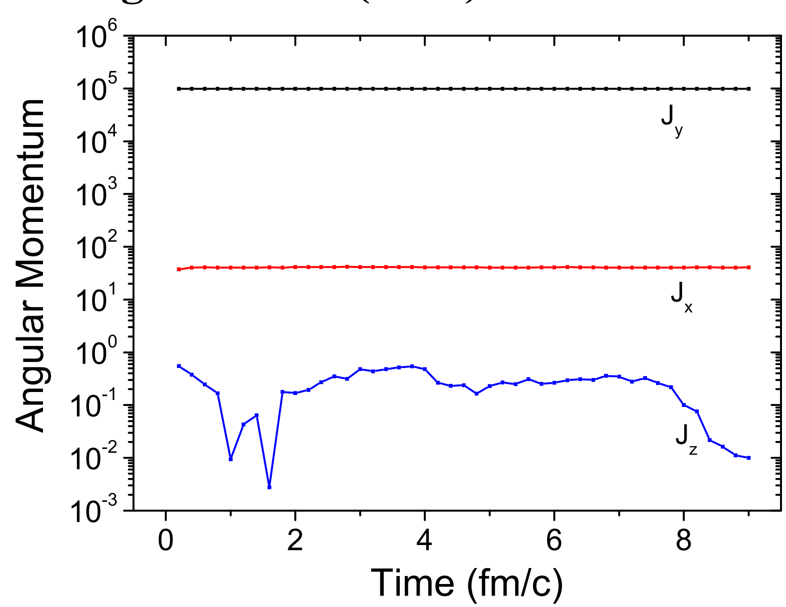
Berndt Muller
Physics 2, 104 (2009)

cf. polarization of Λ and $\bar{\Lambda}$

Fruitful physics coming!

Becattini-Inghirami-Rolando-Beraudo (2015)

Jiang-Lin-Liao (2016)



Large *J* and long life time (unlike *B*)!

Rotation ~ B

$$B \sim \mu\Omega$$

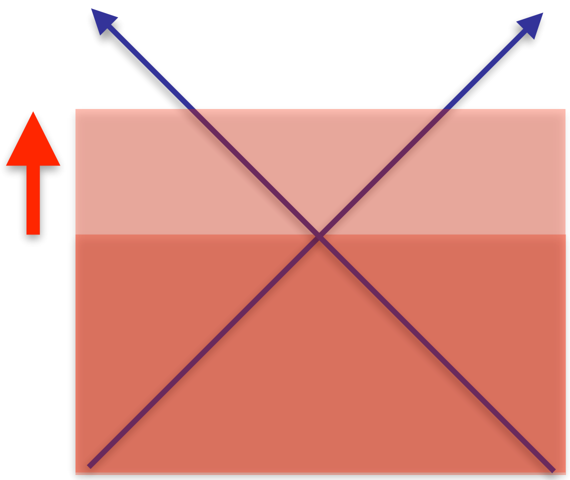
Chiral Magnetic Effect ~	**Chiral Vortical Effect**
Gauge Effect	**Geometrical Effect**
Can be homogeneous	**Must be inhomogeneous**
No upper limit	**Causality limit**
Gauge Theory	**General Relativity Fluid Dynamics**

$\mu\Omega$ in Neutron Star

$\mu \sim 500$ MeV $\times$ $\Omega \sim 10^3\ \mathrm{s}^{-1}$ (millisecond pulsar)

$\mu\Omega \sim 10^{-15}\ \mathrm{MeV}^2$ (extremely tiny!!!)

Rotation ~ Chemical Potential



Rotating fermions are given finite momenta, and the Dirac sea is "pushed up" just like chemical potentials.

