EFFECTS OF MACROSCOPIC QCD OBSERVED IN HEAVY-ION COLLISIONS

I.M. DREMIN

Lebedev Physical Institute

ISMD-2010, 24 September 2010

FIRST SURPRISES FROM LHC pp-RUN!

$\sqrt{s}$=0.9; 2.36; 7 TeV

1. High particle densities $dN/d\eta|_{\eta=0}$ comparable to heavy-ion results at RHIC (ALICE, CMS, ATLAS)

2. Large size of the emission region at high multiplicities (CMS)

3. Ridge-like structure at high multiplicities ($N_{ch} \geq 110$) (CMS-talk, 22.09)

FIRST HEAVY-ION RUN IN NOVEMBER

Pb+Pb at $\sqrt{s}$= 2.76A TeV

RHIC EXPERIMENT - AA $\neq$ sum of independent pp
THEORY - notion of QGP (asks for in-medium QCD)

Electrodynamics - in-vacuum (LL II); in-medium (LL VIII)

MICRO- and MACRO-APPROACHES

Main experimental tests - energy losses of charged probes (e^-, partons) in the medium (ED-plasma or QGP)
Micro - CGC, Glasma, QGP + medium impact on a probe
Macro - collective medium excitations induced by a probe

Micro - **v** changes - scattering, bremsstrahlung, synchrotron rad.
Macro - **v** $\approx$ const - dielectric (or chromo-) permittivity ϵ - Cherenkov photons (gluons), wake, transition radiation.
Purely coherent collective response of the matter!

Polarization - $(\epsilon \neq 1)$

$$\mathbf{P} = \frac{\epsilon - 1}{4\pi}\mathbf{E},$$

$$\frac{\Delta E}{E} = (\gamma^2 - 1)\frac{\Delta v}{v} \gg \frac{\Delta v}{v} \qquad (\gamma \gg 1)$$

HOW TO FORMULATE
MACROSCOPIC CHROMODYNAMICS

IN-MEDIUM GLUODYNAMICS

I.D., Eur. Phys. J. C **56** (2008) 81; arXiv:0802.4022

1. Introduce the chromopermittivity, denote it also by ϵ.
2. Replace $\mathbf{E}_a$ by $\epsilon\mathbf{E}_a$.
For fields

$$\epsilon(\mathrm{div}\mathbf{E}_a - gf_{abc}\mathbf{A}_b\mathbf{E}_c) = \rho_a,$$

$$\mathrm{curl}\mathbf{B}_a - \epsilon\frac{\partial\mathbf{E}_a}{\partial t} - gf_{abc}(\epsilon\Phi_b\mathbf{E}_c + [\mathbf{A}_b\mathbf{B}_c]) = \mathbf{j}_a.$$

The permittivity = the matter response to the induced fields due to internal current sources in the medium.
$(\rho, \mathbf{j})$ - external current sources.

For potentials

$$\triangle \mathbf{A}_a - \epsilon \frac{\partial^2 \mathbf{A}_a}{\partial t^2} = -\mathbf{j}_a - g f_{abc} \Big(\frac{1}{2} \mathrm{curl} [\mathbf{A}_b, \mathbf{A}_c] + \frac{\partial}{\partial t} (\mathbf{A}_b \Phi_c) + \frac{1}{2} [\mathbf{A}_b \mathrm{curl} \mathbf{A}_c] - \epsilon \Phi_b \frac{\partial \mathbf{A}_c}{\partial t} - \epsilon \Phi_b \mathrm{grad} \Phi_c - \frac{1}{2} g f_{cmn} [\mathbf{A}_b [\mathbf{A}_m \mathbf{A}_n]] + g \epsilon f_{cmn} \Phi_b \mathbf{A}_m \Phi_n \Big),$$

$$\triangle \Phi_a - \epsilon \frac{\partial^2 \Phi_a}{\partial t^2} = -\frac{\rho_a}{\epsilon} + g f_{abc} \Big(2 \mathbf{A}_b \mathrm{grad} \Phi_c + \mathbf{A}_b \frac{\partial \mathbf{A}_c}{\partial t} - \epsilon \frac{\partial \Phi_b}{\partial t} \Phi_c \Big) + g^2 f_{amn} f_{nlb} \mathbf{A}_m \mathbf{A}_l \Phi_b .$$

$A \propto J \propto g$, classical equations are as in ED, higher order corrections $\propto g^3$ can lead to color rainbow!

