Conformal anomaly as a source of photon production in heavy-ion collisions

Vladimir Skokov

BROOKHAVEN NATIONAL LABORATORY

G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

A. Bzdak, V.S., arXiv:1208.5502

RBRC lunch seminar, 13 September 2012

Making sense of the photon azimuthal anisotropy

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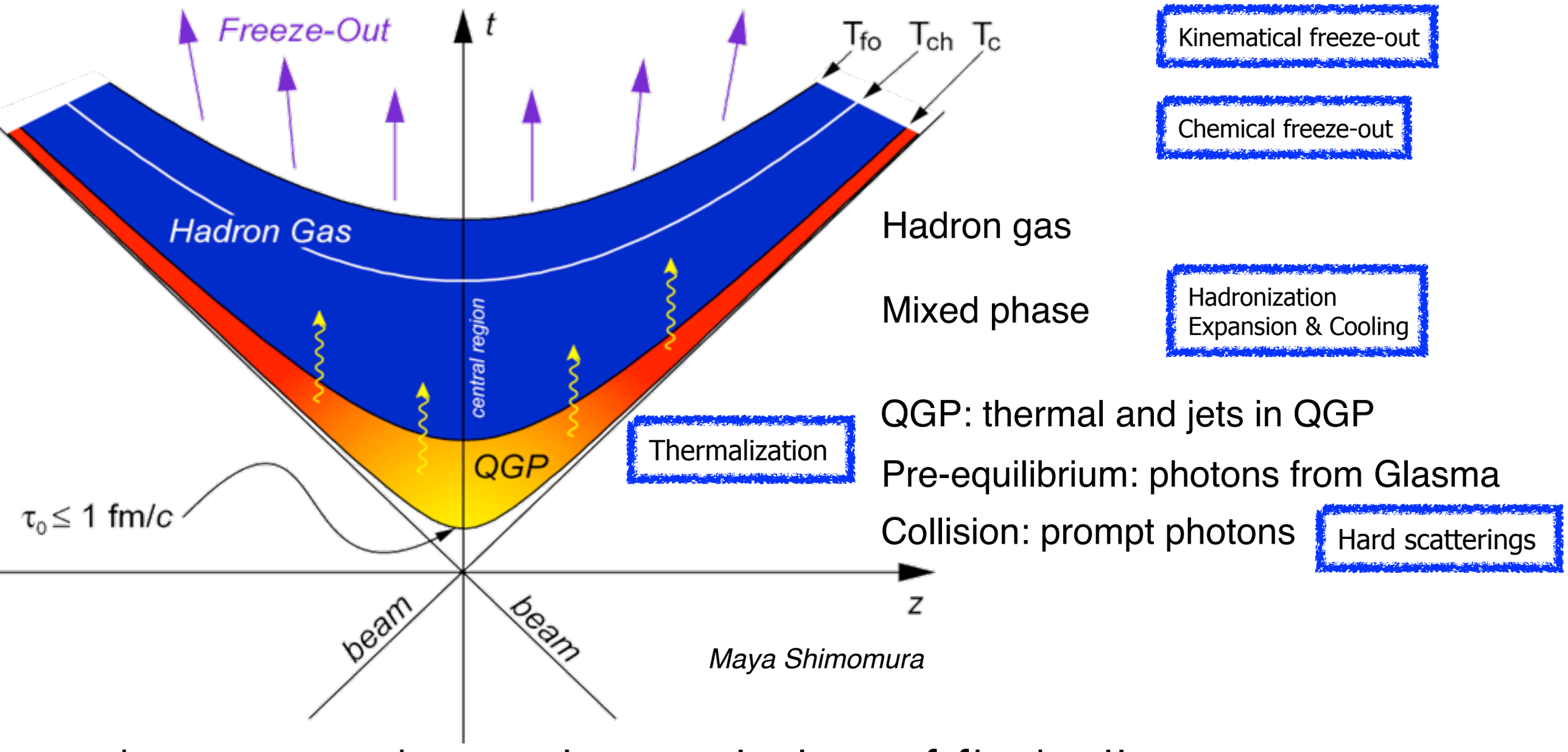
Outline

- motivation: photon puzzle
- another source of anisotropy: magnetic field in HIC
- scale anomaly and production of γ
- comparison to PHENIX data
- proposal for experimental test of new mechanism for generation of azimuthal anisotropy

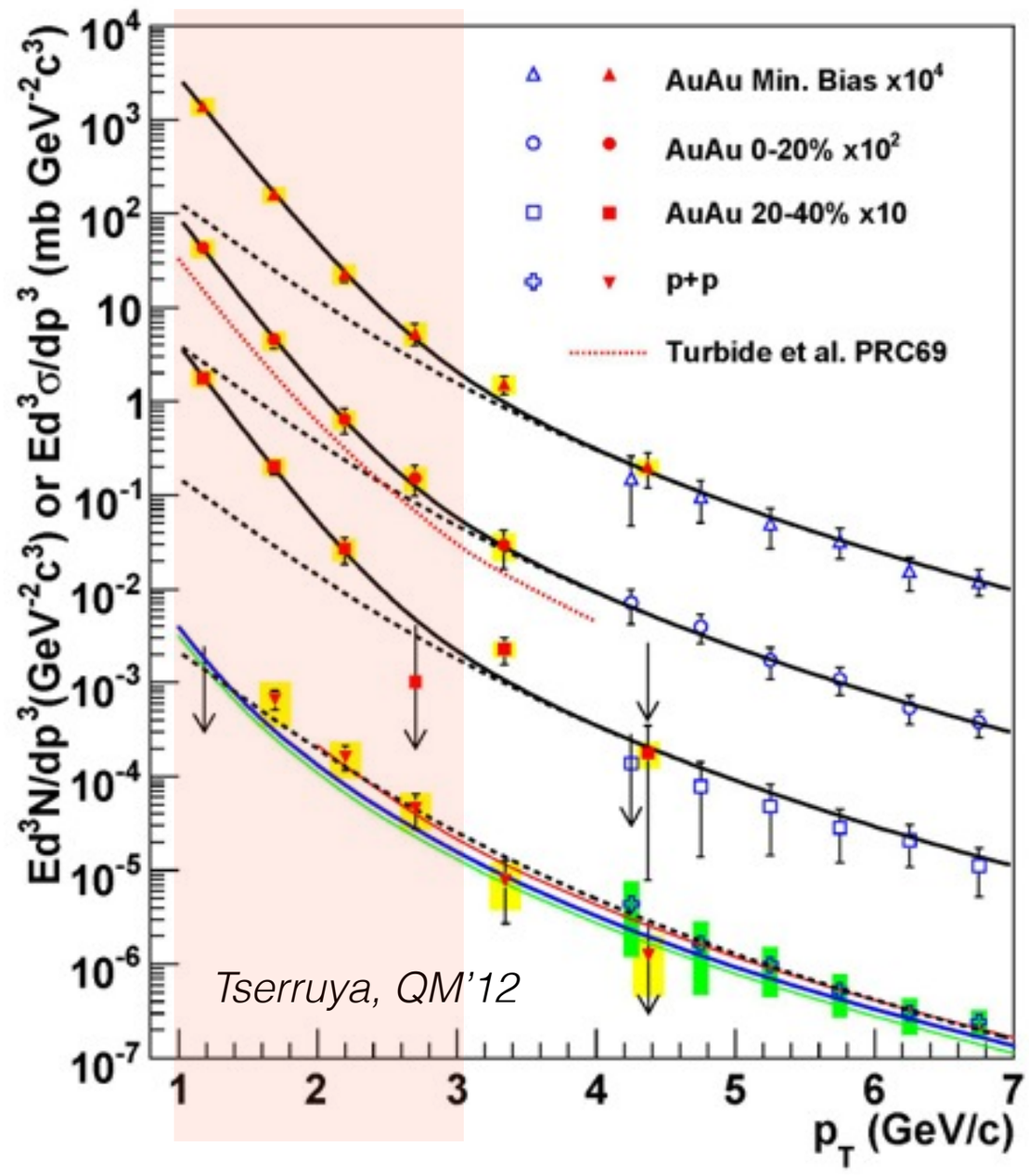
HIC evolution and γ



- photons probe entire evolution of fireball
- no free lunch: rather small emission rate and large background

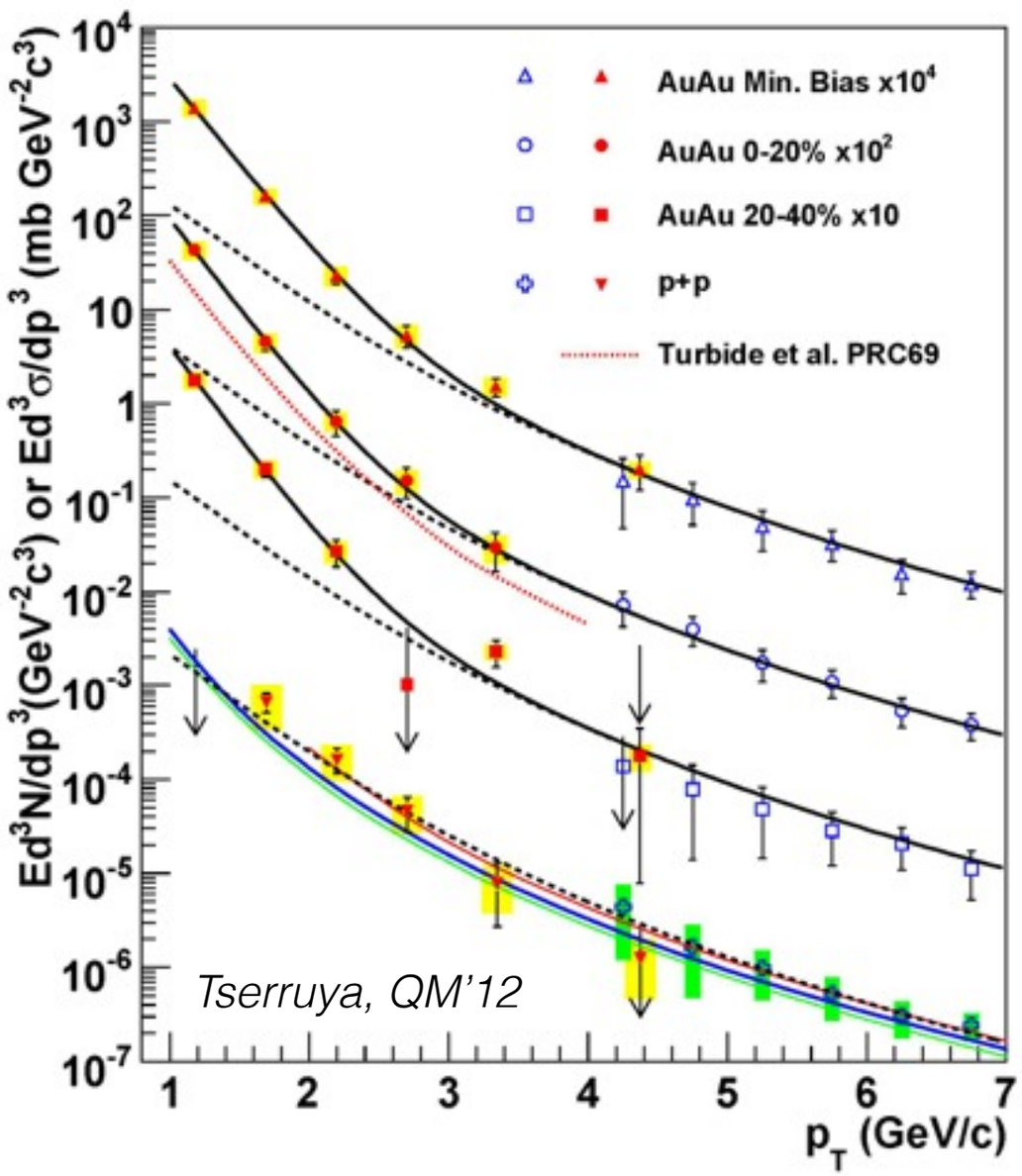
Experimental facts about γ

- transverse momentum spectrum
  T_{ave} = 221 MeV ➙
  T_{ini} = 300 to 600 MeV τ_0 = 0.15 to 0.6 fm/c
- T_{ave} is higher then phase transition temperature: semiQGP
- or thermalizing Glazma?!
  (L. McLerran and Co: arXiv:1202.3679)
- or something else?!



