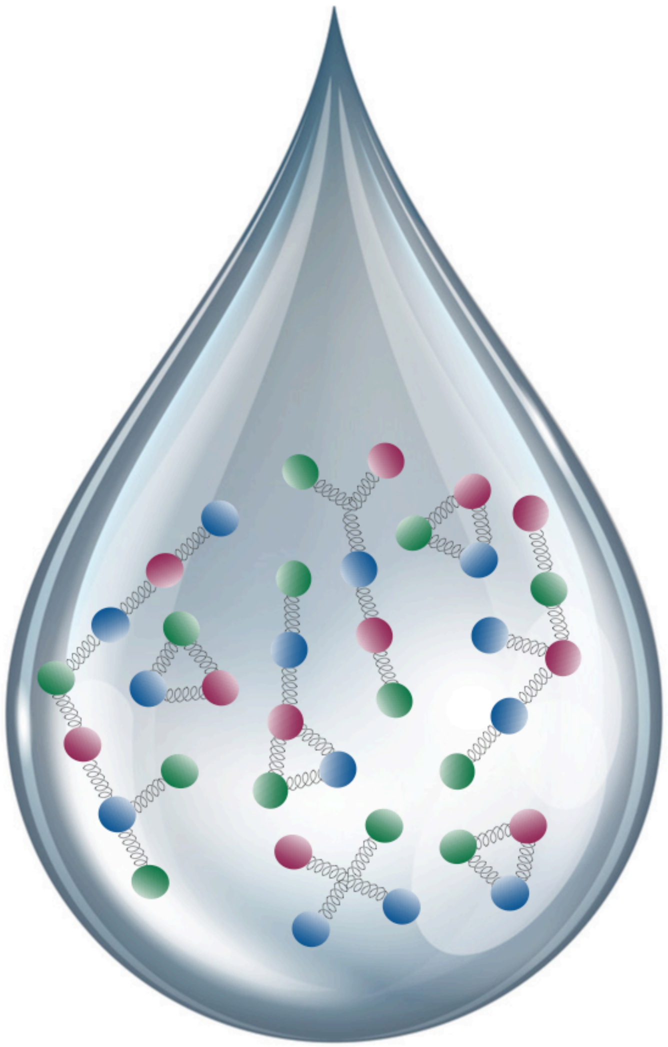
Magnetic catalysis, Chern-Simons diffusion and spin transport in QGP

Umut Gürsoy

Utrecht University

AdS4CME workshop, 15/3/2022

QGP hydrodynamics



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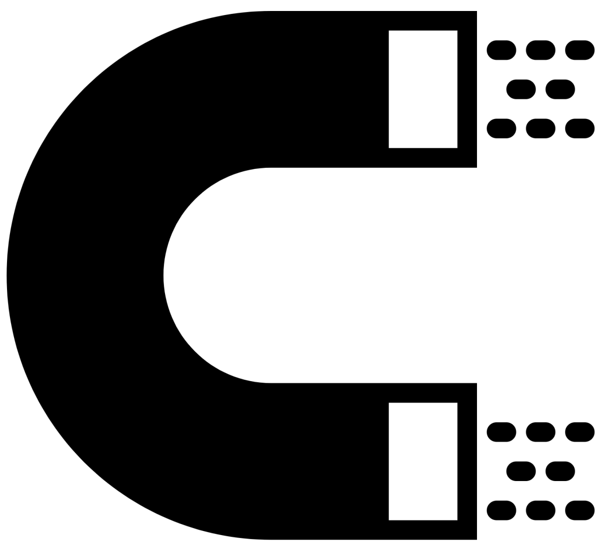
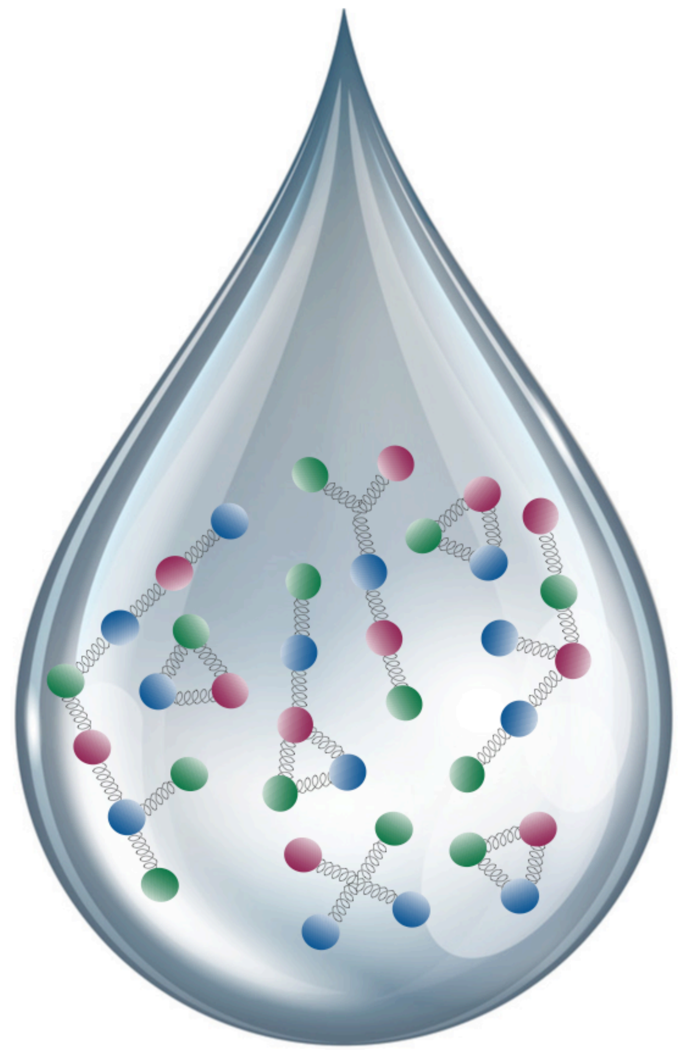


Magnetic field

$B \sim 10^{14} B_{MRI}$



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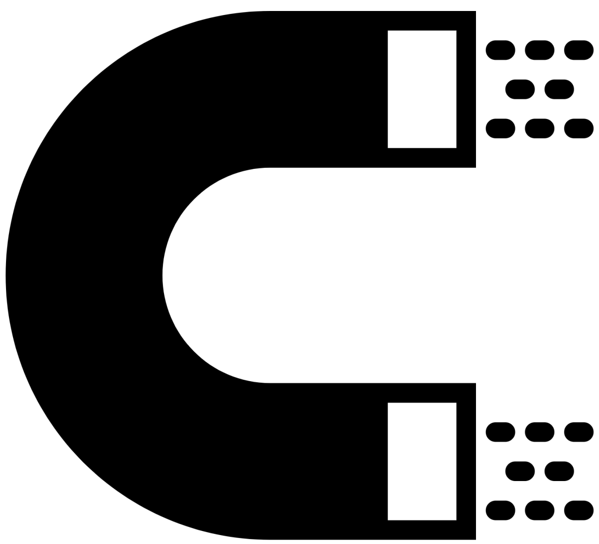

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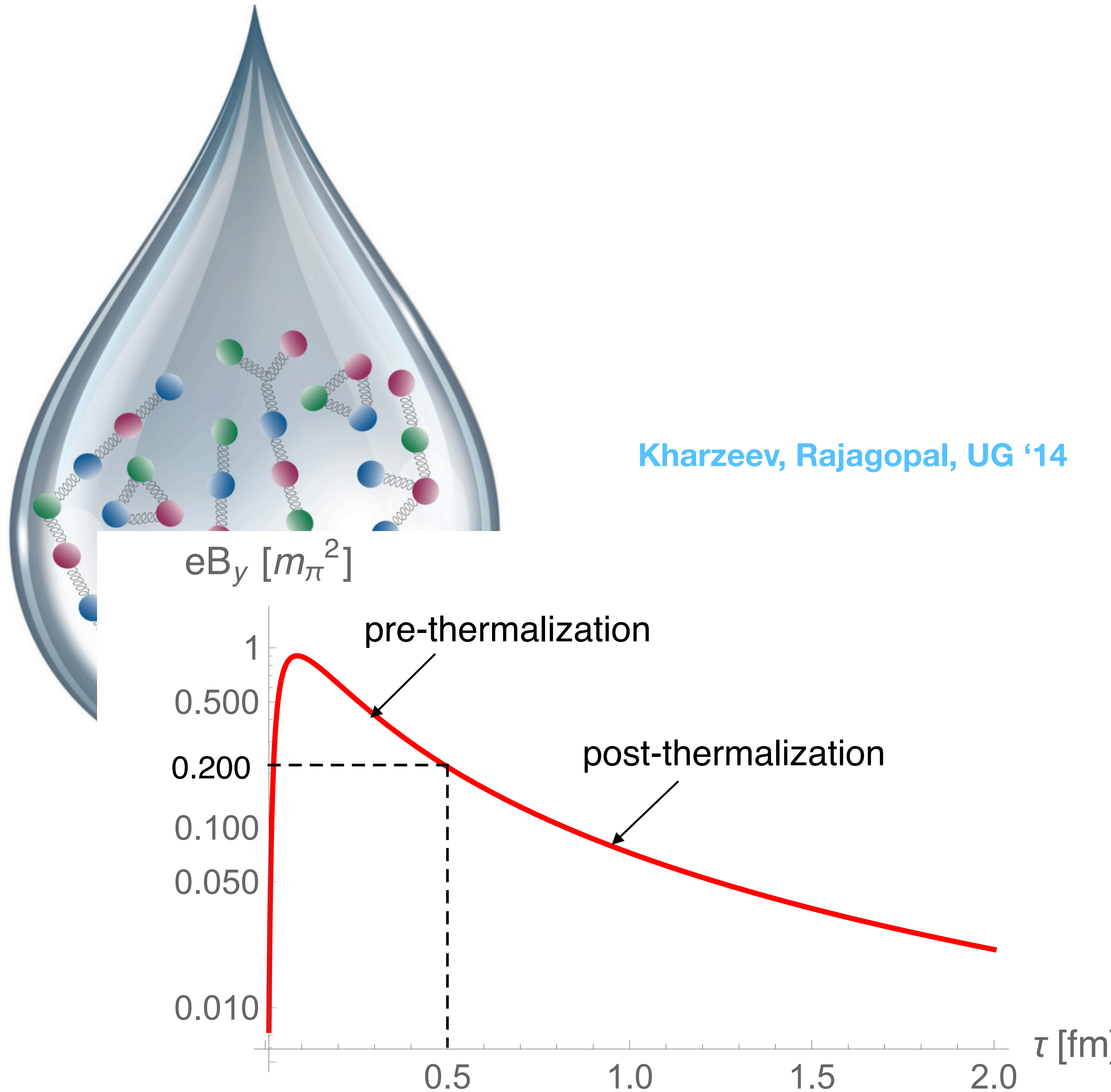

Kharzeev, Rajagopal, UG '14

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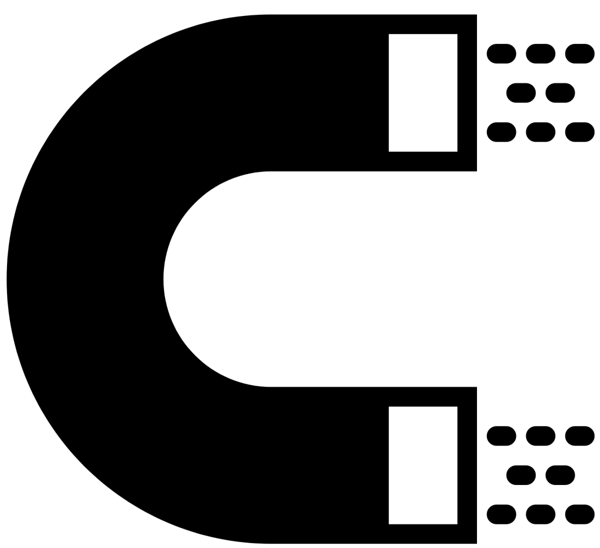
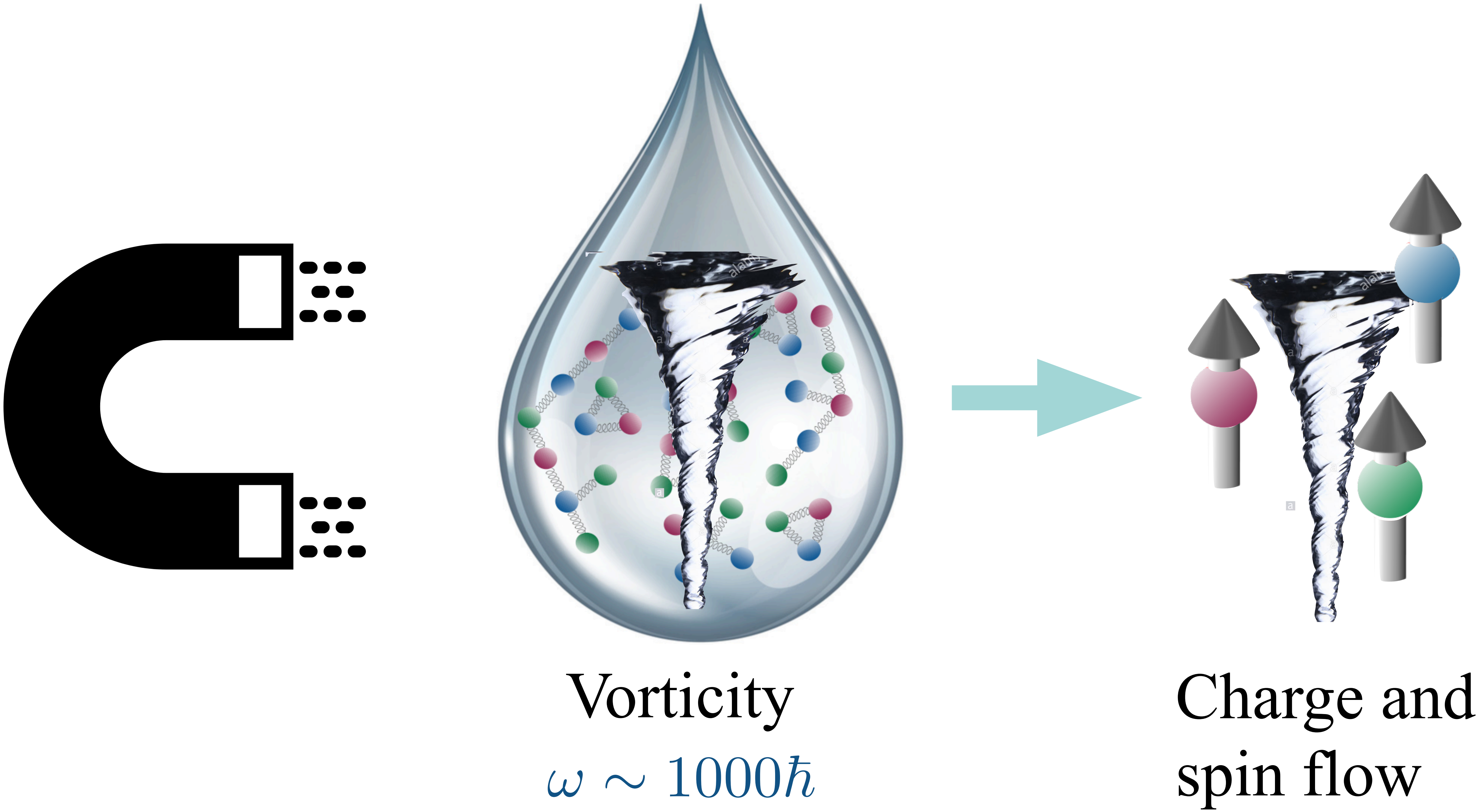
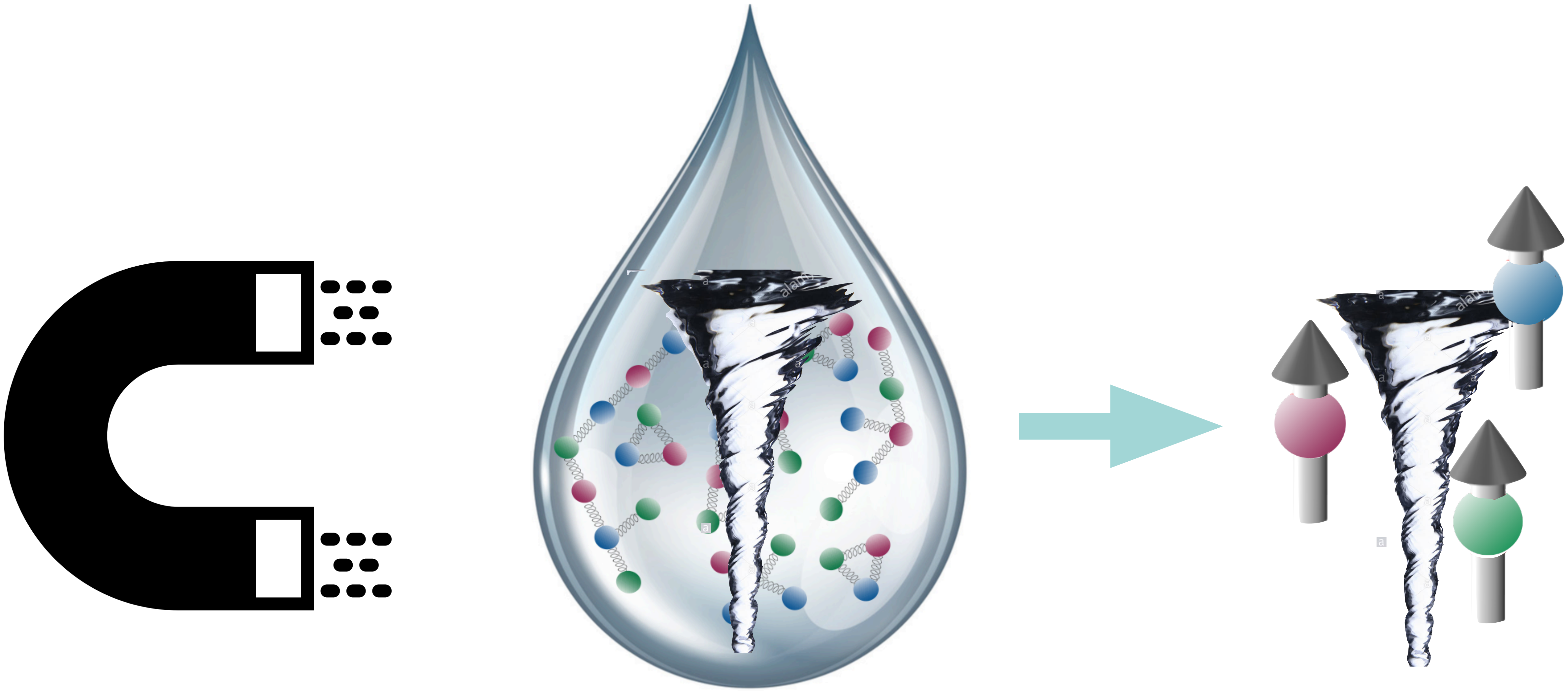


