Radiation Dominated Electromagnetic Shields

S. V. Bulanov

ELI BEAMLINES, Za Radnicí 835, Dolní Břežany, 25241, Czech Republic
&
National Institutes for Quantum and Radiological Science and Technology (QST)
Kizugawa, Kyoto, Japan

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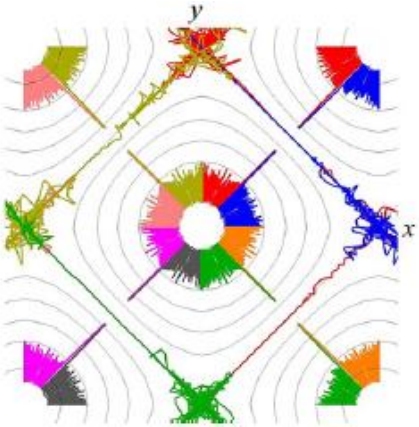

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D.R. Khikhlukha and G. Korn
ELI-Beamlines, Dolni Brezany, Czech Republic

Z. Gong and X. Q. Yan
PU, Beijing, China

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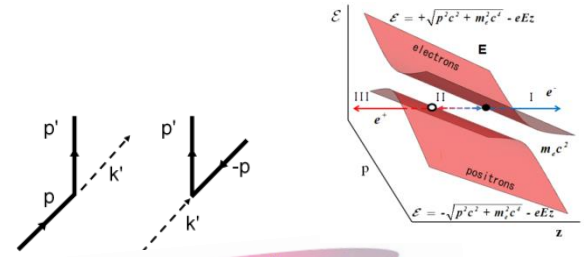
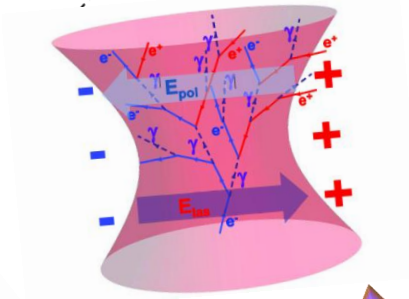
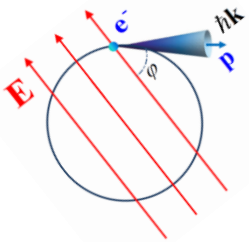
Extreme Field Limits in High Power Laser Interaction with Matter & Vacuum

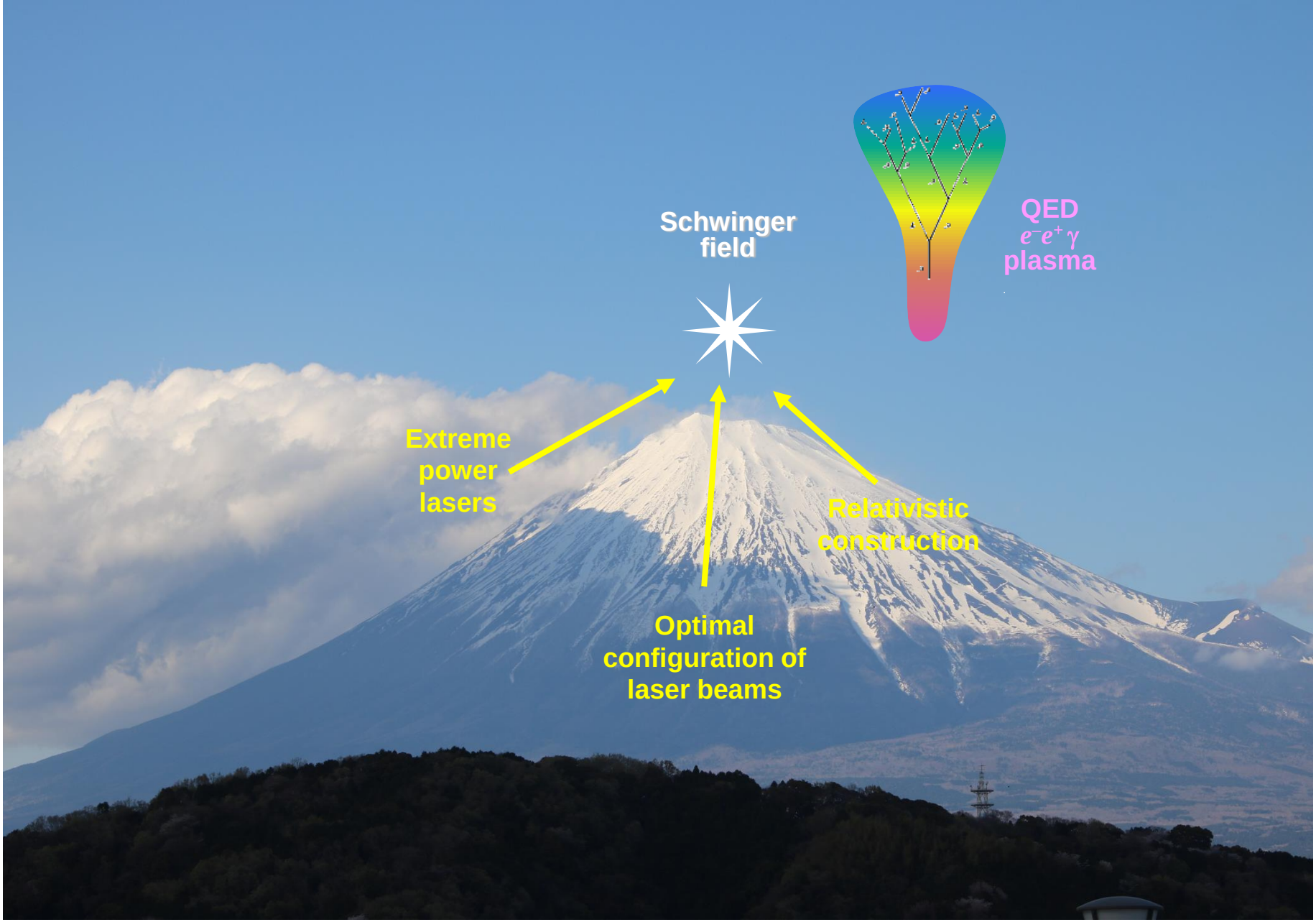
Focused intensity (W/cm^2)

non - perturbative QED $E \leq E_S = m_e^2 c^3 / e\hbar$	$10^{27} \sim 10^{29}$ nonlinear - dissipative vacuum
multiphoton QED processes $e + N\,\hbar\omega_0 \rightarrow \hbar\omega_\gamma + e'$ $\hbar\omega_\gamma + N\,\hbar\omega_0 \rightarrow e^- + e^+$	$10^{27} / \gamma_e^2$ lepton - gamma - plasma
radiation reaction $a_0 > (\lambda\!\!\!^{-} / r_e)^{1/3} \approx 400$	$10^{24} / \gamma_e^2$ X, γ - rays
relativistic nonlinear optics $a_0 = eE_0 / m_e \omega_0 c > 1$	$10^{23} / \gamma_e^{2/3}$ plasma
bound electrons $E_0 \leq e^2 / a_B = m_e^2 e^5 / \hbar^4$	10^{18}