Most well-known example: Deformed Nuclei

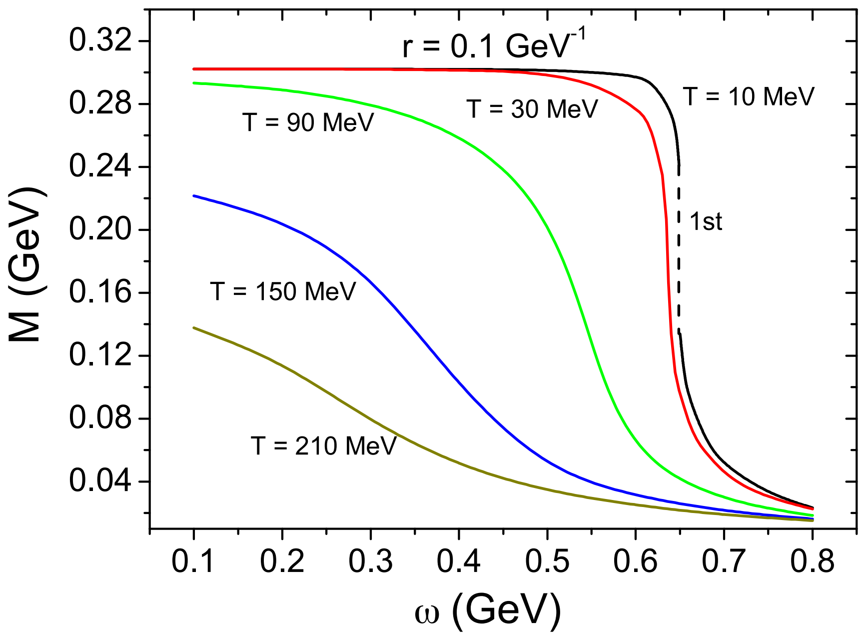
Cranking model $H_{\text{rot}} = H \underline{- \Omega J_z}$

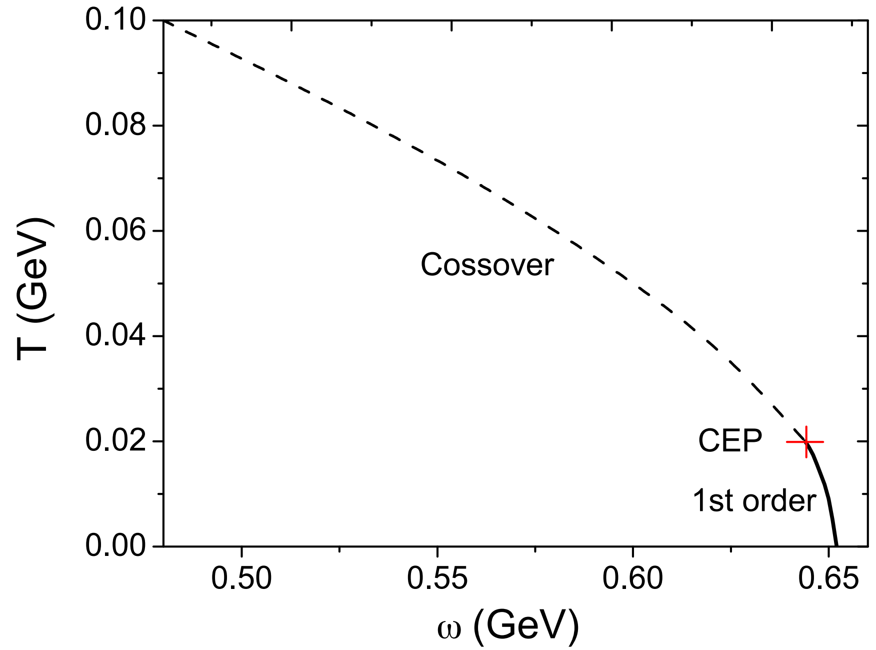
Looks like a chemical potential for matter

$\mu \sim \Omega J_z \sim M(\Omega R)^2$ (extremely huge!!!)

Phase transition solely by J ?

Jiang-Liao, 1606.03808





Complete analogy to chemical potential… BUT!

Phase transition solely by J ?

Effective density (Pauli blocked): ΩJ_z

Finite size effect (IR cutoff): J_z / R

Causality: $\Omega < 1/R$

No mode can be Pauli blocked
→ No phase transition solely by *J*

Situations changed by *T* / *μ* / *B*

Coupling to Magnetic Field

If B is imposed along the rotation axis, the wave-function should be *localized in the Larmor radius*

