Conformal anomaly and photon anisotropy in heavy ion collisions

Gökçe Başar

Stony Brook University

04/11/2013

GB, D. Kharzeev & V. Skokov arXiv:1206.1334
Phys. Rev. Lett. **109**, 202303 (2012)

Outline

- Direct photons in heavy ion collisions
- Magnetic fields in heavy ion collisions
- Conformal anomaly and bulk viscosity
- Explanation of the mechanism
- Comparison with PHENIX data and experimental signatures
- Future outlook and conclusions

Direct photons

- Small cross section: information on various stages of evolution

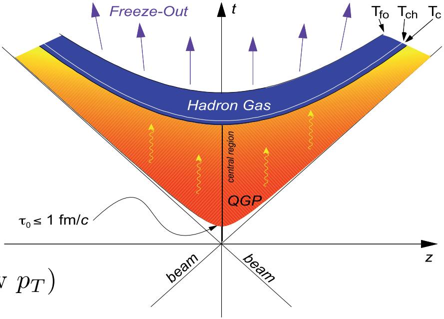
- Prompt (high P_T)
  - Initial hard scatterings
  - Fragmentation

  good agreement with pp data

- Medium effects
  - Jets + medium
  - Thermal photons (QGP, HG) (low p_T)

- Other sources?
  - Glasma (Chiu,..,Liao, McLerran et. al.)
  - B field (GB, Kharzeev, Skokov, Fukushima, Tuchin)

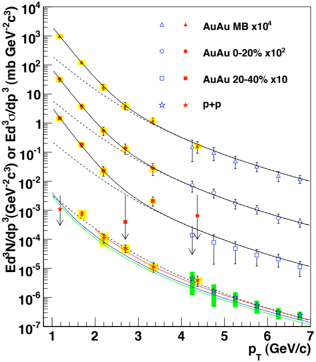
    ⋮



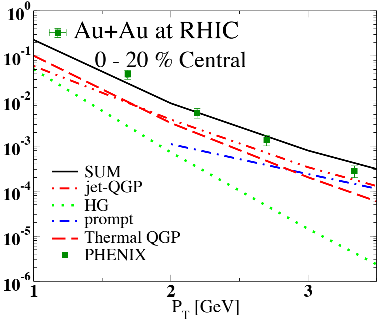
(figure:R. Stock)

Direct photons

experiment (PHENIX):



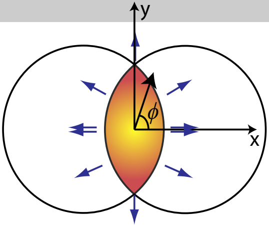
theory (Gale et al.):



- Enhancement at low p_T, steep slope → high T, early time
- T_{ave}=221 MeV , T_{in}=300-600 MeV (τ_0=0.15-0.6 fm)

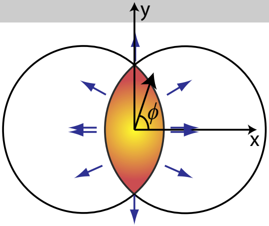
Direct photons: azimuthal anisotropy

$$\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T}\sum_{n=1}^{\infty}(1 + 2v_n\cos(n\phi))$$



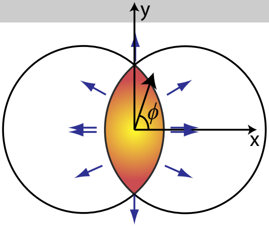
Direct photons: azimuthal anisotropy

$$\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T}\left(1 + 2v_2\cos(2\phi) + \dots\right)$$

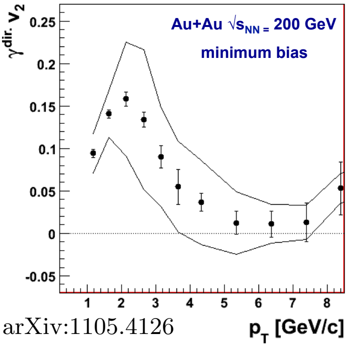


Direct photons: azimuthal anisotropy

$$\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T}\left(1 + 2v_2\cos(2\phi) + \dots\right)$$



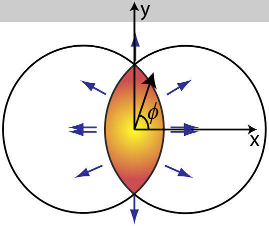
experiment (PHENIX) :



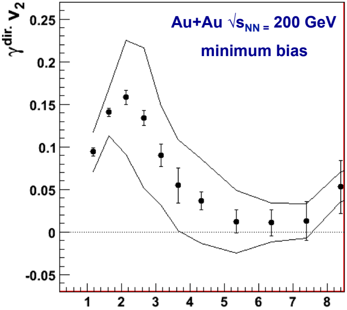
arXiv:1105.4126

Direct photons: azimuthal anisotropy

$$\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T}\left(1 + 2v_2\cos(2\phi) + \dots\right)$$