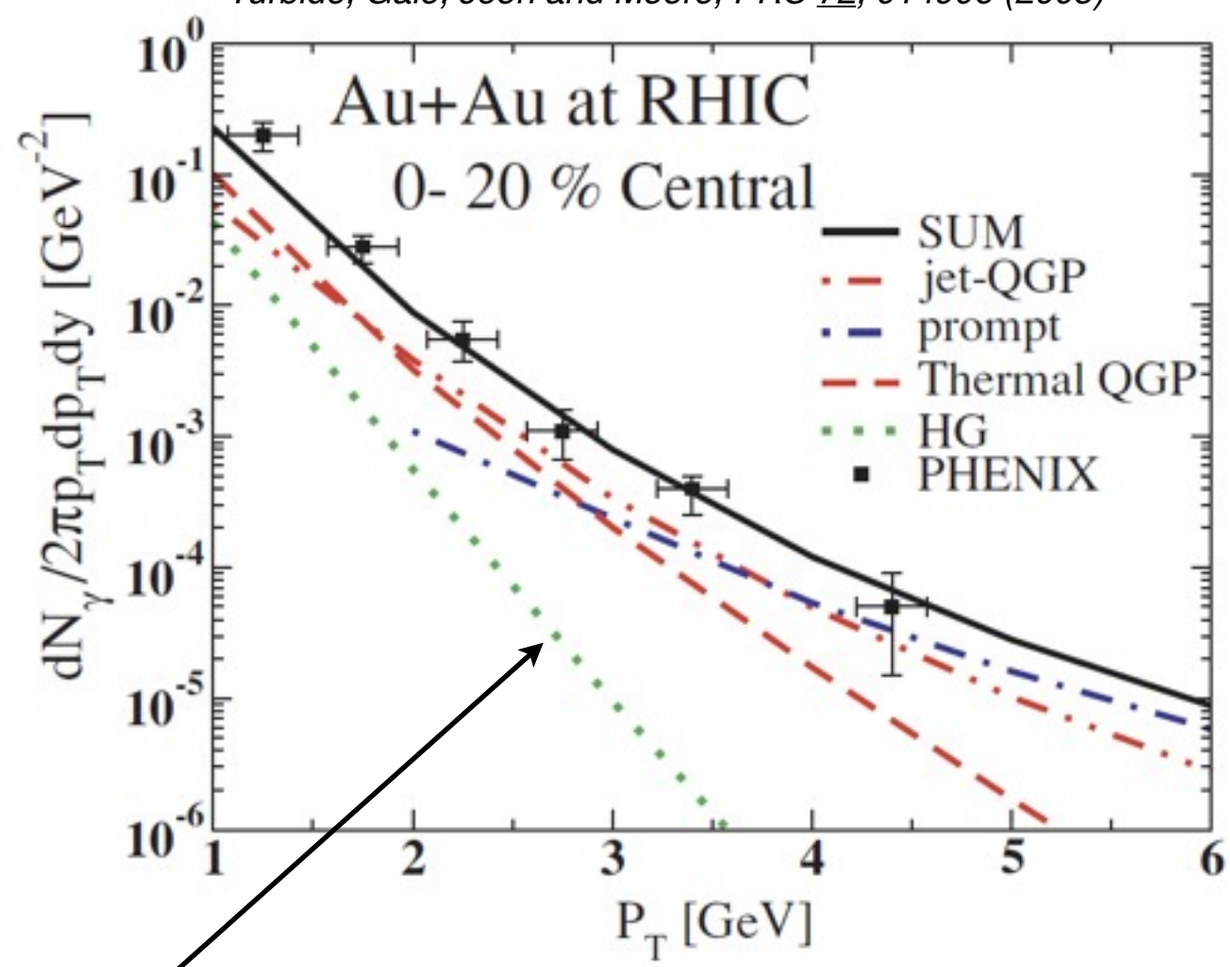
QGP source of soft photons

- T_{ave} = 221 MeV



- theory: hydro calculations +prompt photons (pQCD)
- $$q_0 \frac{d\Gamma}{d^3q} = \frac{1}{(2\pi)^3} \frac{\mathrm{Tr}[\mathrm{Im}\Pi^r]}{1-\exp\beta q_0}, \beta = 1/T$$

Turbide, Gale, Jeon and Moore, PRC 72, 014906 (2005)



hadron gas contribution

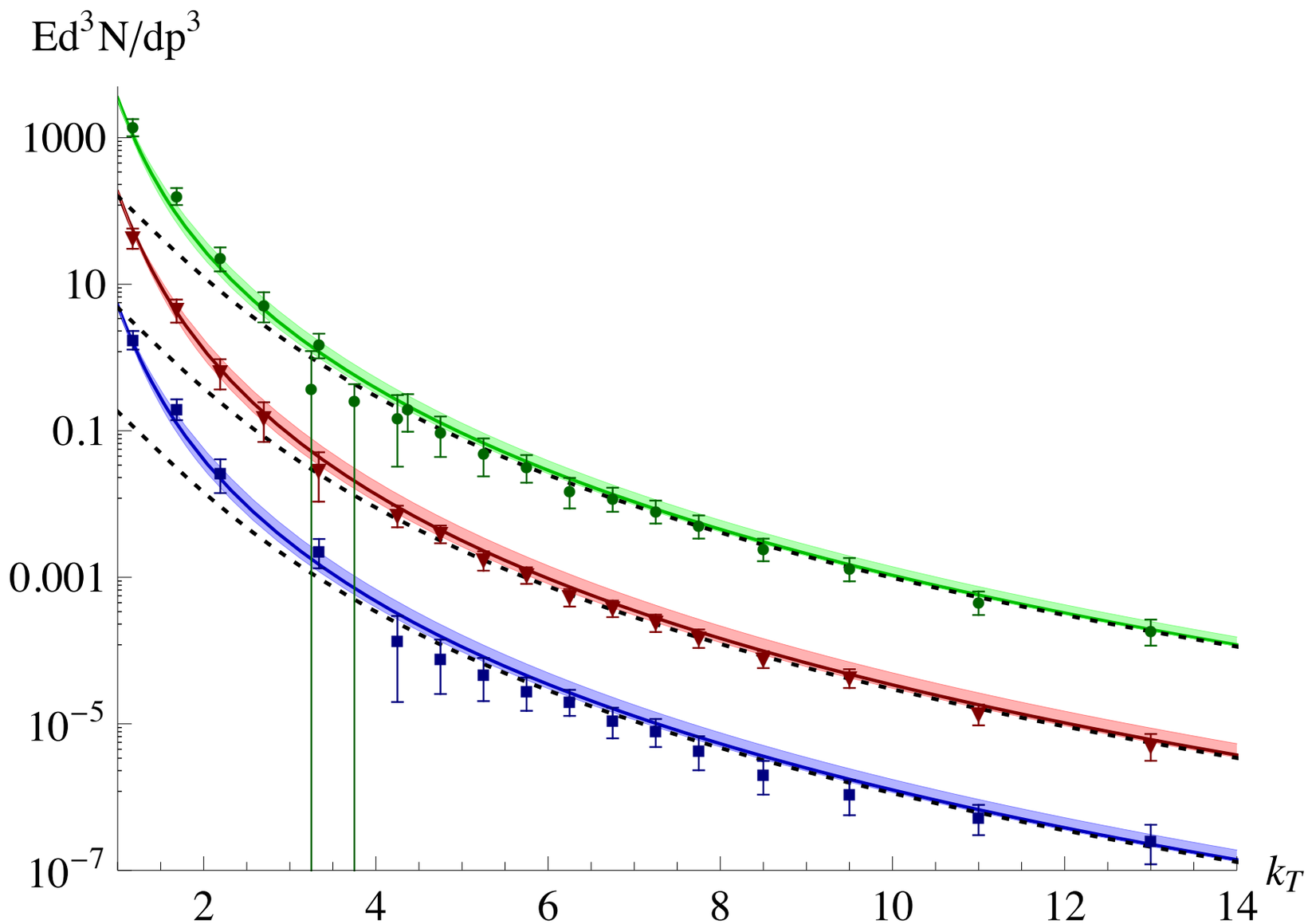
Glasma as source of photons

M. Chiu, ...,L. McLerran, ..., arXiv: 1202.3679

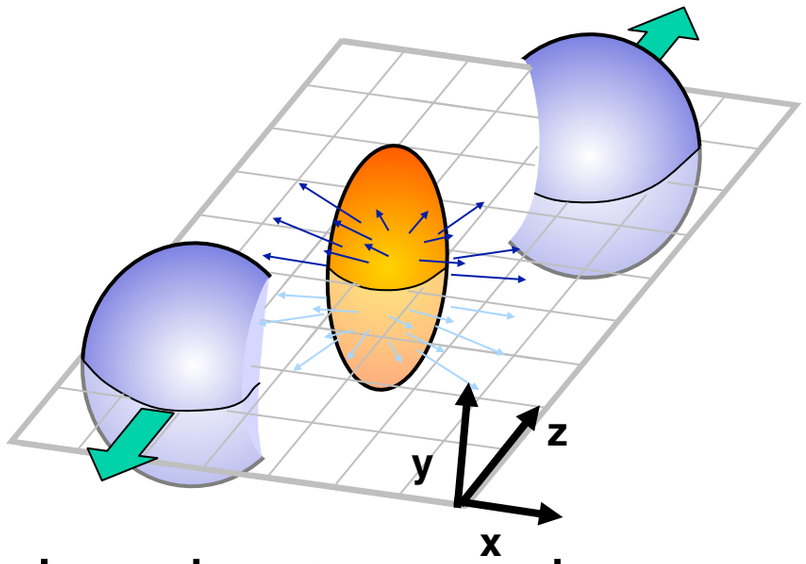
Model parameters:

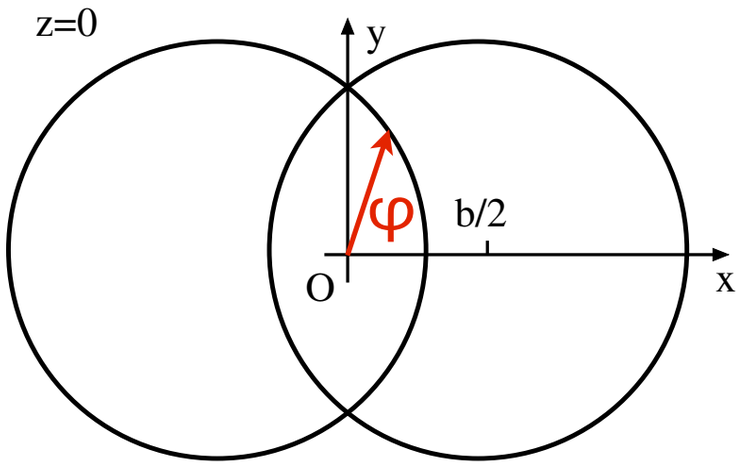
For each of three color bands, the η (or δ) varies as

$\eta = 6.65 \mp 0.60 \quad (\delta \simeq 0.144 \pm 0.045) \quad \text{at} \quad \lambda = 0.29$



Intro: Azimuthal anisotropy





- Azimuthal anisotropy is quantified by Fourier coefficients

$$\frac{dN}{p_\perp dp_\perp d\phi} = \frac{dN}{2\pi p_\perp dp_\perp}\left[1 + \sum_k 2 v_k(p_\perp)\cos(k\phi)\right]$$

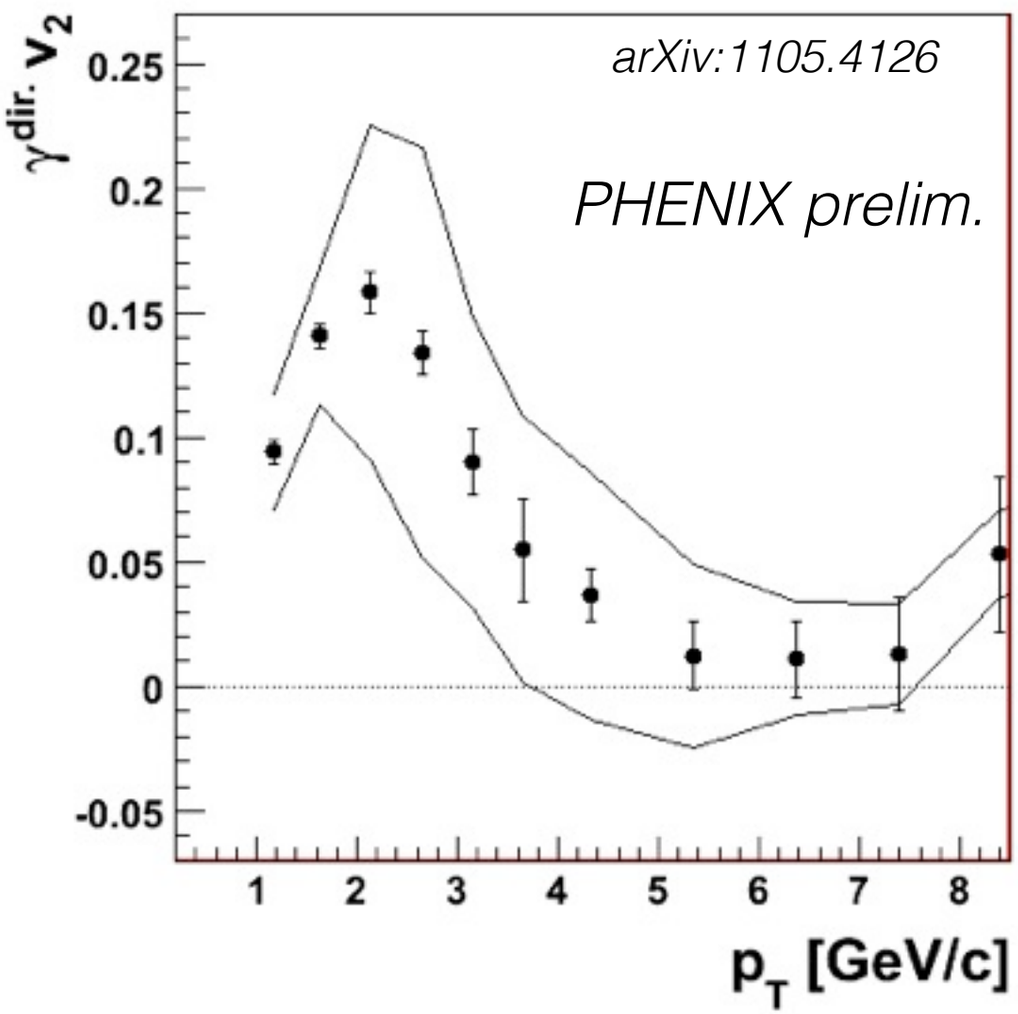
- In this talk: v_2 and v_4:

$$v_2^\gamma(p_\perp) = \frac{\int d\phi \cos(2\phi)\frac{dN^\gamma}{dp_\perp d\phi}}{\frac{dN^\gamma}{dp_\perp}}$$

$$v_4^\gamma(p_\perp) = \frac{\int d\phi \cos(4\phi)\frac{dN^\gamma}{dp_\perp d\phi}}{\frac{dN^\gamma}{dp_\perp}}$$