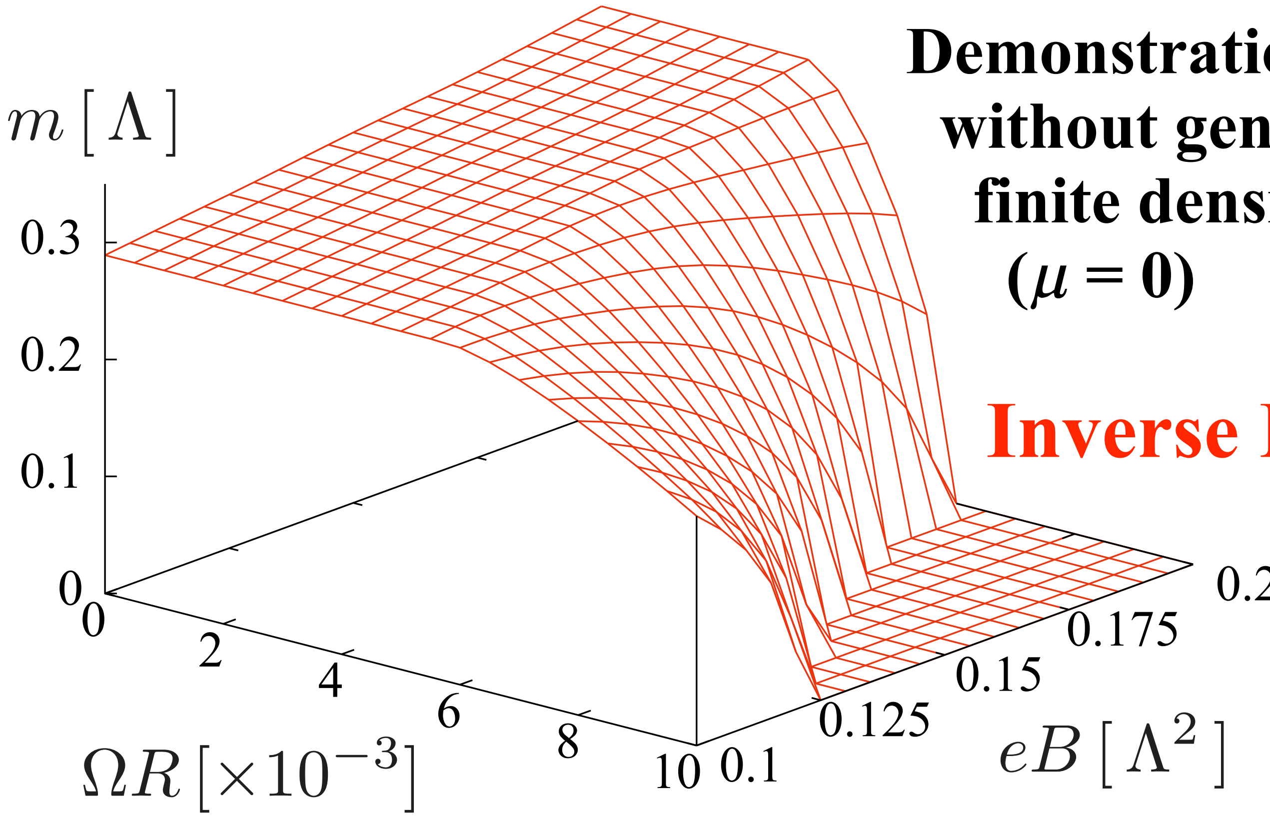
We can forget about the boundary effect for

$$\sqrt{eB} \gg R^{-1}$$

Roughly speaking, the Landau quantization (pushing many states into LLL) works stronger than the quantization from the boundary effect.

Chiral Restoration by Ω

Chen-KF-Huang-Mameda (2015)



Demonstration even without genuine finite density ($\mu = 0$)

Inverse MC

Slower than millisecond pulsars

~ 10^{18} gauss

Emergent Finite Density

Straightforward computation of the density:

$$\frac{\Omega}{\pi^2 R^2} \sum_{\ell=0}^{N} (\ell + 1/2) = \frac{eB\Omega}{4\pi^2}(N+1)$$

$N \;=\; eBR^2/2$ fixed to match the Landau degeneracy factor

B + Rotation = Density !?

Anomaly

Hattori-Yin, 1607.01513

$$\Delta j_V^0 = q_f \frac{C_A}{2} (\boldsymbol{B} \cdot \boldsymbol{\Omega})$$

$$C_A = 1/2\pi^2$$

$$\frac{\Omega}{\pi^2 R^2} \sum_{\ell=0}^{N} (\ell + 1/2) = \frac{eB\Omega}{4\pi^2}(N + \boxed{1})$$

Theoretical controversies…

$$n_{\rm anom} \sim \frac{(eB)^2(\Omega R)R}{8\pi^2}$$

QCD Scale in HIC!