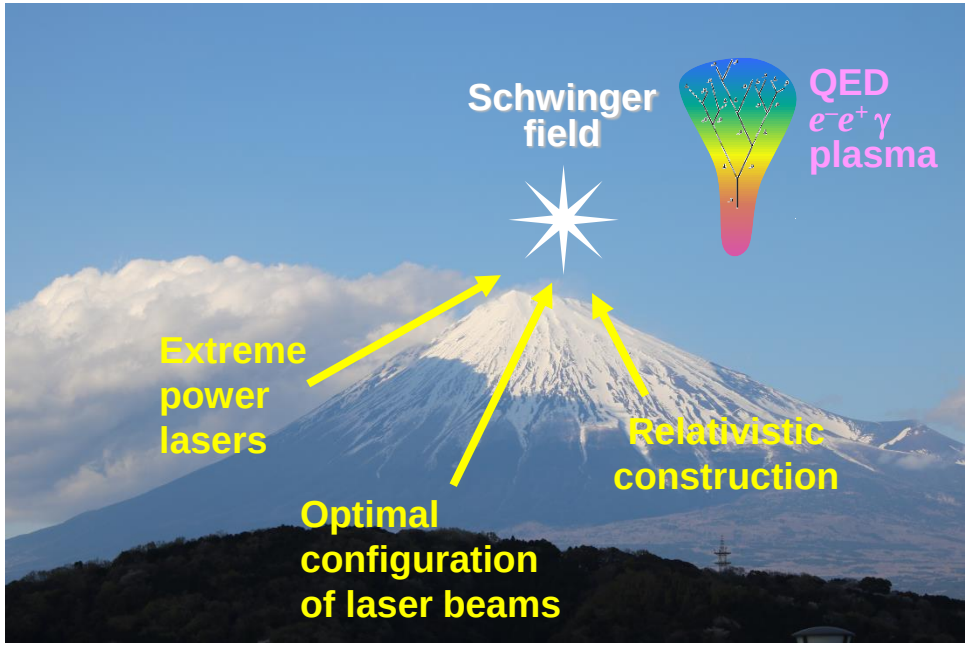





Schwinger field
QED
$e^-e^+\gamma$
plasma
Extreme power lasers
Relativistic construction
Optimal configuration of laser beams

N. B. Narozhny

Laser Driven $e^-e^+\gamma$ Plasma

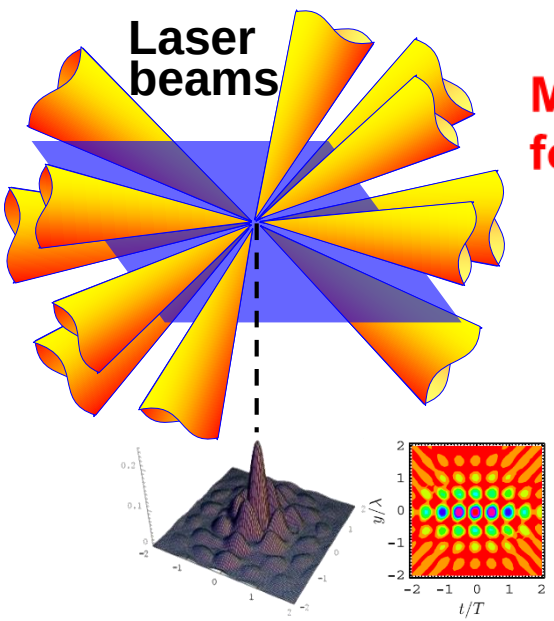


Electron-positron pairs can be created before the laser field reaches the Schwinger limit, due to a large phase volume occupied by a high-intensity EM field.

S. S. Bulanov, N. B. Narozhny, V. D. Mur, V.S. Popov, "Electron-positron pair production by electromagnetic pulses". JETP, 102, 9 (2006).

A. R. Bell & J. G. Kirk, "Possibility of Prolific Pair Production with High-Power Lasers". Phys. Rev. Lett. 101, 200403 (2008).

A. M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, "Limitations on the Attainable Intensity of High Power Lasers". Phys. Rev. Lett. 105, 080402 (2010).

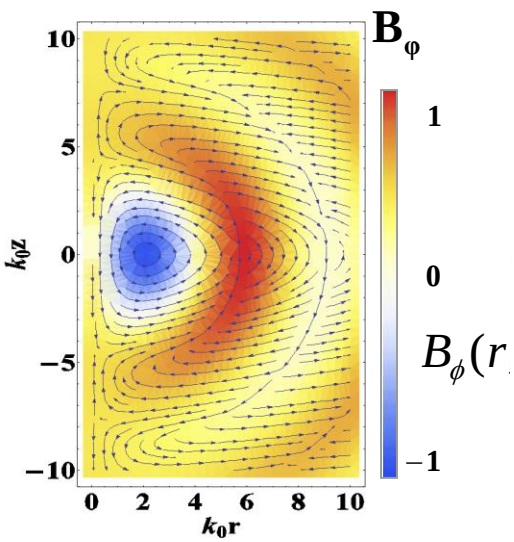


Multiple 10kJ beam system provides necessary conditions for e^-e^+ pairs creation.

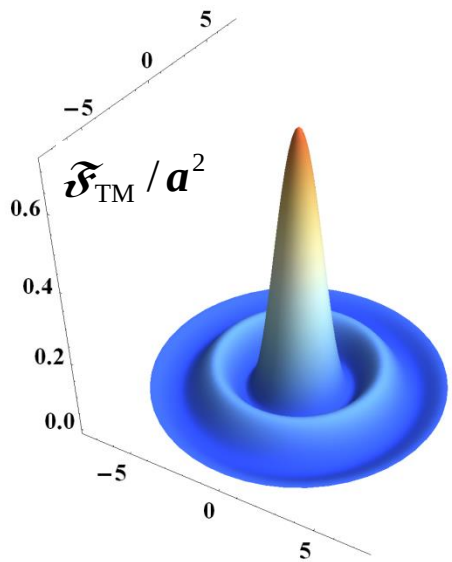
Number of pulses	Number of e^-e^+ with 10kJ pulses	Required power (kJ) to create one pair
2	9×10^{-19}	40
4	3×10^{-9}	20
8	4	10
16	1.8×10^{3}	8
24	4.2×10^{6}	5.1

S.S.Bulanov, V.D.Mur, N.B.Narozhny, J.Nees, V.S.Popov, Phys. Rev. Lett. 104, 220404 (2010).