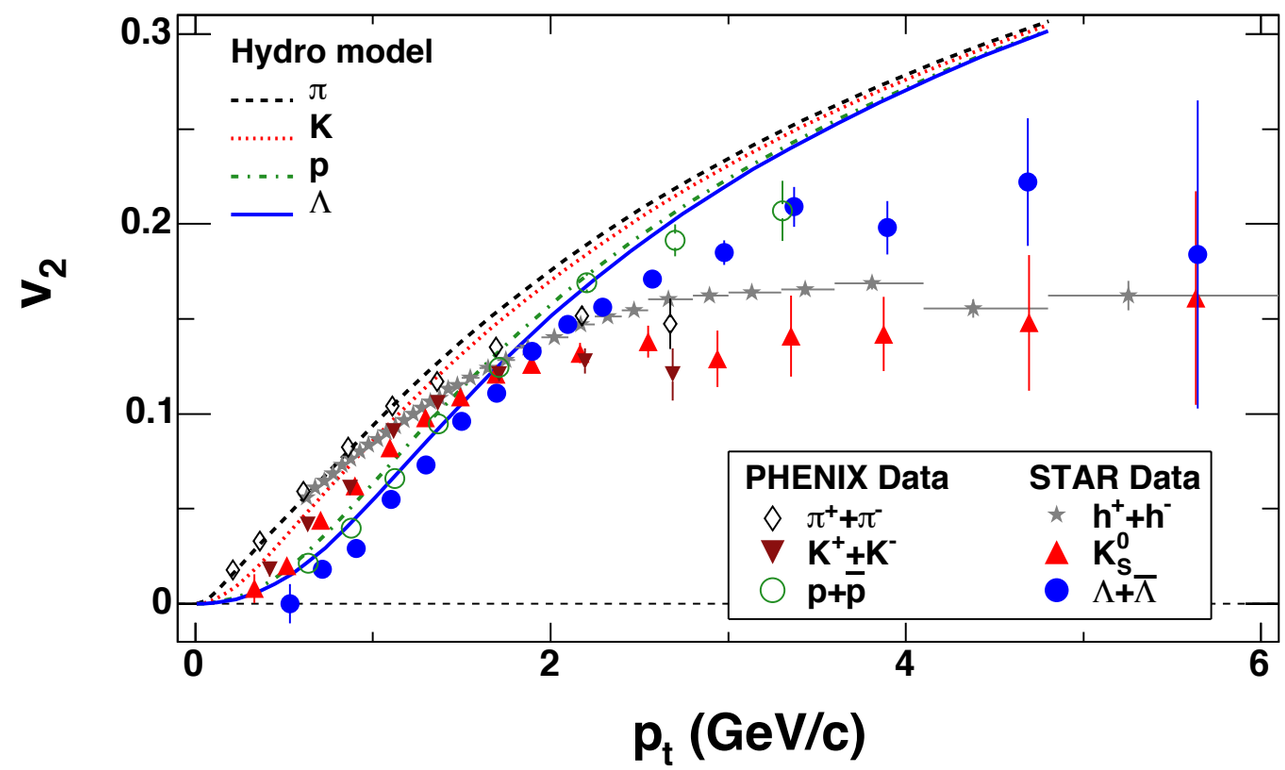
Azimuthal anisotropy

- Direct photons:



Contradiction to expectations

- Hadrons:



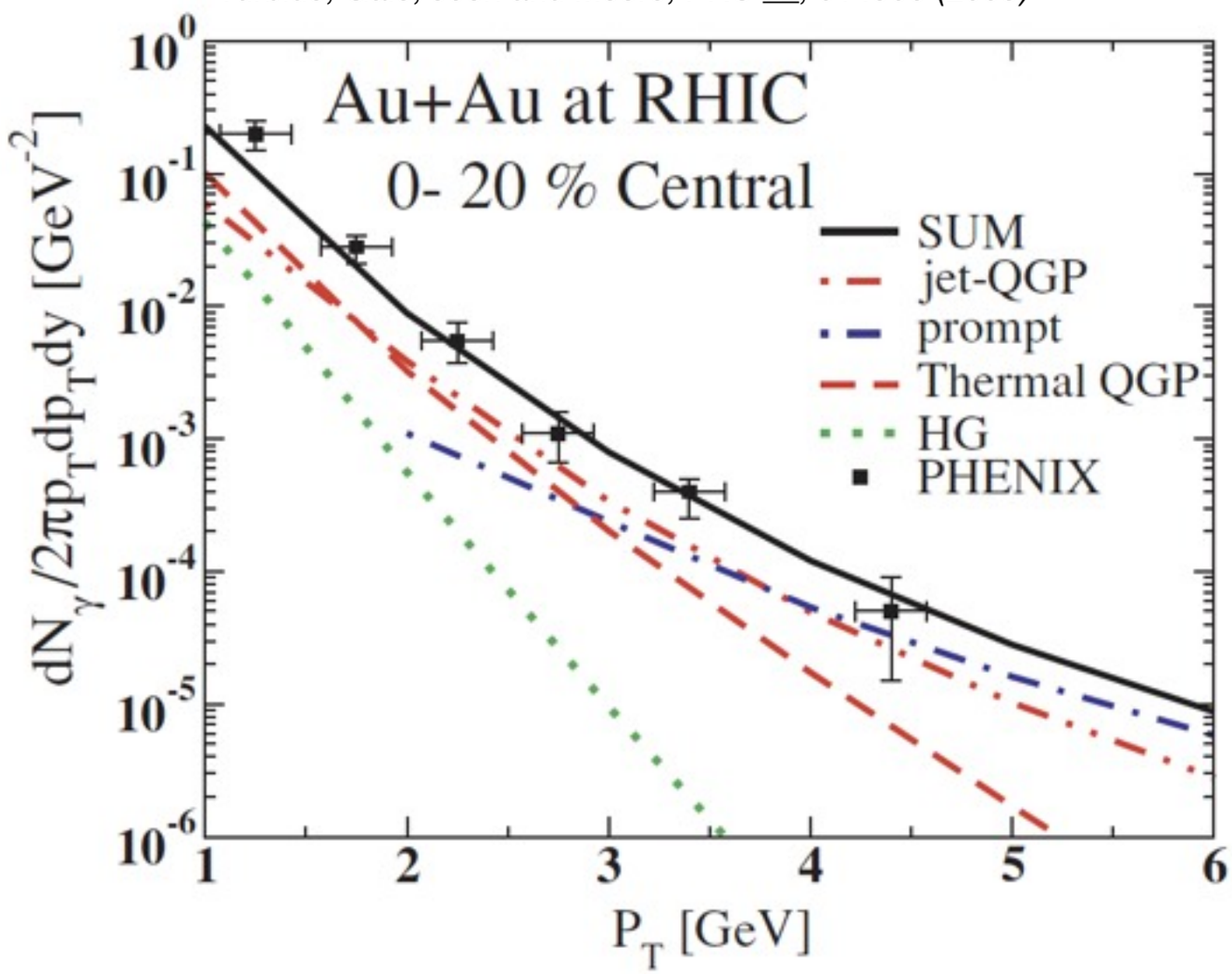
- Photon v_2 ~ hadron v_2

- High T_{ave} -> early emission
- High v_2 -> late emission

Large photon v_2 is difficult to explain with dominant QGP source

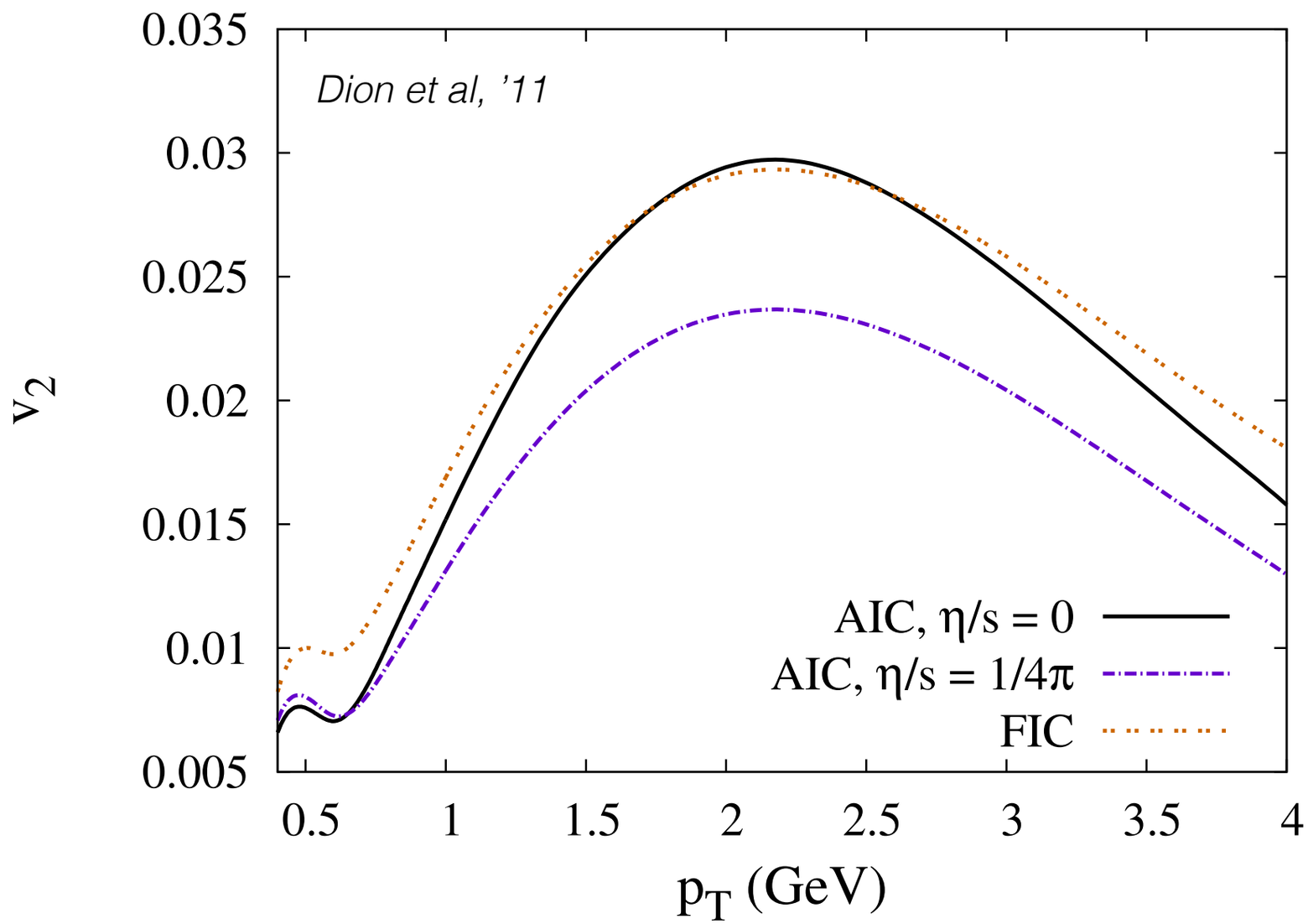
Theory: Hydrodynamics I

Turbide, Gale, Jeon and Moore, PRC 72, 014906 (2005)



- hydro model, which describes hadronic observables
- many ingredients
- overall good description
- hadron gas does not contribute significantly