KF-Mameda (soon)

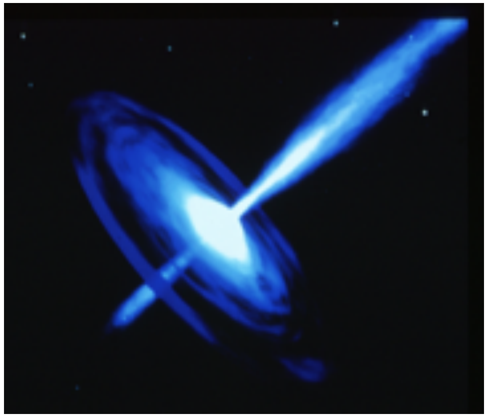
Chemical freezeout could be shifted to higher density

Chiral Vortical Effect

Landsteiner-Megias-Pena-Benitez (2011)

$$\nabla_\mu j_A^\mu = C_F \epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda} + C_R \epsilon^{\mu\nu\rho\lambda} R_{\mu\nu}{}^{\alpha\beta} R_{\rho\lambda\alpha\beta}$$

Density and Current from Gauge and Gravitational Anomalies



HIC @ a few GeV (finite-T, μ, B, Ω)

Experiment to investigate physics of Kerr metric in the Universe

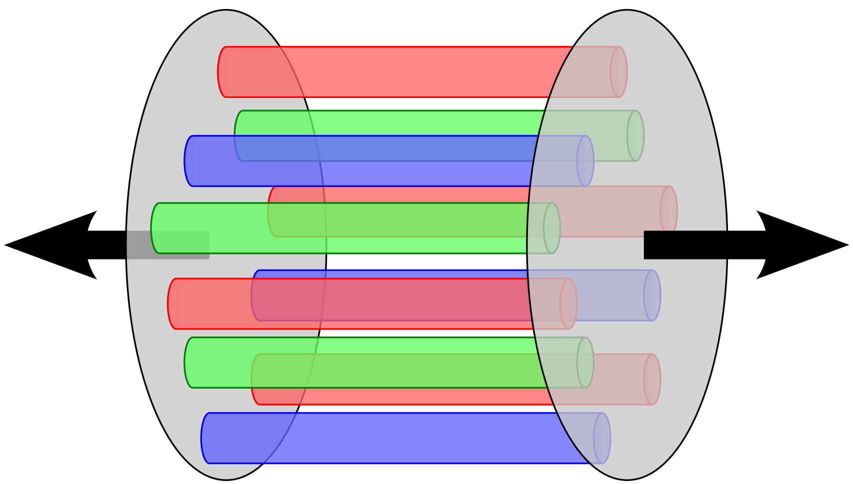
A lot of theoretical works are ongoing now!

E and inhomogeneous *B* in the "worldline formalism"

Vital Question in HIC

Initial condition of HIC = Glasma
(Coherent chromo-*E* and chromo-*B* fields)

see KF, 1603.02340 [nucl-th]



Quark production from classical fields (not slow!)

Time-dep. *E* and Space-dep. *B* (known)
Space-dep. *E* and Time-dep. *B* (difficult)

Particle Production from E

Schwinger Mechanism (vacuum)
Landau-Zener Effect (material)

Insulation breakdown caused by *E*

Suppressed by "activation energy"

$$\sim e^{-\pi m^2/(eE)}$$

quark mass (hep)
residual mass (cond-mat)

Particle Production from E and B

Euler-Heisenberg (well-known) Answer

$$\Im\Gamma = \frac{e^2 EB}{(2\pi)^2} \coth\left(\frac{B\pi}{E}\right) \exp\left(-\frac{\pi m^2}{eE}\right)$$

E → Produced chiral charges (particles/anti-particles) accelerated by ***E*** → ***B***