3D EM configuration TM - mode



$\boldsymbol{E}(r,z)$



TM configuration:

Magnetic field

$$\boldsymbol{B}(R,\theta) = \boldsymbol{e}_\phi \frac{B_0 \sin(\omega_0 t)}{(8\pi k_0 R)^{1/2}} J_{n+1/2}(k_0 R) L_n^l(\cos\theta)$$

Electric field

$$\boldsymbol{E} = i k_0^{-1} (\nabla \times \boldsymbol{B})$$

The vector field shows r- and z-components of the poloidal electric field in the plane (r,z):

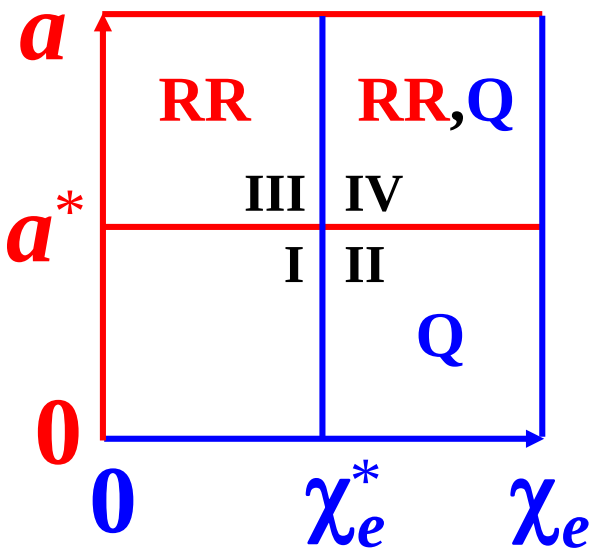
The color density shows toroidal magnetic field distribution.
The first Poincare invariant

$$\mathfrak{F}_{\mathrm{TM}} / \boldsymbol{a}_0^2 = (\mathbf{E}^2 - \mathbf{B}^2)/2\boldsymbol{a}_0^2$$

S.S.Bulanov, T. Zh.Esirkepov, A.Thomas, J.Koga, S.V.Bulanov, "On the Schwinger limit attainability with extreme power lasers" Phys. Rev. Lett. 105, 220407 (2010)

Electron Motion in Circularly Polarized EM Wave

4 regimes



Dimensionless amplitude

$$a = eE/m_e\omega c$$

At $a=a^*$ emitted energy becomes equal to the energy received from EM wave.

$$a^* = \left(\frac{3\lambda}{4\pi r_e}\right)^{1/3} \qquad r_e = \frac{e^2}{m_e c^2}$$

The radiation reaction measure:

$$\varepsilon_{rad} = \frac{2q^2\omega}{3mc^3} \approx 1.1804\times 10^{-8}\left(\frac{q^2}{e^2}\frac{m_e}{m}\right)\left(\frac{1\mu\mathrm{m}}{\lambda}\right)$$

When the recoil of the emitted photon is significant, the emission probability is characterized by

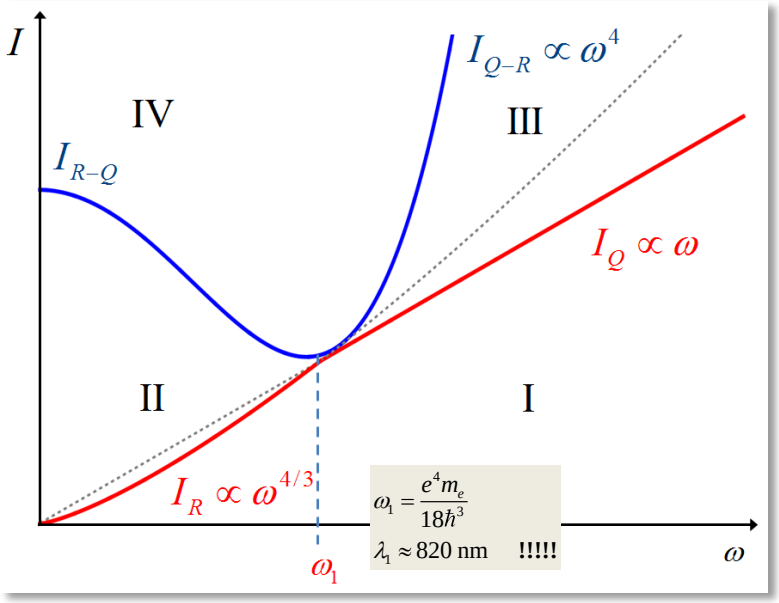
χ_e parameter (Lorentz and gauge inv)

$$\chi_e = (\gamma_e/E_S)[(\mathbf{E}+\boldsymbol{\beta}\times\mathbf{B})^2 - (\boldsymbol{\beta}\cdot\mathbf{E})^2]^{1/2}$$

At $\chi_e = \chi_e^* < 1$ QED effects come into play.

Four Interaction Domains

SVB et al, (2013, 2015)



$$I_R = \frac{m_e^4 c^5 e^2}{144\pi\hbar^4}\left(\frac{\omega}{\omega_1}\right)^{4/3} = 3.8\times10^{23}\left(\frac{\omega}{\omega_1}\right)^{4/3}\frac{\mathrm{W}}{\mathrm{cm}^2}$$

$$I_Q = \frac{m_e^4 c^5 e^2}{144\pi\hbar^4}\left(\frac{\omega}{\omega_1}\right) = 3.8\times10^{23}\left(\frac{\omega}{\omega_1}\right)\frac{\mathrm{W}}{\mathrm{cm}^2}$$

$$I_{R-Q} = \frac{m_e^4 c^5 e^2}{9\pi\hbar^4} = 5.6\times10^{24}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$$

$$I_{Q-R} = 87\,\frac{c^5\hbar^8\omega^4}{e^{14}} = 8.2\times10^{21}\left(\frac{\omega}{\omega_1}\right)^4\frac{\mathrm{W}}{\mathrm{cm}^2}$$

Curves $I_R(\omega)$, $I_Q(\omega)$ and $I_{R-Q}(\omega)$, $I_{Q-R}(\omega)$ subdivide (I, ω) plane to 4 domains:

I) Relativistic electron - EM field interaction with neither radiation friction nor QED effects

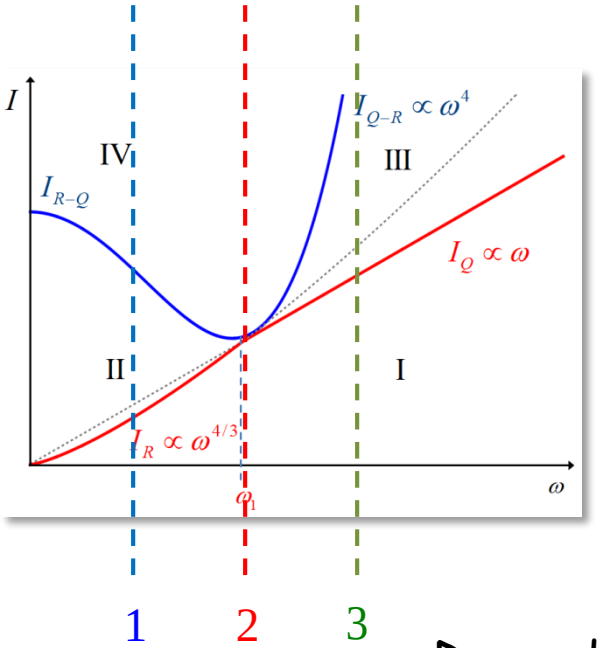
II) Electron - EM wave interaction is dominated by radiation friction