Strong vortical structure

$$\omega \sim 1000\hbar$$

QGP hydrodynamics





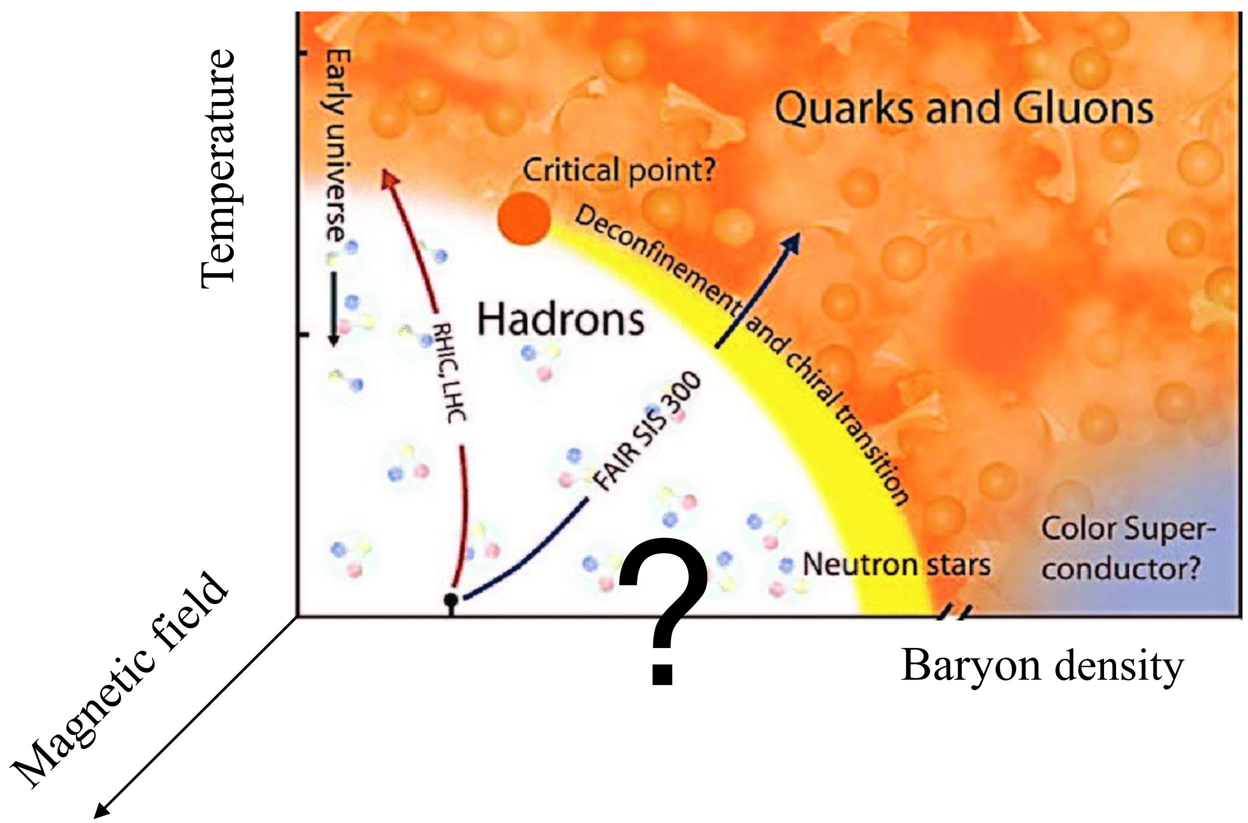
Chiral magnetic and vortical effect

Matter antimatter asymmetry

Part I: magnetic fields, anisotropic QCD

Open questions

- ✳ Ground state: dependence of $\langle \bar{q}q \rangle$ on B   (inverse) magnetic catalysis
- ✳ Thermodynamics: phase diagram of QCD at finite B



- ✳ Hydrodynamics and transport: 2 conductivities, 2 shear, 3 bulk viscosities
  B dependence of η, ζ   Hernandez, Kovtun '17
  Grozdanov, Hofman, Iqbal '17
- ✳ Fully back-reacted magneto-hydrodynamics: HIC, neutron star mergers
- ✳ Anomalous transport: chiral magnetic and vortical effects, Chern-Simons diffusion rate
- ✳ Out of equilibrium: initial conditions for hydro, generation of chiral imbalance

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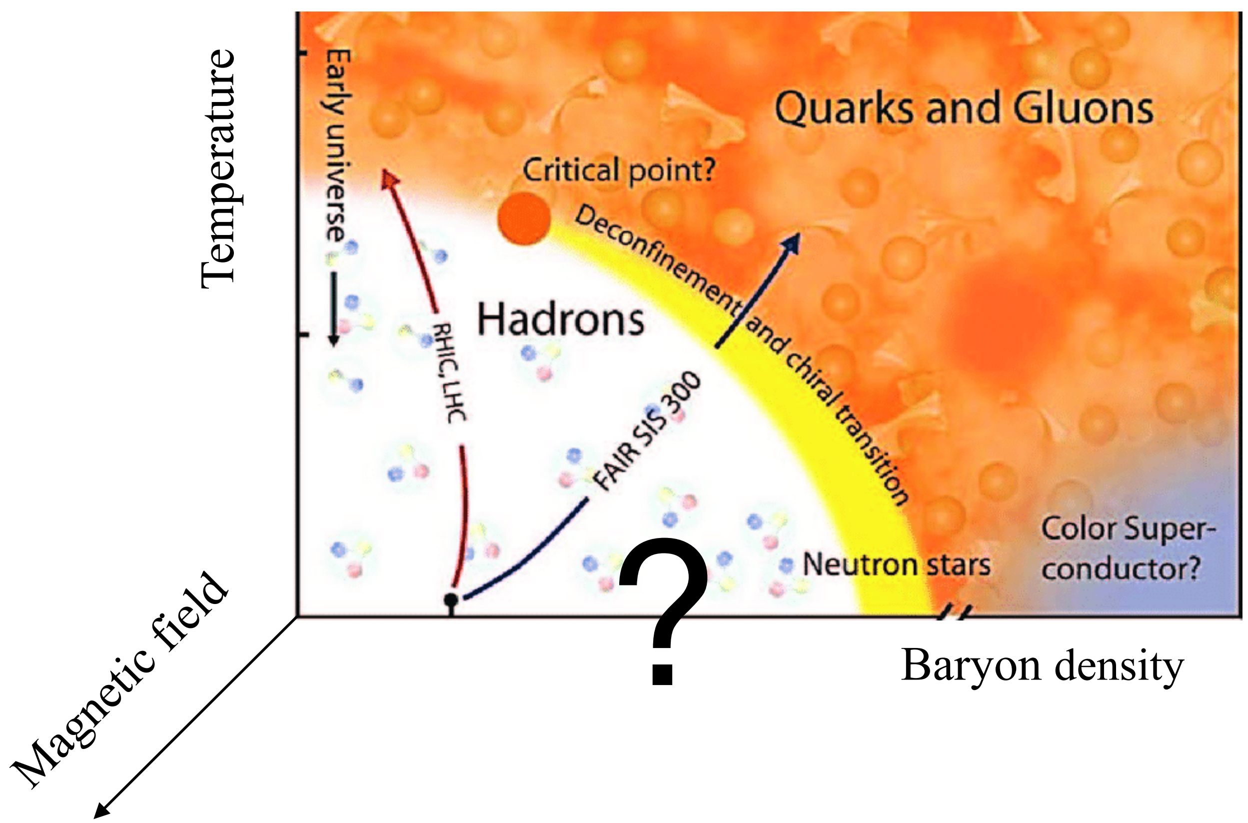

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Jarvinen, Kiritsis '11; Alho et al '12

- QCD has infinite operators unlike N=4 sYM
- General bulk⇔boundary should apply to QCD for $\lambda \gg 1$ Polyakov '98 '00
- Integrating out fast modes in the 5D non-critical string

  $\Longrightarrow$ effective 5D gravity + matter
- IR sum-rules in QCD: OPA semi-closed on relevant/marginal operators

  Shifman, Vainshtein, Zakharov '79

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Write down a bulk 5D action for $T_{\mu\nu},\ \mathrm{tr}\, G^2,\ \mathrm{tr}\, G \wedge G,\ \bar{q}q,\ J_\mu$

Color tube ⇔ fundamental string, flavor ⇔ D5 branes

Determine the potentials + integration const. from the basic features of QCD:
Confinement, asymptotic freedom, χSB, gapped discrete spectrum, anomalies

Systematic errors largely reduced by fixing the large field limits of potentials

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Glue sector

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$\mathrm{tr}\, G \wedge G$

CP-odd sector

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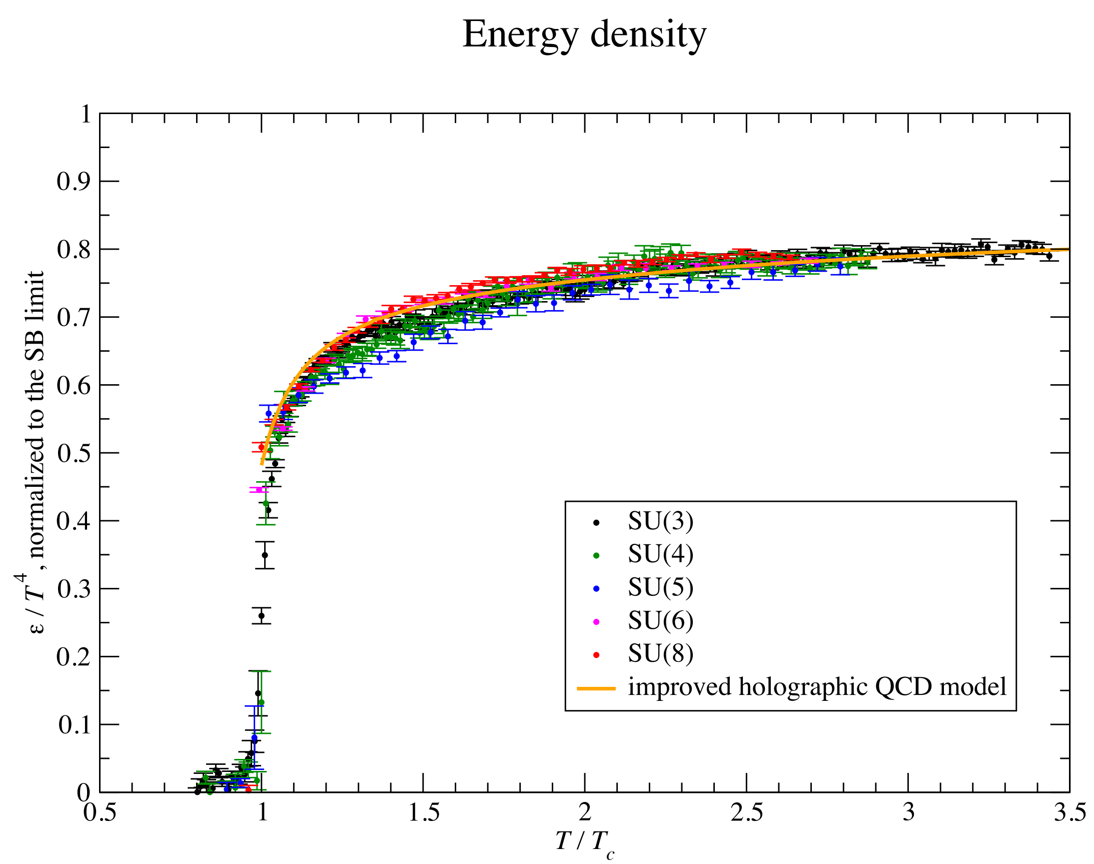
Fixing the potentials

- Fix V_g by non-singular IR, linear confinement, linear mass spectrum, lowest glueball mass, $\Delta S(T_c)$



Panero '09

- Fix V_f , $\kappa(\lambda)$ by non-singular IR, qualitative features of the phase diagram in μ and x, condensate anomalous dimension, chiral anomaly, meson mass spectrum

Jarvinen, Kiritsis '11; Alho et al '12 '13

- Choose $w(\lambda) = \kappa(c\lambda)$ by conductivity, diffusion const. of the plasma

Iatrakis, Zahed '12; Alho et al '13

$$w(\lambda) = \kappa(c\lambda) = \frac{(1+\log(1+c\,\lambda))^{-\frac{1}{2}}}{\left(1+\frac{3}{4}\left(\frac{115-16x}{27}-\frac{1}{2}\right)c\,\lambda\right)^{4/3}}$$

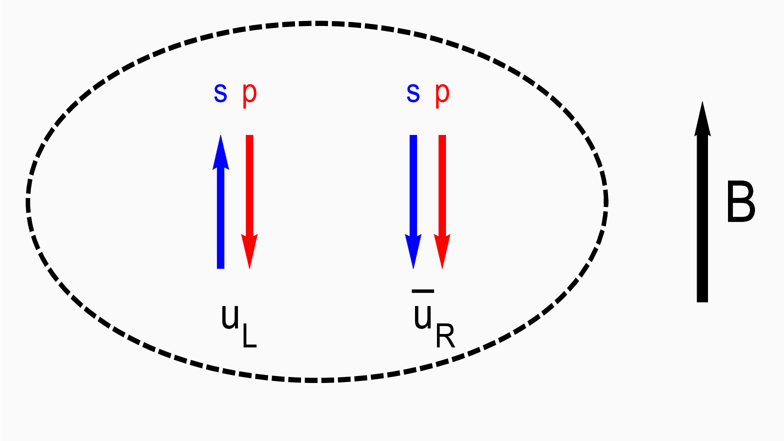
- Fix Z by topological susceptibility, axial glueball spectrum

$$Z(\lambda) = Z_0\left(1 + c_4\lambda^4\right)$$

$$0 \lesssim c_1 \lesssim 5, \quad 0.06 \lesssim c_4 \lesssim 50.$$

Magnetic catalysis

Klevansky, Lemmer '89; Suganuma, Tatsumi '91; Gusynin, Miransky, Shovkovy '94

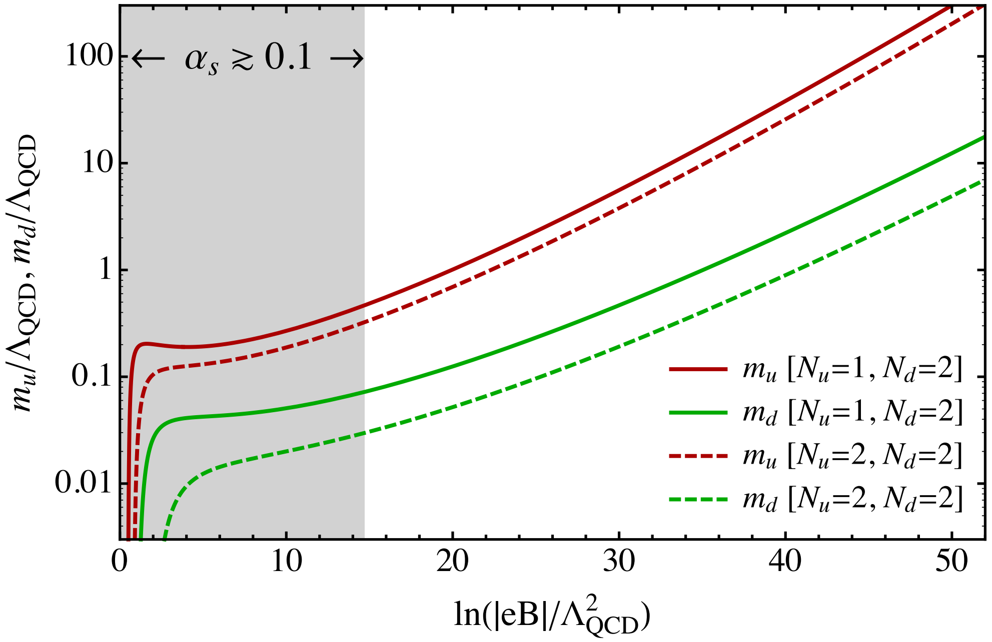


- B catalyses chiral symmetry breaking
- Generic: QED, NJL, free(!) … 2+1, 3+1
- B aligns spins, effectively reduces 3+1⇒ 1+1
- Stronger correlation between opposite chiralities

Free chiral fermions in 2+1: $$\langle\bar{q}q\rangle = \frac{|eB|}{2\pi}$$

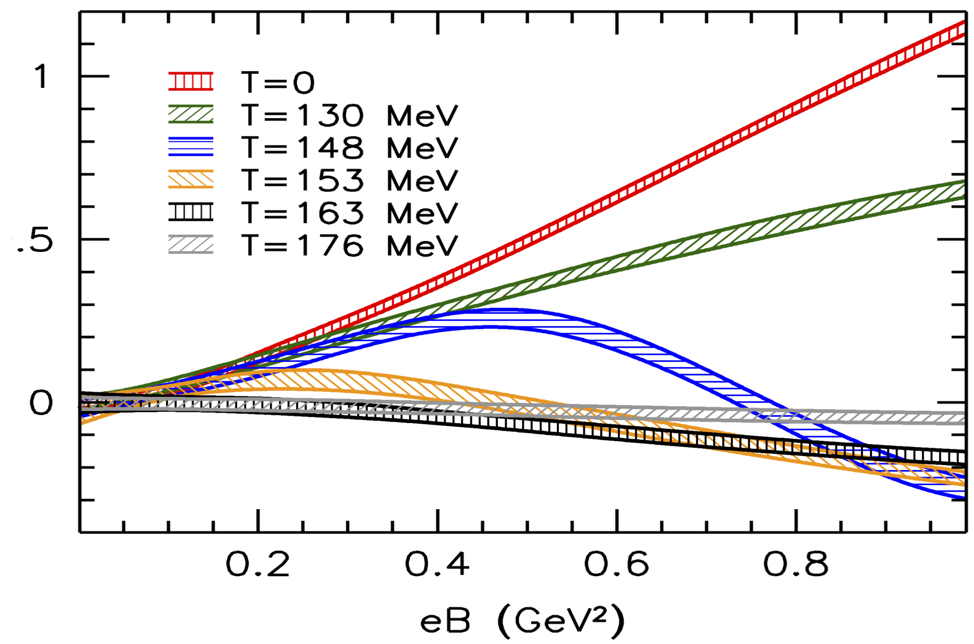
NJL in 3+1(supercritical): $$\langle\bar{q}q\rangle = \langle\bar{q}q\rangle_0 \left(1 + \frac{|eB|^2}{3G^4(\langle\bar{q}q\rangle_0)^4 \log(\Lambda/G\langle\bar{q}q\rangle_0)^2}\right)^{\frac{1}{2}}$$

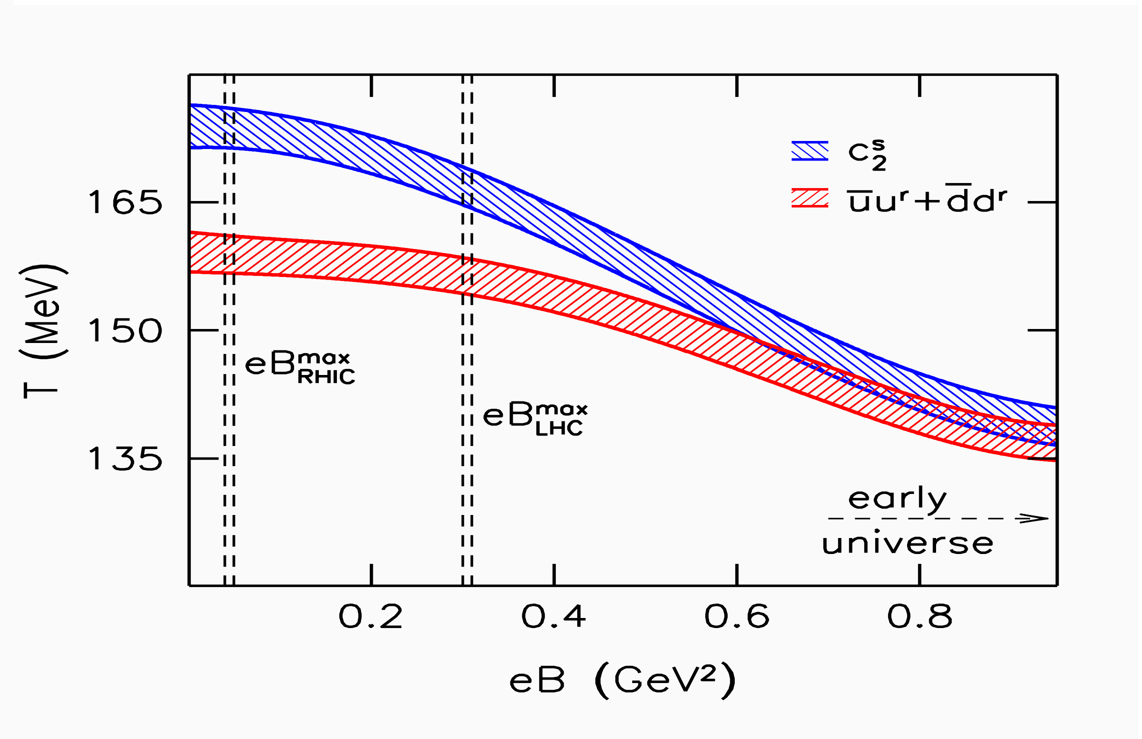
Gap equation in resummed pQCD



Magnetic catalysis on the lattice

Bali, Schafer et al '11 '12





- B acts destructively for $T \gtrsim T_c$
- Inverse effect missed in earlier studies with large m & coarse lattices

D'Elia et al '11

Magnetic catalysis generally

- **Banks-Casher relation** $\langle\bar{\psi}\psi\rangle = \pi\rho(0)$ Banks, Casher '80

  Condensate $\Longleftrightarrow$ Dirac spectrum around zero

  In LL_0 approx $\langle\bar{q}q\rangle \propto eB$

  Likely to fail in presence of strong correlations

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- **Two competing contributions in general:** D'Elia, Negro '11; Bruckmann, Endrodi, Kovacs '13

$$\langle\bar{q}q\rangle = \int \mathcal{D}A e^{-S[A]} \mathrm{det}(D(A,B)+m)\,\mathrm{tr}(D(A,B)+m)^{-1}$$

Banks-Casher applies to valence contribution $\Longrightarrow$ catalysis
Sea contribution acts destructively near $T_c \Longrightarrow$ decatalysis:
Sea prefers A configurations that order the Polyakov loop near T_c
$\Longrightarrow$ punishes configurations with small Dirac eigenvalues

Bruckmann, Endrodi, Kovacs '13

Questions for holography

- Valence vs. sea separation fails at larger B, conjecture still holds?
- Lattice does not cover large B, what happens there?
- Are there other mechanisms at work?
- Magnetic catalysis at finite μ?
- Are there new phases at finite T-B-μ?