Ohm's current → $\propto \ \sigma \boldsymbol{E}$

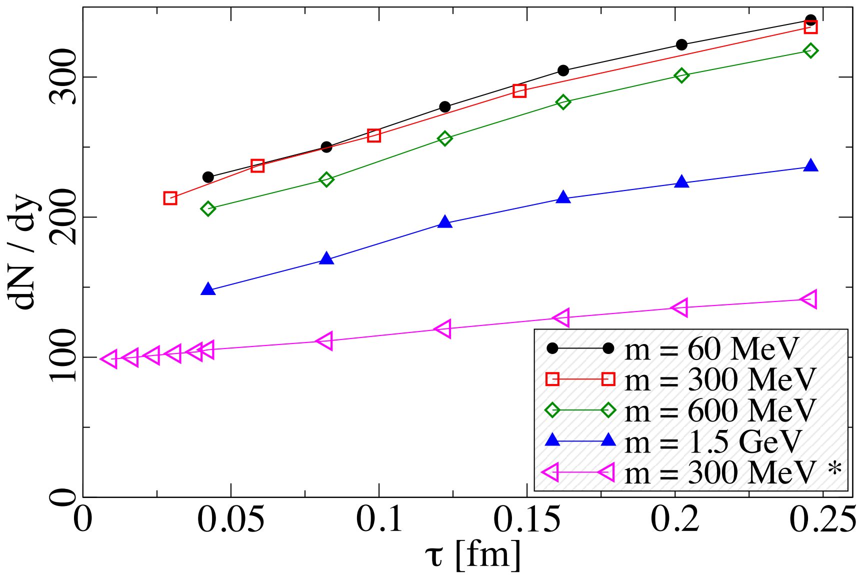
Topological current → $\propto \ (\boldsymbol{E}\cdot\boldsymbol{B})\,\boldsymbol{B}$

Negative magnetoregistance in Weyl semimetals

CGC Calculation

Quark production from CGC *not yet* fully quantified
Quark mass dependence *not yet* systematically studied

Only available indication so far:



Gelis-Kajantie-Lappi (2005)

Quark production is very fast (comparable to *B*'s lifetime)

In principle all these (anomaly) effects should be included…

Dynamically Assisted SM

Schutzhold-Gies-Dunne, PRL101, 130404 (2008)

Keldysh (1965)
Atomic Ionization $\left\langle \begin{array}{l} \text{favored by time-dep. } E \\ \text{disfavored by space-dep. } E \end{array} \right.$

$$\boldsymbol{E}(t) = \frac{E}{\cosh^2(\Omega t)}\boldsymbol{e}_z + \frac{\varepsilon}{\cosh^2(\omega t)}\boldsymbol{e}_z$$

Strong / Slow **Weak / Fast**

$$\frac{\pi m^2}{eE} \to \frac{m^2}{eE}\left[2\arcsin\left(\frac{\pi}{2\gamma}\right) + \frac{\pi}{2\gamma^2}\sqrt{4\gamma^2 - \pi^2}\right]$$

Keldysh Parameter $\gamma \equiv \dfrac{m\omega}{eE}$

Worldline Formalism

Proper-time representation of determinant

$$\Gamma = -\frac{1}{2}\int_0^\infty \frac{dT}{T}\, e^{-m^2 T} \int_{\text{periodic}} \mathcal{D}x\, e^{-\int_0^T d\tau\left(\frac{\dot{x}^2}{4} + ieA\cdot\dot{x}\right)}\,\Phi$$

$$\Phi = \mathrm{tr}\mathcal{P}e^{\frac{ie}{2}\int_0^T d\tau\,\sigma_{\mu\nu}F_{\mu\nu}}$$

QFT = QM in 4+1 dims

Stationary point approx. (WKB)
4+1 dims "classical" eom
(Worldline Instantons)

$$\frac{m\ddot{x}_\mu}{\sqrt{\int_0^1 du\,\dot{x}^2}} = ieF_{\mu\nu}\dot{x}_\nu$$

Decomposition

$$\Gamma = -2\int_0^\infty \frac{dT}{T}\, e^{-m^2 T}\, \gamma_E(T; A_3, A_4)\cdot\gamma_B(T; A_1, A_2)$$

$$\gamma_E = \int \mathcal{D}x_3\,\mathcal{D}x_4\, \cos\left(\int_0^T d\tau\, eE\right) e^{-\int_0^\tau [\frac{1}{4}(\dot{x}_3^2+\dot{x}_4^2)+ieA_3\dot{x}_3+ieA_4\dot{x}_4]}$$

$$\gamma_B = \int \mathcal{D}x_1\,\mathcal{D}x_2\, \cosh\left(\int_0^T d\tau\, eB\right) e^{-\int_0^\tau [\frac{1}{4}(\dot{x}_1^2+\dot{x}_2^2)+ieA_1\dot{x}_1+ieA_2\dot{x}_2]}$$