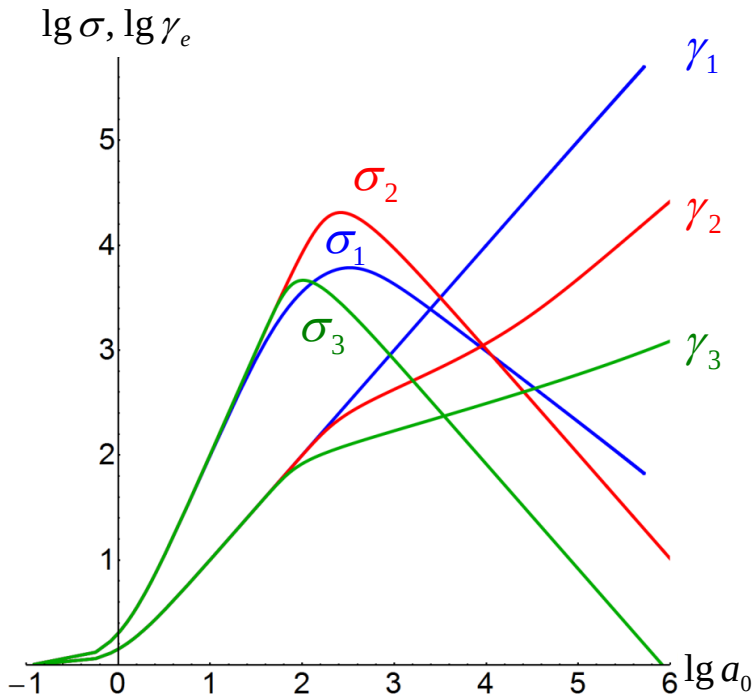
III) QED effects important with insignificant radiation friction effects

IV) Both QED and radiation friction determine radiating charged particle dynamics in the EM field

What Can be Measured?

Cross Section σ and Electron Energy γ_e v.s. EM Wave Amplitude:





Dependences of $\lg(\sigma/\sigma_T)$ & $\lg\gamma_e$ on $\lg a_0$

1) $\omega = \omega_1/12.5$ (I → II)

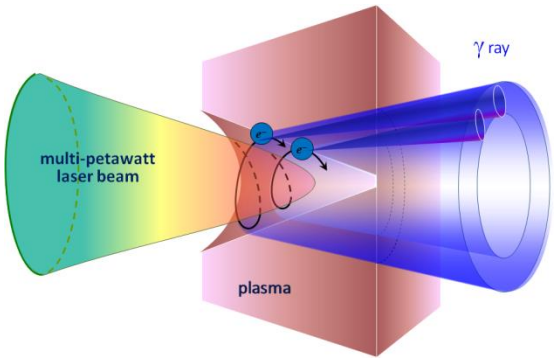
2) $\omega = \omega_1$ (I → IV)

3) $\omega = 12.5\omega_1$ (I → III)

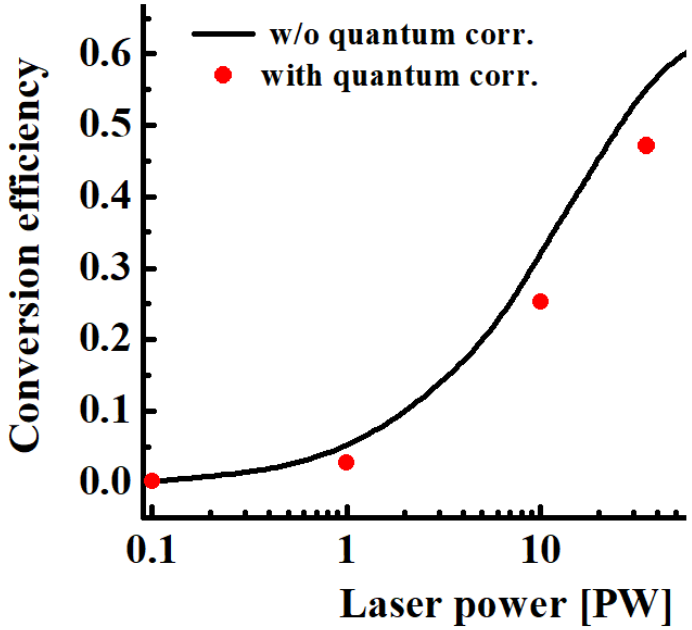
SVB et al, Plasma Phys. Reports 41, 1 (2015)

High Power Gamma-Ray Source

Concept of high power gamma-flash generation:



T. Nakamura et al. Phys. Rev. Lett. 108, 195001 (2012)



Multiple Colliding Pulses

PHYSICAL REVIEW E **95**, 013210 (2017)

High-efficiency γ-ray flash generation via multiple-laser scattering in ponderomotive potential well

Z. Gong,[1] R. H. Hu,[1] Y. R. Shou,[1] B. Qiao,[1] C. E. Chen,[1] X. T. He,[1] S. S. Bulanov,[2] T. Zh. Esirkepov,[3] S. V. Bulanov,[3,4] and X. Q. Yan[1,5,*]

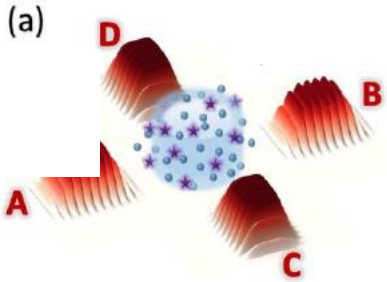
[1]*State Key Laboratory of Nuclear Physics and Technology, and Key Laboratory of HEDP of the Ministry of Education, CAPT, Peking University, Beijing 100871, China*

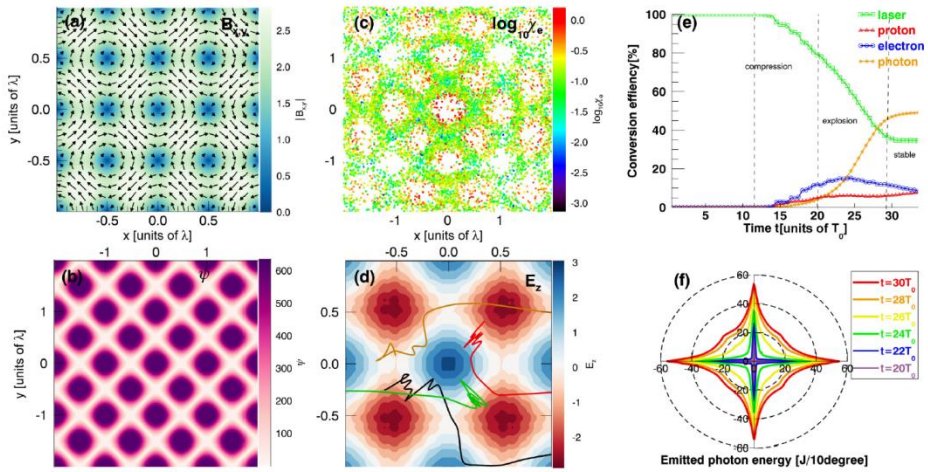
[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

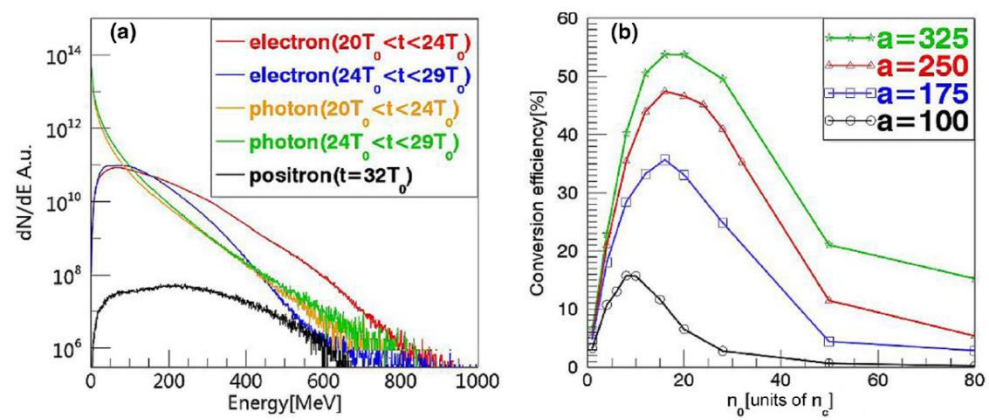
[3]*QuBS, Japan Atomic Energy Agency, Kizugawa, Kyoto 619-0215, Japan*