Cherenkov gluons as a classical solution

Phase and coherence length (role of ϵ!)

$$\Delta\phi = \omega\Delta t - k\Delta z\cos\theta = k\Delta z(\frac{1}{v\sqrt{\epsilon}} - \cos\theta).$$

For Cherenkov effects

$$\cos\theta = \frac{1}{v\sqrt{\epsilon}}.$$

Coherence $\Delta\phi = 0$ independent of Δz.

Specific for Cherenkov radiation only.

The external current

$$\mathbf{j}(\mathbf{r},t) = \mathbf{v}\rho(\mathbf{r},t) = 4\pi g\mathbf{v}\delta(\mathbf{r}-\mathbf{v}t).$$

$$\mathbf{A}^{(1)}(\mathbf{r},t) = \epsilon\mathbf{v}\Phi^{(1)}(\mathbf{r},t).$$

We consider the polarization losses (not bremsstrahlung!).

$$\Phi^{(1)}(\mathbf{r}, t) = \frac{g}{2\pi^2\epsilon} \int d^3k \frac{\exp[i\mathbf{k}(\mathbf{r} - \mathbf{v}t)]}{k^2 - \epsilon(\mathbf{kv})^2}.$$

Cylindrical coordinates:

$d\phi \rightarrow J_0(k_\perp r_\perp)$, $dk_z \rightarrow$**poles,**

$\int dk_\perp J_0 \sin(k_\perp ...) \rightarrow \theta$**.**

$$\Phi^{(1)}(\mathbf{r}, t) = \frac{2g}{\epsilon} \frac{\theta(vt - z - r_\perp\sqrt{\epsilon v^2 - 1})}{\sqrt{(vt - z)^2 - r_\perp^2(\epsilon v^2 - 1)}}.$$

Cherenkov cone (shock wave!) and wake ($1/\epsilon$-term)

$$z = vt - r_\perp\sqrt{\epsilon v^2 - 1}.$$

Poynting vector

$$S_x = -S_z \frac{(z - vt)x}{r_\perp^2}, \; S_y = -S_z \frac{(z - vt)y}{r_\perp^2}.$$

Cherenkov angle

$$\tan^2 \theta = \frac{S_x^2 + S_y^2}{S_z^2} = \epsilon v^2 - 1.$$

(the same as from coherence condition $\Delta\phi = 0$)

The intensity (Tamm-Frank formula)

$$\frac{dW}{dl} = 4\pi\alpha_S C_R \int \omega d\omega (1 - \frac{1}{v^2\epsilon})\Theta(1 - \frac{1}{v^2\epsilon}).$$

The dispersion and imaginary part of $\epsilon(\omega, \mathbf{q}) = \epsilon_1(\omega, \mathbf{q}) + i\epsilon_2(\omega, \mathbf{q})$.

Energy loss

$$\frac{dW}{dz} = -gE_z,$$

First order:

$$\Phi_a^{(1)}(k) = 2\pi g Q_a \frac{\delta(\omega - kv\zeta)v^2\zeta^2}{\omega^2\epsilon(\epsilon v^2\zeta^2 - 1)}, \quad A_{z,a}^{(1)}(k) = \epsilon v \Phi_a^{(1)}(k),$$

$$E_z^{(1)} = i \int \frac{d^4k}{(2\pi)^4}[\omega A_z^{(1)}(\mathbf{k},\omega) - k_z \Phi^{(1)}(\mathbf{k},\omega)]e^{i(\mathbf{kv}-\omega)t},$$

$$\frac{dW_a^{(1)}}{dzd\zeta d\omega} = \frac{g^2 C_R \omega}{2\pi^2 v^2 \zeta} \mathrm{Im}\left(\frac{v^2(1-\zeta^2)}{1-\epsilon v^2\zeta^2} - \frac{1}{\epsilon}\right).$$

Cherenkov gluons (first term) + **wake** (second term)

$$\frac{dN^{(1)}}{dzdxd\omega} = \frac{dW^{(1)}}{\omega dzd\zeta^2 d\omega} = \frac{\alpha_S C_R}{2\pi}\left[\frac{(1-x)\Gamma_t}{(x-x_0)^2 + (\Gamma_t)^2/4} + \frac{\Gamma_l}{x}\right],$$

$x = \zeta^2 = \cos^2\theta,\ x_0 = \epsilon_{1t}/|\epsilon_t|^2 v^2,\ \Gamma_j = 2\epsilon_{2j}/|\epsilon_j|^2 v^2,\ \epsilon_j = \epsilon_{1j} + i\epsilon_{2j}.$

ANALITICAL RESULTS!