This decomposition is possible as long as

A_1 and A_2 not depending on x_3 and x_4

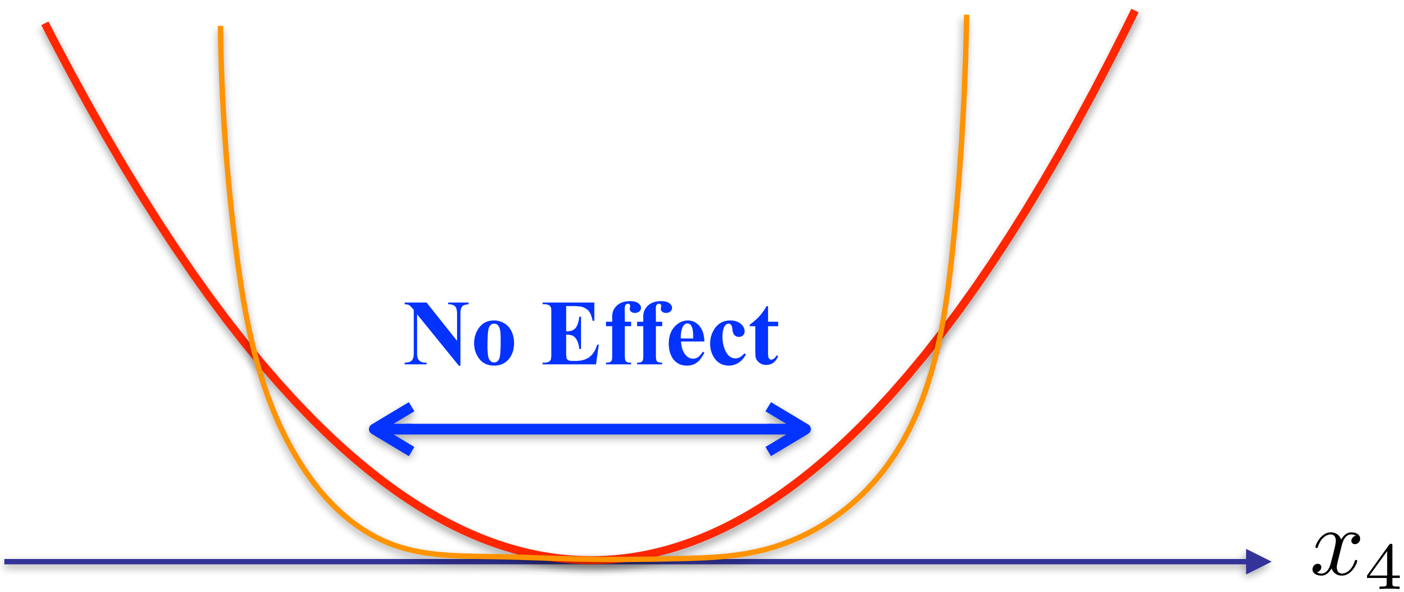
A_3 and A_4 not depending on x_1 and x_2

This can hold for time-dep. *E* and space-dep. *B* !

(4+1)-dim QM for E

$$\boldsymbol{E}(t) = \frac{E}{\cosh^2(\Omega t)}\boldsymbol{e}_z + \frac{\varepsilon}{\cosh^2(\omega t)}\boldsymbol{e}_z$$

Potential energy reads: $\propto \left[\frac{E\tan(\Omega x_4)}{\Omega} + \frac{\varepsilon\tan(\omega x_4)}{\omega}\right]^2$