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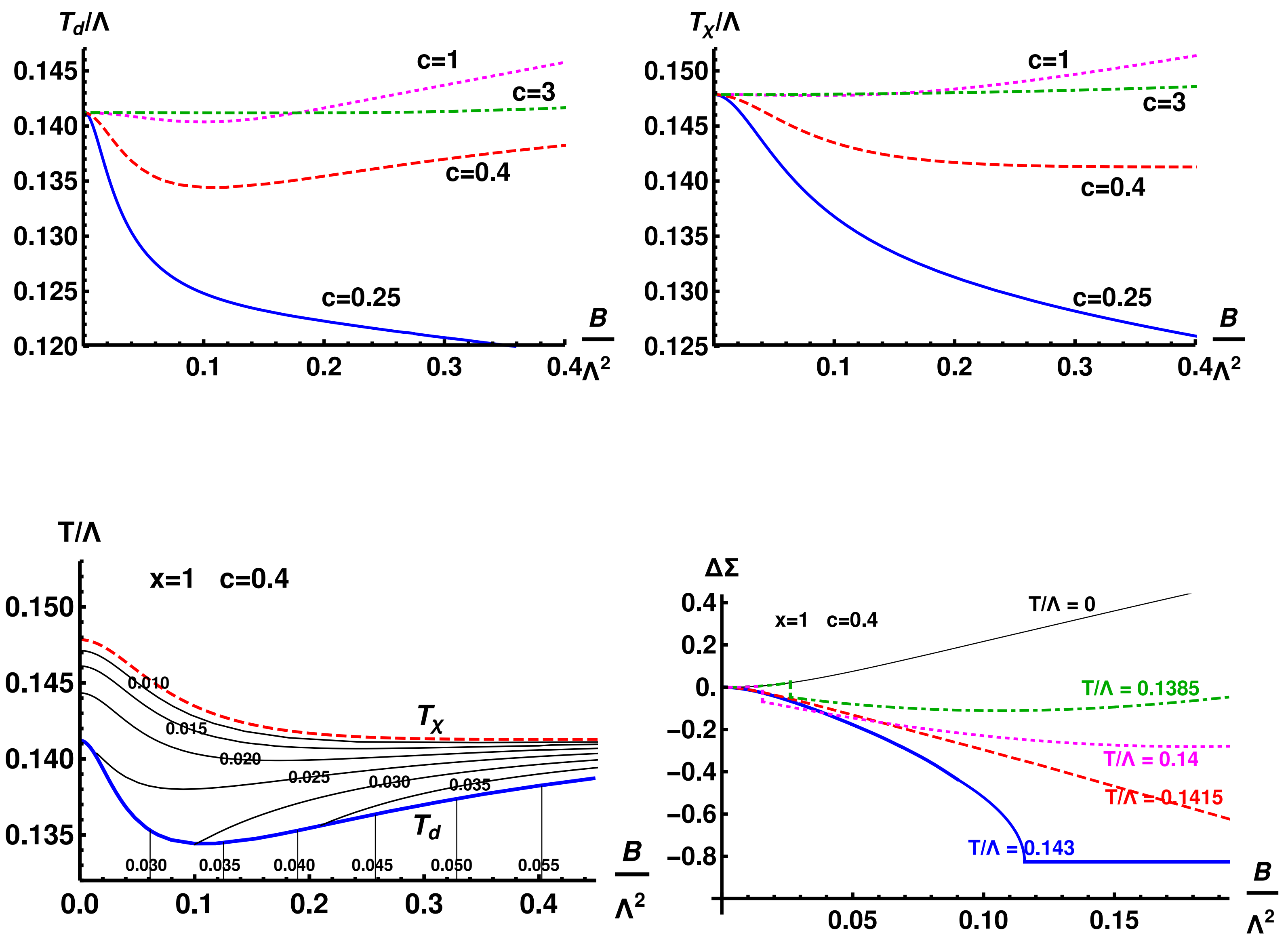
$U(1)_B$ ⇔ magnetic field $\qquad U(1)_A \qquad \bar{q}q$

Introduce μ and B in $\quad V_\mu = (V_0(r), -x_2 B/2, x_1 B/2, 0, 0)$

Quark condensate in $\quad \tau = m_q r(-\log \Lambda r)^{-\rho} + \langle \bar{q} q \rangle (-\log \Lambda r)^{\rho} + \ldots$

Magneto-holographic QCD: inverse magnetic catalysis

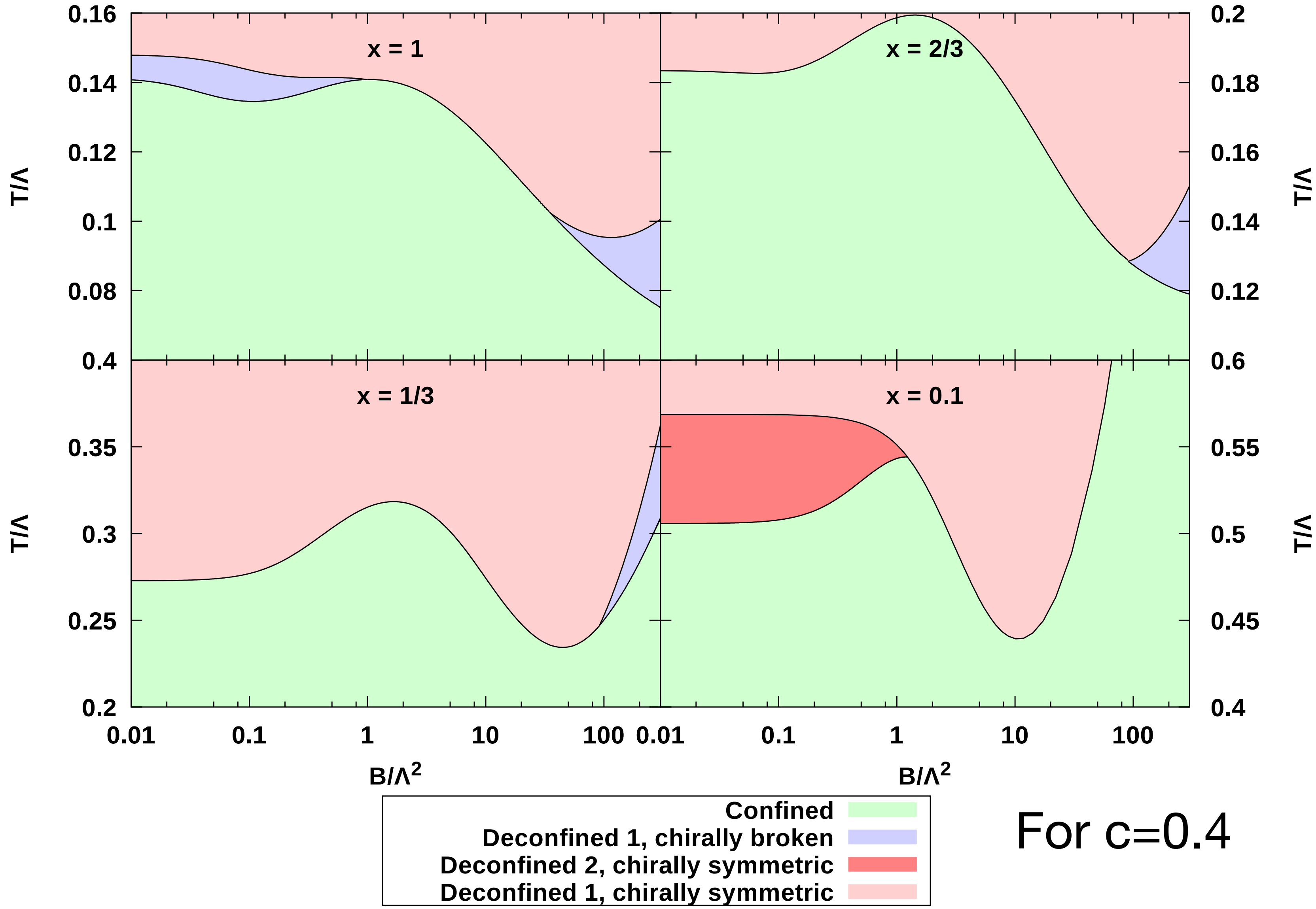
Preis, Rebhan, Schmitt ’10; Mamo ’15; Noronha et al ’15; Evans et al ’16;
Iatrakis, Jarvinen, Nijs, UG ’16;



- Both T_χ and T_c generically decrease with B
- Clear sign of inverse magnetic catalysis around $T_\chi \sim T_c$ for small B
- Inverse catalysis more pronounced for small c
- Catalysis comes back at larger B
- T dependence suppressed in the confined phase as $1/N^2$

Magneto-holographic QCD: phase diagram

Iatrakis, Jarvinen, Nijs, UG ’16



For c=0.4

- Generically 3 separate phases with 1st and 2nd order boundaries
- Both T_χ and T_c generically decrease with B
- New deconfined/chirally broken phase at very large B consistent with pQCD

Testing the valence vs. sea explanation

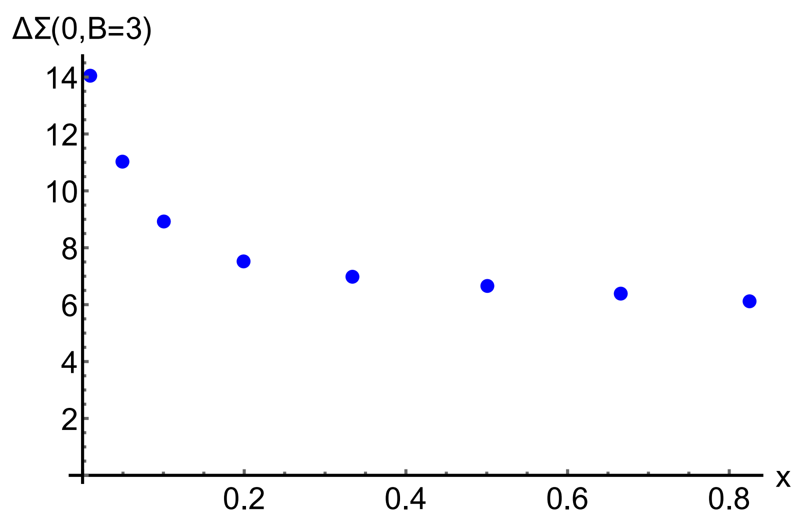
Iatrakis, Jarvinen, Nijs, UG ’16

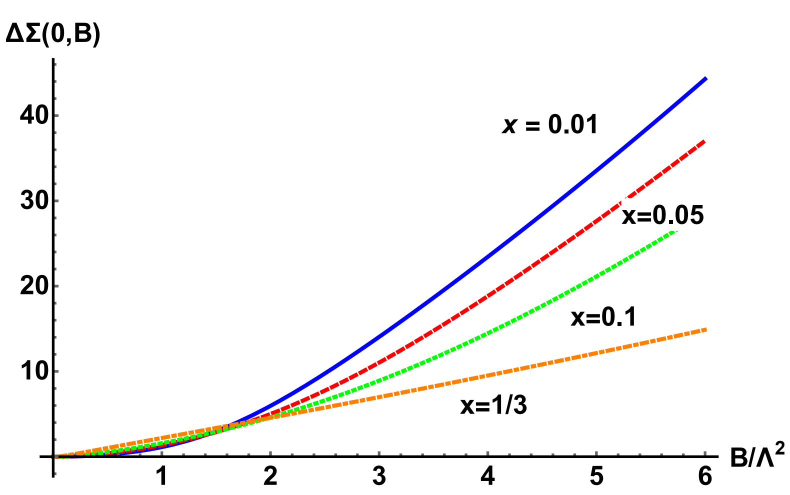
Two separate dependence on B: 1.Explicit dependence in the EOM for τ
2.Implicit dependence through the background fields

Tempting to identify 1 with the valence 2 with the sea

At large B explicit dependence vanishes ⟹ sea quarks

B influences background functions only through x ⟹ large x, more sea quarks

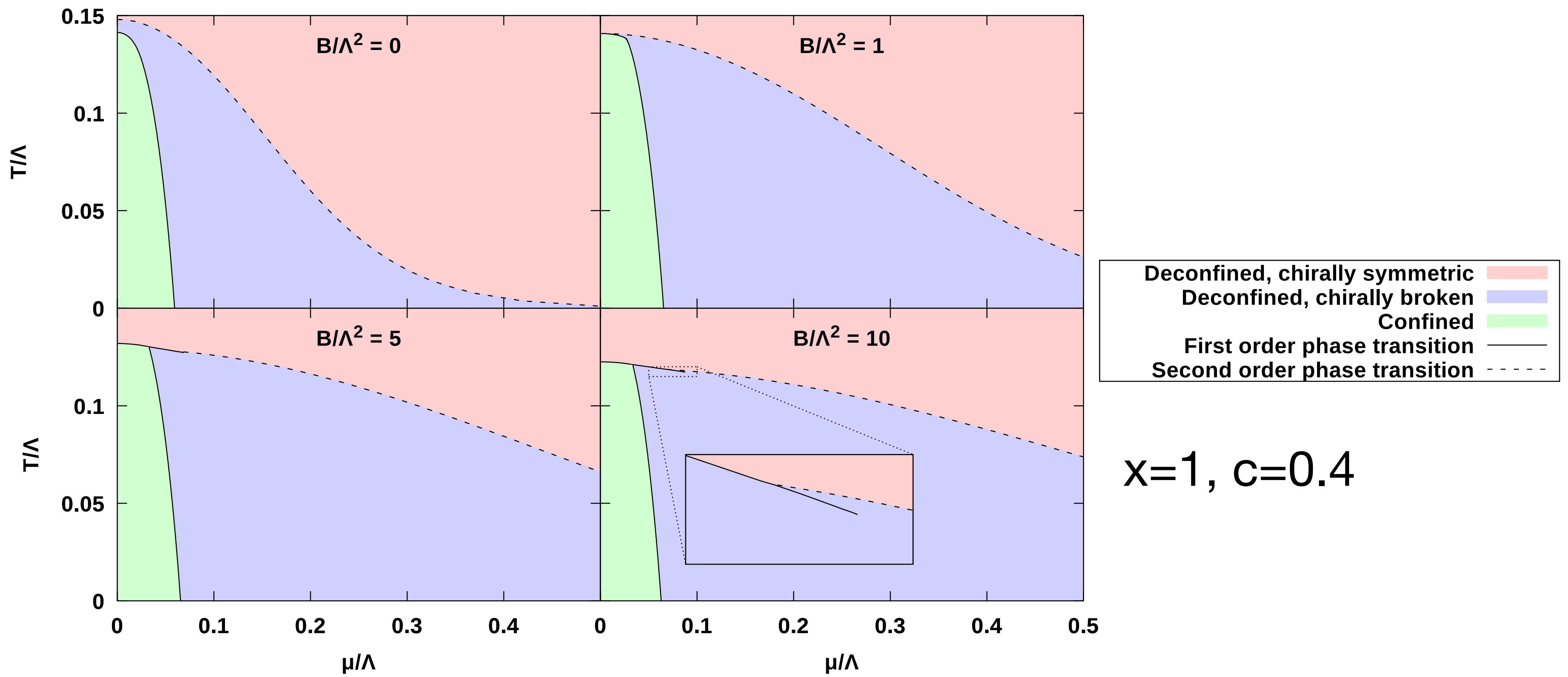




Holography supports the valence vs. sea explanation

Finite μ

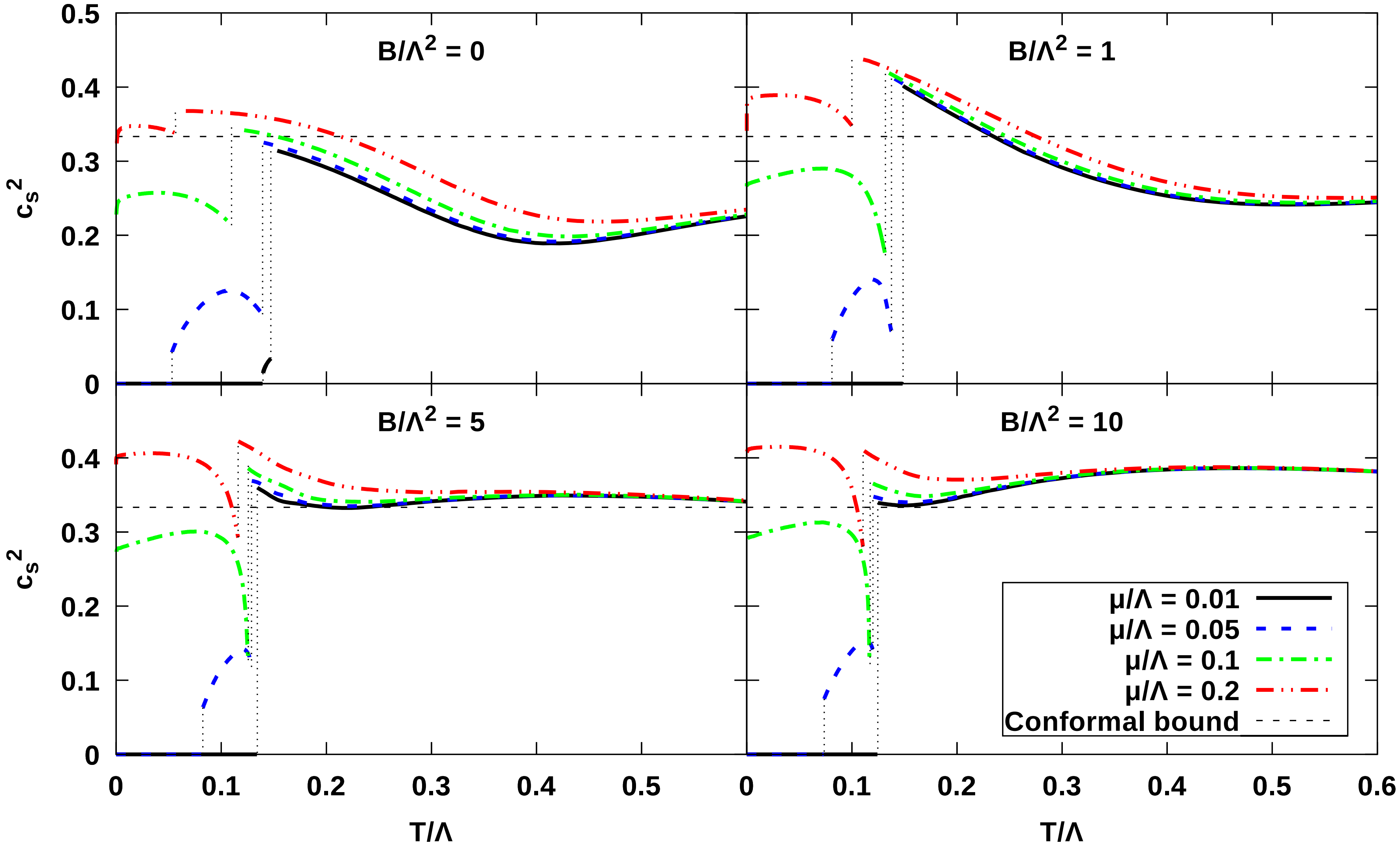
Jarvinen, Nijs, UG ’17



x=1, c=0.4

- Deconfined/chiral asymmetric phase enlarged at finite μ
- Separation between confinement and χSB scales shrink at larger B