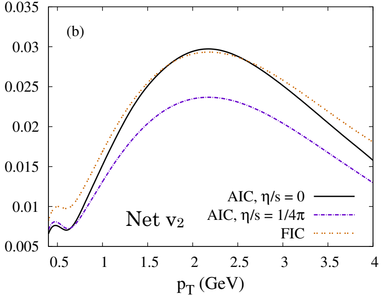


experiment (PHENIX) :



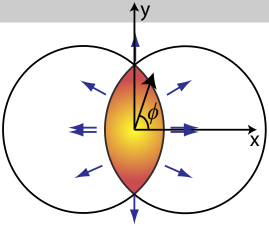
arXiv:1105.4126

theory (hydro, Gale et al.) :

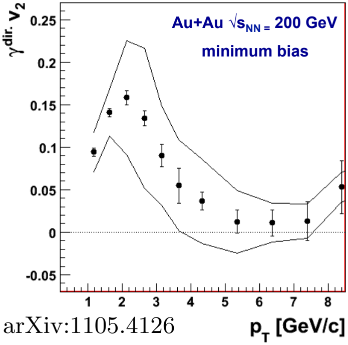


Direct photons: azimuthal anisotropy

$$\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T}\left(1 + 2v_2\cos(2\phi) + \dots\right)$$

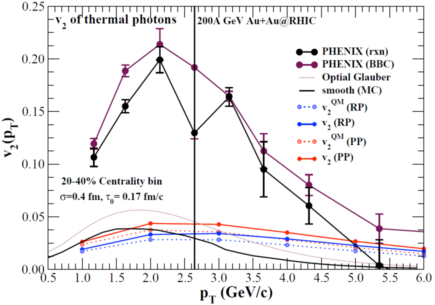


experiment (PHENIX) :



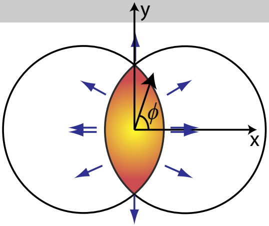
arXiv:1105.4126

theory (hydro, Chatterjee et al.) :

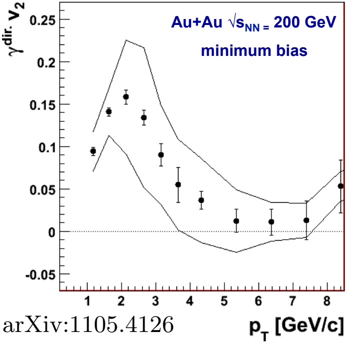


Direct photons: azimuthal anisotropy

$$\frac{dN}{d^2p_T} = \frac{dN}{2\pi p_T dp_T}\left(1 + 2v_2\cos(2\phi) + \dots\right)$$

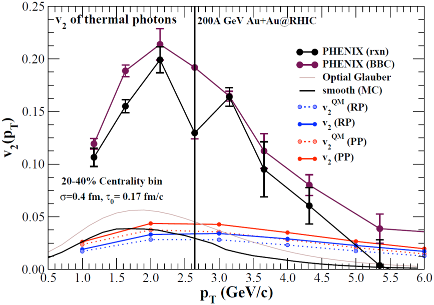


experiment (PHENIX) :



arXiv:1105.4126

theory (hydro, Chatterjee et al.) :



- puzzle: high T ↔ early time , v_2 ↔ flow, late time

anisotropy $\neq$ flow

anisotropy $\neq$ flow

background magnetic field $\rightarrow$ source of anisotropy

anisotropy $\neq$ flow

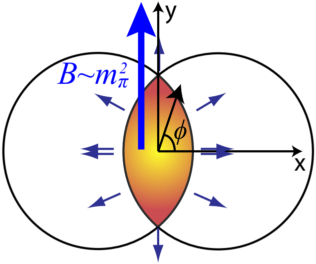
background magnetic field $\rightarrow$ source of anisotropy

magnetic field + bulk modes of plasma $\rightarrow$ photons!

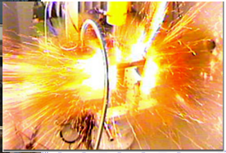
Magnetic fields in heavy ion collisions

Strong magnetic fields are generated by the spectators

$$B \sim m_\pi^2 \sim 10^{14} T$$



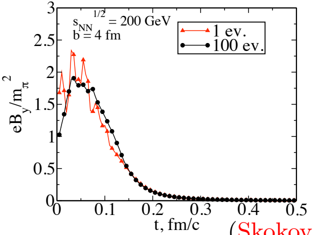
- Refrigerator magnet $\sim 10^{-2} T$
- MRI $\sim 10^0 T$
- Levitating frog: $14T$ (Berry, Geim)
- Strongest continuous field: $45T$ (NHMFL)
- Strongest non-destructive pulsed field $\sim 10^2 T$
- Strongest destructive pulsed field $\sim 10^3 T$
- Neutron star $\sim 10^6 T$
- Magnetar $\sim 10^9 T$



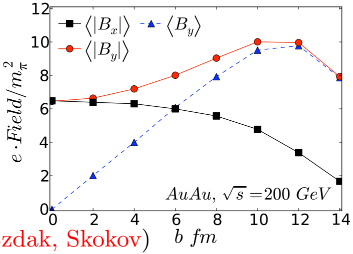
Magnetic fields in heavy ion collisions

Strong magnetic fields are generated by the spectators
(Kharzeev,McLerran,Warringa; Skokov, Illarionov, Toneev, Bzdak)

$$B \sim m_\pi^2 \sim 10^{14} T$$



(Skokov et al.)