[4]*A. M. Prokhorov Institute of General Physics RAS, Moscow 119991, Russia*

[5]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China*

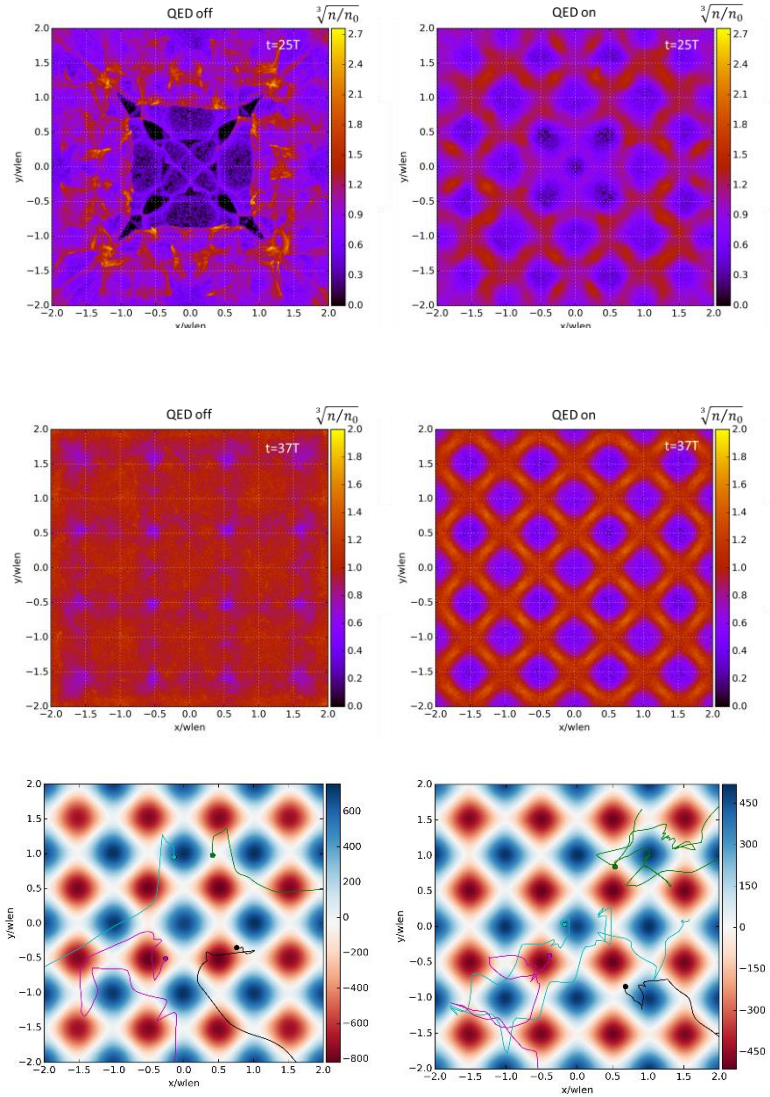




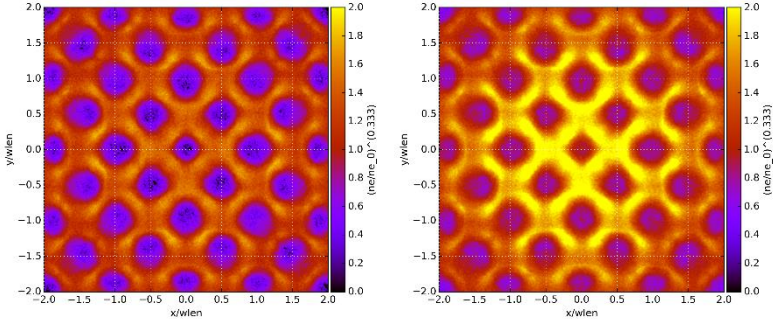


VRANIC, M., GRISMAYER, T., FONSECA, R. A. & SILVA, L. O.
Electron–positron cascades in multiple-laser optical traps.
Plasma Phys. Control. Fusion 59, 014040 (2017)

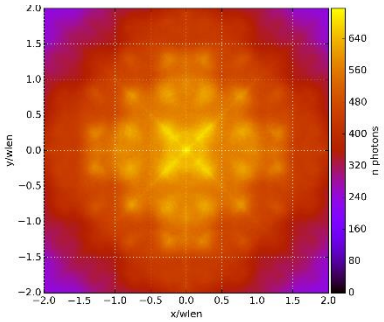
4 s-waves, a_0=250, n_0=16n_c



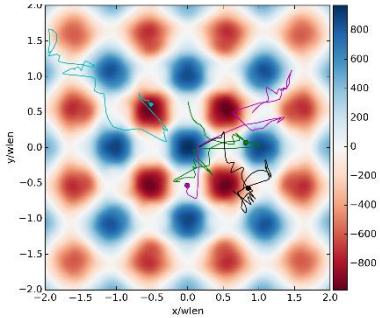
a_0=500 n_e n_{BW}



a_0=500 photon density



a_0=500 trajectories



D. Khikhlukha

Survey of random walk, Lévy ights, limit circles, attractors and structurally determinate patterns

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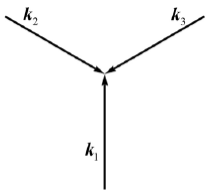
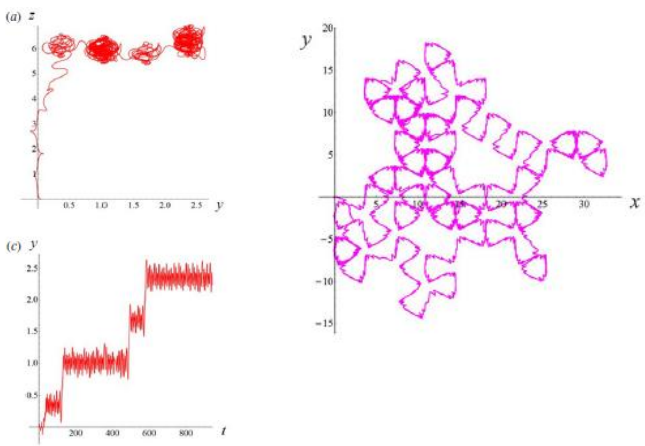
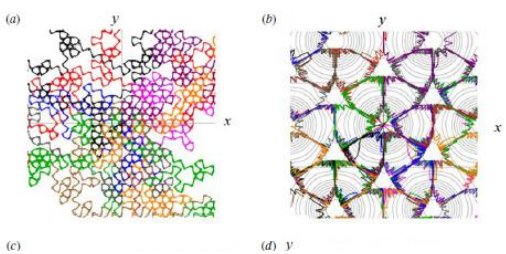
doi:10.1017/S0022377817000186