Speed of sound at finite μ and B

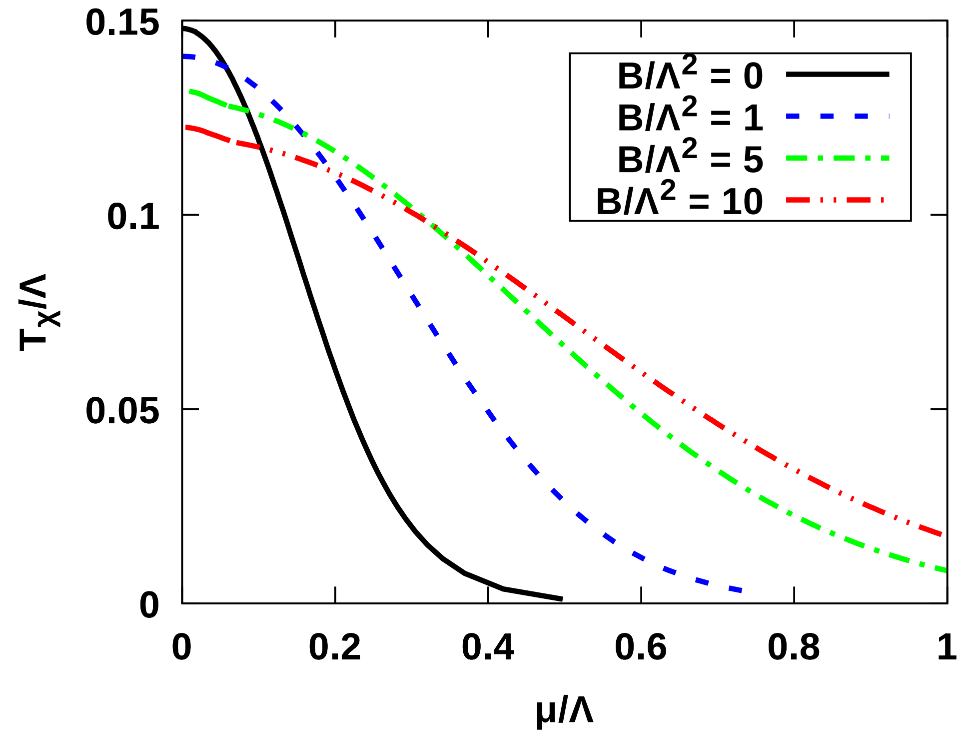


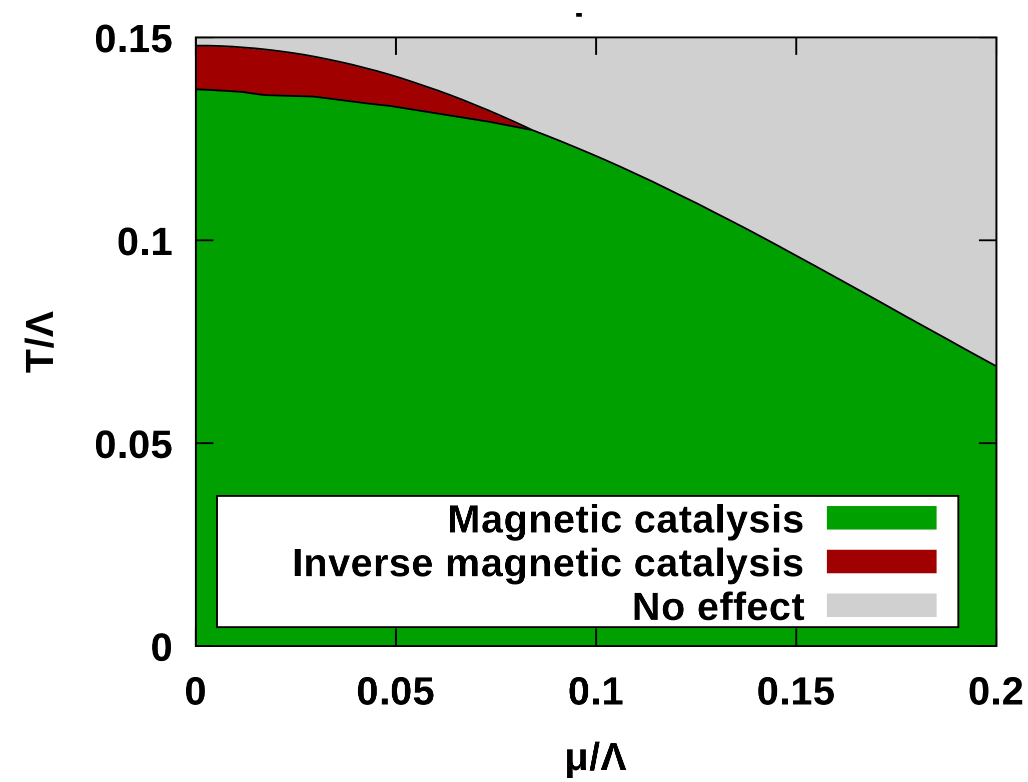
$$c_s^2 = \left.\frac{s\,\mathrm{d}T + n\,\mathrm{d}\mu}{T\,\mathrm{d}s + \mu\,\mathrm{d}n + B\,\mathrm{d}M}\right|_{n/s,B}\,.$$

- Jumps at the phase boundaries
- Tends to increase both with μ and B
- Exceeds the conformal value 1/3 generically
- Limits to 1/3 from below at larger T, in agreement with earlier results

Cherman, Cohen, Nellore ’09; Hohler, Stephanov ’09

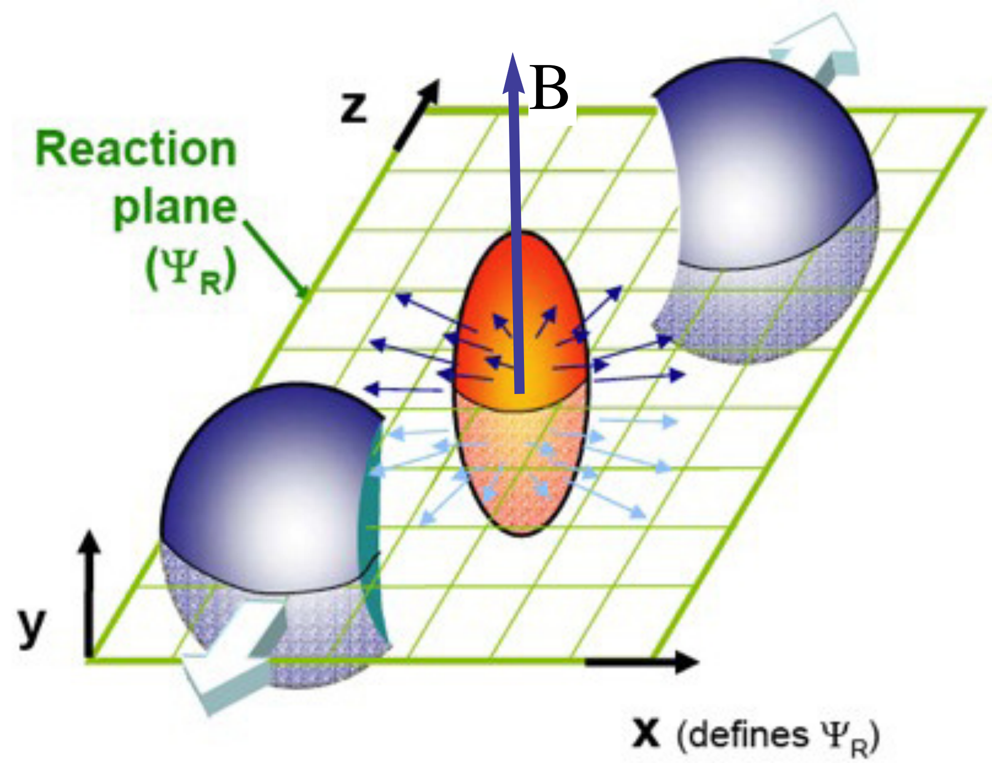
Chiral condensate at finite μ





- B facilitates the chiral transition for $\mu < 0.1 \Rightarrow$ inverse catalysis for small μ
- Magnetic catalysis instead at $\mu > 0.1$
- A small region of inverse magnetic catalysis in the phase diagram

Dynamics induced by anisotropy



- Anisotropic QGP produced in off-central collisions due to different pressure gradients
- Does anisotropy act similar to B?
- How to distinguish the effects of anisotropy from B?

$\Longrightarrow$ consider an anisotropic but neutral plasma

A heuristic discussion

Jarvinen, Nijs, Pedraza, UG ‘18

Introduce anisotropy through space dependent θ-term: θ=a z

$$Z[A_5,\theta] = \int \mathcal{D}q\,\mathcal{D}A^a e^{-\int L[A^a,q]+A_5\cdot J^5+\theta \mathrm{Tr}\star F\wedge F}$$

invariant under $A_5 \to A_5 + d\lambda_5, \qquad \theta \to \theta - c_a\lambda_5\,.$

because of the anomaly $d\star J_5 = c_a\,\mathrm{Tr}F\wedge F\,.$

Rotate θ into the quark propagator:

$$\langle \bar{q}q\rangle_a = \frac{1}{\mathcal{Z}(a)}\int \mathcal{D}A^a_\mu e^{-S_g}\det(\not{D}(a))\mathrm{Tr}\,(\not{D}(a))^{-1}\,,$$

$$\not{D}(a) = \gamma^\mu\left(\partial_\mu + A^a_\mu T^a\right) + \frac{a}{c_a}\gamma^3\gamma^5\,.$$

Do valence and sea also have opposite effects?

Holographic, anisotropic, non-conformal, neutral plasma

Giataganas, Pedraza, UG '17

Nonconformality ⇔ a scalar ϕ, anisotropy ⇔ another scalar χ

$$S = \frac{1}{2\kappa^2}\int d^5x\,\sqrt{-g}\,[R+\mathcal{L}_M]\,,$$
$$\mathcal{L}_M = -\frac{1}{2}(\partial\phi)^2 + V(\phi) - \frac{1}{2}Z(\phi)(\partial\chi)^2,$$

$$ds^2 = e^{2A(r)}\left[-f(r)dt^2 + d\vec{x}_\perp^2 + e^{2h(r)}dx_3^2 + \frac{dr^2}{f(r)}\right],$$
$$\phi = \phi(r), \qquad \chi = a\,x_3. \qquad \phi \to j r^{4-\Delta}$$

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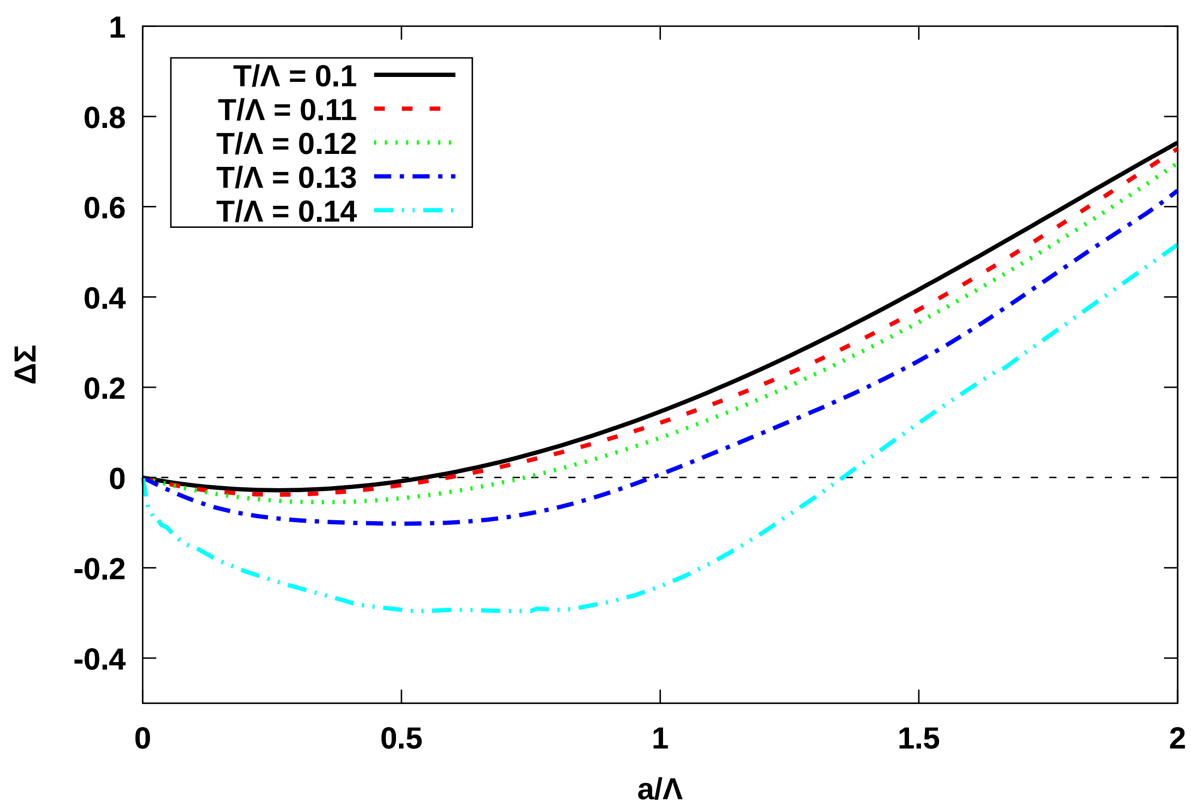


Inverse anisotropic catalysis

Conclusions I

- Holography reproduces inverse magnetic catalysis generically
- Supports valence vs. sea competition

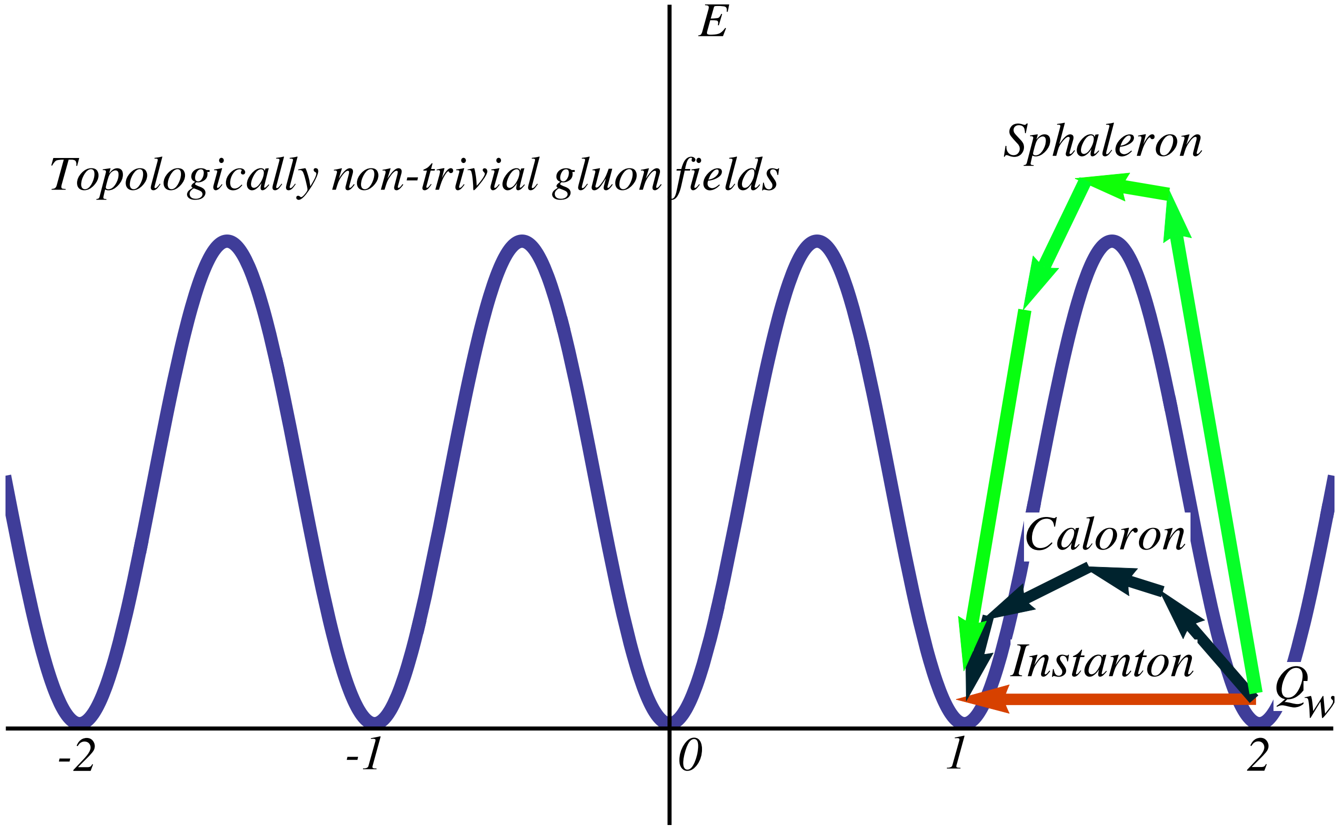
  Valence ⇔ explicit dependence in the tachyon equation
  Sea ⇔ implicit dependence through background functions

- Inverse magnetic catalysis only for small μ
- Inverse anisotropic catalysis:

  source of IMC anisotropy rather than charge dynamics caused by B ?
- New phases: confined-chiral symmetric, anisotropic confinement

Part II: Chern-Simons diffusion rate

Chern-Simons diffusion rate



$$\Delta N_{CS} = \frac{g^2}{32\pi^2} \int \text{tr}\; G \wedge G$$

Probability per unit time x volume of a CS number changing process:

$$\Gamma_{CS} = \frac{\langle \Delta N_{CS}^2 \rangle}{Vt} = \int d^4x \langle \frac{g^2}{32\pi^2} \text{tr} G \wedge G(x) \frac{g^2}{32\pi^2} \text{tr} G \wedge G(0) \rangle$$

Chern-Simons diffusion rate

Perturbative result: $$\Gamma_{CS}/T^4 \approx 193\alpha_s^5$$ Moore et al '99

N=4 sYM: $$\Gamma_{CS}/T^4 = \frac{(g^2N)^2}{256\pi^3} \approx 0.045$$ Son, Starinets '02

Chern-Simons diffusion rate

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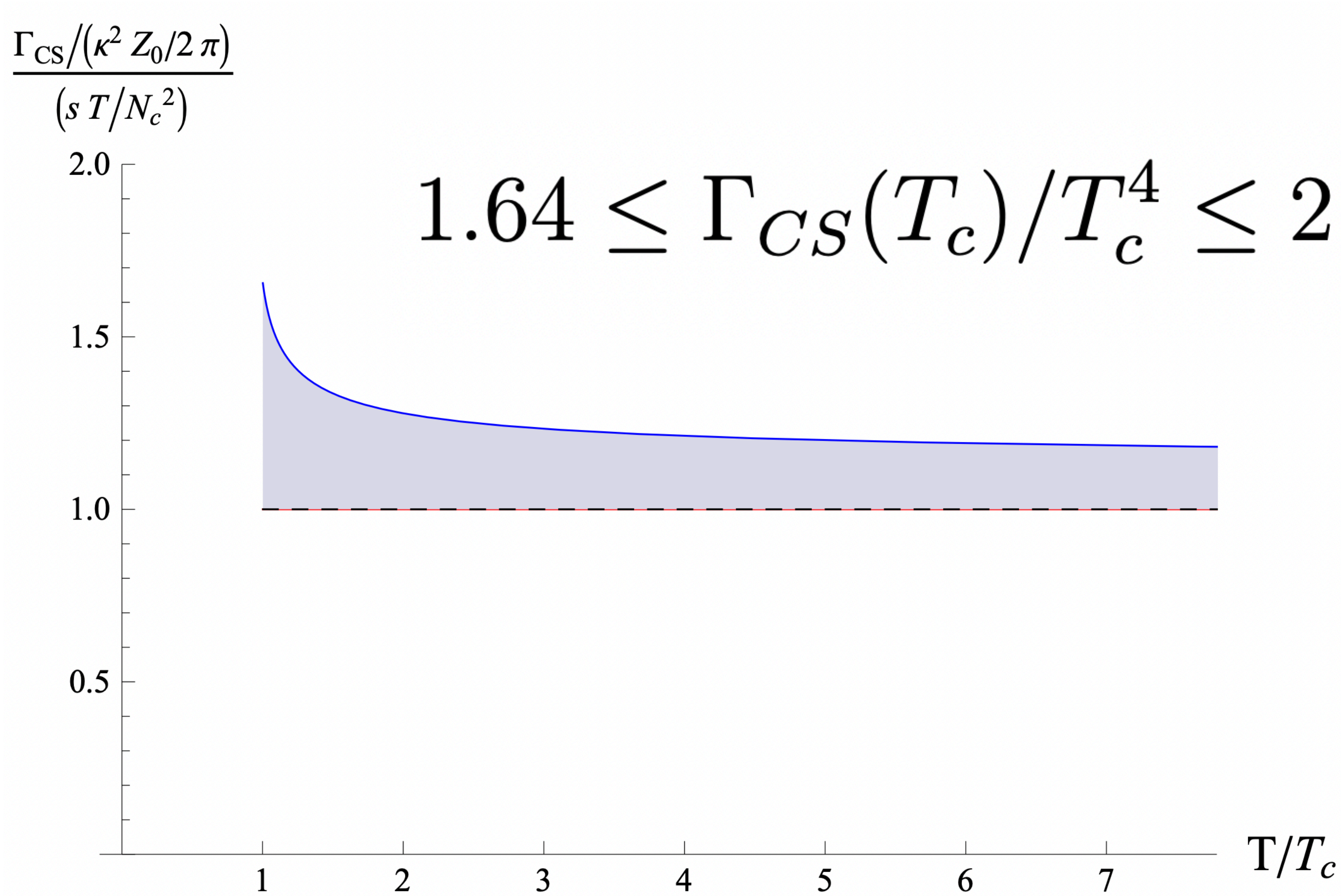
Improved hQCD:

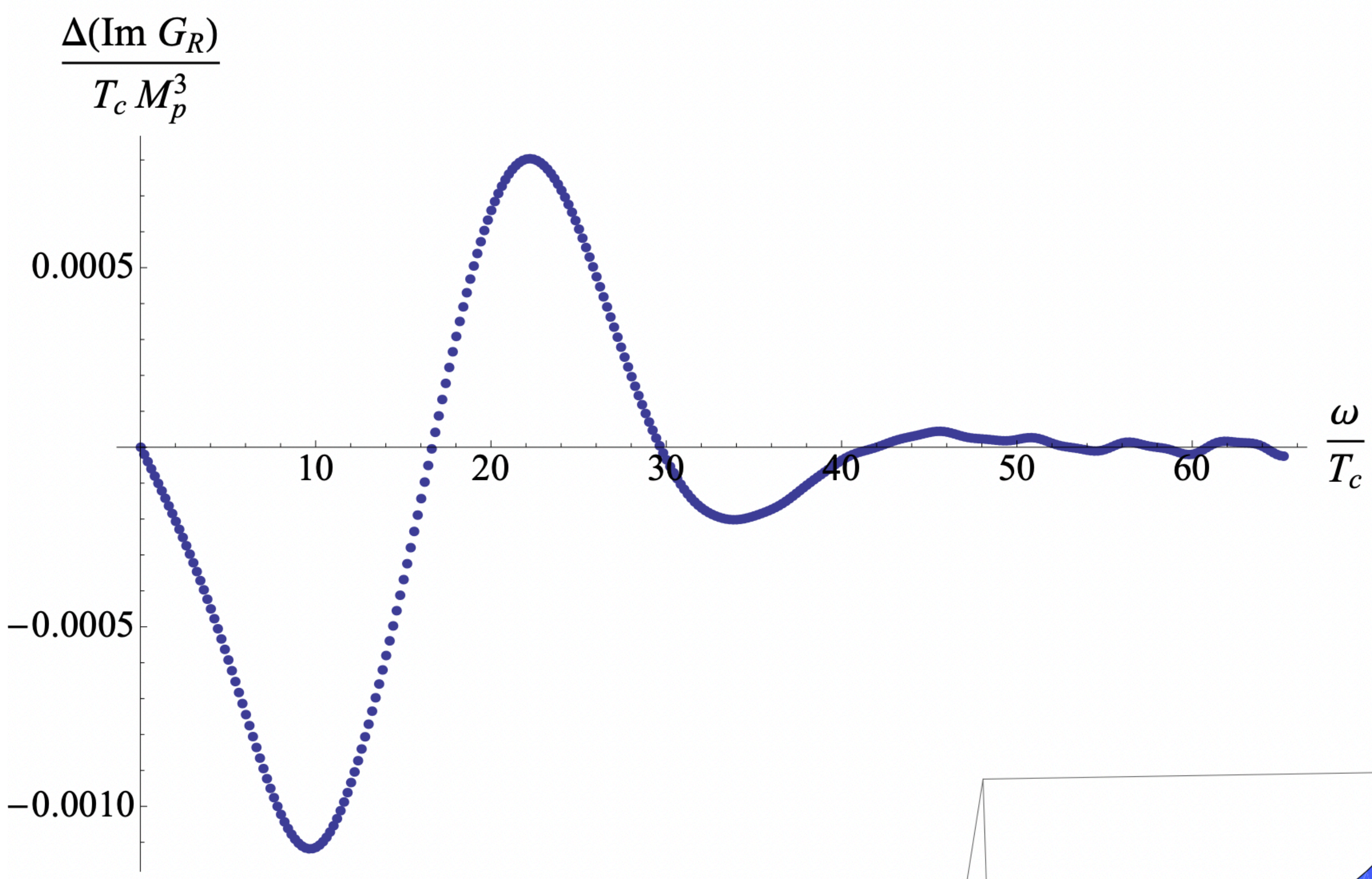
$$\Gamma_{CS} = \frac{1}{N^2}\frac{sT}{2\pi}Z(\lambda_h)$$

Iatrakis, Kiritsis, O'Bannon, UG '12



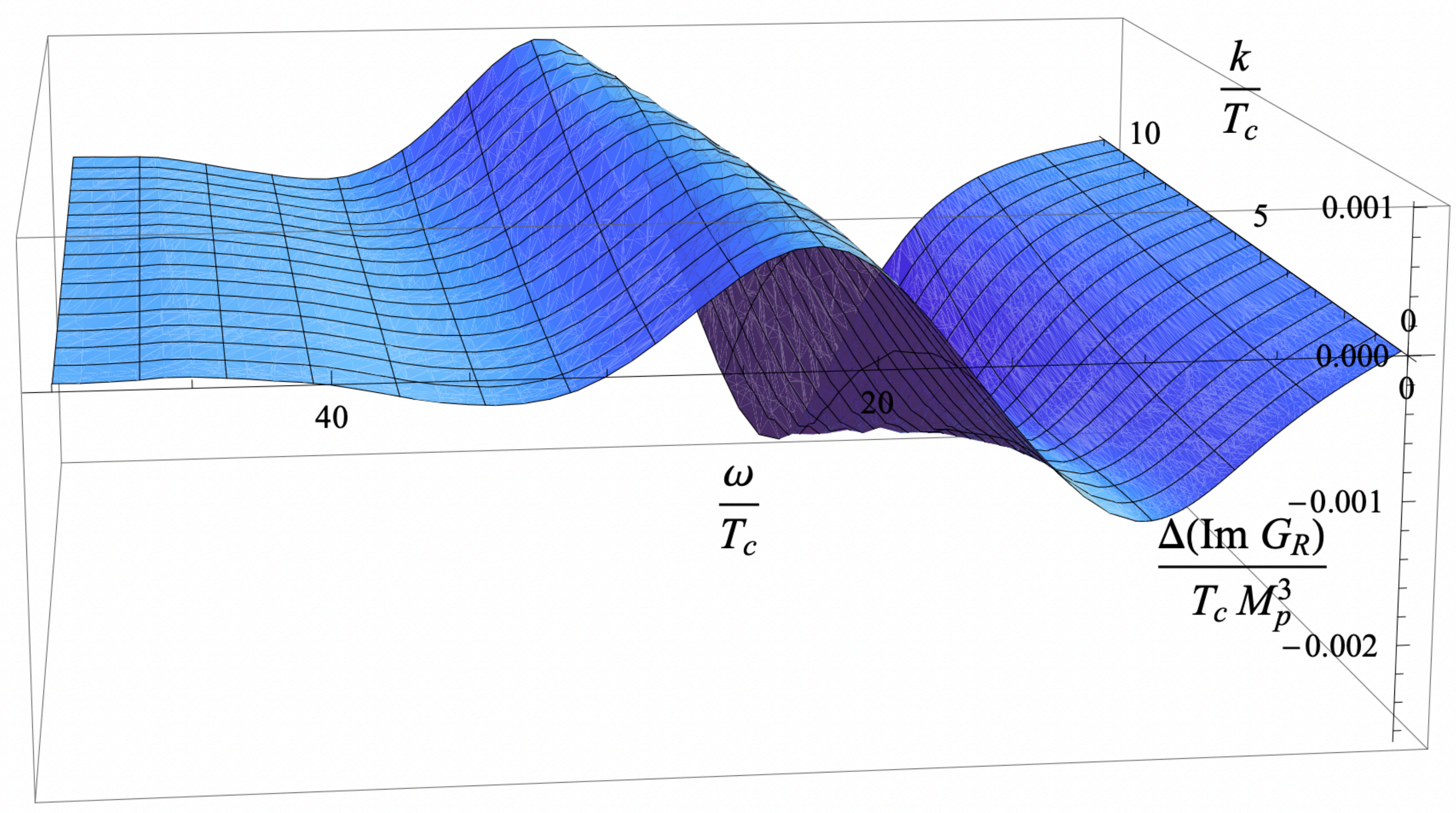
$$1.64 \leq \Gamma_{CS}(T_c)/T_c^4 \leq 2.8.$$

Frequency and momentum dependence



$$\Delta \mathrm{Im}\, G_R(\omega, \vec{k} = 0; T_c, 2T_c)$$

$$\Delta \mathrm{Im}\ G_R(\omega, \vec{k}, T_c, 2T_c)$$



Iatrakis, Kiritsis, O'Bannon, UG '12

Conclusions II

- Improved holographic models predict larger Γ_{CS}
- Nontrivial ω and k depence $\Rightarrow$ spatial modulation of Γ_{CS}

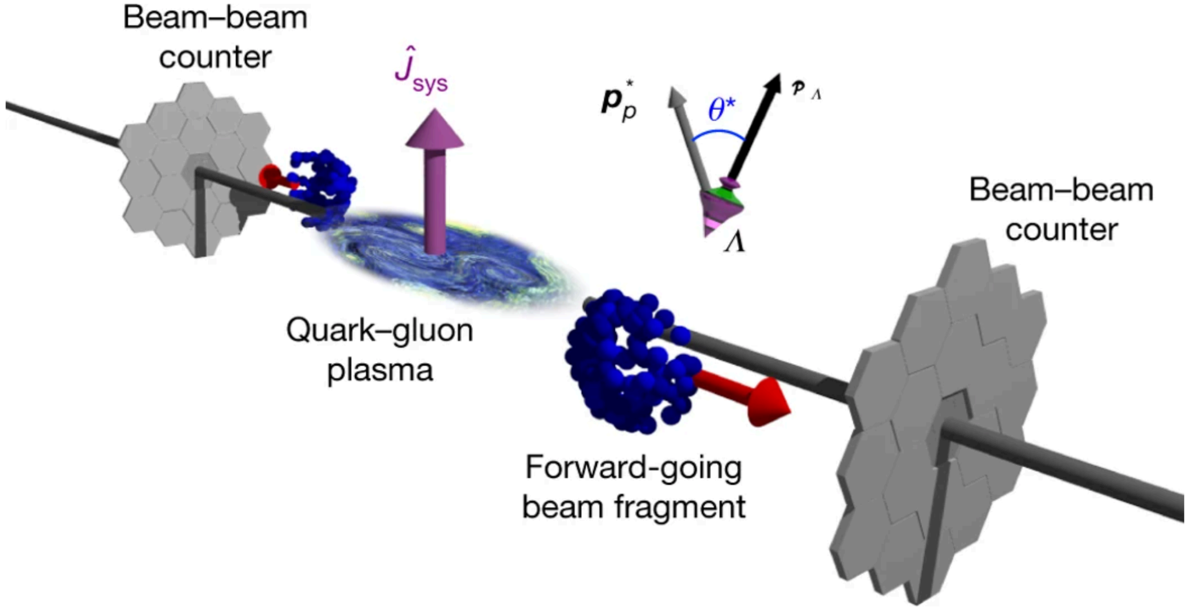
Part III: Spin currents in QGP

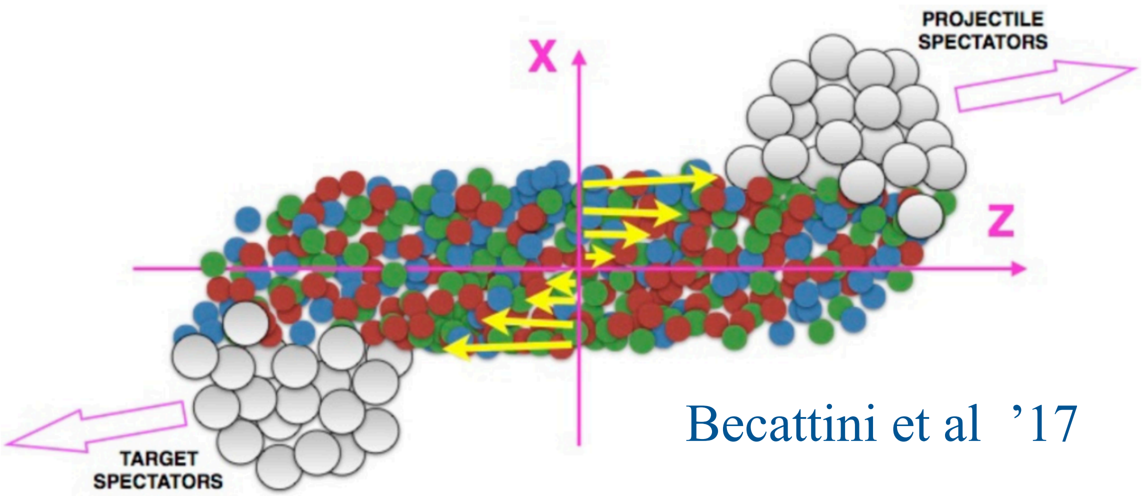
Spin-hydrodynamics

Strong vortical structure

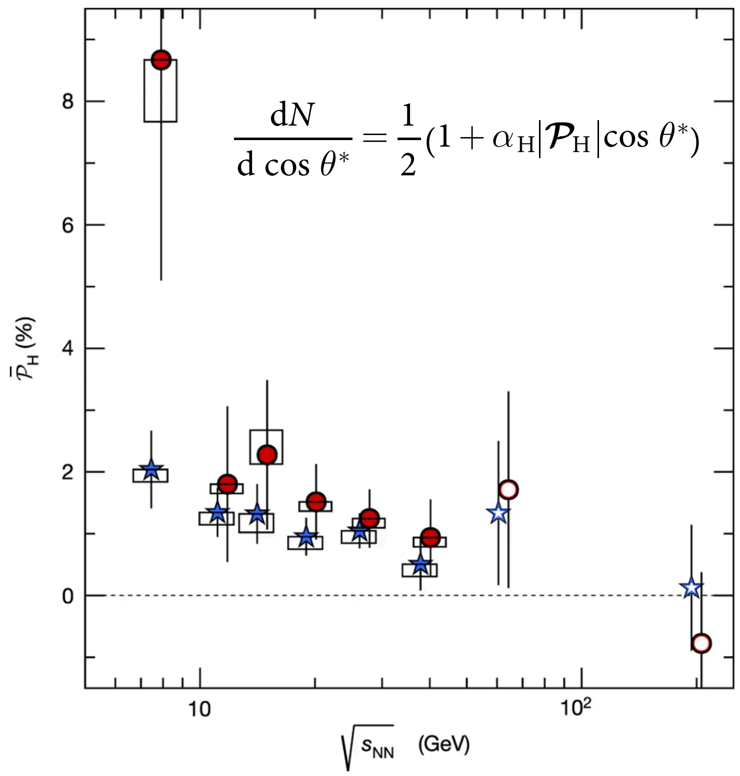
$\omega \sim 10^{22}\ s^{-1}$

Global spin polarization





Becattini et al '17

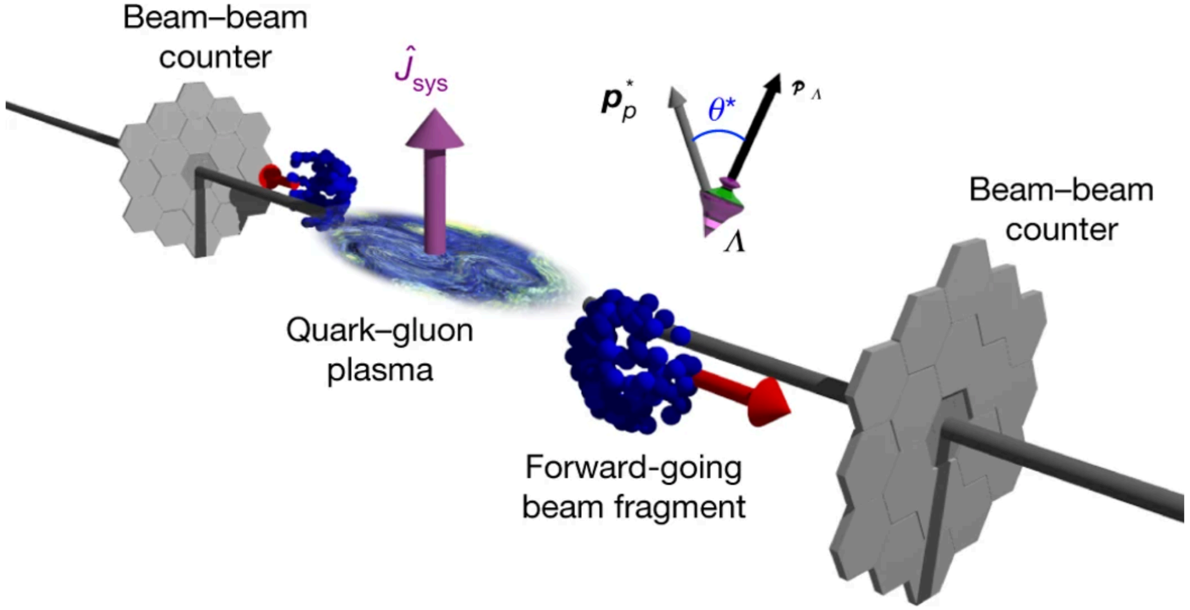


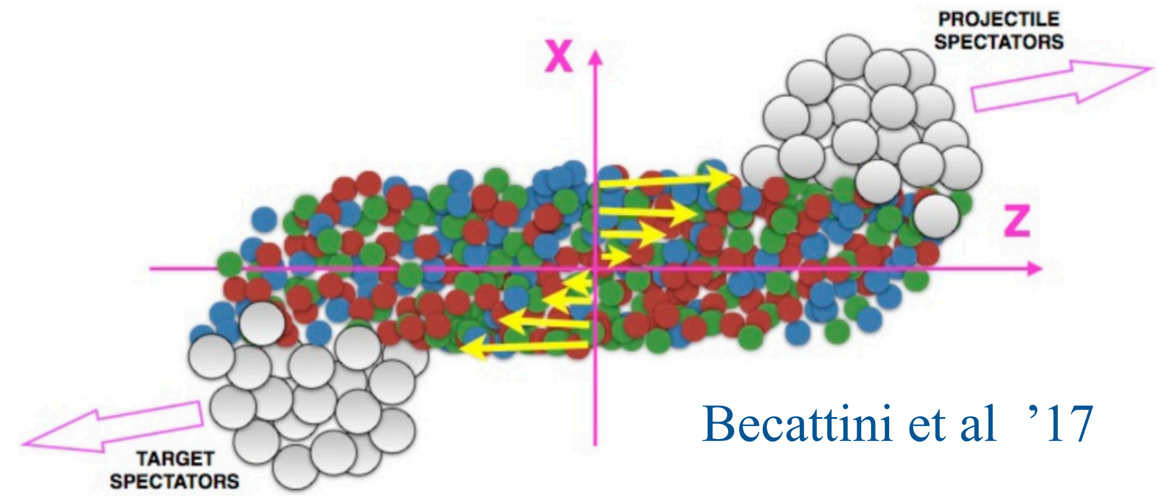
Global hyperon polarization at RHIC
by spin-orbit coupling $\vec{S} \cdot \vec{J}$

QGP: most vortical fluid: $\omega \sim 10^{22}\ s^{-1}$

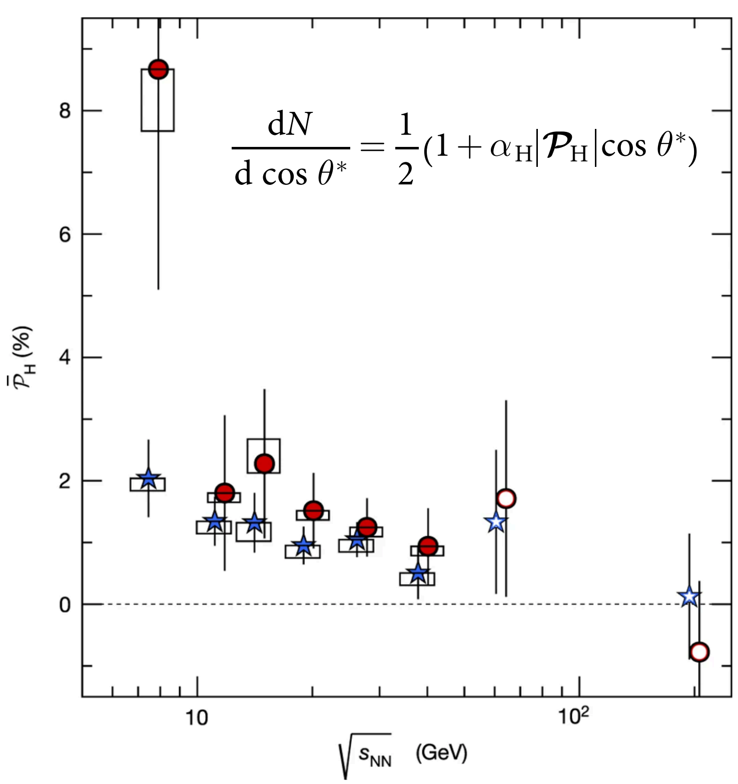
STAR collaboration, RHIC `19

Global spin polarization





Becattini et al '17



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STAR collaboration, RHIC `19

$\Longrightarrow$ hydrodynamic description?