Theory: Hydrodynamics II



Hydro:
10 times smaller v_2
then in experiment

AIC: averaged initial conditions
FIC: fluctuating initial conditions

Large photon v_2 is difficult to explain with dominant QGP source

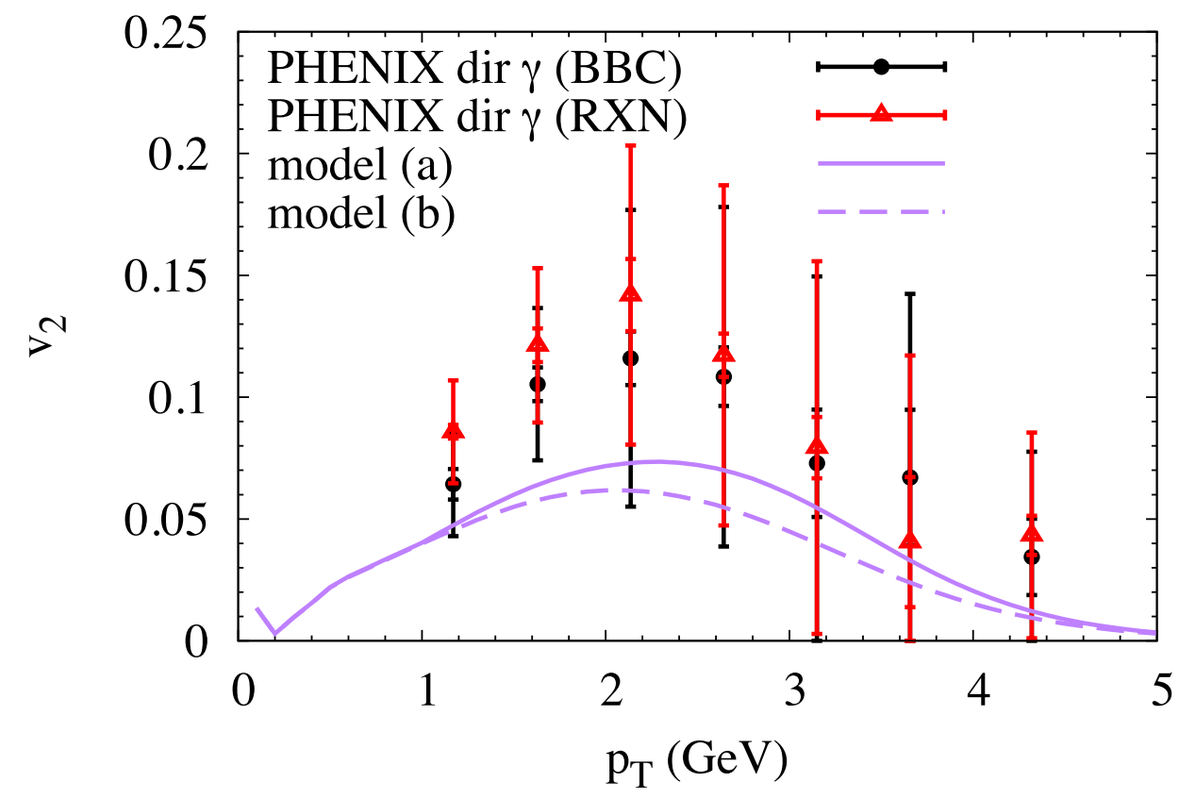
Theory: Another approach

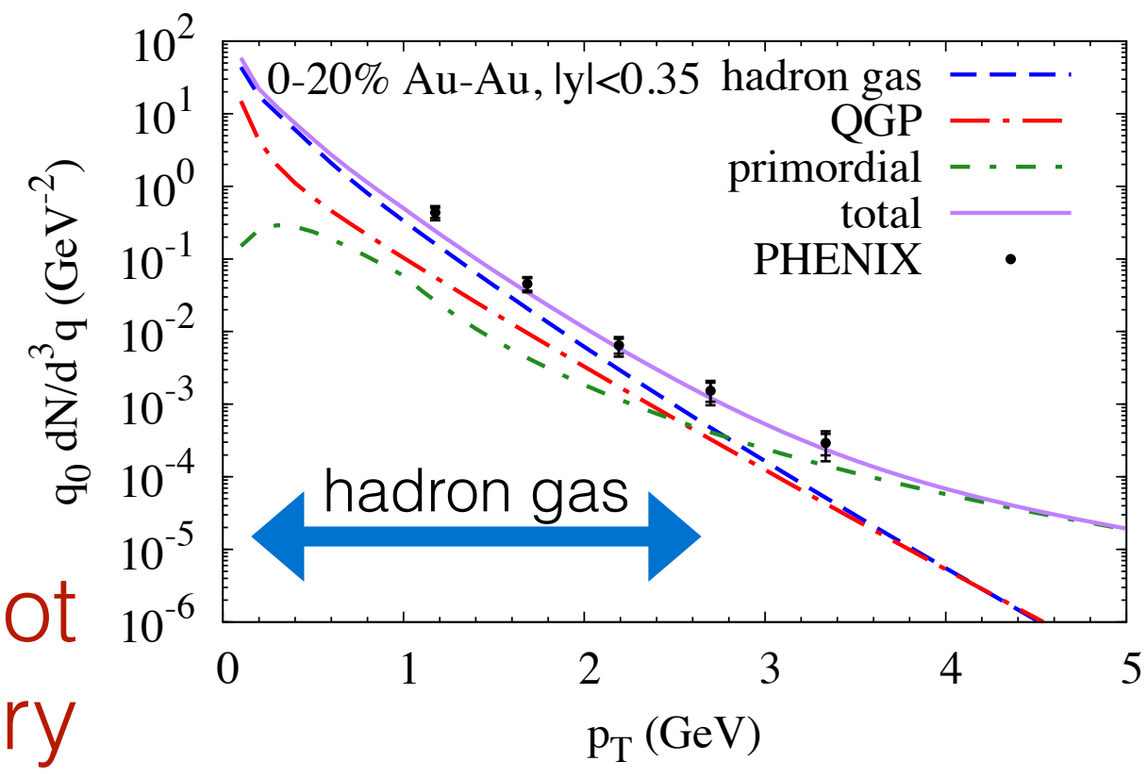
Hadron source is the first candidate

- photon v_2 to constrain evolution of fireball
- evolution contradicts to (1+n)-d hydro
- large acceleration in fireball expansion
- hadron gas gives major contribution to v_2 and photon spectra

interesting, but not satisfactory

H. van Hees, C. Gale and R. Rapp, '11

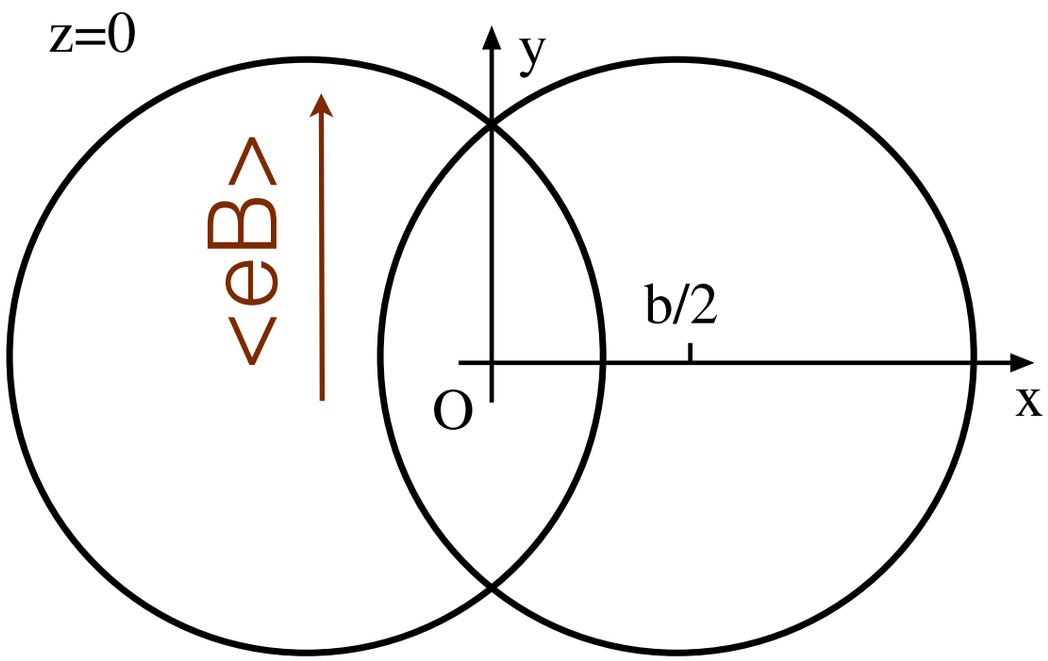




Another source of anisotropy?

- anisotropy ≠ flow!
- other sources for anisotropy not related to flow?!
- magnetic field?! Perfect candidate for anisotropic photon production.

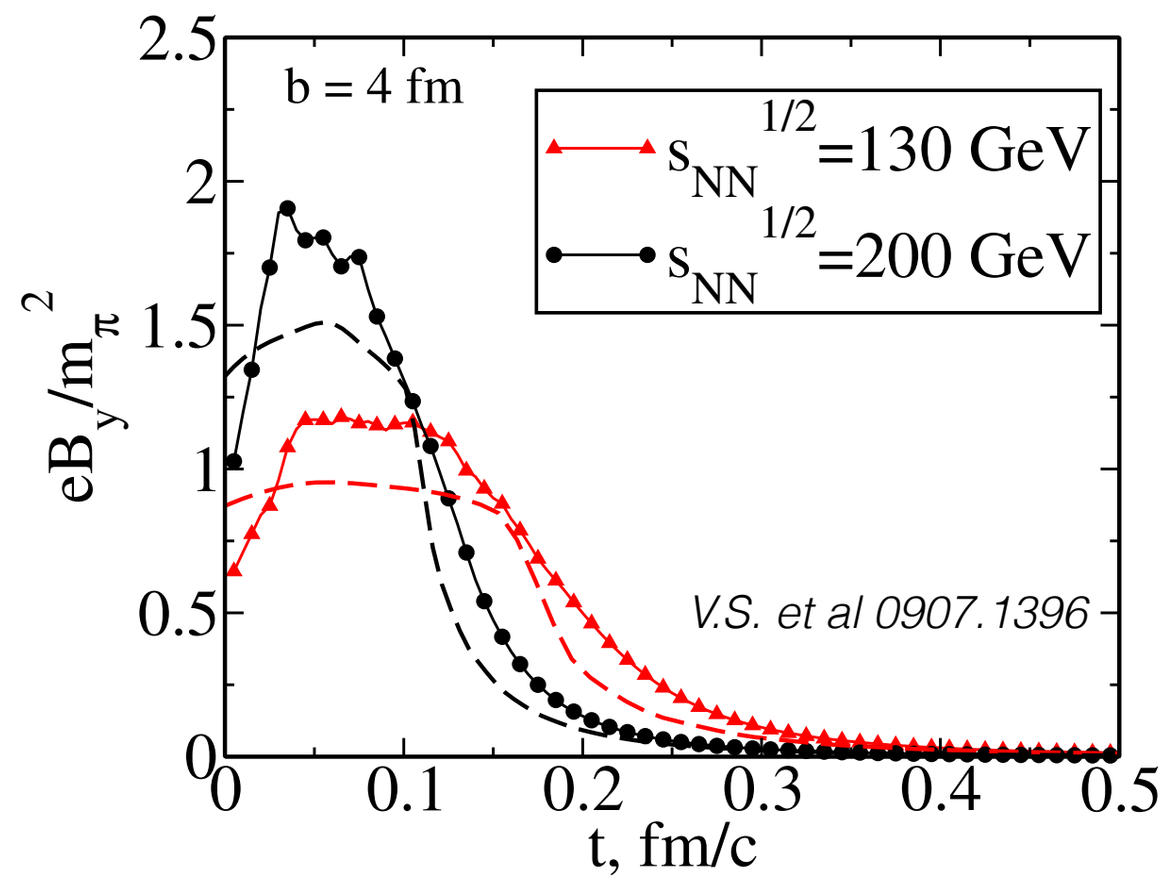
Magnetic field in HIC I



- spectators form two currents
- resulting average magnetic field
  $\langle eB_y \rangle \sim m_\pi^2$ (out-plane)
  $\langle eB_x \rangle \sim 0$ (in-plane)
- magnetic field is anisotropic!

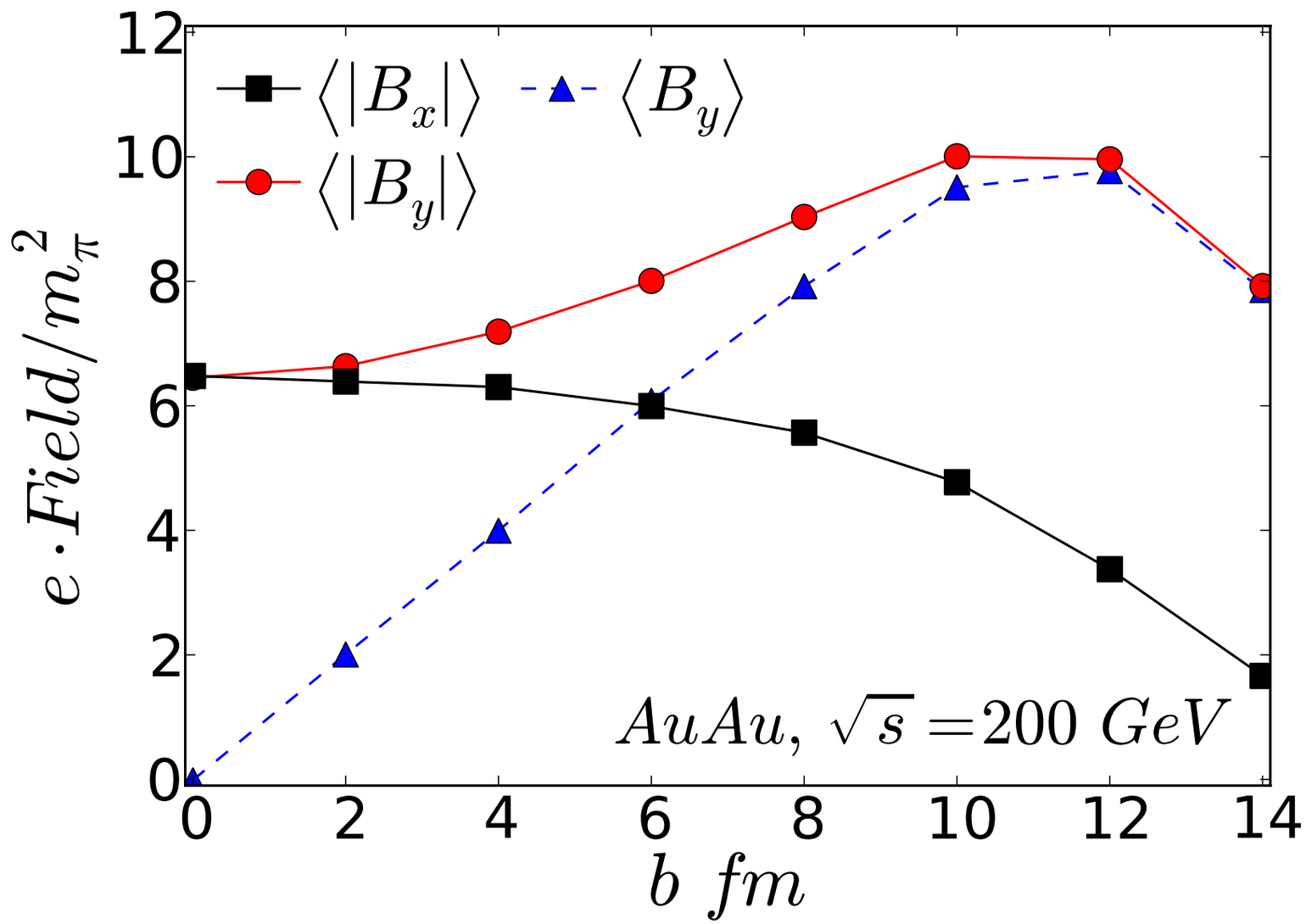
- maximal eB ~ $\sqrt{s}$
- maximum at $t_M \sim 1/\sqrt{s}$
- life time $t_{lt} \sim 1/\sqrt{s}$

D. Kharzeev, L. McLerran, H. Warringa, 0711.0950
V.S. et al, 0907.1396



Magnetic field in HIC II

- Dependence on impact parameter b:



- fluctuations can play important role
- <eB$_y$> is linear as a function of impact parameter
- this is common feature of <eB> and eccentricity ε_2