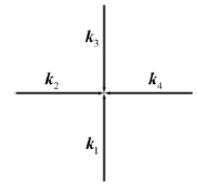
Charged particle dynamics in multiple colliding electromagnetic waves. Survey of random walk, Lévy flights, limit circles, attractors and structurally determinate patterns

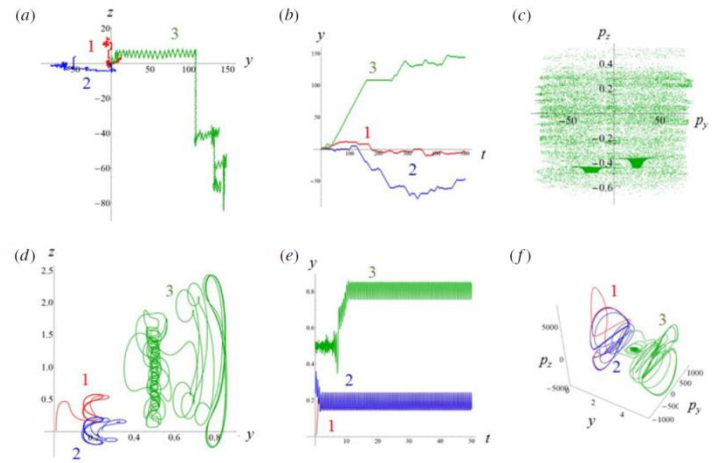
S. V. Bulanov[1,†], T. Zh. Esirkepov[1], J. K. Koga[1], S. S. Bulanov[2], Z. Gong[3], X. Q. Yan[3,4] and M. Kando[1]

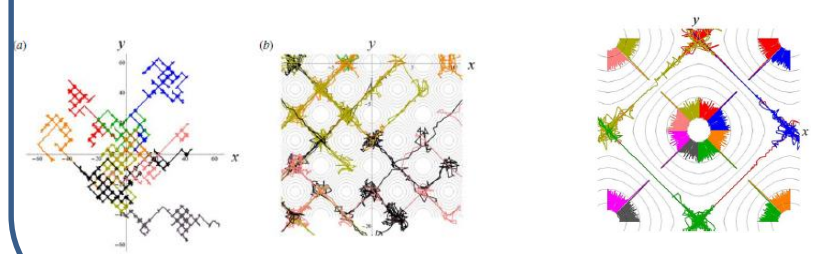




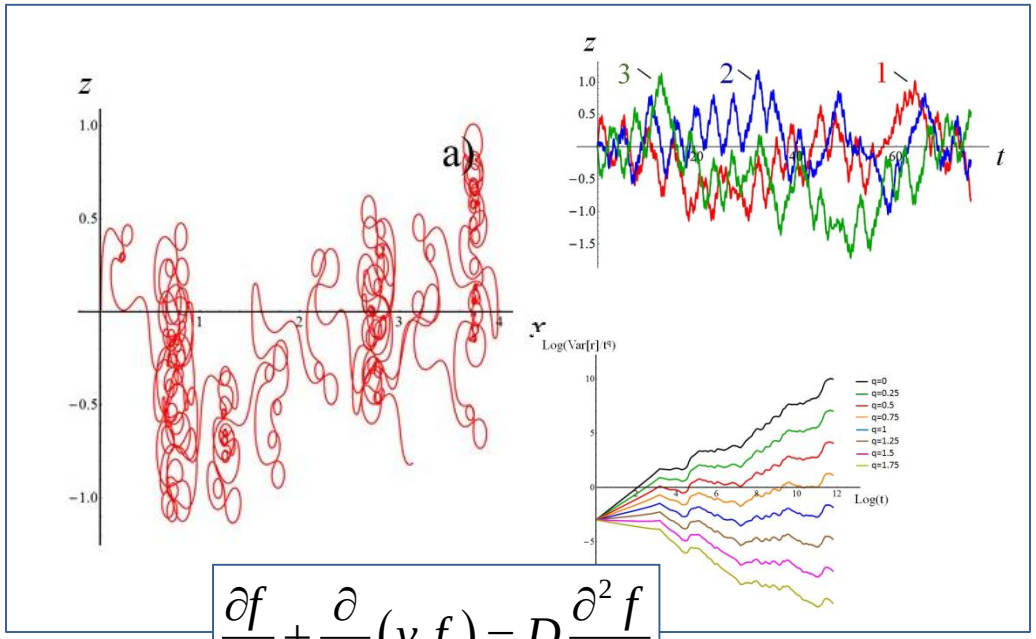




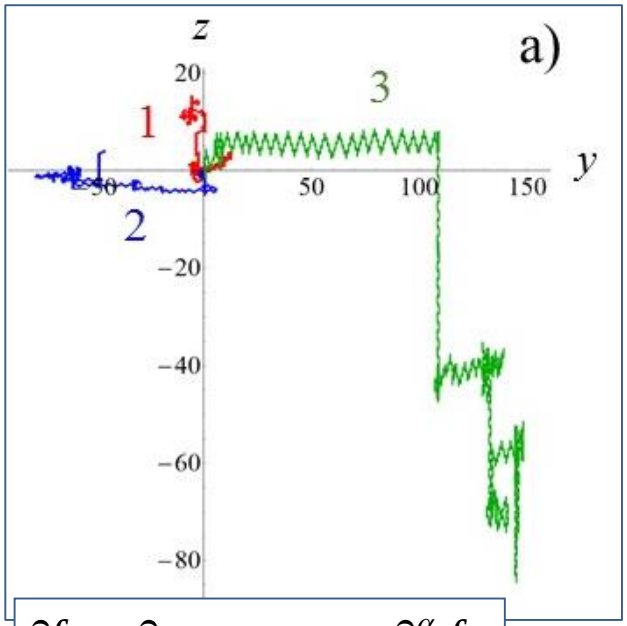




Lévy Flights

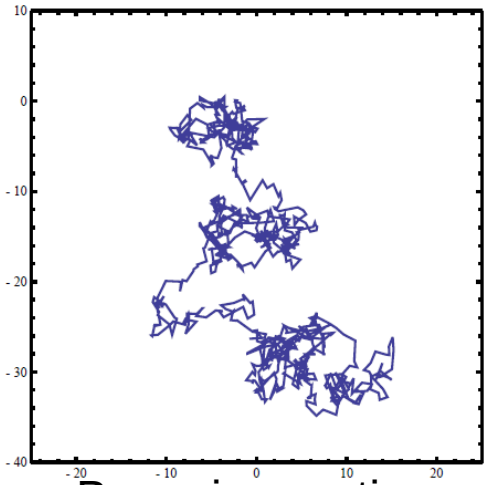


$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}(v\, f) = D\frac{\partial^2 f}{\partial x^2}$$



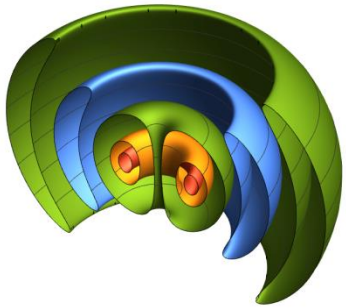
$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}(v\, f) = D\frac{\partial^\alpha f}{\partial |x|^\alpha}$$