(Bzdak, Skokov)

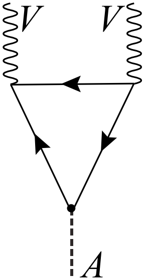
- magnitude: $B \sim \sqrt{s}$
- pulse width: $t_0 \sim 1/\sqrt{s}$

$< B_x >= 0$, fluctuations:
$< |B_x| >, < |B_y| > \sim m_\pi^2$

Magnetic fields in heavy ion collisions

Magnetic field + axial anomaly:

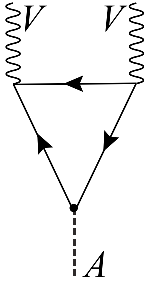
- Chiral magnetic effect → Charge separation
  (Fukushima, Kharzeev, McLerran, Warringa, Zhitnitsky)
- Chiral magnetic wave → Charge dependent v_2
  (Burnier, Kharzeev, Liao ,Yee)
- Chiral magnetic spiral → In plane current correlations
  (GB, Dunne, Kharzeev)



Magnetic fields in heavy ion collisions

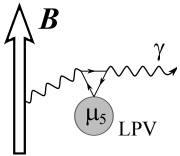
Magnetic field + axial anomaly:

- Chiral magnetic effect → Charge separation (Fukushima, Kharzeev, McLerran, Warringa, Zhitnitsky)
- Chiral magnetic wave → Charge dependent v_2 (Burnier, Kharzeev, Liao ,Yee)
- Chiral magnetic spiral → In plane current correlations (GB, Dunne, Kharzeev)



Photons from magnetic field:

- Photons from local parity violation (Fukushima, Mameda)

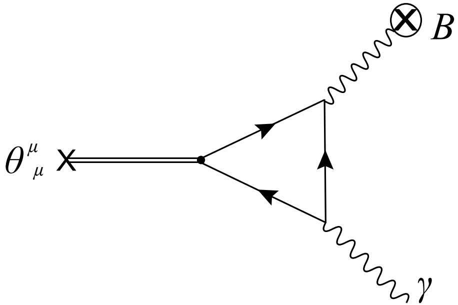


- Synchrotron radiation of quarks (Tuchin)

Magnetic fields heavy ion collisions

This talk :

Magnetic field + conformal anomaly ⇒ anisotropic photon production

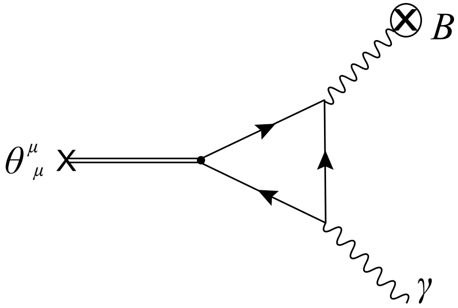


"conversion of bulk modes of QGP into real photons

Magnetic fields heavy ion collisions

This talk :

Magnetic field + conformal anomaly $\Rightarrow$ anisotropic photon production



"conversion of bulk modes of QGP into real photons

in the presence of magnetic field through conformal anomaly"

Conformal anomaly in QCD

scale transformation:

$$x^\mu \to \lambda\, x^\mu$$

associated current: dilatational current

$$\partial_\mu S^\mu = \theta^\mu_\mu = m_f \bar{\psi}_f \psi_f$$

Conformal anomaly in QCD

scale transformation:

$$x^\mu \rightarrow \lambda\, x^\mu$$

associated current: dilatational current

$$\partial_\mu S^\mu = \theta^\mu_\mu = 0$$

Conformal anomaly in QCD

scale transformation:

$$x^\mu \to \lambda\, x^\mu$$

associated current: dilatational current

$$\partial_\mu S^\mu = \theta^\mu_\mu = \, - \, \frac{\beta(g)}{2g}\, \mathrm{tr}(G^2)$$

Conformal anomaly in QCD

scale transformation:

$$x^\mu \to \lambda\, x^\mu$$

associated current: dilatational current

$$\partial_\mu S^\mu = \theta^\mu_\mu = \; -\frac{\beta(g)}{2g}\,\mathrm{tr}(G^2)$$