Hydrodynamics with spin current

Gallegos, Yarom, UG `21

Slow variables: energy-momentum and spin current

$$T_{\mu\nu} \qquad\qquad S^{\lambda}_{\mu\nu}$$

Earlier work: Becattini et al ’08; Becattini, Piccinini ’08
Karabali, Nair ’14
Florkowski et al ’18 ’19; Hattori, X.-G. Huang et al ’19
Gallegos, UG ’19; Li, Stephanov, Yee ’20

Hydrodynamics with torsion

- Metric couples to energy-momentum, contorsion sources spin :

$$\omega_\mu^{ab} = \mathring{\omega}_\mu^{ab} + K_\mu^{ab}, \qquad \mathring{\omega} \sim \partial e$$

Hydrodynamics with torsion

- Metric couples to energy-momentum, contorsion sources spin :

$$\omega_\mu^{ab} = \mathring{\omega}_\mu^{ab} + K_\mu^{ab}, \qquad \mathring{\omega} \sim \partial e$$

- Hydrodynamics on a manifold with non-trivial torsion:

$$T^{\mu\nu} = \frac{\delta W}{\delta e_\mu^a} e_a^\nu, \qquad S_{ab}^\lambda = \frac{\delta W}{\delta \omega_\lambda^{ab}}$$

Hydrodynamic equations

$$\mathring{\nabla}_\mu T^{\mu\nu} = \frac{1}{2} R^{\rho\sigma\nu\lambda} S_{\rho\lambda\sigma} - T_{\rho\sigma} K^{\nu ab} e^\rho{}_a e^\sigma{}_b$$ 4 equations

$$\mathring{\nabla}_\lambda S^\lambda{}_{\mu\nu} = 2T_{[\mu\nu]} - 2S^\lambda{}_{\rho[\mu} e_{\nu]}{}^a e_\rho{}^b K_{\lambda ab} \, ,$$ 6 equations

Hydrodynamic equations

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$$\mathring{\nabla}_\lambda S^\lambda{}_{\mu\nu} = 2T_{[\mu\nu]} - 2S^\lambda{}_{\rho[\mu} e_{\nu]}{}^a e_\rho{}^b K_{\lambda ab} \,,$$ 6 equations

10 dynamical variables:

$$T \qquad u^\mu \qquad \mu^{ab} = \omega_\mu^{ab} u^\mu$$

Spin "chemical" potential

Analogous to electric potential

$$\mu_E = A_\mu u^\mu$$

Conformal spin hydro

Equations of motion + constitutive relations: determine T, u and $\mu^{\alpha\beta}$

$$\mu^{ab} = 2u^{[a}\underbrace{m^{b]}}_{\text{“electric”}} + \epsilon^{abcd}u_c\underbrace{\tilde{M}_d}_{\text{“magnetic”}}$$

$$u^\alpha \mathcal{D}_\alpha T = \hat{\eta}\sigma_{\alpha\beta}\sigma^{\alpha\beta}\,,$$

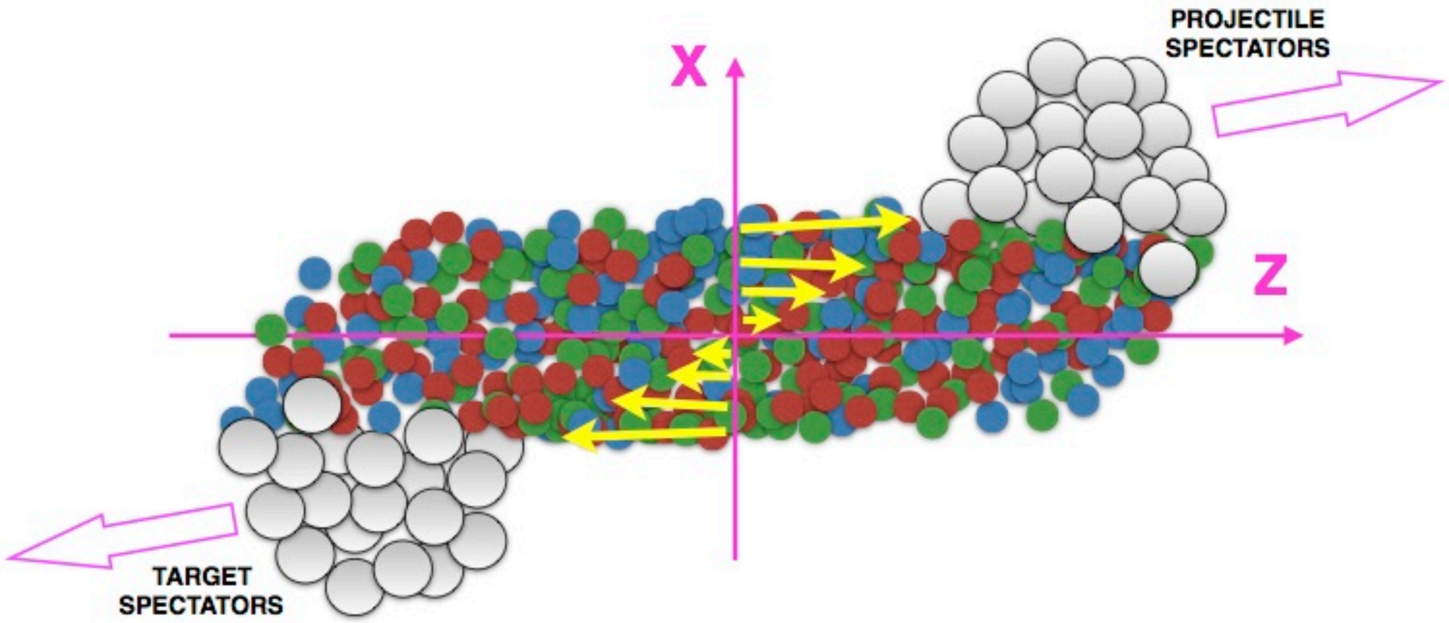
$$\Delta^\nu_\beta \mathcal{D}_\alpha \sigma^{\alpha\beta} = \left(\frac{\Delta^{\nu\beta}}{3\hat{\eta}} - \frac{3\sigma^{\nu\beta}}{T}\right)\mathcal{D}_\beta T\,,$$

$$\Delta^\lambda_\beta u^\alpha \mathcal{D}_\alpha m^\beta = c_1 \Delta^\lambda_\beta \mathcal{D}_\alpha \sigma^{\alpha\beta} + c_2 \Delta^\lambda_\beta \mathcal{D}_\alpha M^{\alpha\beta} + c_4 \sigma^{\lambda\alpha} m_\alpha + c_7 M^{\lambda\alpha} m_\alpha + c_8 \Omega^{\lambda\alpha} m_\alpha\,,$$

$$\Delta^\rho_\alpha \Delta^\sigma_\beta u^\lambda \mathcal{D}_\lambda M^{\alpha\beta} = -\hat{\sigma}\Delta^\rho_\alpha \Delta^\sigma_\beta u^\lambda \mathcal{D}_\lambda \Omega^{\alpha\beta} + c_3 \Delta^{\alpha[\rho}\Delta^{\sigma]\beta}\mathcal{D}_\alpha m_\beta + c_5 \sigma^{\alpha[\rho} {M^{\sigma]}}_\alpha + c_6 \sigma^{\alpha[\rho} {\Omega^{\sigma]}}_\alpha + c_9 M^{\alpha[\rho} {\Omega^{\sigma]}}_\alpha$$

Need: initial conditions + transport coefficients

Application to HIC



Polarization of hyperon:

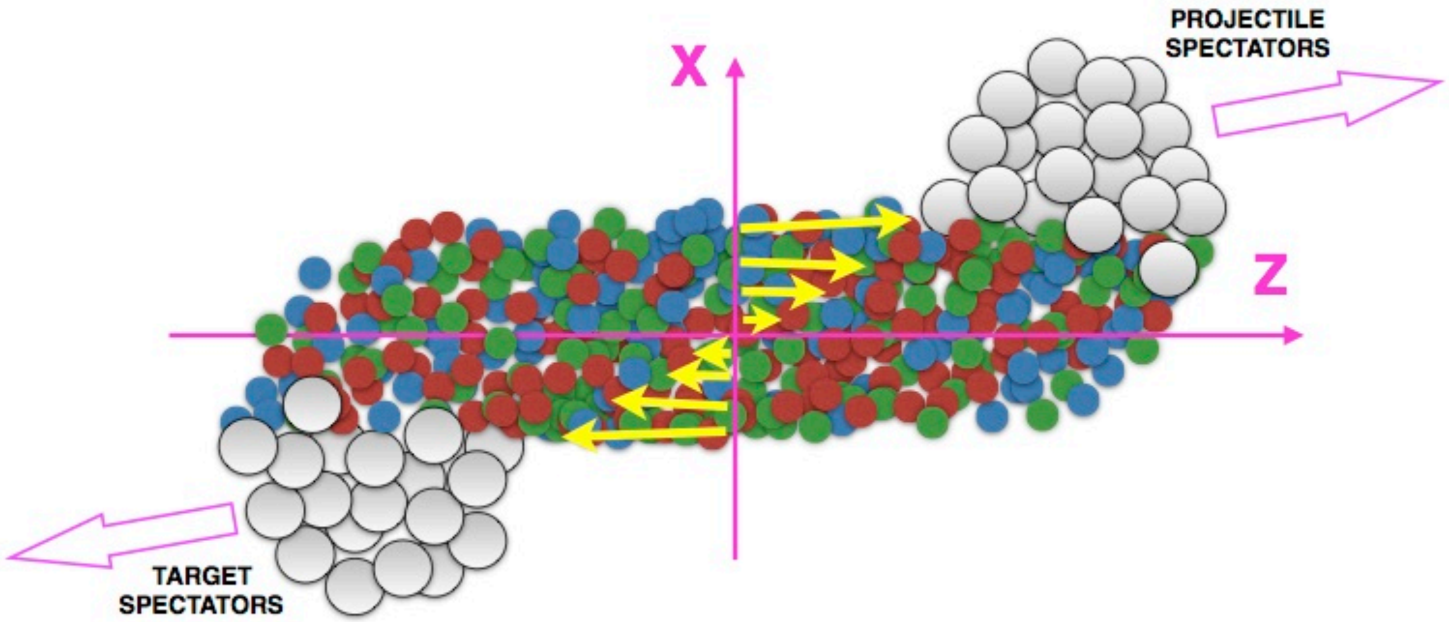
$$\Pi_\mu(p) = -\frac{1}{4}\epsilon_{\mu\rho\sigma\beta}\frac{p^\beta}{m}\frac{\int d\Sigma_\lambda p^\lambda B(x,p)\mu^{\rho\sigma}}{2\int d\Sigma_\lambda p^\lambda n_F}$$

spin potential

Boltzmann type distribution

freezout surface

Application to HIC



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spin potential

freezout surface

Boltzmann type distribution

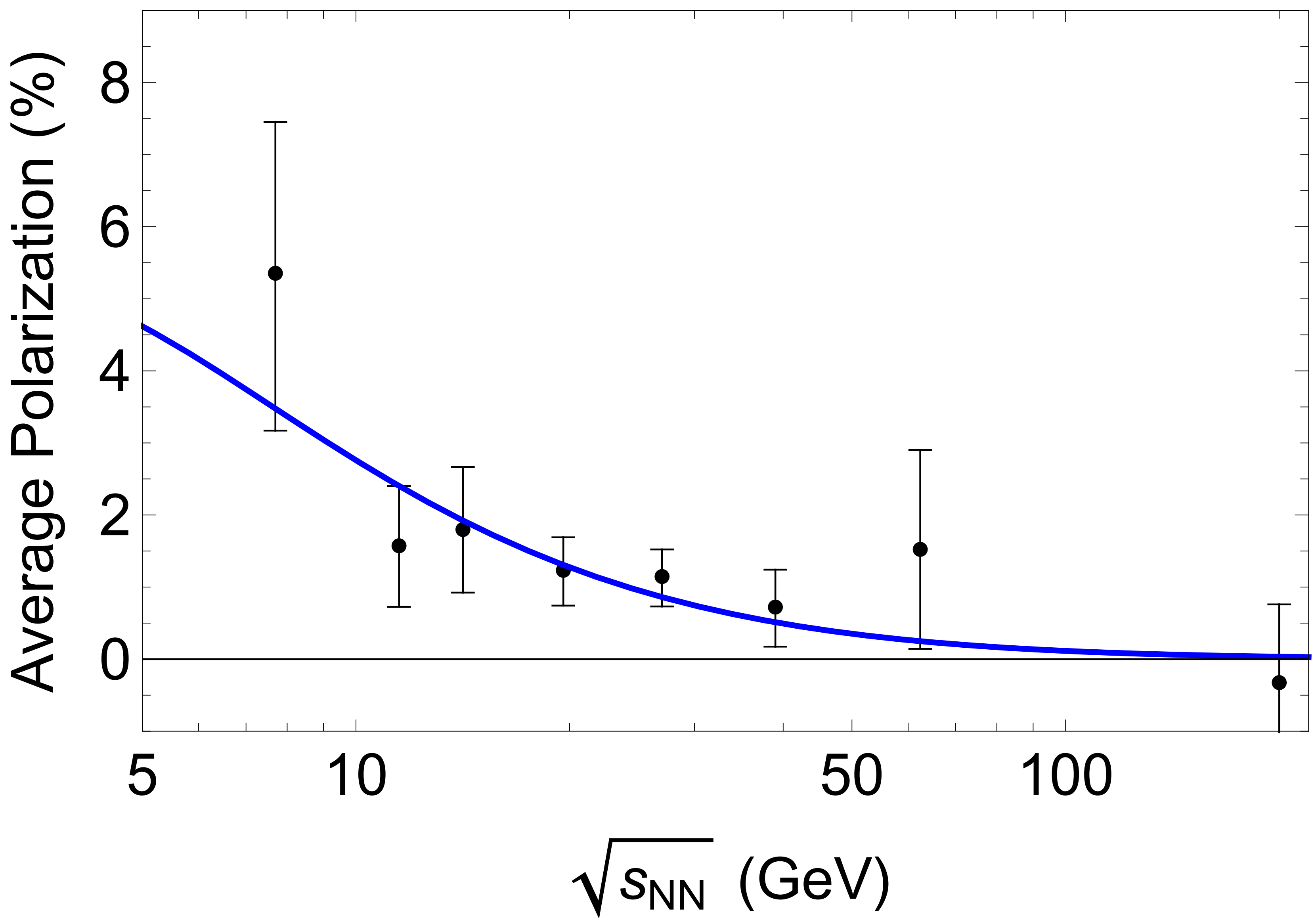
Spin hydrodynamics $\Longrightarrow$ spin potential

Comparison to data

Hydrodynamic solution, for small "kinematic viscosity"/time $\frac{3\eta_0}{4\epsilon_0}\frac{1}{T\tau} \ll 1$

Floerschinger, Wiedemann '11

$$\delta m^x(\tau) \propto \tau^{-\frac{8}{3}} e^{-\frac{9q^2\eta_0\tau_0}{16T_0\epsilon_0}\left(\frac{\tau}{\tau_0}\right)^{\frac{4}{3}}}, \qquad \delta M^{x\eta}(\tau) \propto q^2\,\tau^{-\frac{5}{3}} e^{-\frac{9q^2\eta_0\tau_0}{16T_0\epsilon_0}\left(\frac{\tau}{\tau_0}\right)^{\frac{4}{3}}}$$



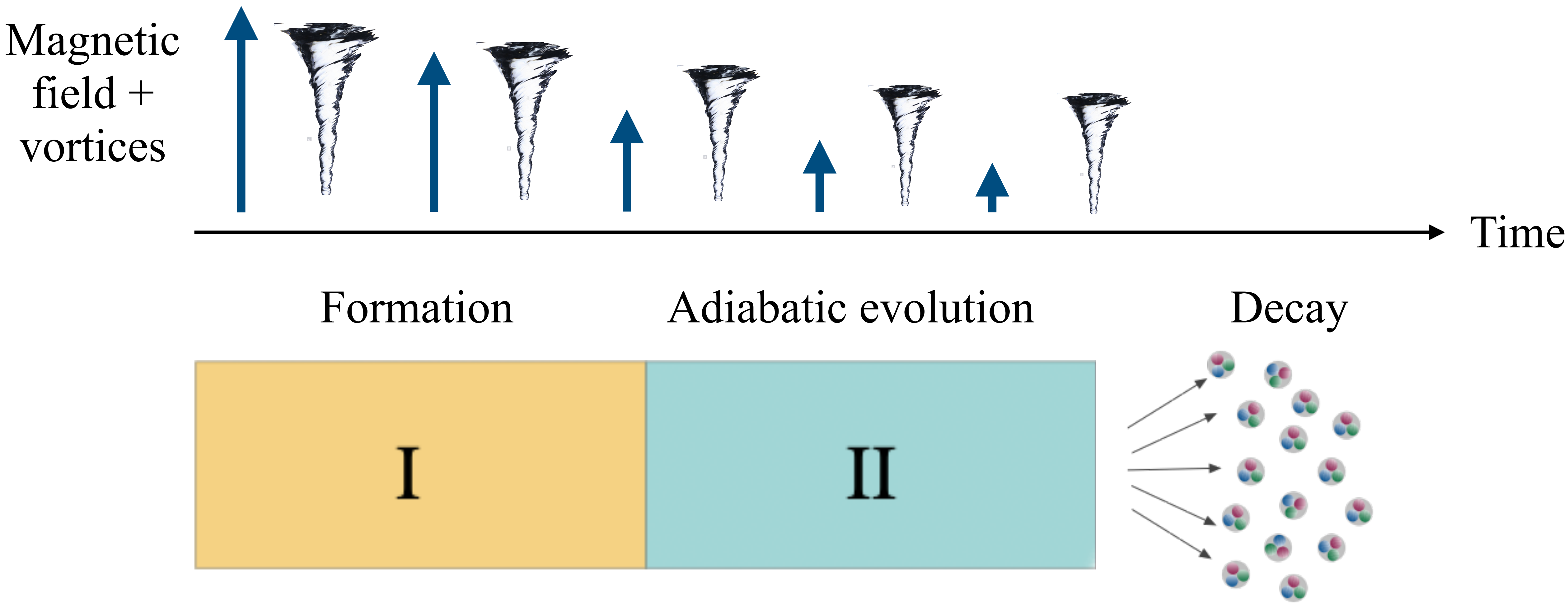
Conclusions III

- Spin-hydrodynamics: a novel theory of relativistic hydro

  Gallegos, Yarom, UG ’22

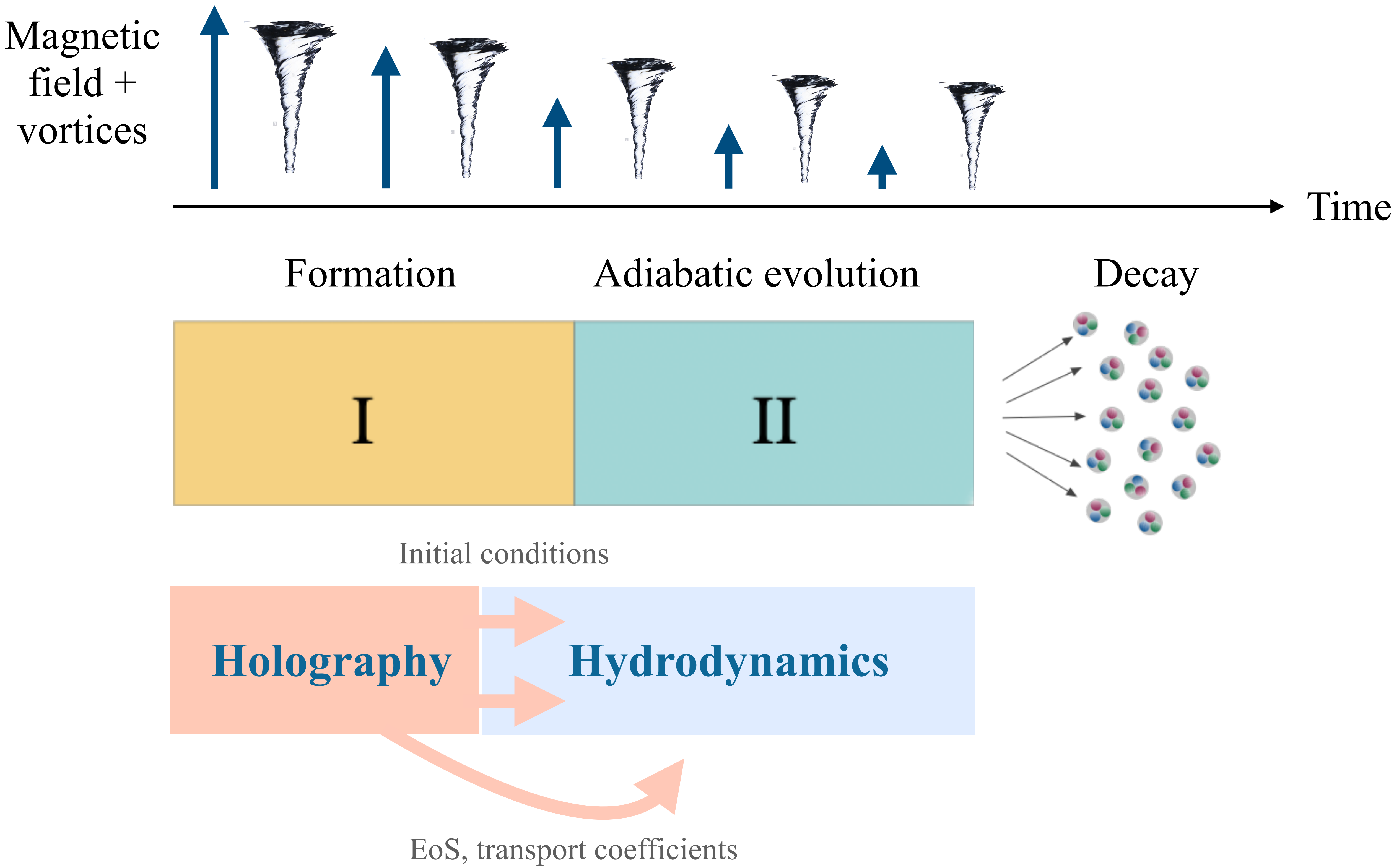
- Belinfante-Rosenfeld ambiguity fixed by torsion
- Reproduces observed global polarization of hyperons