Experimental effects

- **Rings around the high-energy partons - non-trigger experiments:** I.D., JETP Lett. **30** (1979) 140; Sov. J. Nucl. Phys. **33** (1981) 726.
- **Rings around the low-energy partons - trigger:** I.D., Nucl. Phys. A**767** (2006) 233; A**785** (2007) 369.
  A. Majumder, X.N. Wang, Phys. Rev. C**73** (2006) 172302.
  V. Koch et al, Phys. Rev. Lett. **96** (2006) 172302.
  I.D., M.R. Kirakosyan, A.V. Leonidov, A.V. Vinogradov, Nucl. Phys. A **825** (2009); arXiv:0809.2472.
- **The low-mass dilepton excess:** I.D., V.A. Nechitailo, Int. J. Mod. Phys. A **24** (2009) 1221; hep-ph/0704.1081
- **Wake:** - I.D., Mod. Phys. Lett. A**25** (2010) 591; arXiv:0911.3233

Reviews:

I.D., A.V. Leonidov, Uspekhi **180** Nov. 2010; Ginzburg memo arXiv:1006.4607
I.D., Phys. Atom. Nucl. **73** (2010) 684;
I.D., Int. J. Mod. Phys. A**22** (2007) 1

CERENKOV GLUONS AND AWAY-SIDE REGION STRUCTURE (TWO HUMPS)

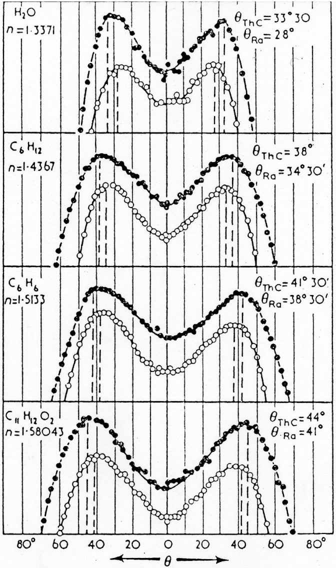
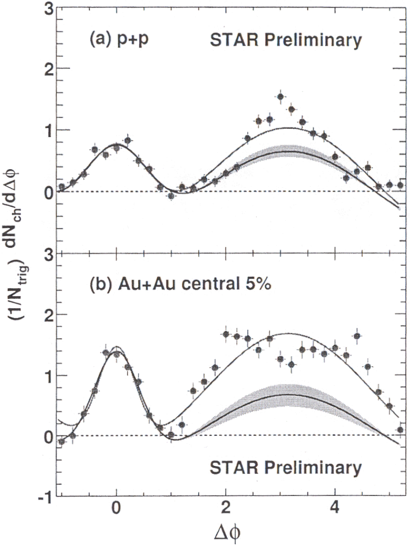
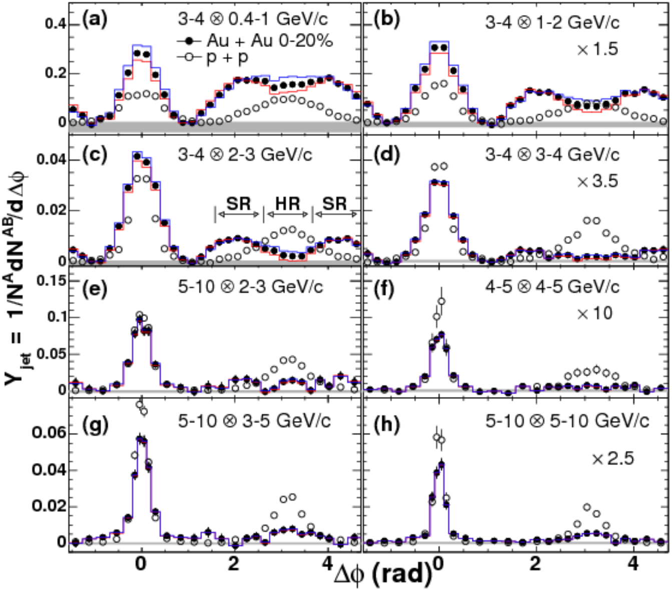


FIG. 1.8. The variation of θ with n, for two different sources of γ-rays. (Čerenkov, 1937d and 1938c.)