$\Downarrow$

quantum corrections

Conformal anomaly in QCD

scale transformation:

$$x^\mu \to \lambda\, x^\mu$$

associated current: dilatational current

$$\partial_\mu S^\mu = \theta^\mu_\mu = \; - \frac{\beta(g)}{2g}\, \mathrm{tr}(G^2) + m_f(1+\gamma(g))\bar{\psi}_f\psi_f$$

$\Downarrow$ $\Downarrow$

quantum corrections

Conformal anomaly in QCD

dilatational current → generates color singlet, scalar states of mass m_σ with amplitude f_σ (dilaton)

$$\langle 0|S^\mu|\sigma\rangle = iq^\mu f_\sigma \qquad \langle 0|\partial_\mu S^\mu|\sigma\rangle = m_\sigma^2 \; f_\sigma$$

Conformal anomaly in QCD

dilatational current → generates color singlet, scalar states of mass m_σ with amplitude f_σ (dilaton)

$$\langle 0|S^\mu|\sigma\rangle = iq^\mu f_\sigma \qquad \langle 0|\partial_\mu S^\mu|\sigma\rangle = m_\sigma^2\ f_\sigma$$

coupling to electromagnetism: $\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma}\sigma\, F^2$ (Ellis et al. '70s)

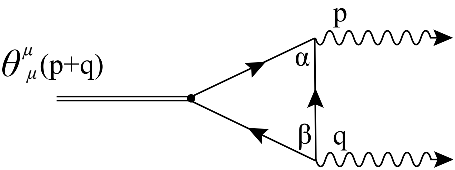
Conformal anomaly in QCD

dilatational current → generates color singlet, scalar states of mass m_σ with amplitude f_σ (dilaton)

$$\langle 0|S^\mu|\sigma\rangle = iq^\mu f_\sigma \qquad \langle 0|\partial_\mu S^\mu|\sigma\rangle = m_\sigma^2\ f_\sigma$$

coupling to electromagnetism: $\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma}\sigma\, F^2$ (Ellis et al. '70s)

$$\int dx dy\, e^{i(px+qy)} \langle \theta^\mu_\mu(0) J_\alpha(x) J_\beta(y)\rangle = (p.q g_{\alpha\beta} - q_\alpha p_\beta)\frac{R\alpha}{3\pi}$$



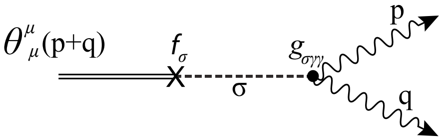
Conformal anomaly in QCD

dilatational current → generates color singlet, scalar states of mass m_σ with amplitude f_σ (dilaton)

$$\langle 0|S^\mu|\sigma\rangle = iq^\mu f_\sigma \qquad \langle 0|\partial_\mu S^\mu|\sigma\rangle = m_\sigma^2\, f_\sigma$$

coupling to electromagnetism: $\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma}\sigma\, F^2$ (Ellis et al. '70s)

$$\int dxdy\, e^{i(px+qy)}\langle\theta^\mu_\mu(0)J_\alpha(x)J_\beta(y)\rangle \to (p.qg_{\alpha\beta} - q_\alpha p_\beta)\frac{R\alpha}{3\pi}\frac{m_\sigma}{(p+q)^2 - m_\sigma^2}$$



$$f_\sigma g_{\sigma\gamma\gamma} = \frac{R\alpha}{6\pi}$$

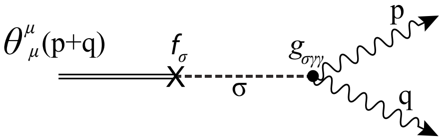
Conformal anomaly in QCD

dilatational current → generates color singlet, scalar states of mass m_σ with amplitude f_σ (dilaton)

$$\langle 0|S^\mu|\sigma\rangle = iq^\mu f_\sigma \qquad \langle 0|\partial_\mu S^\mu|\sigma\rangle = m_\sigma^2\ f_\sigma$$

coupling to electromagnetism: $\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma}\sigma\, F^2$ (Ellis et al. '70s)

$$\int dxdy\, e^{i(px+qy)}\langle\theta^\mu_\mu(0)J_\alpha(x)J_\beta(y)\rangle \to (p.qg_{\alpha\beta} - q_\alpha p_\beta)\frac{R\alpha}{3\pi}\frac{m_\sigma}{(p+q)^2 - m_\sigma^2}$$

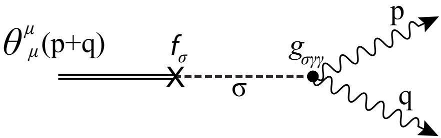


$$f_\sigma g_{\sigma\gamma\gamma} = \frac{R\alpha}{6\pi}$$

PCDC (Gell-Mann, Carruthers)

"Partially zero trace" P0T (Ellis, Crewther)