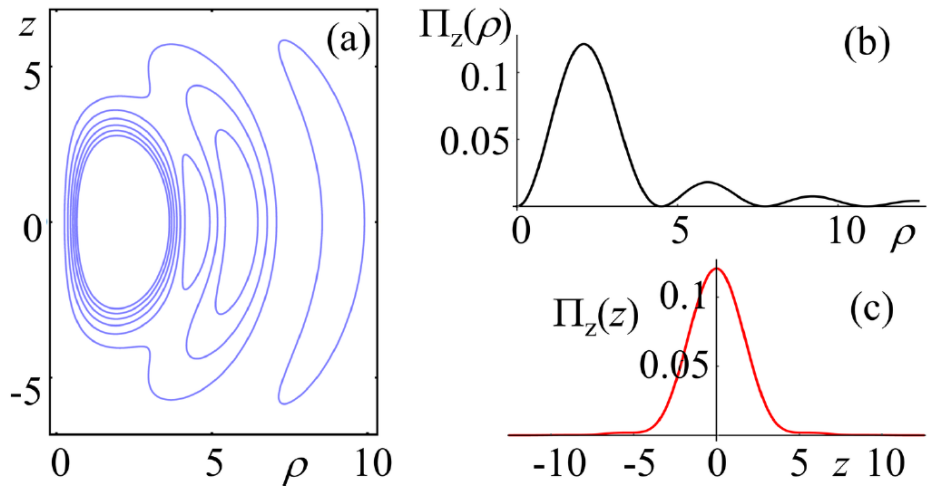
Sharks' hunting style



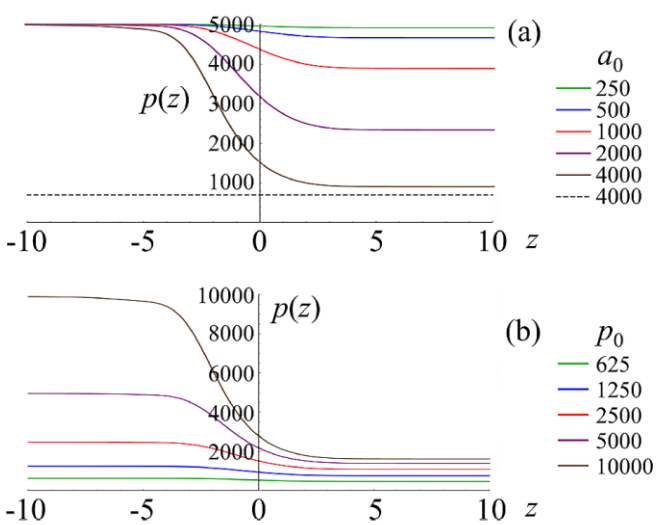
Brownian motion

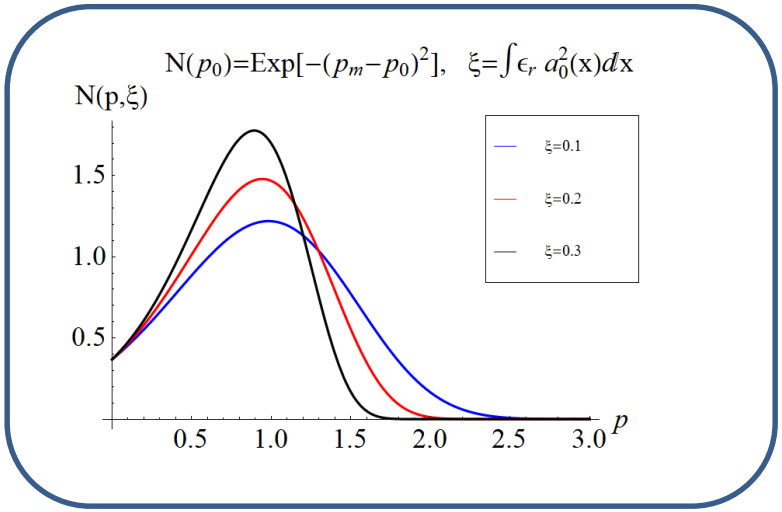
Radiation Dominated Electromagnetic Shield (TE+TM)



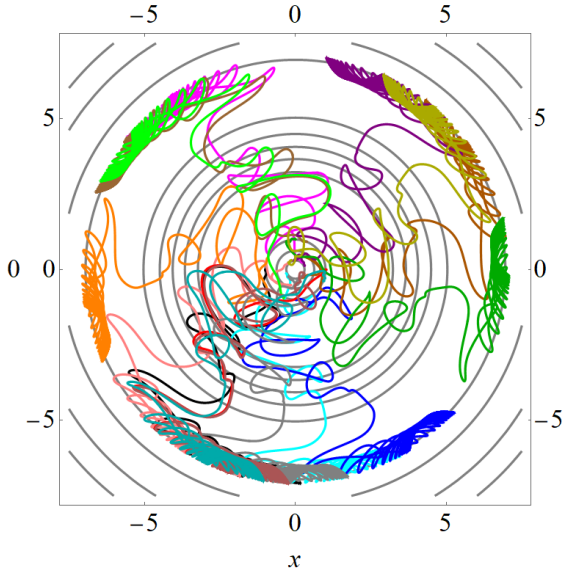


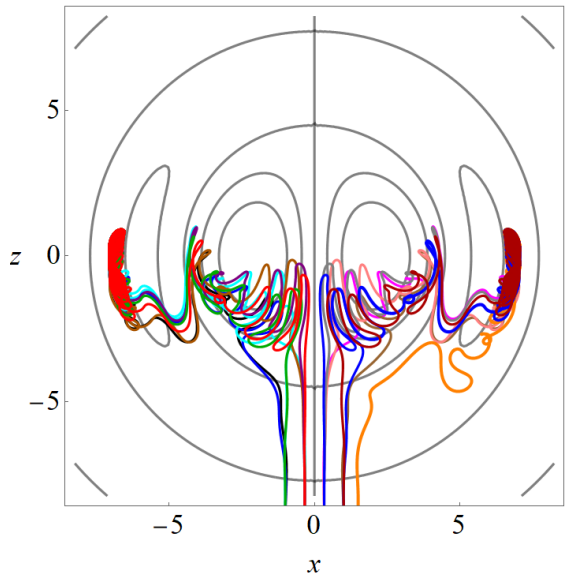
$$\frac{dp}{dz} = -\frac{2}{\pi}\varepsilon_{rad}\, p^2\, a_0^2 \rho_0^2 \left\{ \frac{z^2[\sin(z) - z\cos(z)]^2 + [(z^2-3)\sin(z) + 3z\cos(z)]^2}{z^8} \right\} \Rightarrow p(z) = \frac{p_0}{1 + (2/\pi) p_0 \varepsilon_{rad}\, a_0^2 \rho_0^2 \Phi(z)}$$