V.S. et al, 0907.1396;
A. Bzdak and V.S., 1111.1949

Magnetic field in HIC III

eB in HIC compared to

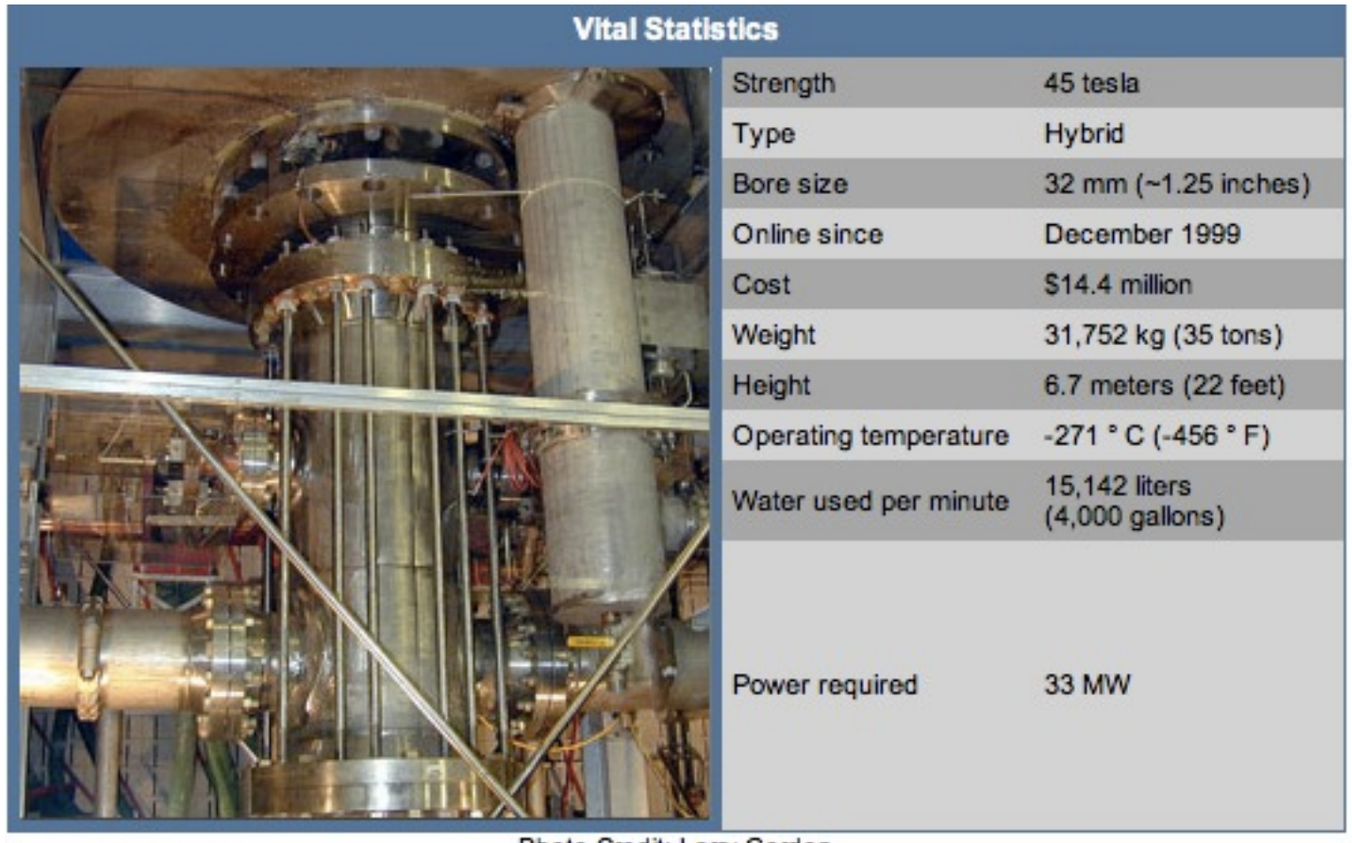
- Hybrid magnet at

  National High Magnetic field Lab

  45 Tesla ~ $4.5\times10^{-13}\ m_\pi^2$

- Pulsed magnets:

  100 Tesla ~$10^{-12}\ m_\pi^2$



Vital Statistics	
Strength	45 tesla
Type	Hybrid
Bore size	32 mm (~1.25 inches)
Online since	December 1999
Cost	$14.4 million
Weight	31,752 kg (35 tons)
Height	6.7 meters (22 feet)
Operating temperature	-271 ° C (-456 ° F)
Water used per minute	15,142 liters (4,000 gallons)
Power required	33 MW

Photo Credit: Larry Gordon

Watch an exploding pulsed magnet at work.

- Radio pulsars:

  10^{-6}-$10^{-5}\ m_\pi^2$

- Magnetars:

  10^{-4}-$10^{-3}\ m_\pi^2$

High eB... So what?

Effects, that can be potentially observed:

- modification of QCD phase diagram (S. Mukherjee,...)
- chiral magnetic effect (D. Kharzeev, L. McLerran, ...)
- chiral magnetic wave (D.Kharzeev, ...)
- **photon production!**

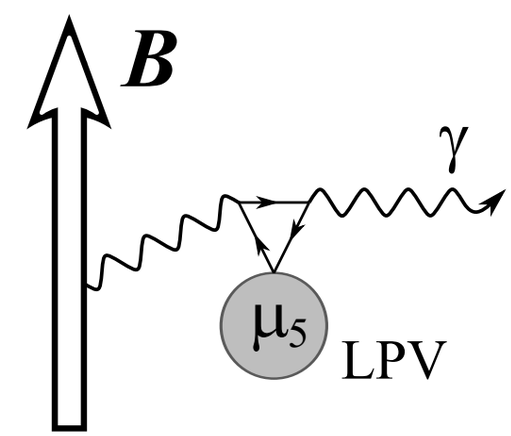
Photon production from eB

Several mechanisms:

- synchrotron radiation of quarks in eB (K. Tuchin)
  unknown: density and distribution function of quarks in early stage

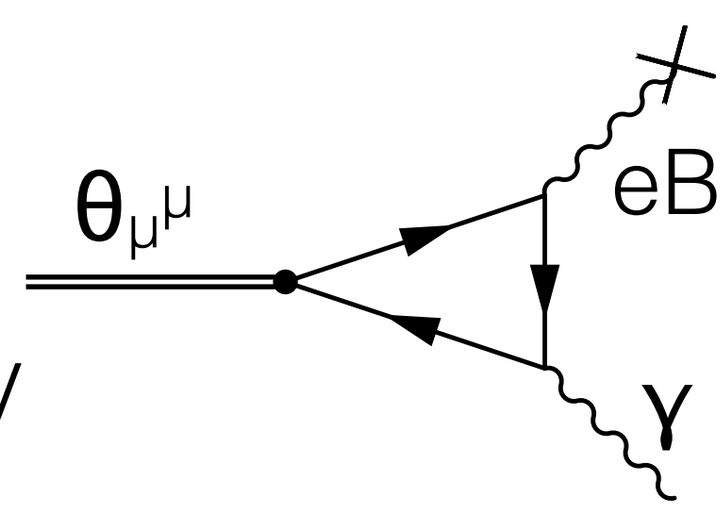
  R. Venugopalan and V.S. Quark production in Glasma

- axial anomaly (K. Fukushima)
  unknown: μ_5 and spectral function of $G\tilde{G}$



  G. Basar and D. Kharzeev

- **conformal anomaly**
  unknown?!: bulk viscosity



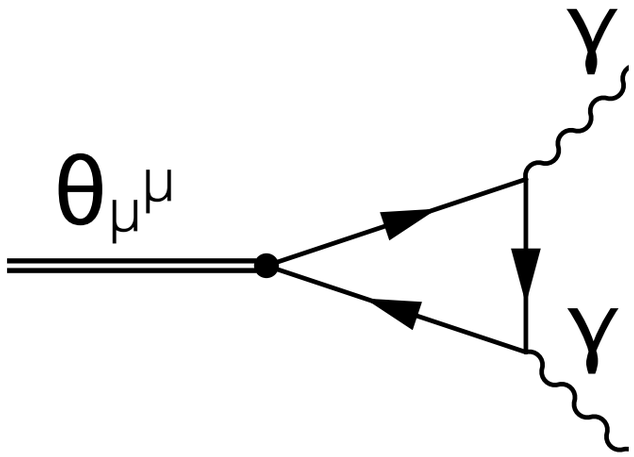
Conformal anomaly

- divergence of dilatation current

$$\partial^\mu S_\mu = \theta^\mu_\mu = \frac{\beta(g)}{2g} G^{\mu\nu a} G_{\mu\nu a} + \sum_q m_q \left[1 + \gamma_m(g)\right] \bar{q} q$$

- color singlet states $\sigma \sim \theta_\mu{}^\mu$ *Migdal, Shifman*

$$\langle 0 | S^\mu | \sigma \rangle = i q^\mu f_\sigma; \quad \langle 0 | \partial_\mu S^\mu | \sigma \rangle = m_\sigma^2 \; f_\sigma$$



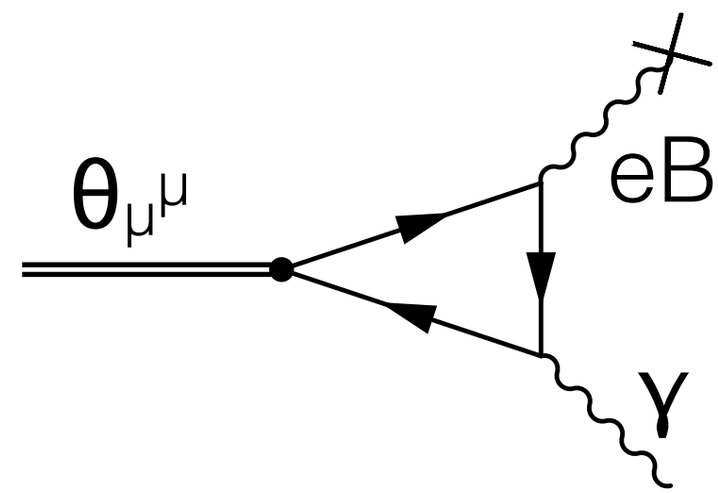
- effective Lagrangian

$$\mathcal{L}_{\sigma\gamma\gamma} = g_{\sigma\gamma\gamma} \; \sigma \; F_{\mu\nu} F^{\mu\nu}$$

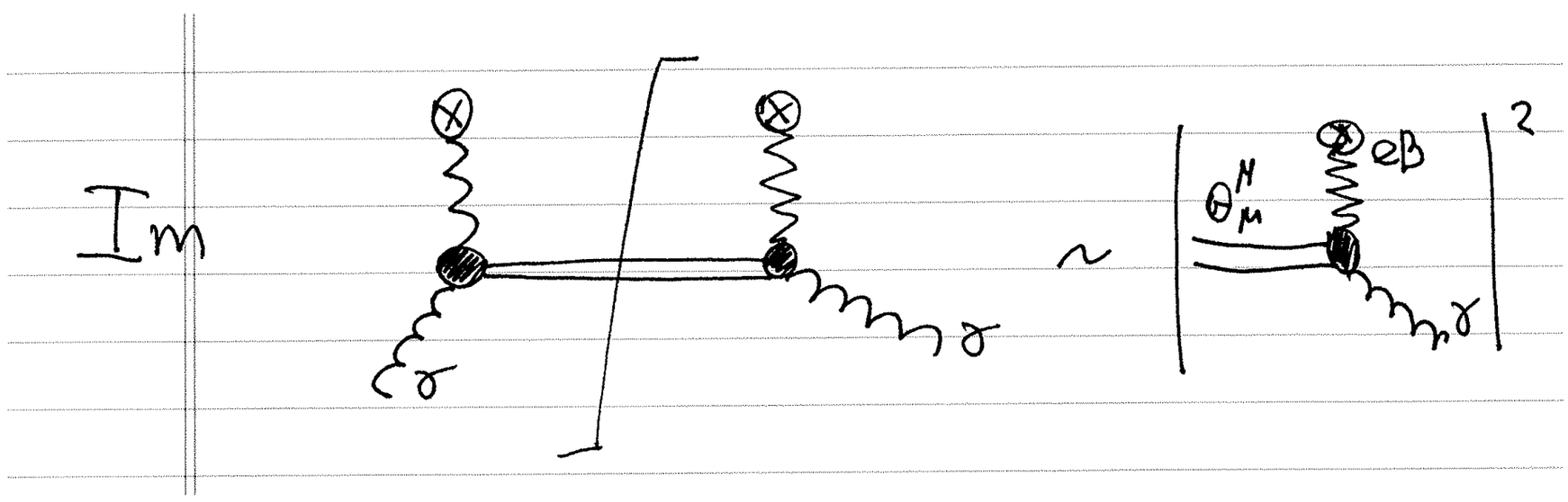
- $g_{\sigma\gamma\gamma} \cong 0.02$ GeV^{-1} *Ellis and Lanik; Crewther; Chanowitz*

Photon production rate

- one of the photons: classical field eB



- production rate, as usual (β=1/T):



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

Spectral function of $\theta_\mu{}^\mu$

- hydro approximation

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

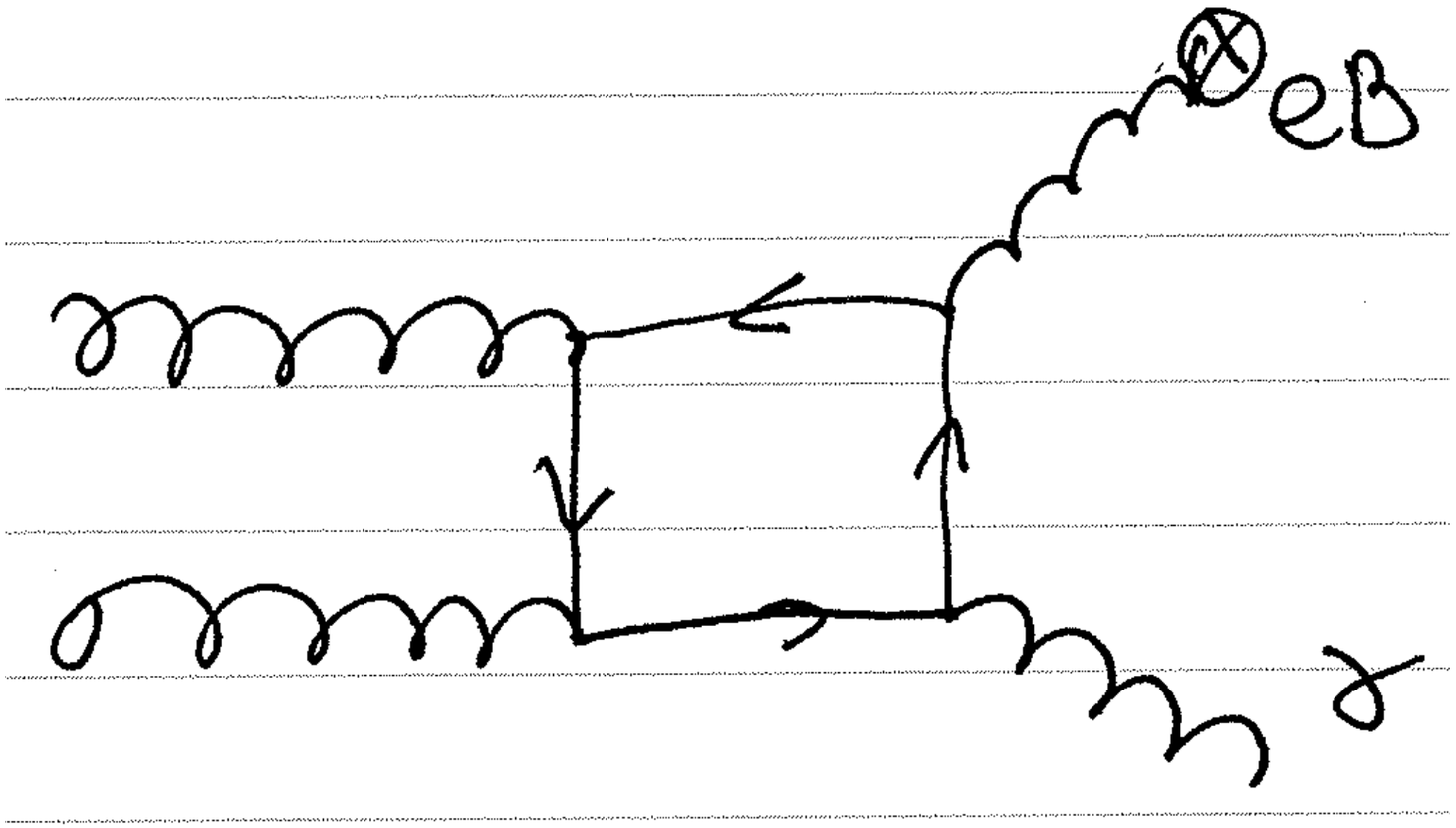
- real photons, sound peak does not contribute:

$$\rho_\theta(q_0,\vec{q}) \approx 9q_0\frac{\zeta}{\pi}$$

- anisotropy:

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

or...