Conformal anomaly in QCD



$$f_\sigma g_{\sigma\gamma\gamma} = \frac{R\alpha}{6\pi}$$

identify σ with lightest scalar meson : $f_0(500)$

$$m_\sigma = 550MeV \quad , \quad \Gamma(\sigma \to \gamma\gamma) = g^2_{\sigma\gamma\gamma}\frac{m^3_\sigma}{4\pi} \approx 5KeV$$

$$R \equiv \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)} = 5 \quad \text{(PDG 2012)}$$

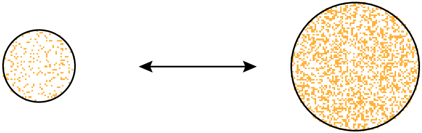
fix:

$$g_{\sigma\gamma\gamma} \approx 0.02GeV^{-1} \qquad f_\sigma \approx 100MeV$$

Bulk viscosity of QGP part I: introduction

In QGP, conformal anomaly is governed by *bulk viscosity* (ζ)

- response to compression/rarefaction

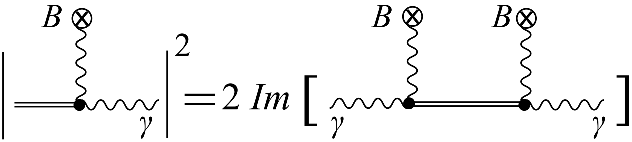


$$\theta_{ij} = P(\epsilon)\delta_{ij} - \eta\left(\partial_i u_j + \partial_j u_i - \frac{2}{3}\delta_{ij}\partial_k u^k\right) - \zeta\,\delta_{ij}\vec{\nabla}\cdot\vec{u}$$

- linear response:

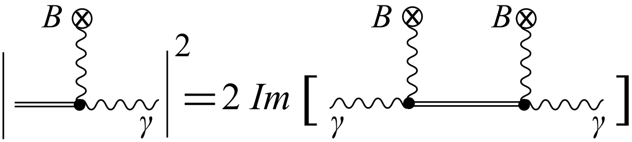
$$\zeta = \frac{1}{9}\lim_{\omega\to 0}\frac{1}{\omega}\int_0^\infty dt\int d^3x\, e^{i\omega t}\langle[\theta_{ii}(x),\theta_{jj}(0)]\rangle = \frac{1}{9}\lim_{\omega\to 0}\frac{G^R_{ii,jj}(\omega,0)}{\omega}$$

Explanation of the mechanism



$$q_0 \frac{d\Gamma}{d^3q} = 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|)$$

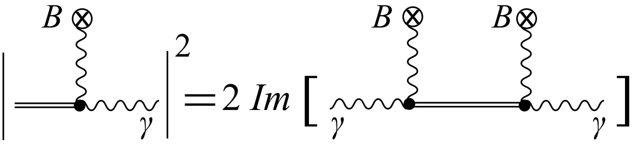
Explanation of the mechanism



$$q_0 \frac{d\Gamma}{d^3q} = 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|)$$

$B_x^2 \neq B_y^2 \quad \Rightarrow$ Anisotropy! $\quad \Rightarrow$ nonzero v_2!

Explanation of the mechanism



$$q_0 \frac{d\Gamma}{d^3q} \;=\; 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \; \rho_\theta(q_0 = |\vec{q}|)$$

$B_x^2 \neq B_y^2 \quad \Rightarrow$ Anisotropy! $\quad \Rightarrow$ nonzero v_2!

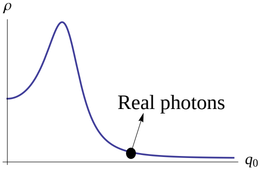
anisotropy $\neq$ flow !

Explanation of the mechanism

$$q_0 \frac{d\Gamma}{d^3q} = 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\vec{q}|)$$

spectral function of bulk modes (hydro) (Hong, Teaney):

$$\rho_\theta(q_0, \vec{q}) = \frac{1}{\pi} \mathcal{I}m[G^R_{\theta,\theta}(q_0, \vec{q})] = \frac{9 q_0 \zeta}{\pi}$$
$$+ \frac{9}{\pi}(\epsilon + p) \left(\frac{1}{3} - c_s^2\right)^2 \frac{q_0 \Gamma_s \vec{q}^4}{(q_0^2 - c_s^2 \vec{q}^2)^2 + (q_0 \Gamma_s \vec{q}^2)^2}$$



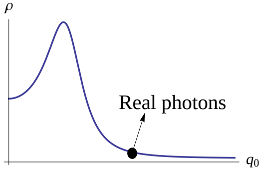
- real photons ($q_0 = |\vec{q}|$) are away from sound peak ($q_0 = c_s |\vec{q}|$)

Explanation of the mechanism

$$q_0 \frac{d\Gamma}{d^3q} \quad = \quad 2\left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2}\right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1}\, \rho_\theta(q_0 = |\vec{q}|)$$

spectral function of bulk modes (hydro) (Hong, Teaney):

$$\rho_\theta(q_0, \vec{q}) = \frac{1}{\pi}\mathcal{I}m[G^R_{\theta,\theta}\,(q_0, \vec{q})] \approx \frac{9q_0\,\zeta}{\pi}$$