The Figure is from the book of J. Jelley "Cherenkov radiation and its applications 1958



The $\Delta\phi$-distribution of particles produced by trigger and companion jets at RHIC shows two peaks in *pp* and three peaks in AuAu-collisions.



(A. Adare et al for PHENIX collaboration, arXiv0705.3238)
Per-trigger yield versus $\Delta\phi$ in *pp* and Au-Au collisions.

COMPLEX $\epsilon = \epsilon_1 + i\epsilon_2$

The angular δ-function $\rightarrow$ a'la BW-shape.
Using the relation of θ with the lab angles $\cos\theta = |\sin\theta_L \cos\phi_L|$ and integrating over θ_L , one gets (quite lengthy) analytical expression for the measured (ϕ_L)-distribution (two-hump structure!).

I.D., M.R. Kirakosyan, A.V. Leonidov, A.V. Vinogradov, Nucl. Phys. A **826** (2009) 190; arXiv:0809.2472

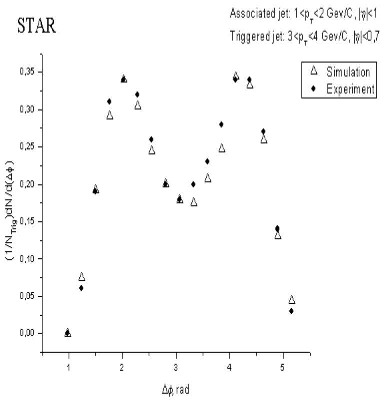
1. PYTHIA for initial partons
2. Cherenkov angular distribution of gluons
3. the gluon fragmentation function to pions (LEP) with gaussian suppression of transverse momenta $\propto \exp(-p_t^2/2\Delta_\perp^2)$

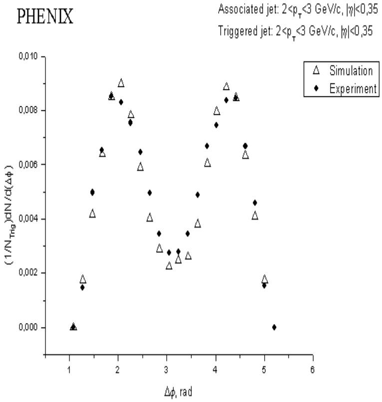
we get the reasonable fits of experimental data with three parameters $(\epsilon_1, \epsilon_2, \Delta_\perp)$

Table 1 Medium chromopermittivity

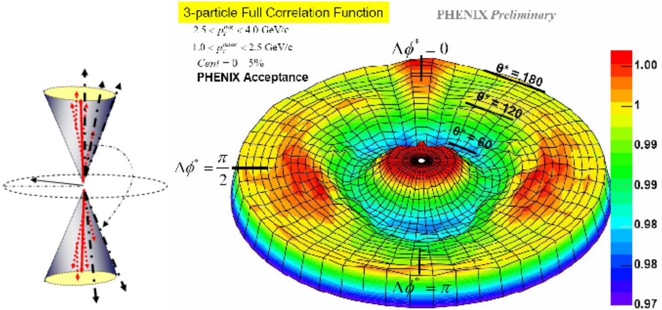
Experiment	$\theta_{\max}$	ϵ_1	ϵ_2	$\Delta_\perp$, GeV/c	new data
STAR	1.04 rad	5.4	0.7	0.7	$\theta_{\max} \approx$1.1 rad
PHENIX	1.27 rad	9.0	2.0	1.1	$\epsilon_1 \approx 6$; $\epsilon_2 \approx 0.8$

NOTE: $(\epsilon_2/\epsilon_1)^2 \leq 0.05 \ll 1$





The 3-particle correlations reveal clearly the ring-like structure around the away-side jet.



(N.N. Ajitanand for PHENIX Collaboration, nucl-ex/0609038)

Coordinate system (left) and full 3-particle correlation surface for charged hadrons in central Au+Au collisions at RHIC.
The trigger is located at $\pi/2$ to the collision axis.
The away-side parton goes in the opposite direction to the trigger parton. Cherenkov gluons form the ring of hadrons just around this direction.