Bulk viscosity

- first principle Lattice QCD:
  H. Meyer SU(3) Yang Mills (YM)
  However, this is very preliminary...

- approximations:

  $\zeta = C_\zeta\, \eta\, (1/3 - c_s^2)^2$ (vs ADS CFT $\zeta \geqq 2\, \eta\, (1/3 - c_s^2)$)

  C_ζ = 15 in relaxation time appr. (S. Weinberg '71)
  C_ζ = 45 in NLO SU(3) YM (K. Dusling and T. Schafer '11)
  C_ζ = 2.5-5 phenomenological constraints
  in this talk: conservative C_ζ = 2.5-5

- also conservative $\eta/s = 1/(4\pi)$. Entropy, s, from matrix model fitted to YM SU(3) (R. Pisarski)

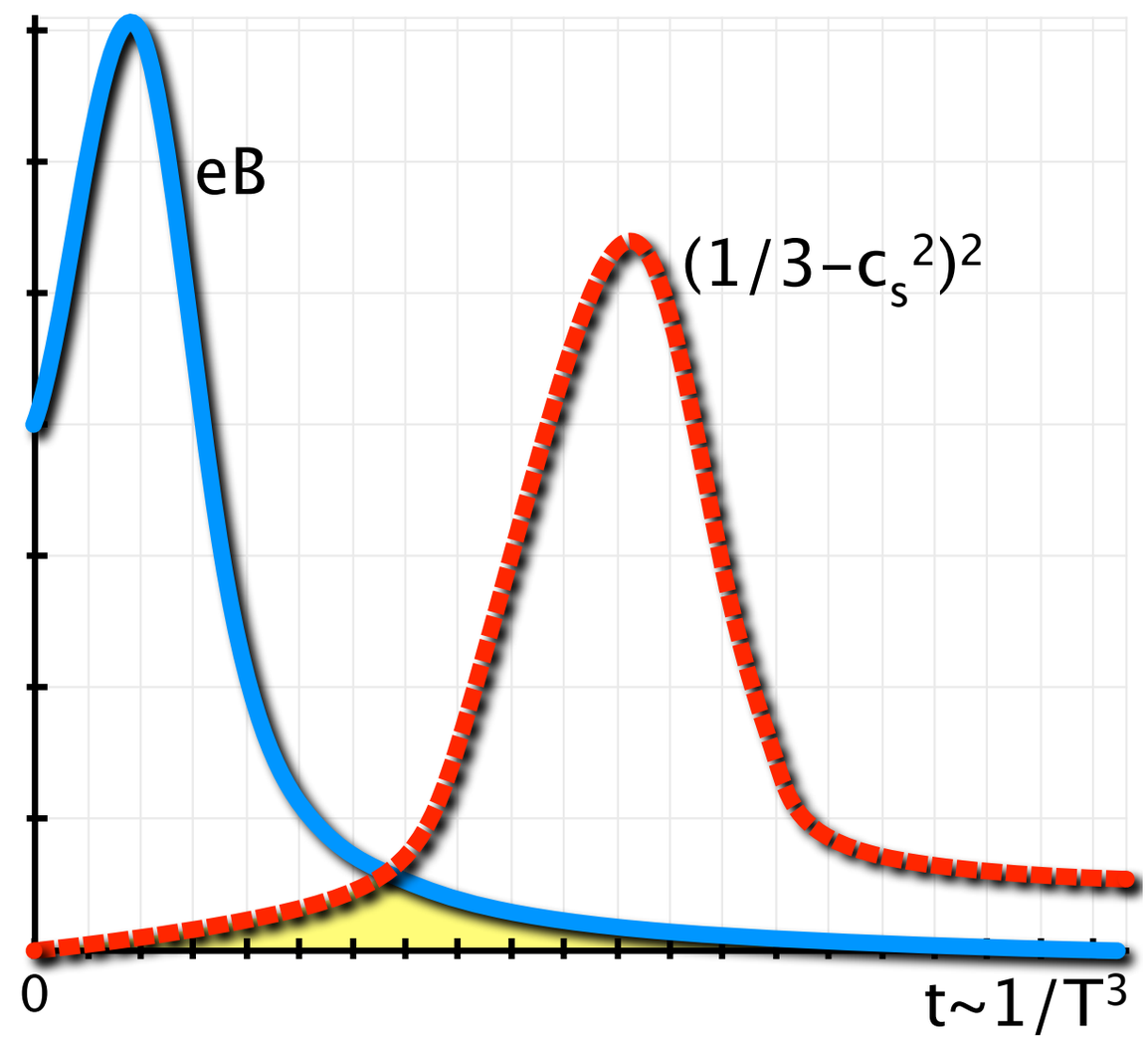
So one would expect...

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

$$\rho_\theta(q_0, \vec{q}) \approx 9q_0 \frac{\zeta}{\pi}$$

$\zeta = C_\zeta\, \eta\, (1/3 - c_s^2)^2$

- negligible contribution from this mechanism?! eB is non-zero at early stage where $(1/3-c_s^2)^2$ is small

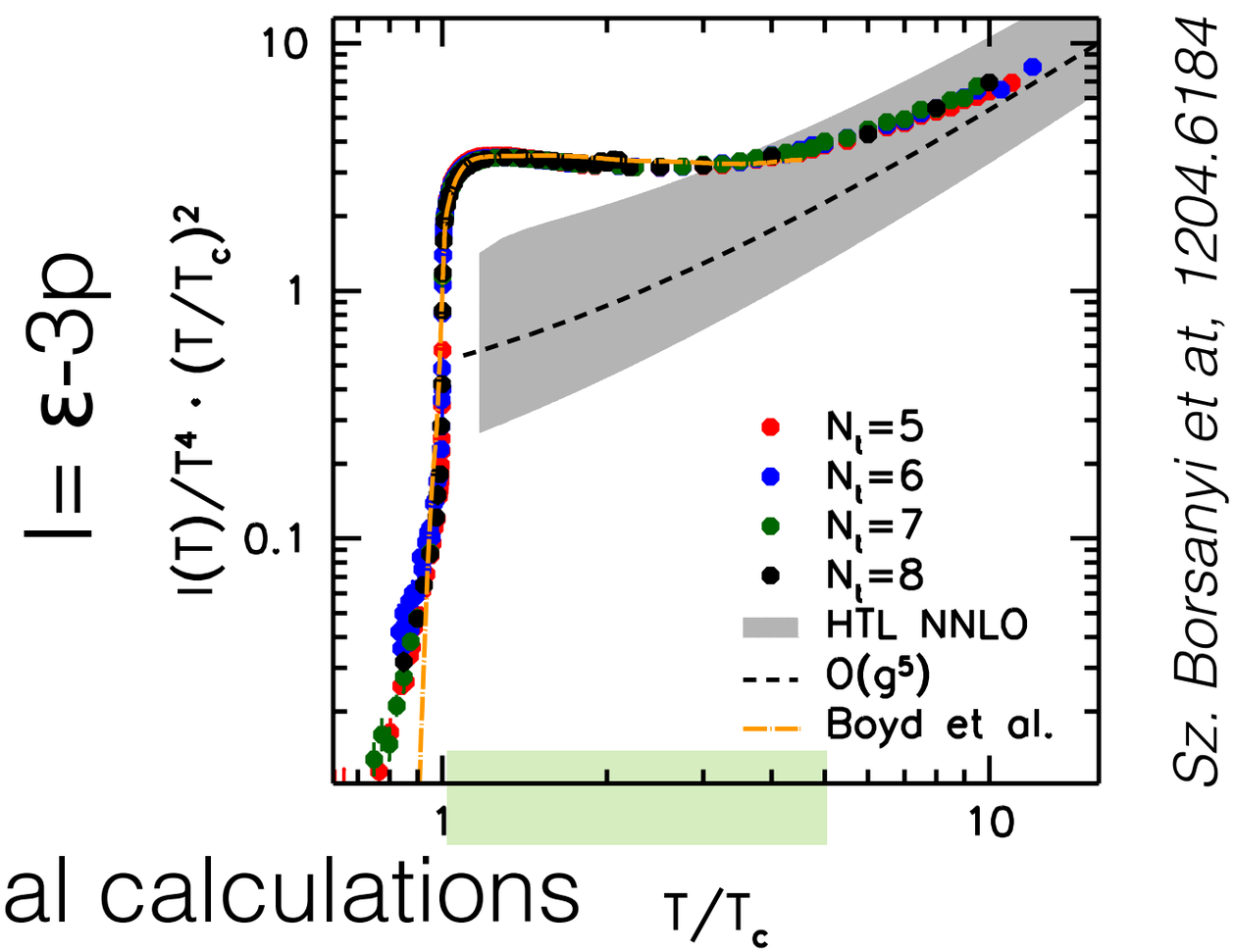


However

- rate is proportional to $(1-c_s^2)^2\, T^3\, (eB)^2$

  rough estimate at early stage
  $(1-c_s^2)\sim(\varepsilon-3p)/T^4\sim$(from LQCD)$\sim$**1 / T^2** (talks by R. Pisarski)
  $(1-c_s^2)^2\, T^3 \sim$**1 / T**$\sim$(Bjorken expansion)$\sim t^{1/3}$
  while $eB\sim 1/(t^2+\text{const})$

  stringy?
  fuzzy bag?
  quasiparticles?
  monopoles?



Sz. Borsanyi et at, 1204.6184

- rigorous answer: numerical calculations

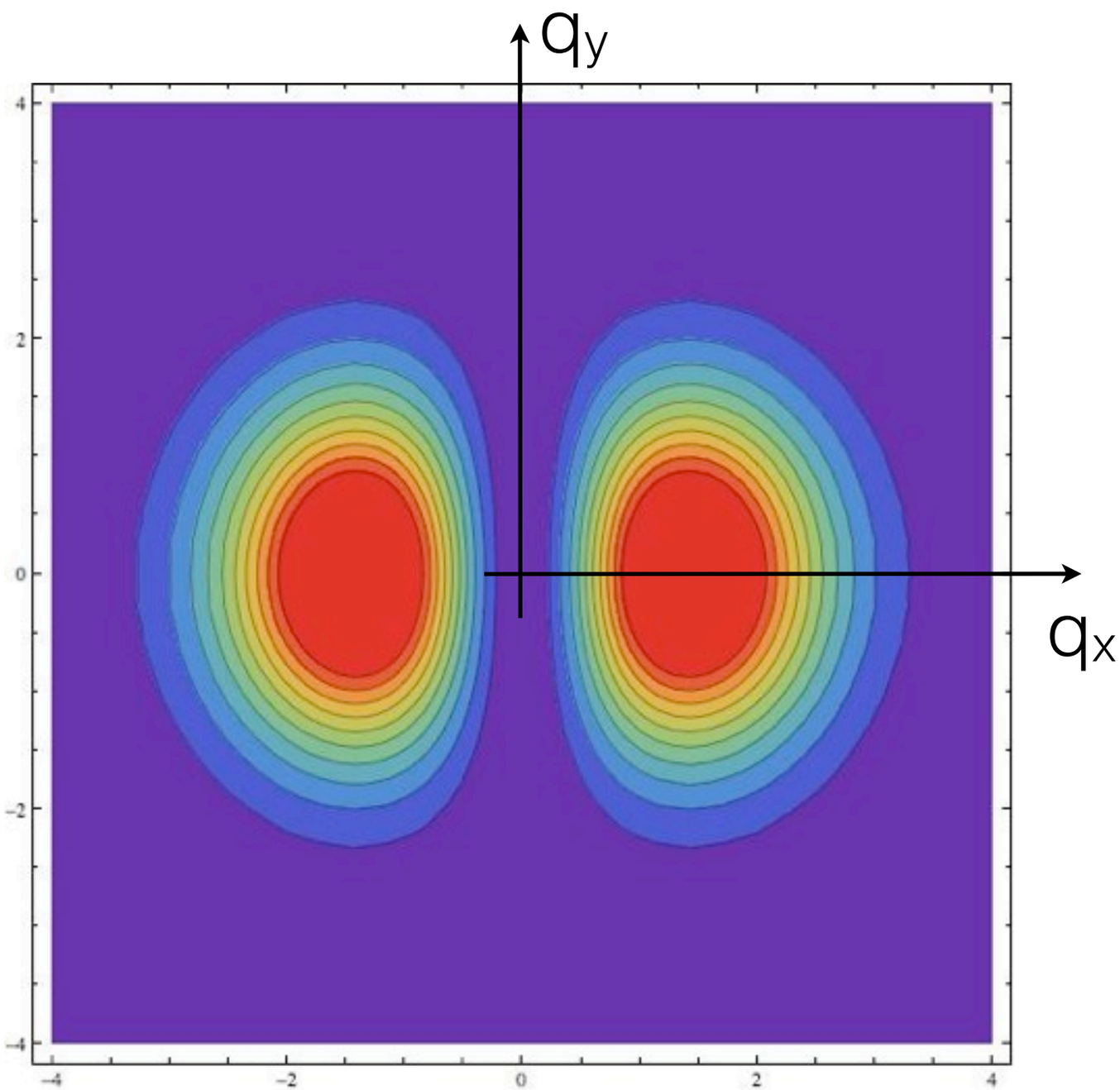
Other parameters

- Bjorken expansion for thermodynamic variables
- initial temperature T = 300 ÷ 400 MeV
- initial time τ=0.1 fm/c (no need for complete equilibrium)
- EoS: matrix model by R. Pisarski et al
- magnetic field from spectators only (with fluctuations taken into account)