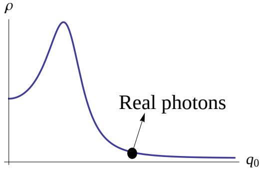
- real photons ($q_0 = |\vec{q}|$) are away from sound peak ($q_0 = c_s|\vec{q}|$)

Explanation of the mechanism

$$q_0 \frac{d\Gamma}{d^3q} \approx 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \frac{9 q_0}{\pi} \zeta$$

spectral function of bulk modes (hydro) (Hong, Teaney):

$$\rho_\theta(q_0, \vec{q}) = \frac{1}{\pi} \mathcal{I}m[G^R_{\theta,\theta}(q_0, \vec{q})] \approx \frac{9 q_0 \zeta}{\pi}$$



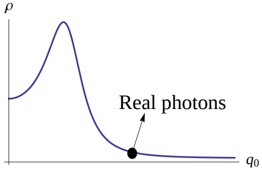
- real photons ($q_0 = |\vec{q}|$) are away from sound peak ($q_0 = c_s |\vec{q}|$)

Explanation of the mechanism

$$q_0 \frac{d\Gamma}{d^3q} \quad \approx \quad 2 \left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2} \right)^2 \frac{B_y^2 q_x^2 + B_x^2 q_y^2}{\exp(\beta q_0) - 1} \frac{9 q_0}{\pi} \zeta$$

spectral function of bulk modes (hydro) (Hong, Teaney):

$$\rho_\theta(q_0, \vec{q}) = \frac{1}{\pi} \mathcal{I}m[G^R_{\theta,\theta}(q_0, \vec{q})] \approx \frac{9 q_0 \zeta}{\pi}$$



- real photons ($q_0 = |\vec{q}|$) are away from sound peak ($q_0 = c_s|\vec{q}|$)

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract
- Kinetic theory (Jeon, Moore, Arnold, Doğan, Dusling, Schäfer)

$$\zeta = C_\zeta \left(\frac{1}{3} - c_s^2 \right)^2 \eta$$

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract
- Kinetic theory (Jeon, Moore, Arnold, Doğan, Dusling, Schäfer)

$$\zeta = C_\zeta \left(\frac{1}{3} - c_s^2 \right)^2 \eta$$

$$\downarrow$$

(deviation from conformality $c_s^2 = 1/3$)

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract ($C_\zeta = 90$)
- Kinetic theory (Jeon, Moore, Arnold, Doğan, Dusling, Schäfer)

$$\zeta = C_\zeta \left(\frac{1}{3} - c_s^2\right)^2 \eta$$

$$\downarrow$$

(deviation from conformality $c_s^2 = 1/3$)

  - photons + hot matter $C_\zeta = 15$ (Weinberg, '71)

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract ($C_\zeta = 90$)
- Kinetic theory (Jeon, Moore, Arnold, Doğan, Dusling, Schäfer)

$$\zeta = C_\zeta \left(\frac{1}{3} - c_s^2 \right)^2 \eta$$

$$\downarrow$$

(deviation from conformality $c_s^2 = 1/3$)

  - photons + hot matter $C_\zeta = 15$ (Weinberg, '71)
  - QCD (RTA) $C_\zeta = 15$ (Dusling, Schäfer, '11)
  - QCD (Leading log, pure glue) $C_\zeta \approx 48$ (Dusling, Schäfer, '11)

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract ($C_\zeta = 90$)
- Kinetic theory (Jeon, Moore, Arnold, Doğan, Dusling, Schäfer)

$$\zeta = C_\zeta \left(\frac{1}{3} - c_s^2 \right)^2 \eta$$

$$\downarrow$$

(deviation from conformality $c_s^2 = 1/3$)

  - photons + hot matter $C_\zeta = 15$ (Weinberg, '71)
  - QCD (RTA) $C_\zeta = 15$ (Dusling, Schäfer, '11)
  - QCD (Leading log, pure glue) $C_\zeta \approx 48$ (Dusling, Schäfer, '11)
  - phenomenological constraints $C_\zeta \approx 2 - 5$

Bulk viscosity of QGP part II: various results

- Lattice SU(3) (Meyer) difficult to extract ($C_\zeta = 90$)
- Kinetic theory (Jeon, Moore, Arnold, Doğan, Dusling, Schäfer)

$$\zeta = C_\zeta \left(\frac{1}{3} - c_s^2\right)^2 \eta$$

$$\downarrow$$

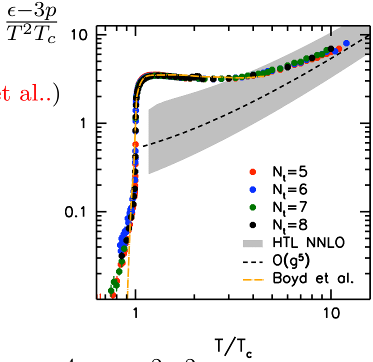
(deviation from conformality $c_s^2 = 1/3$)