Outlook

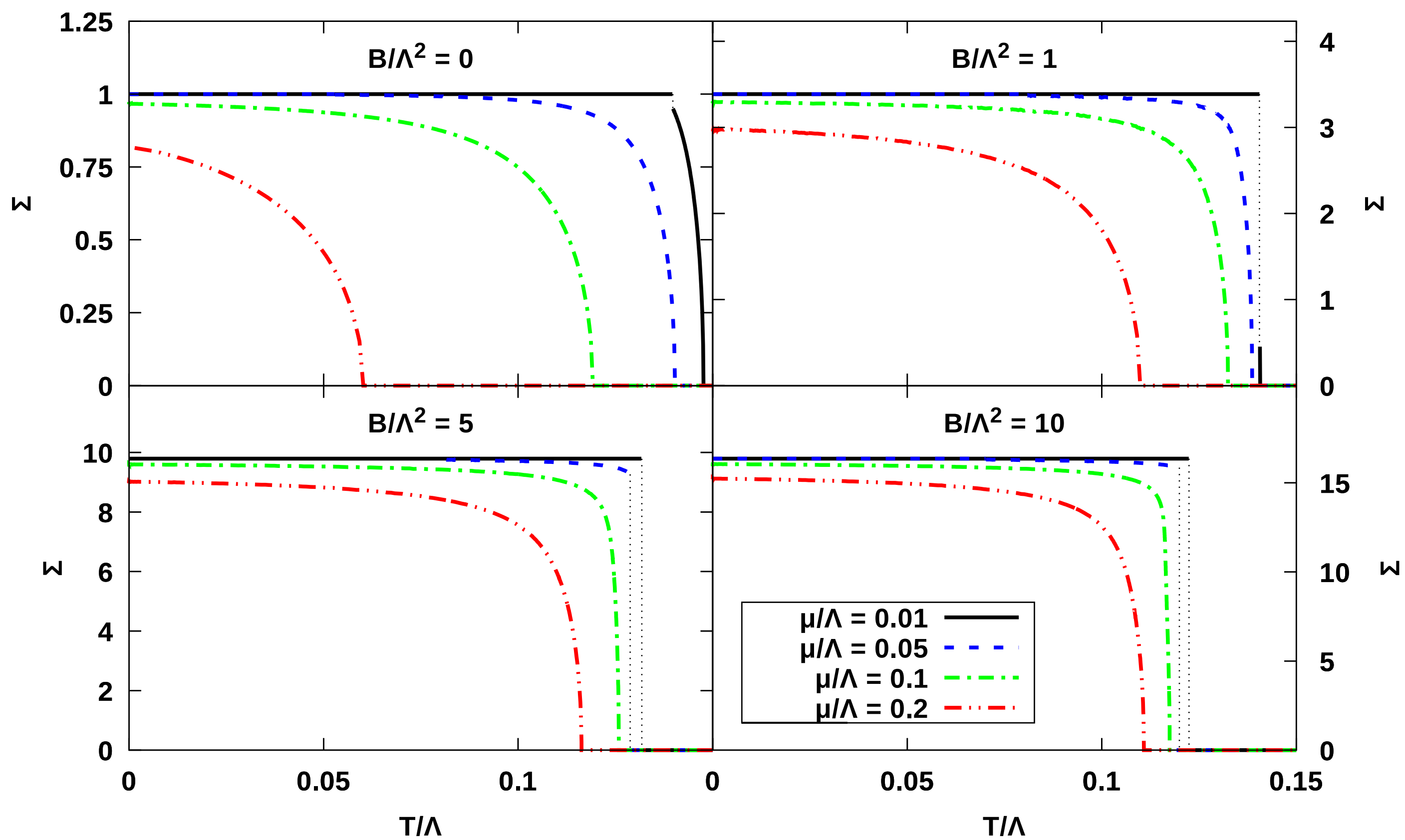


Hydrodynamics

Outlook

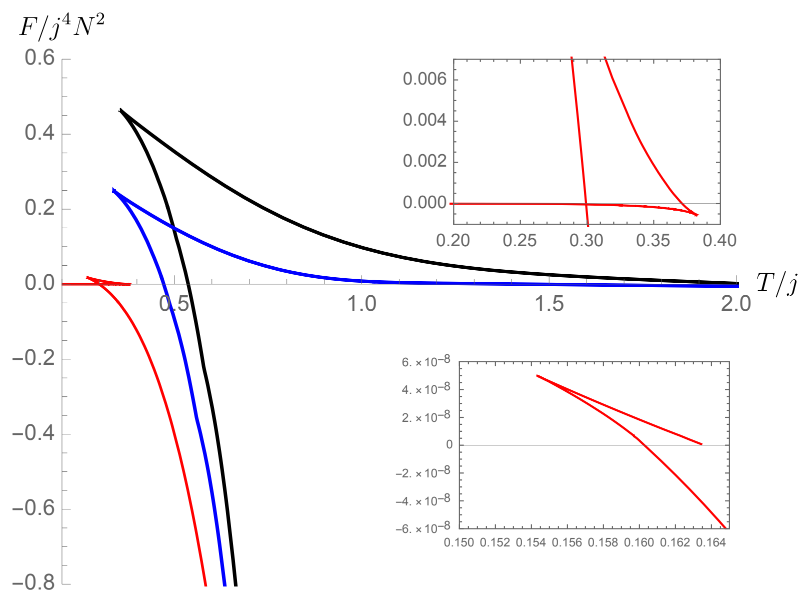

Magnetic field + vortices
Time
Formation
Adiabatic evolution
Decay
I
II
Initial conditions
Holography
Hydrodynamics
EoS, transport coefficients

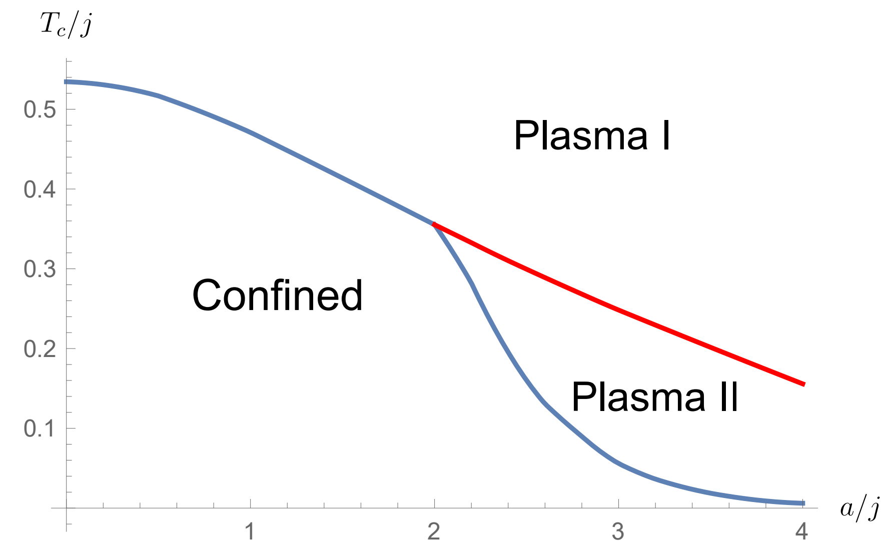
Chiral condensate at finite μ



- μ decreases the condensate at fixed B
- B generically increases the condensate, except around T_χ and for $\mu < 0.1$
- No T dependence in the confined phase, due to $1/N^2$ suppression

Thermodynamics of the anisotropic theory





- T_c decreases with anisotropy
- A new plasma phase and two phase boundaries

$\Longrightarrow$ **inverse anisotropic catalysis?**

Holographic, anisotropic, non-conformal, neutral plasma

Giataganas, Pedraza, UG '17

Nonconformality ⇔ a scalar φ, anisotropy ⇔ another scalar χ

$$S = \frac{1}{2\kappa^2}\int d^5x\,\sqrt{-g}\,[R + \mathcal{L}_M]\,,$$

$$\mathcal{L}_M = -\frac{1}{2}(\partial\phi)^2 + V(\phi) - \frac{1}{2}Z(\phi)(\partial\chi)^2,$$

$$V(\phi) = 12\cosh(\sigma\phi) + b\,\phi^2, \qquad Z(\phi) = e^{2\gamma\phi},$$

$$ds^2 = e^{2A(r)}\left[-f(r)dt^2 + d\vec{x}_\perp^2 + e^{2h(r)}dx_3^2 + \frac{dr^2}{f(r)}\right],$$

$$\phi = \phi(r), \qquad \chi = a\,x_3. \qquad \phi \to j r^{4-\Delta}$$

IR geometry is hyper scaling violating:

$$ds^2 = \tilde{L}^2(ar)^{2\theta/3z}\left[\frac{-dt^2 + d\vec{x}_\perp^2 + dr^2}{a^2r^2} + \frac{c_1\,dx_3^2}{(ar)^{2/z}}\right],$$

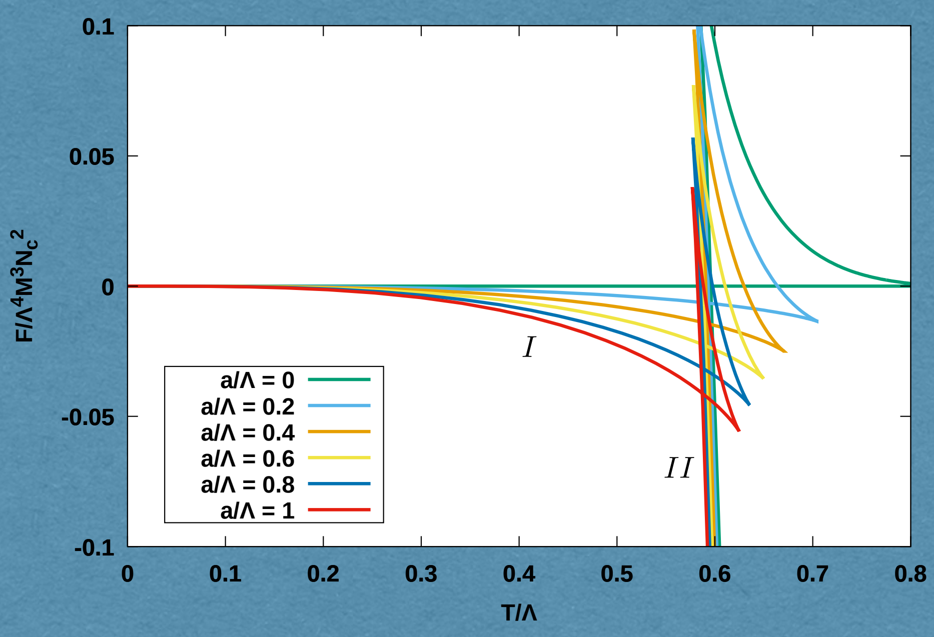
$$\phi = c_2\log(ar) + \phi_0.$$

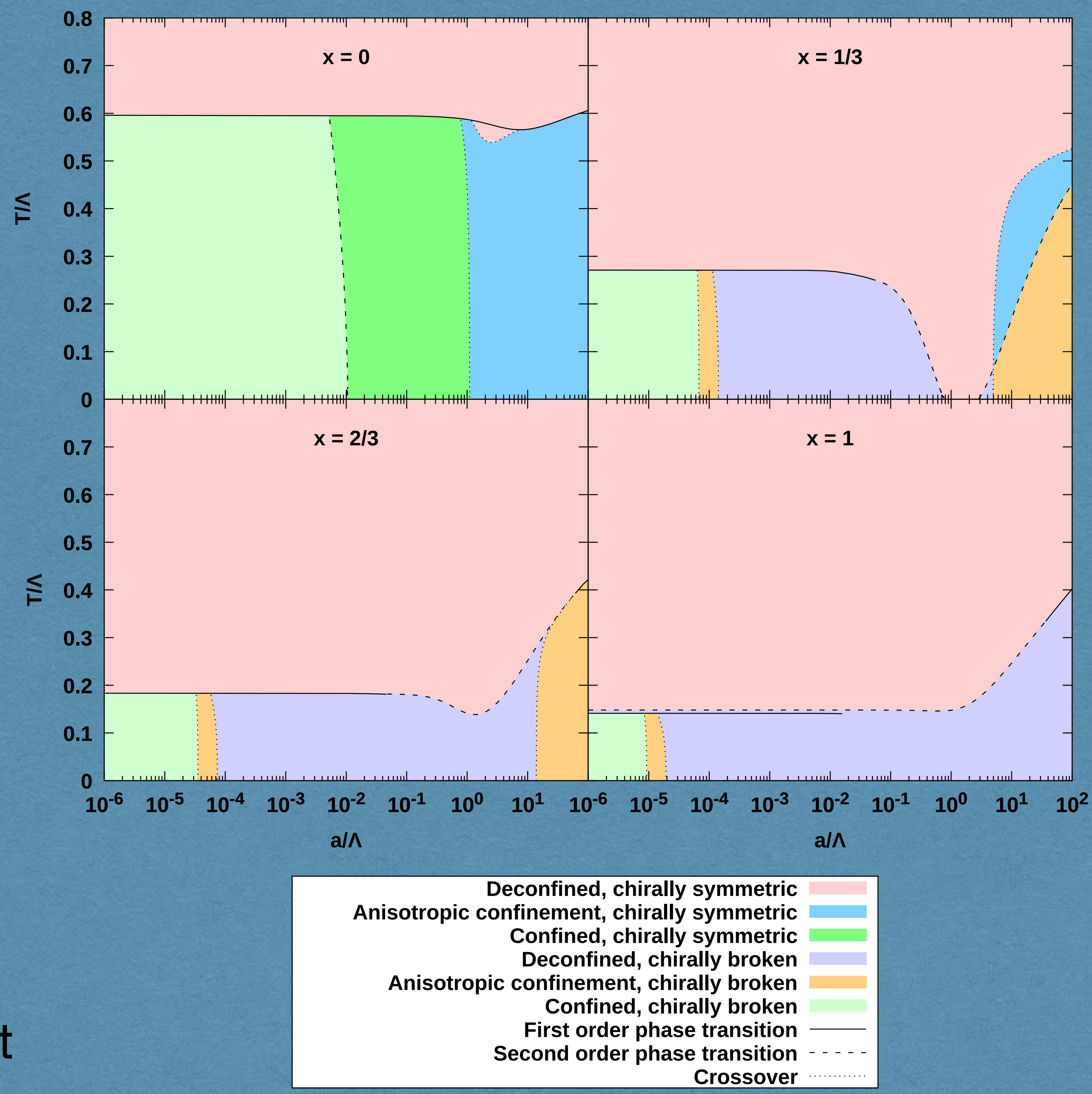
$$ds \to \lambda^{\theta/3z}ds\,.$$

$$t \to \lambda t, \quad \vec{x}_\perp \to \lambda\vec{x}_\perp, \quad r \to \lambda r, \quad x_3 \to \lambda^{\frac{1}{z}}x_3\,.$$

Thermodynamics

Jarvinen, Nijs, Pedraza, UG ‘18





x=0

- $F \sim -T^4$ at large T; $F \sim -T^3$ at small T
- Very different than a=0 case
- Black hole is “confining”

- T_χ decreases with a generically
- Possibility of anisotropic confinement
- Quantum critical point for x=1/3
- Possibility of a confined chirally symmetric phase!?

Magnetic QCD

Anisotropy

B reduces original Lorentz : $SO(3,1) \Longrightarrow \underbrace{SO(1,1)}_{\text{boost // B}} \times \underbrace{SO(2)}_{\text{rotation} \perp \text{B}}$

propagators, transport coefficients decomposed using projectors

$$\Delta_{\mu\nu} = \eta_{\mu\nu} + u_\mu u_\nu - \frac{B_\mu B_\nu}{B^2} \qquad \text{etc.}$$

Anisotropic confinement: $\sigma_\perp > \sigma_{\parallel}$

Bonati, D'Elia et al. '14

Chiral symmetry breaking

B reduces original chiral symmetry: u +2/3, d -1/3:

$$SU(N_u)_L \times SU(N_u)_R \times SU(N_d)_L \times SU(N_d)_L \times U(1)_{A-} \Longrightarrow SU(N_u)_V \times SU(N_d)_V$$

IR effective theory: χPT of $N_u^2 + N_d^2 - 1$ NG bosons

Magnetic QCD

Fundamental scales at vanishing temperature and density

$1/\sqrt{eB}$	Magnetic screening length
$\Lambda_{QCD}(B)$	Confinement scale
$m_{dyn}(B)$	Dynamically generated quark mass

Separation of scales:

$$m_{dyn} \ll k \ll \sqrt{eB}$$ χSB

$$k \ll m_{dyn}$$ confinement

Additional scales T, μ

$T \neq 0, \;\; \mu = 0$ pQCD + χPT + lattice QCD

$T \neq 0, \;\; \mu \neq 0$ Holographic models

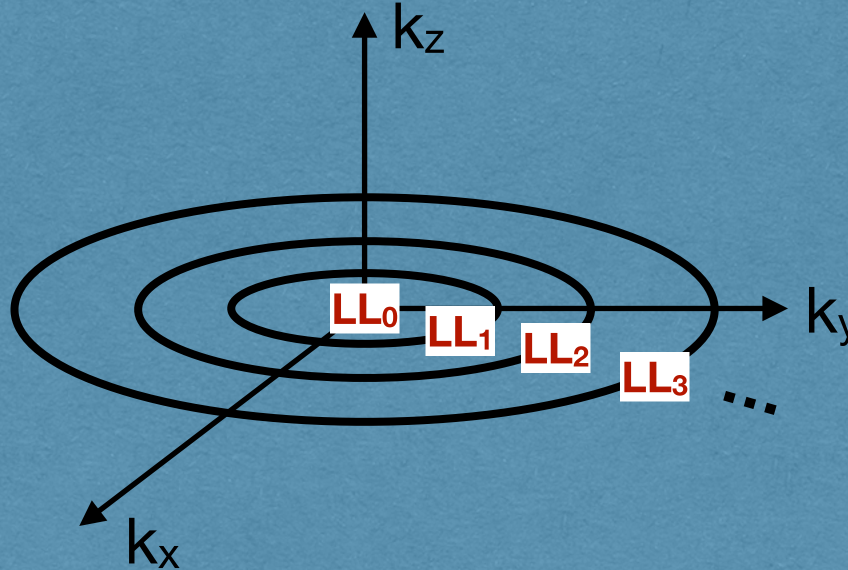
Various regimes

I. $eB \gg \Lambda^2_{QCD}$ Perturbative QCD $\frac{1}{\alpha_s} \approx b \, \log \frac{|eB|}{\Lambda^2_{QCD}}$ Kabat, Lee, Weingerg ‘02

II. $eB \approx \Lambda^2_{QCD}$ Lattice QCD, NJL effective theory, holography

III. $eB \ll \Lambda^2_{QCD}$ Perturbative EM

QCD in strong B (regime I)



Landau quantization

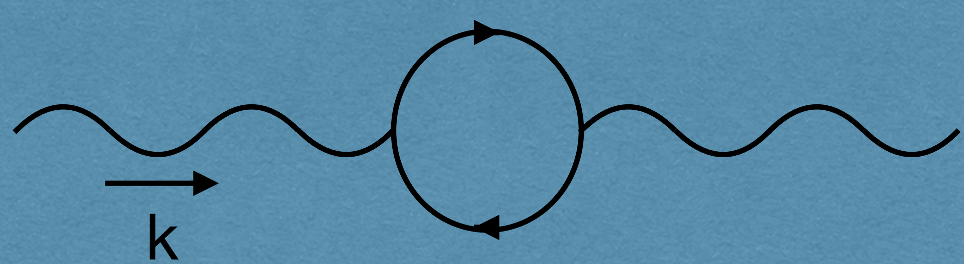
$$E_n(k_z) = \pm\sqrt{m^2 + 2|eB|n + k_z^2}$$