Anisotropy of production rate

- in this mechanism:

$dN/d\varphi = C_1 + C_2 \cos(2\varphi)$

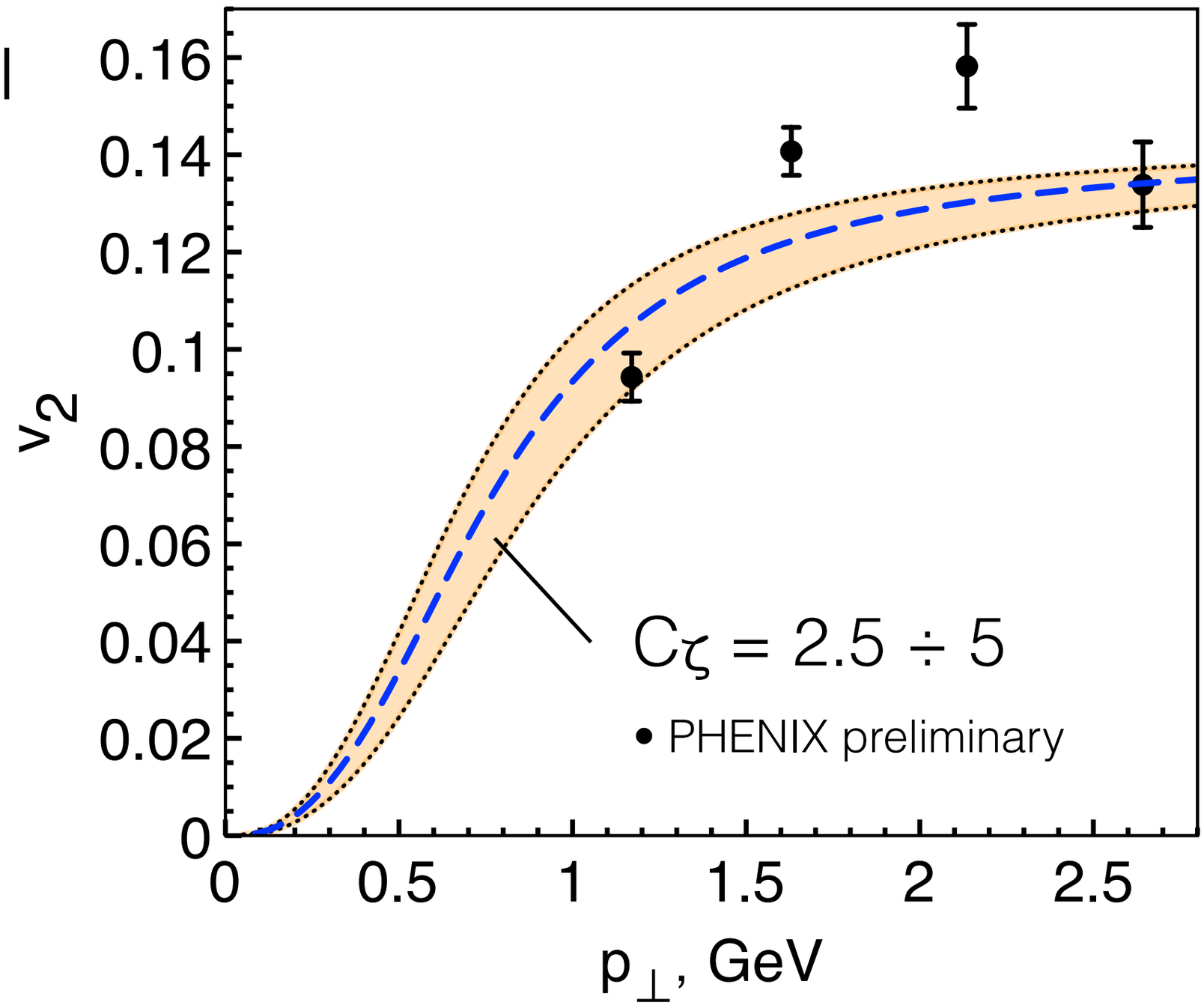


consequently:

- non-zero v_2
- small v_n, n=4,...
  in contrast to hadronic v_4
  PHENIX: $v_4/v_2^2 \sim 1$
  our prediction for photons: $v_4/v_2^2 \ll 1$
- number of photons in out-plane (q_y) is smaller then in in-plane (q_x) direction
- in-plane polarization of photons

Numerical calculations: v_2

- ingredients: thermal photons and photons from conformal anomaly +eB
- significant contribution to v_2
- higher $p_\perp$: prompt photons



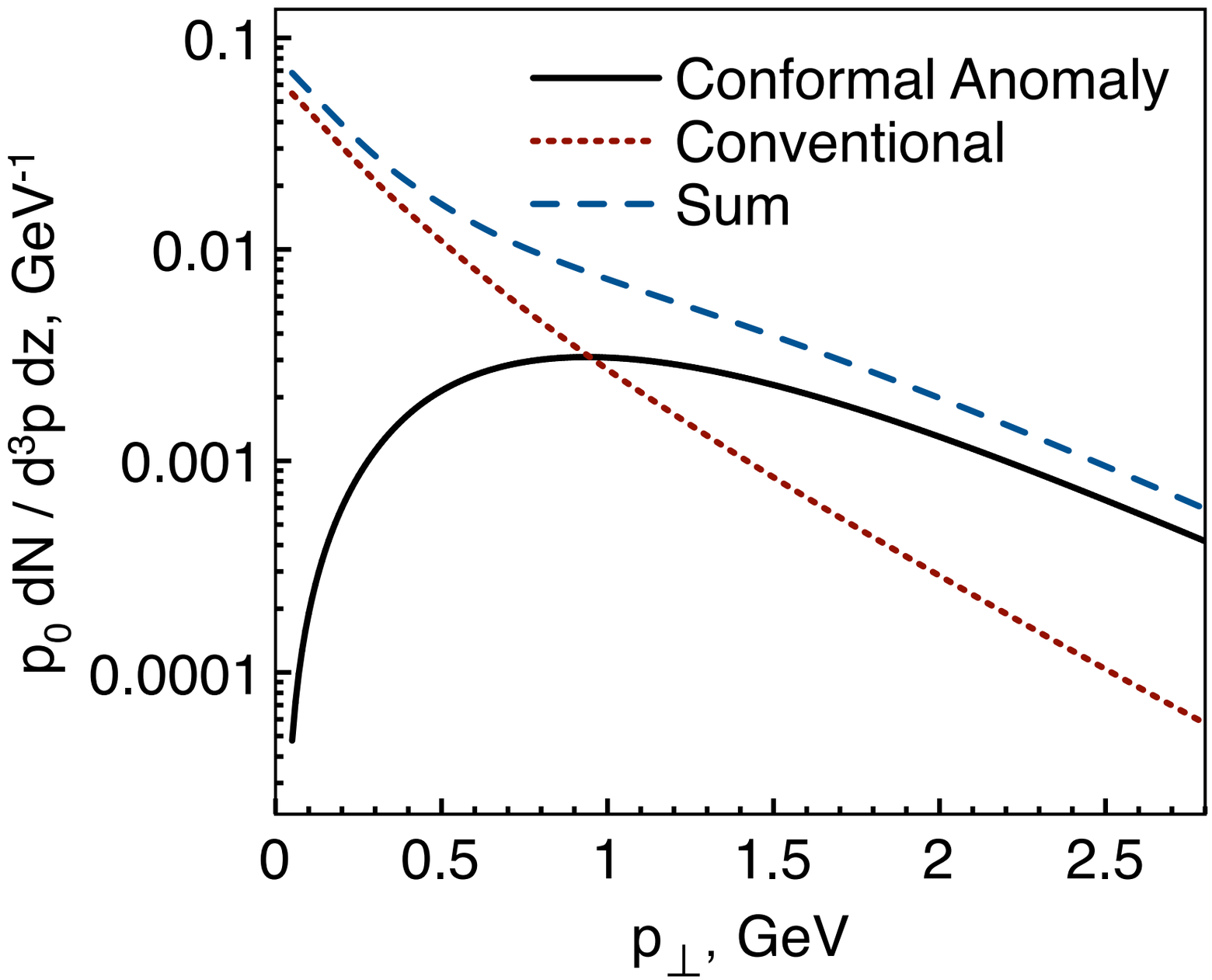
G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

Transverse momentum spectra

- conformal anomaly:
  $dN/dp_\perp \sim \mathbf{p_\perp^2} / [\exp(p_0/T)-1]$
  similar to effect of direct flow

- higher than thermal photons for $p_\perp > 1$ GeV

- higher $p_\perp$: prompt photons



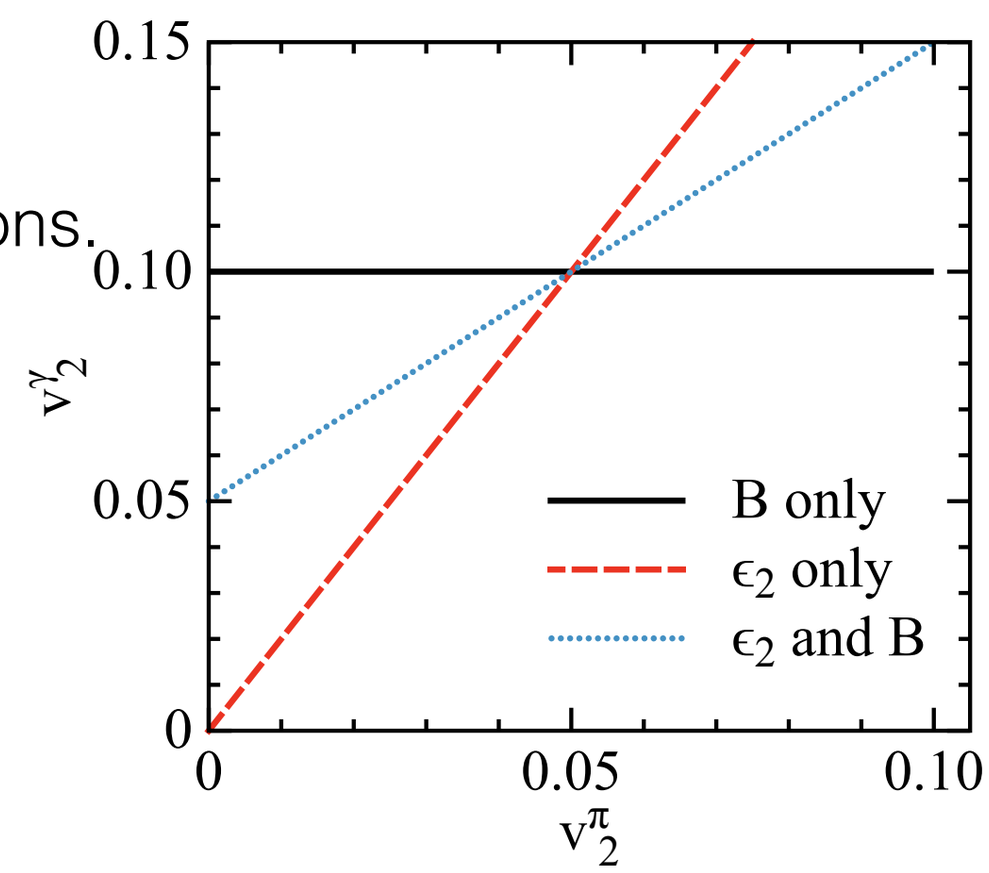
G. Basar, D. Kharzeev, V.S., arXiv:1206.1334

Experimental tests I

- 1) magnetic field is generated mostly by spectators
- 2) hadronic flow: initial eccentricity
- so switch off either 1) or 2)
- central U+U collisions: negligible eB but non-zero eccentricity
- non-central collisions: fluctuations of eccentricity

in given centrality class (e.g. 45-50% defined by ZDC), eB = const; while hadronic v_2 fluctuates because of initial eccentricity fluctuations.
Limiting case:
non-central collisions (➞ eB≠0) with zero v_2.

thus in such events anisotropy of photon production is due to eB.



A. Bzdak and V.S., 1208.5502

Experimental tests II

- small v_4; violation of scaling $v_4 \sim v_2^2$
- number of photons $N_{in\text{-}plane} > N_{out\text{-}plane}$
  $(N_{in\text{-}plane} - N_{out\text{-}plane}) \sim eB^2$ and thus is quadratic function of impact parameter
- in-plane polarization of photons (presumably difficult to measure)

Outlook:LHC energies

- Higher initial temperatures ➞ lower bulk viscosity
  T_{ave} = 304 MeV

- Large γ ➞ short time scales for non-zero magnetic field
  $t_{LHC} = t_{RHIC}\, \Upsilon_{RHIC} / \Upsilon_{LHC}$ ➞ $t_{LHC} \propto 0.01$ fm/c vs $t_{RHIC} \propto 0.1$ fm/c

- Stay tuned! Predictions to come soon!