  - photons + hot matter $C_\zeta = 15$ (Weinberg, '71)
  - QCD (RTA) $C_\zeta = 15$ (Dusling, Schäfer, '11)
  - QCD (Leading log, pure glue) $C_\zeta \approx 48$ (Dusling, Schäfer, '11)
  - phenomenological constraints $C_\zeta \approx 2 - 5$
- use the most conservative values: $C_\zeta = 2 - 5$, $\frac{\eta}{s} = \frac{1}{4\pi}$

Bulk viscosity of QGP part III: equation of state

- Lattice calculation of $\langle\theta^\mu_\mu\rangle = \epsilon - 3p$
- Effective theory for $T = 1.2 - 4T_c$ (Pisarski et al..)
- Mean field potential V_{eff} for $q \sim A_0$
  $V = \sum_n c_n \ \mathrm{tr}[\mathbf{L}^n + \mathbf{L}^{\dagger\, n}]$, (Ünsal,Yaffe)

$$V_{eff}(q) = V_{pert}(q)\,T^4 + V_{non}(q)T_c^2\,T^2$$

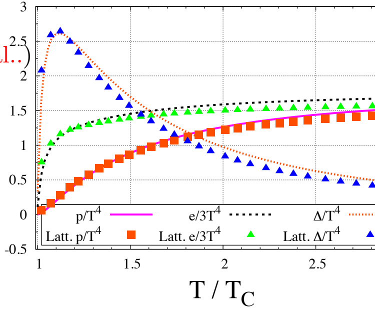


$$\frac{dV_{eff}}{dq}|_{q=<q>} = 0 \quad , \quad p(T) = -V_{eff}(\langle q\rangle) = a\,T^4 + b\,T_c^2 T^2$$

- V_{non}: strings, monopoles, dyons, bions...?? $\rightarrow$ fitted to lattice

Bulk viscosity of QGP part III: equation of state

- Lattice calculation of $\langle \theta^\mu_\mu \rangle = \epsilon - 3p$
- Effective theory for $T = 1.2 - 4T_c$ (Pisarski et al..)
- Mean field potential V_{eff} for $q \sim A_0$
  $V = \sum_n c_n \, \mathrm{tr}[\mathbf{L}^n + \mathbf{L}^{\dagger\, n}]$, (Ünsal, Yaffe)



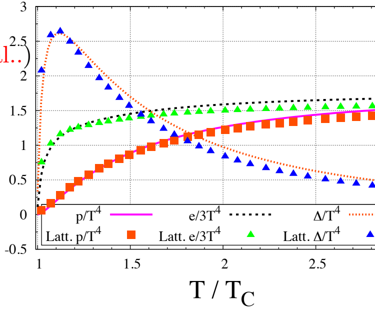
$$V_{eff}(q) = V_{pert}(q)\, T^4 + V_{non}(q) T_c^2\, T^2$$

$$\frac{dV_{eff}}{dq}|_{q=<q>} = 0 \quad , \quad p(T) = -V_{eff}(\langle q \rangle) = a\, T^4 + b\, T_c^2 T^2$$

- V_{non}: strings, monopoles, dyons, bions...?? → fitted to lattice

Bulk viscosity of QGP part III: equation of state

- Lattice calculation of $\langle \theta^\mu_\mu \rangle = \epsilon - 3p$
- Effective theory for $T = 1.2 - 4T_c$ (Pisarski et al..)
- Mean field potential V_{eff} for $q \sim A_0$
  $V = \sum_n c_n \,\mathrm{tr}[\mathbf{L}^n + \mathbf{L}^{\dagger\, n}]$, (Ünsal, Yaffe)



$$V_{eff}(q) = V_{pert}(q)\, T^4 + V_{non}(q) T_c^2\, T^2$$

$$\frac{dV_{eff}}{dq}|_{q=<q>} = 0 \quad , \quad p(T) = -V_{eff}(\langle q \rangle) = a\, T^4 + b\, T_c^2 T^2$$

- V_{non}: strings, monopoles, dyons, bions...?? $\rightarrow$ fitted to lattice

  $\Rightarrow$ use the model for $s(T), c_s^2(T)$

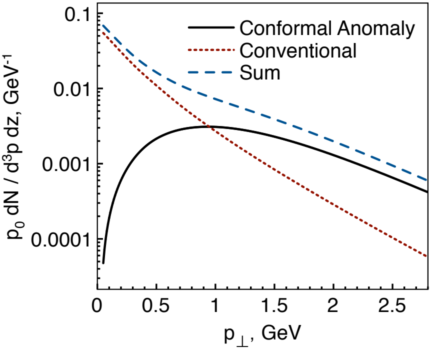
Explanation of the mechanism: parameters

$$p_0 \frac{d\Gamma}{d^3p} = \frac{9p_0}{2\pi^4} \left(\frac{g_{\sigma\gamma\gamma}}{f_\sigma m_\sigma^2}\right)^2 \frac{B_y^2 p_x^2 + B_x^2 p_y^2}{\exp(\beta p_0) - 1} \left(\frac{1}{3} - c_s^2\right)^2 s(T)$$