CHERENKOV EFFECT AND ASYMMETRY OF SHAPES OF ALL IN-MEDIUM RESONANCES

I.D., V.A. Nechitailo, Int. J. Mod. Phys. A**24** (2009) 1221; arXiv: hep-ph/ 0704.1081

$\epsilon > 1$ **is the necessary condition for Cherenkov effect.**

$$\Delta\epsilon = \mathrm{Re}\epsilon - 1 = 4\pi N \mathrm{Re} F(E, 0^o)/E^2 \propto \frac{m_\rho^2 - M^2}{M\Gamma}\theta(m_\rho^2 - M^2).$$

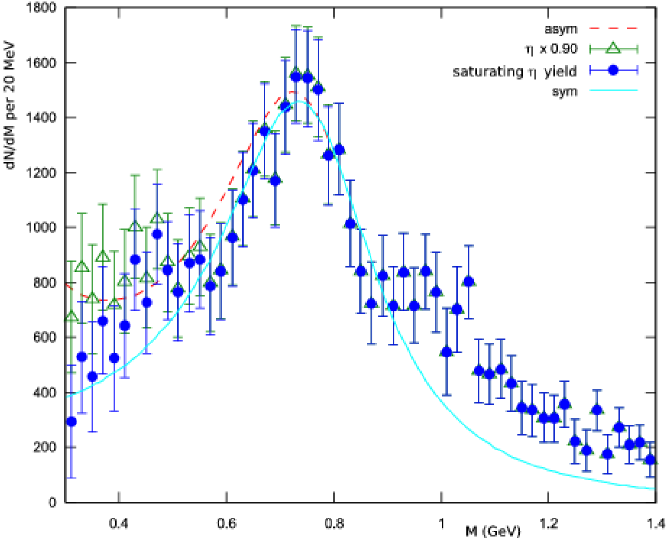
NOTE: $\Delta\epsilon$ **is proportional to the density** N **of scatterers!** $\mathrm{Re}F(E, 0^o) >$**0 - necessary condition.**

$$\frac{dN_{ll}}{dM} = \frac{A}{(m_\rho^2 - M^2)^2 + M^2\Gamma^2}\left(1 + w\frac{m_\rho^2 - M^2}{M\Gamma}\theta(m_\rho^2 - M^2)\right)$$

M is the total c.m.s. energy of two colliding objects (the dilepton mass), m_ρ=775 MeV is the in-vacuum ρ-meson mass. The second term is proportional to $\mathrm{Re}F(E, 0^o)$.

Universal prediction for ALL in-medium resonances!

Excess at left (low-mass) wing of the resonance (where $\mathrm{Re}F(E, 0^o) > 0$ for any Breit-Wigner resonance)



Excess dilepton mass spectrum in semi-central In-In collisions at 158 AGeV (SPS NA60 data) compared to the in-medium ρ-meson peak with additional Cherenkov effect (dashed line).

THE WAKE (TRAIL) EFFECT

I.D., Mod. Phys. Lett. A**25** (2010) 591; arXiv:0911.3233

The wake effect: $\mathrm{div}\mathbf{E}(\mathbf{r},\omega) = \rho(\mathbf{r},\omega)/\epsilon(\omega)$

or in space-time

$$\mathrm{div}\mathbf{E}(\mathbf{r},t) = \rho(\mathbf{r},t) + \int_0^\infty d\tau \rho(\mathbf{r},t-\tau) \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{1-\epsilon(\omega)}{\epsilon(\omega)} \exp(i\omega\tau)$$

which for $\epsilon(\omega) \to 0$ gives

$$\Delta\rho(\mathbf{r},t) = g\delta(x)\delta(y)\Theta(t-z)\omega \sin[\omega(z-t)] \exp[-\delta(t-z)].$$

Note the damped oscillations along the trail $t > z$**!**

The ratio **[wake/Cherenkov]** at maximum of Cherenkov:

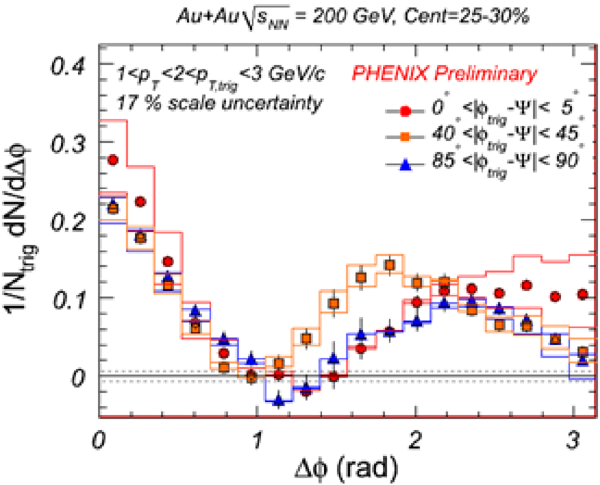
$$\frac{\Gamma_t\Gamma_l}{4x_0(1-x_0)} \approx \frac{\epsilon_{2t}\epsilon_{2l}}{\epsilon_{1t}(1-\epsilon_{1t}/|\epsilon|^2)} \approx 4\cdot 10^{-3} \ll 1.$$

They become comparable at

$$x_e \approx \frac{x_0^2}{2x_0+1}$$

i.e. at $\pi - \Delta\phi_L \approx 1.43$ rad and **maximum shifts** (next Fig.)!

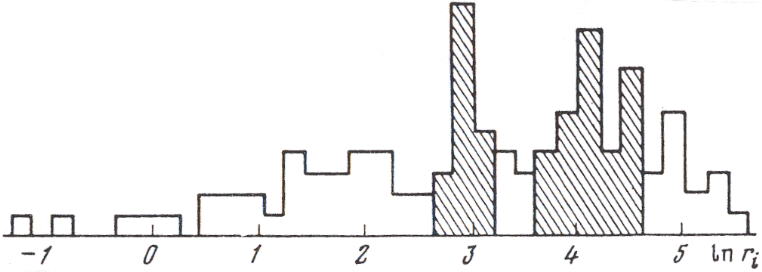
The trail behind the parton radiates as a dipole.



Au+Au $\sqrt{s_{NN}}$ = 200 GeV, Cent=25-30%
1<p_T<2<$p_{T,trig}$<3 GeV/c
17 % scale uncertainty
PHENIX Preliminary
0° <|ϕ_{trig}-Ψ|< 5°
40° <|ϕ_{trig}-Ψ|< 45°
85° <|ϕ_{trig}-Ψ|< 90°
1/N_{trig} dN/dΔφ
Δφ (rad)
0
0.1
0.2
0.3
0.4
1
2
3

THE COSMIC RAY DATA:

RINGS AND FANS



The distribution of produced particles in the stratospheric event (1979) at 10^{16} eV as a function of the distance from the collision axis (pseudorapidity) has two pronounced peaks - **the ringlike INDIVIDUAL event**.

$\epsilon - 1 = \Delta\epsilon \ll 1$ (it differs from RHIC!)

New regime at high energies for "forward"non-trigger jets

FAN-shaped events or alignment in CR data

(S.A. Slavatinsky, Nucl. Phys. B Suppl. **122** (2003) 3)

remind RIDGE! (see RHIC and CMS data)

Why coplanar emission? Who ordered it? Energy threshold?

CONFIDENT IS OFTEN WRONG

It ai'nt what you do not know that gets you into trouble.

It is what you know for sure that just ai'nt so.

Mark Twain

CONCLUSIONS

CHERENKOV GLUONS AND WAKE (TRAIL) EFFECT ARE OBSERVED IN EXPERIMENT AND THE NUCLEAR MEDIUM PROPERTIES ARE DETERMINED.

THE NUCLEAR MEDIUM PROPERTIES

1. The chromopermittivity $|\epsilon| \approx 6$ at rather low energies of jets (with $\epsilon_2 \ll \epsilon_1$) while $\Delta\epsilon \ll 1$ at high energies
2. The density of partons; $N_s \approx 20$ per nucleon
3. The energy loss of Cherenkov gluons is LARGE: $\approx C_R$ GeV/fm
4. The free path length of gluons - fm.

New predictions (*under investigation*):

1. Forward rings at LHC.

2. Transition radiation at LHC.

3. Instabiities.

4. Color rainbow (quantum effect at higher orders)