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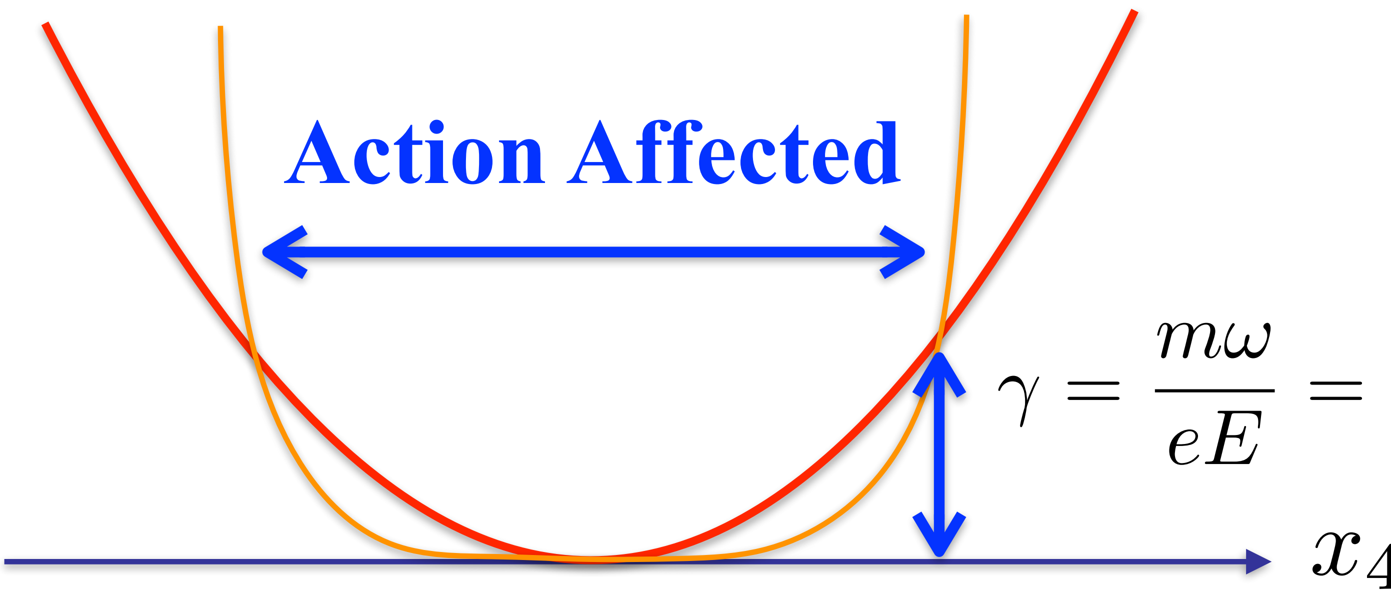


$$\gamma = \frac{m\omega}{eE} = \frac{\pi}{2}$$

Spatially Inhomogeneous B

Solvable example:

$$\boldsymbol{B}(x) = B\,\mathrm{sech}^2(\kappa x_1)\boldsymbol{e}_3$$

In more general:

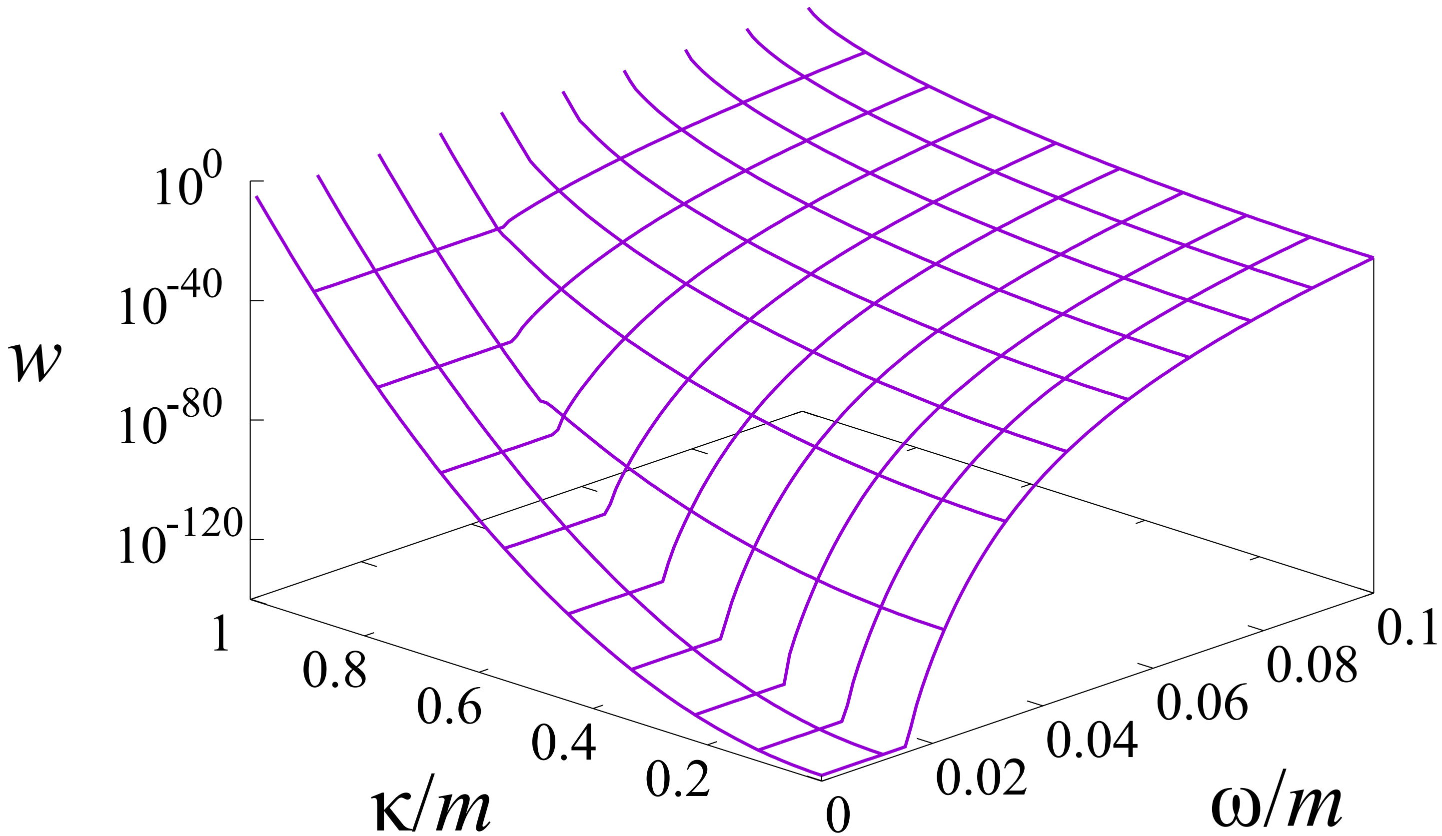
$$\boldsymbol{B}(x) \simeq \left[B - B\kappa^2(x_1^2 + x_2^2)\right]\boldsymbol{e}_3$$

$$\Gamma = -2\int_0^\infty \frac{dT}{T}\, e^{-m^2 T}\, \gamma_E(T; A_3, A_4)\cdot\gamma_B(T; A_1, A_2)$$

$$m^2 \to \tilde{m}^2 = m^2 - \kappa^2 \quad \leftarrow \quad e^{+\kappa^2 T}$$

Copinger-KF (2016)

Enhanced Particle Production

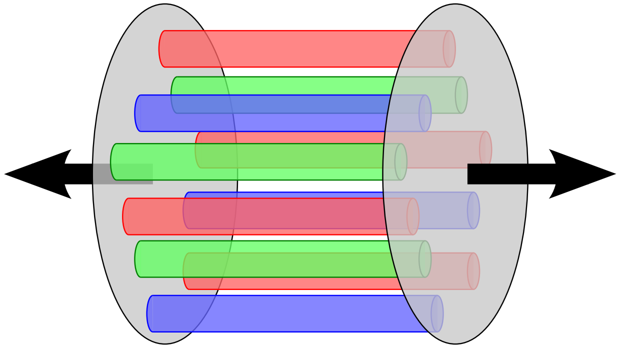


Space-dep. *B* **Time-dep. *E***

Spatially Assisted Magnetic Catalysis

$$\kappa^2 > m^2 \ (\tilde{m}^2 < 0)$$

T-integration does not converge…
Dynamical mass should be generated
Chiral symmetry MUST be broken



$Q_s > m_q \rightarrow$ explosive quark production

Forming condensate to make quarks as massive as $Q_s \sim$ a few GeV
(or fields decay before that)

Summary

Strong *B* in Heavy-Ion Collisions

- □ Life-time depends on electric conductivity
- □ May survive better at high density ?
- □ Observables at freezeout affected (~magnetometer)

Strong *B* and Rotation in Heavy-Ion Collisions

- □ Rotation NOT decay inducing anomalous effects

Strong *B* and Rotation in Neutron Stars

- □ Chiral condensate and thus EoS affected MUCH!

Strong (chromo) *B* and Inhomogeneity in CGC in Heavy-Ion Collisions

- □ Quark production in CGC (not slow but fast process)