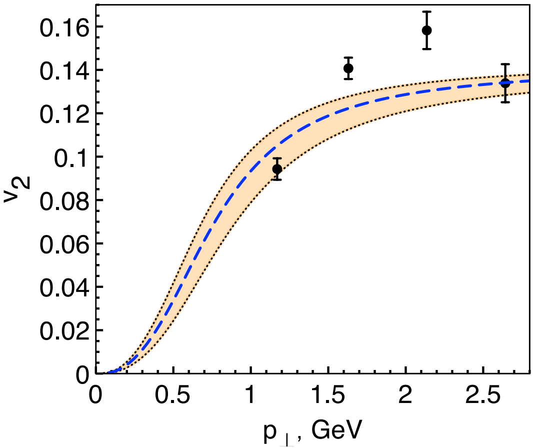
- Bjorken expansion $\frac{T}{T_0} = \left(\frac{\tau_i}{\tau}\right)^{1/3}$
- Initial time: $\tau_i = 0.1 fm/c$
- Initial temperature: $T \approx 350 MeV$
- Equation of state: effective theory
- Magnetic field: spectators + fluctuations, time dependent
- Overall normalization: P0T ($\sigma \to \gamma\gamma$)

Transverse momentum spectrum

- vanishes as p_T^2 at low p_T
- overcomes thermal rate above 1 GeV
- higher p_T: prompt photons



v_2: comparison with PHENIX data



GB, Kharzeev, Skokov arXiv:1206.1334
data: PHENIX arXiv:1105.4126

Experimental signatures

- Polarization of photons
- Violation of $v_4 \sim v_2^2$ scaling
- Turn off magnetic field ? $\rightarrow$ central U-U collision
- Turn off flow ? $\rightarrow$ non central events without hadron v_2
  (Bzdak, Skokov) fluctuations in initial geometry
- Impact parameter dependence

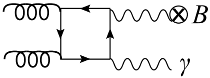
Experimental signatures

- Polarization of photons
- Violation of $v_4 \sim v_2^2$ scaling
- Turn off magnetic field ? $\rightarrow$ central U-U collision
- Turn off flow ? $\rightarrow$ non central events without hadron v_2
  (Bzdak, Skokov) fluctuations in initial geometry
- Impact parameter dependence

need good statistics!!

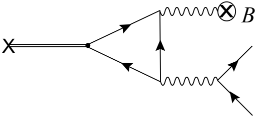
Future

- Non-equilibrium dynamics: Glasma + B field $\rightarrow \gamma$



  - Photons from glasma ($Q_s^{-1} < t < t_{therm}$) (McLerran et. al.)
  - Need fluctuations around classical gluonic fields; $\rho_\theta(q_0, \vec{q})$
- Topological charge fluctuations in QGP + B field $\rightarrow \gamma$

  in progress (GB, Kharzeev, Loshaj)
- Anomaly + B field $\rightarrow$ dileptons



- Induced magnetic field in the plasma: MHD

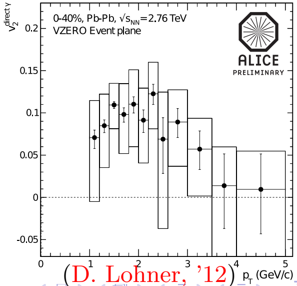
Future

- Lower energies: beam energy scan at RHIC
  - as $\sqrt{s} \downarrow$, B goes down but t_0 goes up
  - Mangeto-hydrodynamics
  - Bulk viscosity increases near T_c (Karch, Kharzeev, Tuchin) possible signatures?

Future

- Lower energies: beam energy scan at RHIC
  - as $\sqrt{s}\downarrow$, B goes down but t_0 goes up
  - Mangeto-hydrodynamics
  - Bulk viscosity increases near T_c (Karch, Kharzeev, Tuchin) possible signatures?

- Higher energies: LHC
  in progress (GB, Kharzeev, Skokov)
- $\sqrt{s} = 2.76 TeV$
- ALICE: $T_{av} = 304 \pm 51 MeV$
- Initial time and temperature?



(D. Lohner, '12)

Conclusions

- Anomalies + magnetic fields $\rightarrow$ observable signatures in HIC
- Conformal anomaly + B $\rightarrow$ *significant* contribution to photon v_2
- Answer to the photon v_2 puzzle: *anisotropic* emission at *early times*
- Experimentally distinguishable properties (need good statistics)
- Improvements are on the way: stay tuned!