Dynamics effectively reduce 3+1 —> 1+1

Degeneracy of states ~ |eB|

Magnetic screening

Gluon polarisation at $|k|^2 << |eB|$ dominated by quarks at LL_0 over gluons and ghosts



$$M_g^2 \approx (2N_u + N_d)\frac{\alpha_s}{3\pi}|eB|$$

Color charge effectively screened in the regime $m_{dyn} \ll k \ll \sqrt{eB}$

Magnetic catalysis in strong B

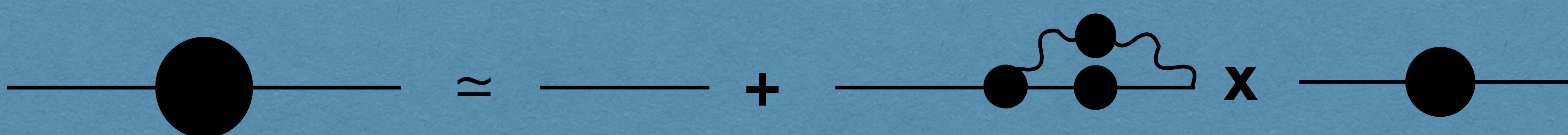
Three energy regimes

$k \gg \sqrt{eB}$ — UV of QCD w/o B

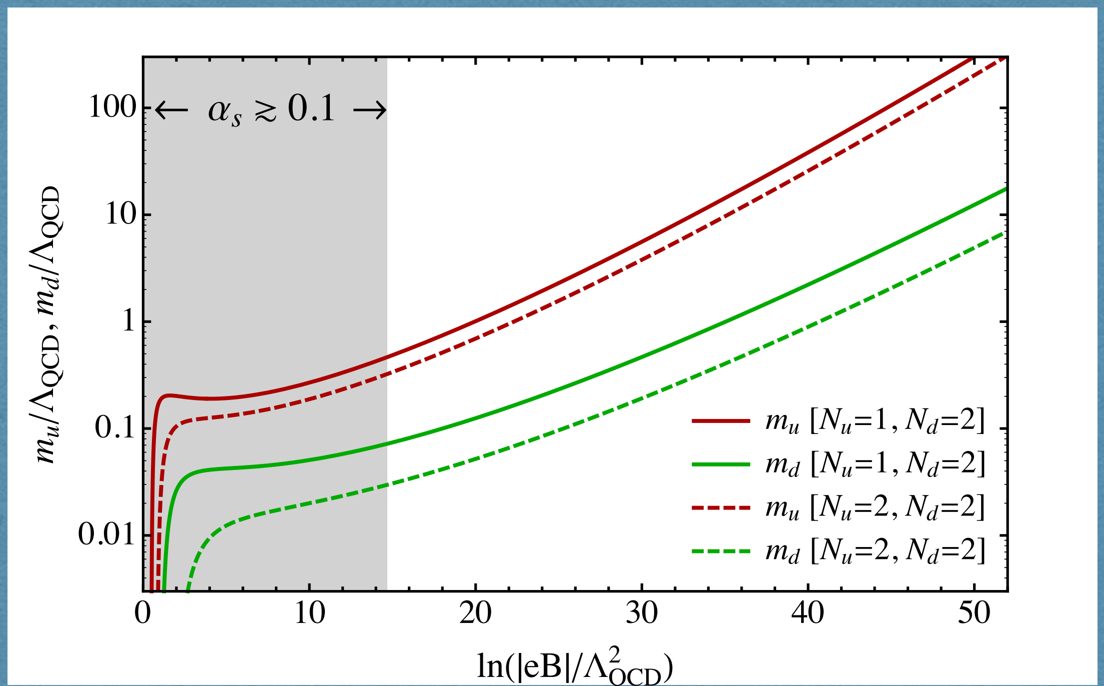
$m_{dyn} \ll k \ll eB$ — Relevant for magnetic catalysis

$k \ll m_{dyn}$ — pure glue, anisotropic confinement

- Regimes relevant for χSB and confinement are separate at finite B!
- Solve the gap equation (improved rainbow approx) to obtain m_{dyn} at $eB \gg \Lambda^2_{QCD}$



Dynamically generated quark mass: Miransky, Shovkovy '15



Magnetic catalysis in strong B

Dynamically generated quark mass for $eB \gg \Lambda_{QCD}^2$

$$m_{dyn}^2 \approx 2|e_q B|(\bar{\alpha}_s)^{\frac{2}{3}} \exp\left[\frac{4N_c\pi}{\alpha_s(N_c^2-1)\log(\bar{\alpha}_s)}\right]$$

with $\bar{\alpha}_s = \alpha_s \frac{2N_u + N_d}{6\pi}\left|\frac{e}{e_q}\right|$ and $\frac{1}{\alpha_s} \approx \frac{11N_c - 2N_f}{12\pi} \log \frac{eB}{\Lambda_{QCD}^2}$

Remark I: Typically magnetic catalysis $m_{dyn} \propto eB$

But pQCD with resummation may exhibit inverse behaviour

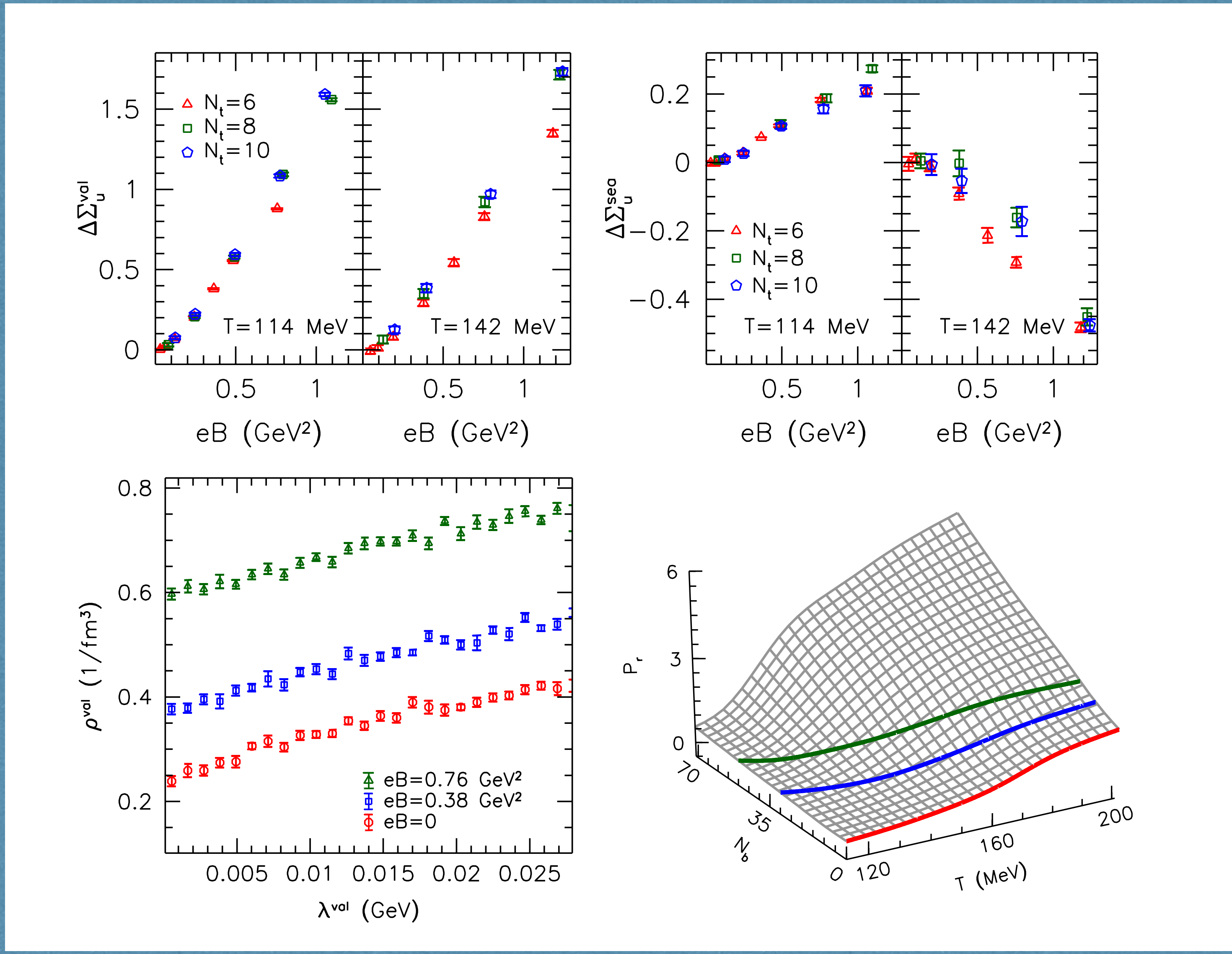
Remark II: ’t Hooft limit is trivial, need to take Veneziano limit:

$$N_c\,, N_f \to \infty, \qquad x = \frac{N_f}{N_c} = \text{const.}$$

Connection to Polyakov loop

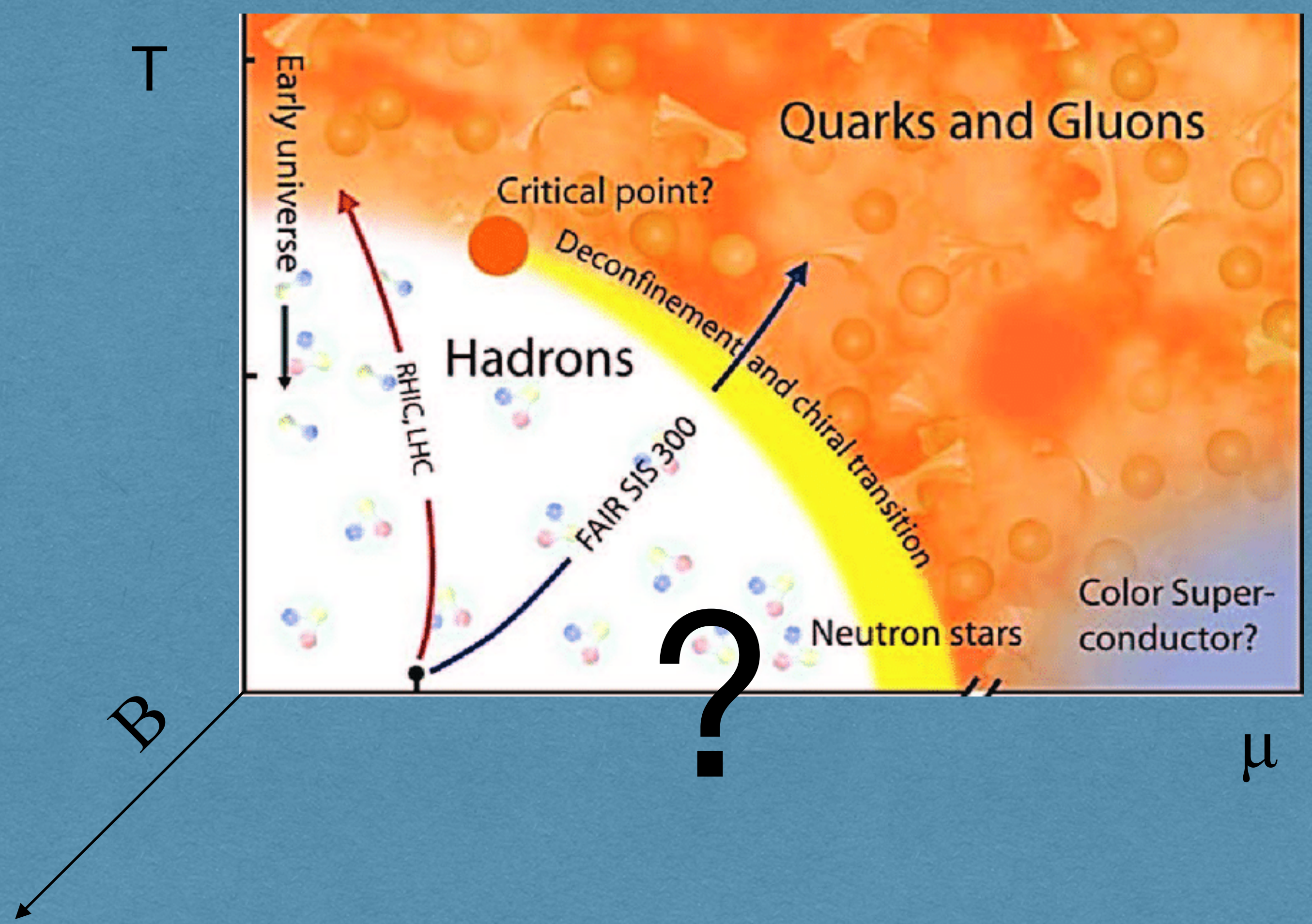
- **Testing the valence vs. sea idea:** Bruckmann, Endrodi, Kovacs '13

$$\bar\psi\psi^{\rm val}(B) = \frac{1}{\mathcal{Z}(0)}\int \mathcal{D}U\, e^{-S_g}\,\det(\not{D}(0)+m)\,{\rm Tr}(\not{D}(B)+m)^{-1},$$
$$\bar\psi\psi^{\rm sea}(B) = \frac{1}{\mathcal{Z}(B)}\int \mathcal{D}U\, e^{-S_g}\,\det(\not{D}(B)+m)\,{\rm Tr}(\not{D}(0)+m)^{-1}.$$



Finite density

Jarvinen, Nijs, UG ’17



- New phases?
- Magnetic catalysis at finite density?
- Urgent call: upcoming RHIC isobar, FAIR, NICA experiments
- Lattice suffers from the sign problem

Inverse anisotropic catalysis

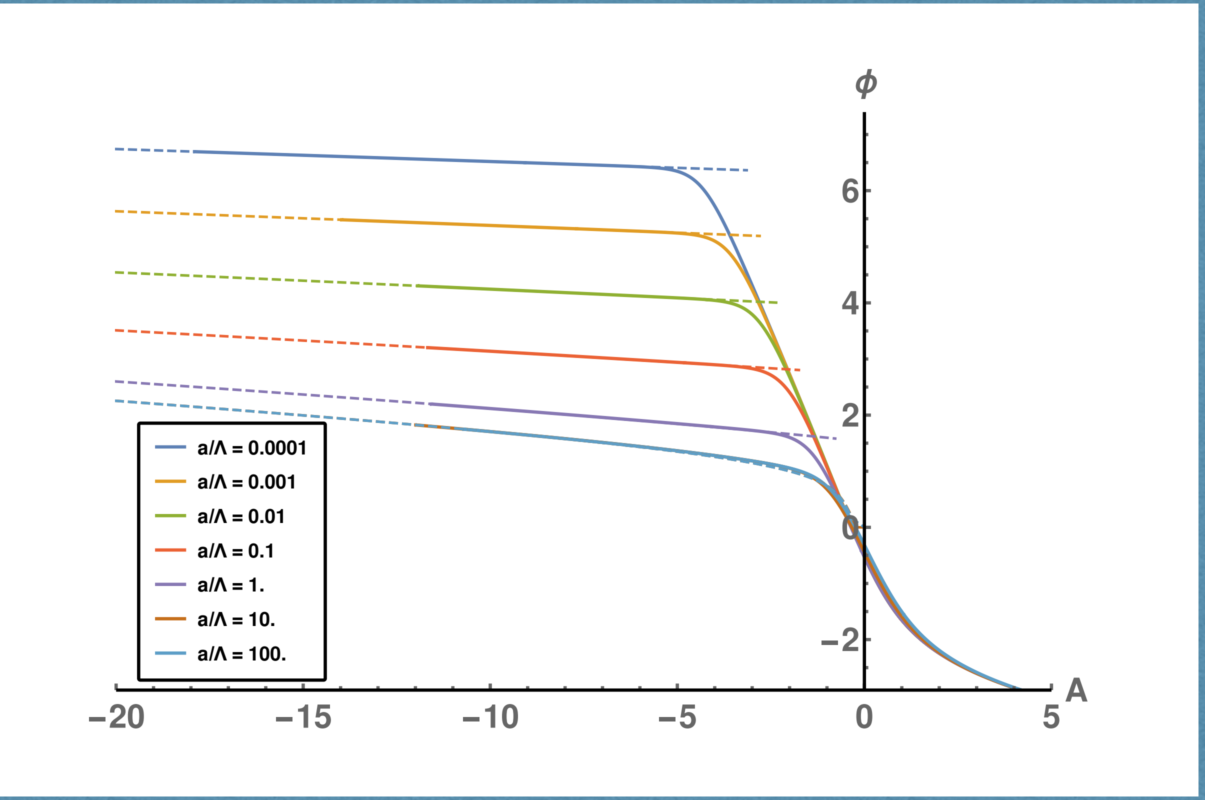
Jarvinen, Nijs, Pedraza, UG ‘18

Improved holographic QCD in the Veneziano limit with anisotropy

Same as before, with μ=0, B=0 but θ=a z with

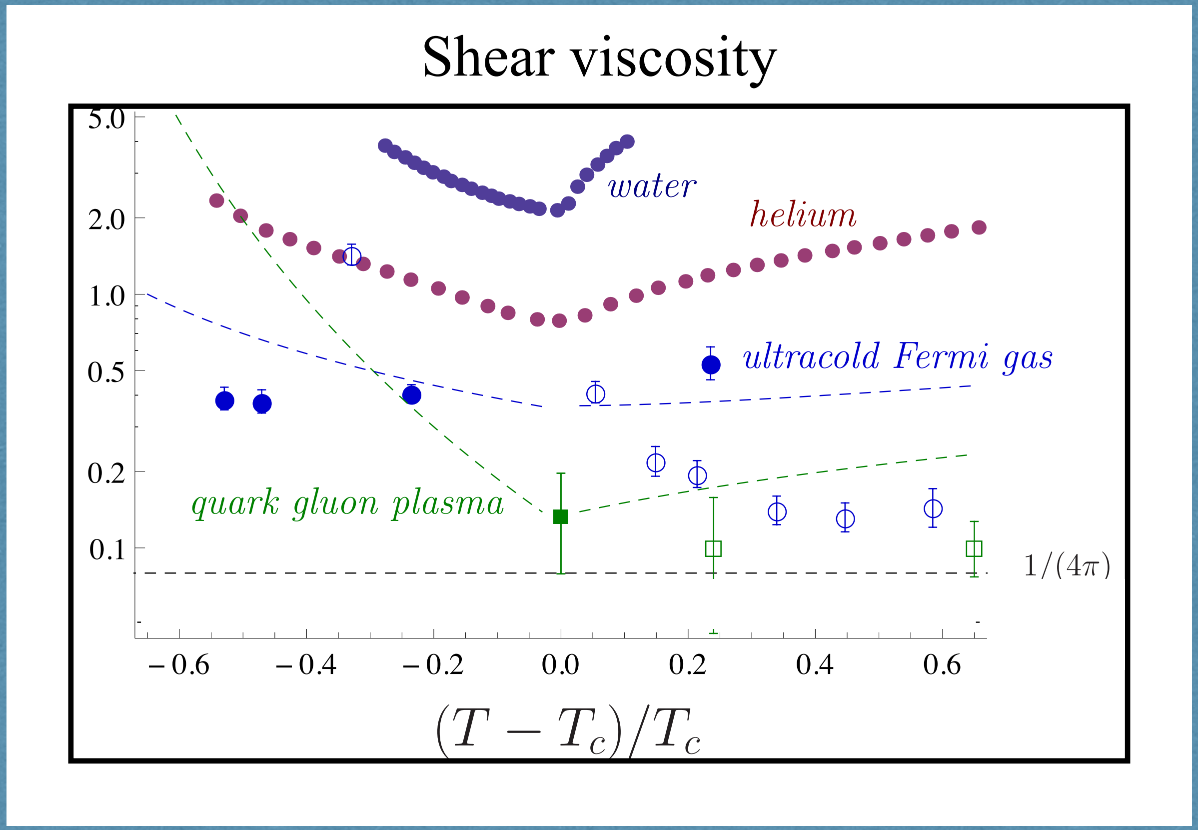
$$Z(\phi) = 1 + e^{4\phi}/10$$

IR geometry is “rolling” AdS_4 x R: assuming broken chiral symmetry



Hydrodynamics in HEP??

One of the most universal theories in physics



Large (cosmic backgrounds, 10^9 ly) to small (quark gluon plasma ~ 10^{-14} m)

Cold (Fermi gas, 10^{-8}K) to hot (quark gluon plasma ~ 10^{12}K)

QGP is an almost ideal, highly magnetised fluid

Theory of slow variables

- Decompose $\varphi = \varphi_{UV} + \varphi_{IR}$, integrate out $\varphi_{UV} \Longrightarrow$ Effective theory for φ_{IR}
- Local field theory $W[\varphi_{IR}]$ for $l_{mfp} \times \partial\varphi_{IR} = l_{mfp} \times L \ll 1$
- At thermal equilibrium, generic φ_{IR} decoheres in τ_{relax}

except conserved quantities: charge, energy, momentum…