- or data first ;)

MAGNETO-HYDRO

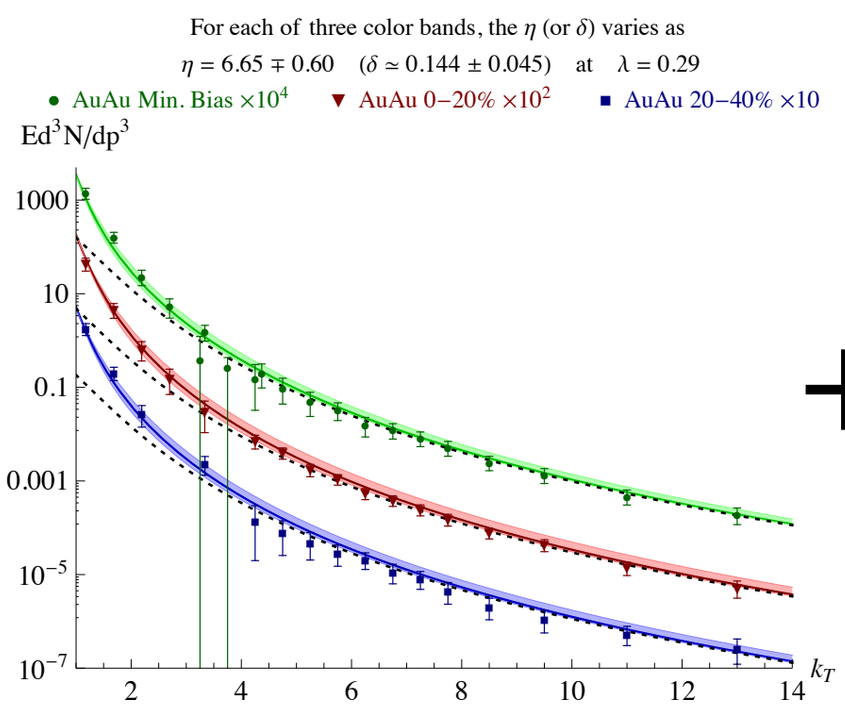
Outlook:RHIC low energy scan

- lower energies -> lower eB, but longer time scales
- in equilibrium: bulk viscosity, ζ, is divergent at critical point (CP)
- in reality (HIC): at CP $\zeta \sim \xi^{2.8}$, ξ is correlation length
- on O(4) line: $\zeta \sim \xi^{2}$ (while shear viscosity is finite)
  see *E. Nakano, V.S. and B. Friman, arXiv:1109.6822*
- rather speculative: small eB can compensate large ζ

MAGNETO-HYDRO

Outlook:Glasma and v_2

- this work: production from thermal YM
- in principle: this mechanism works also for photon production in Glasma
- could be a nice combination of results



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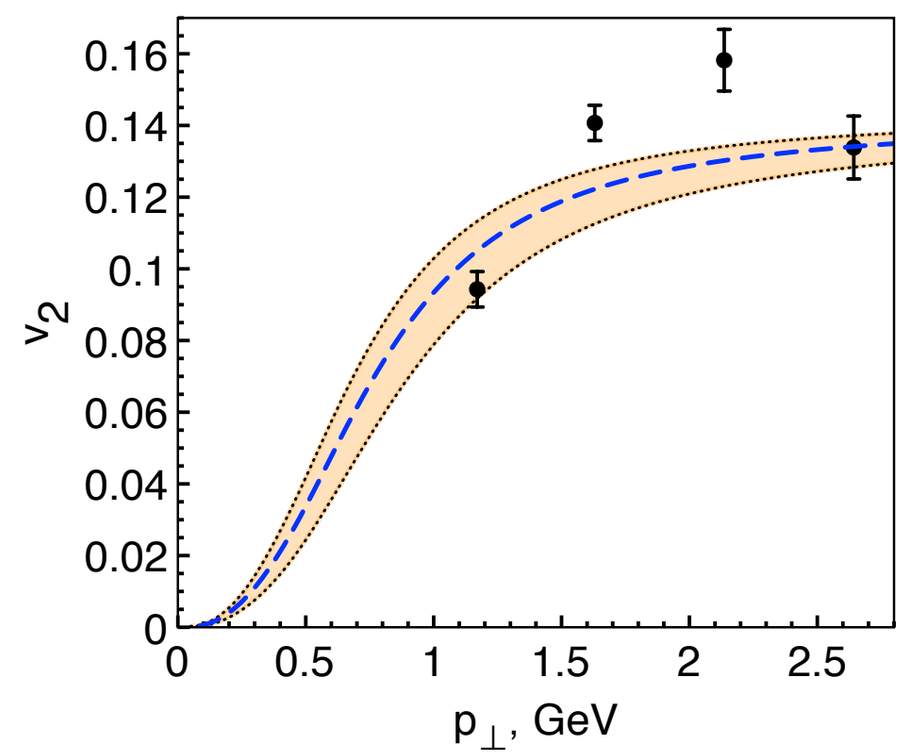


M. Chiu, ...,L. McLerran, ..., arXiv: 1202.3679

Even more general Outlook

- implementing in hydro or even magneto-hydro
- “state of the art” hadronic contribution
  jet in QGP
  prompt photons
  etc.
- bulk viscosity? at least can be done consistently with EoS: R. Pisarski and V.S.

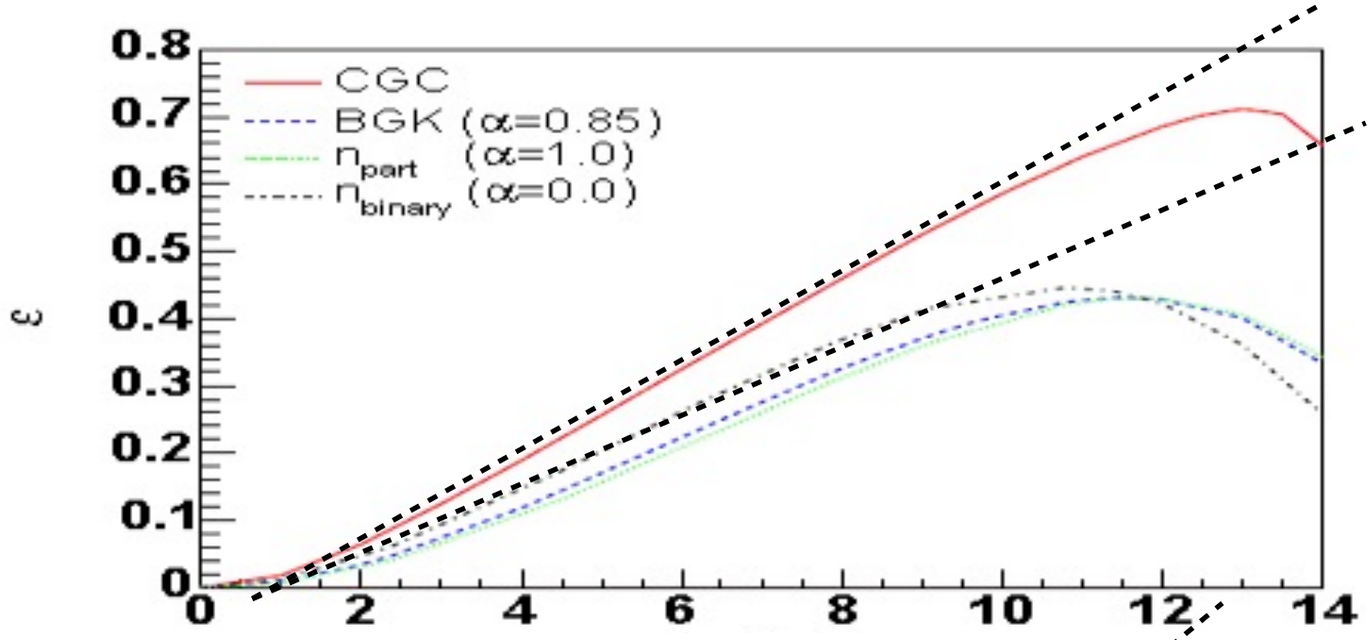
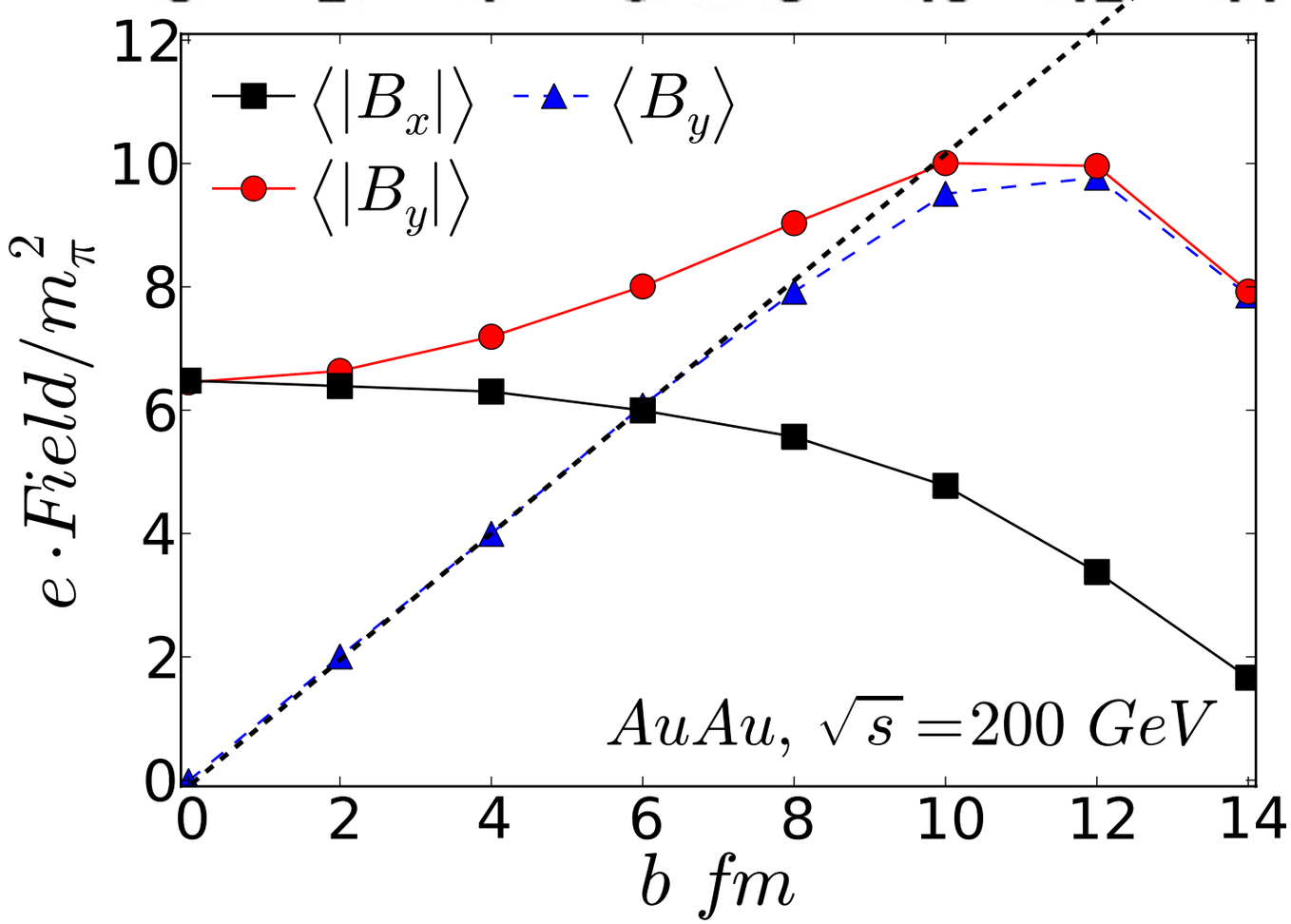
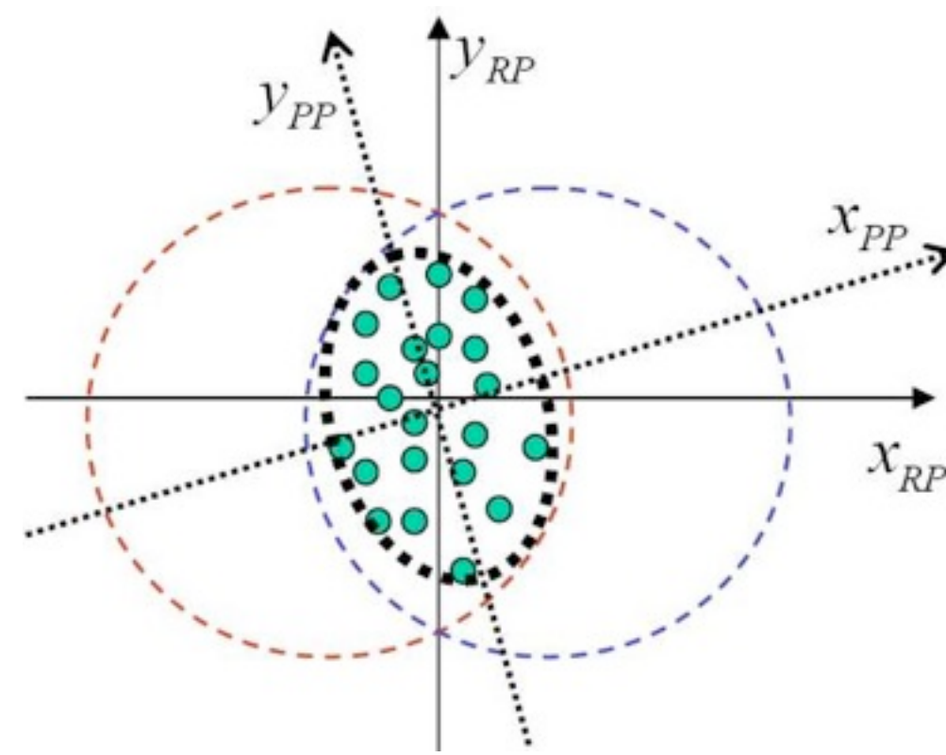
Summary

- photon v_2 puzzle:
  - hadronic “state of the art” physics?!
  - or QEDxQCD conformal anomaly in non-zero magnetic field?!

- there are ways to discriminate between hadronic and anomaly related mechanisms of v_2!

- axial anomaly: similar effect, but unknown μ_5 (similar to CME)
  Synchrotron radiation: similar effect: but unknown quark distribution in initial state

Backup



Drescher Dumitru Hayashigaki Nara, nucl-th/0605012