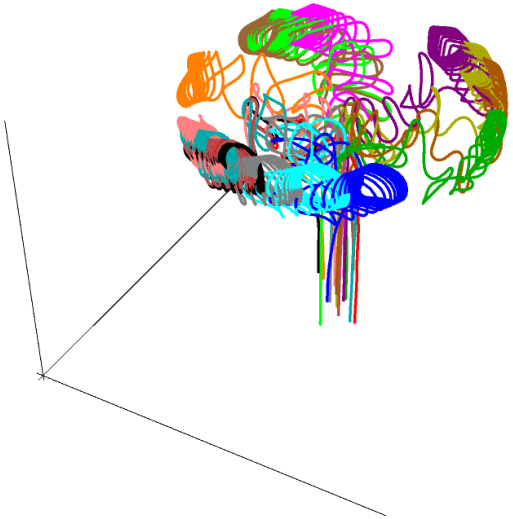


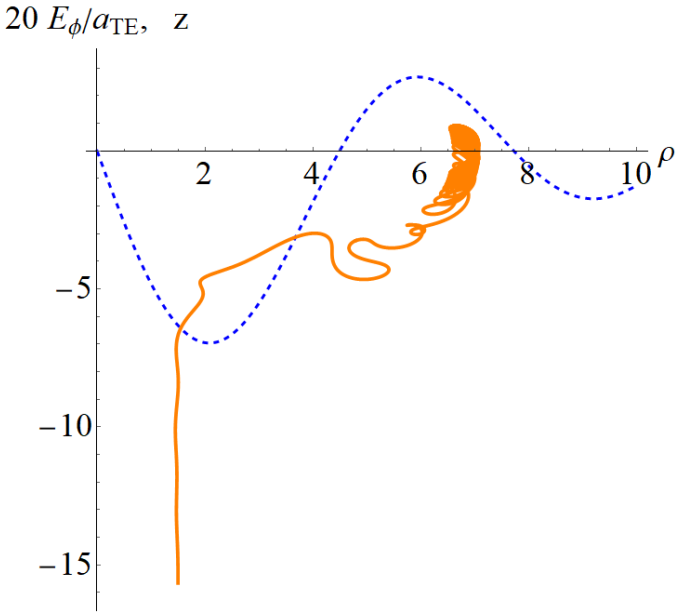


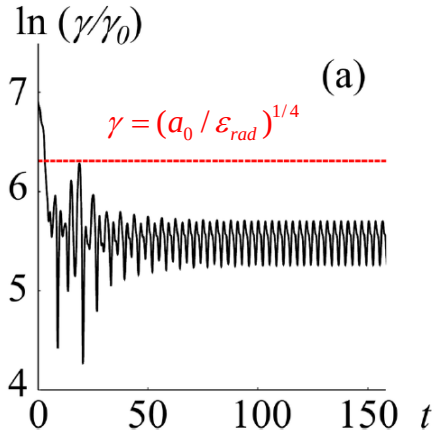
Electron Stopping and Trapping

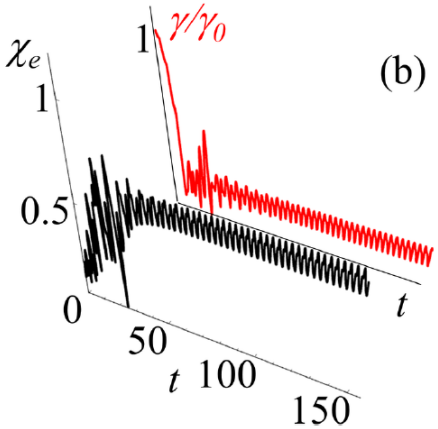








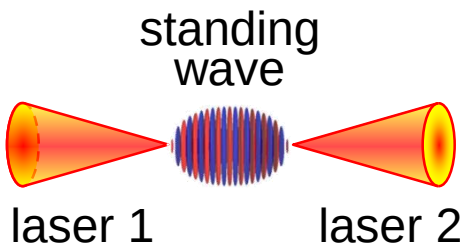




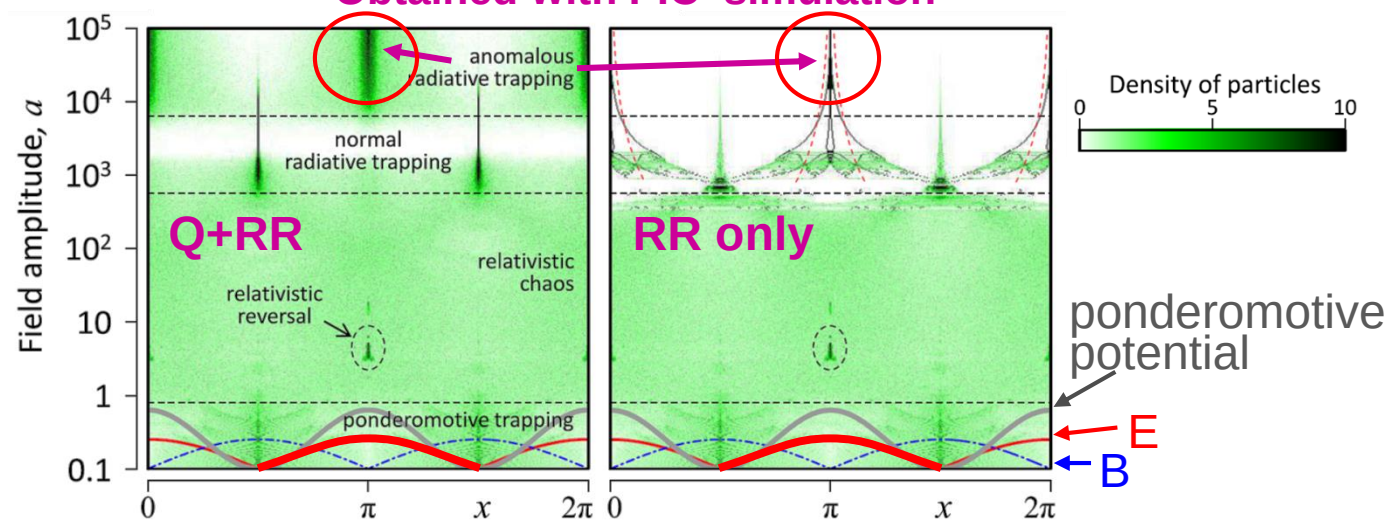
Strong nonlinear friction

Anomalous Radiative Trapping in Laser Fields of Extreme Intensity

A. Gonoskov, et al., Phys. Rev. Lett. 113 (2014) 014801

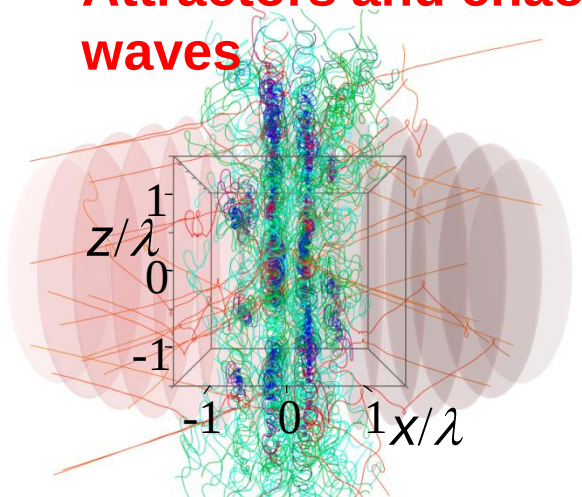


Obtained with PIC simulation

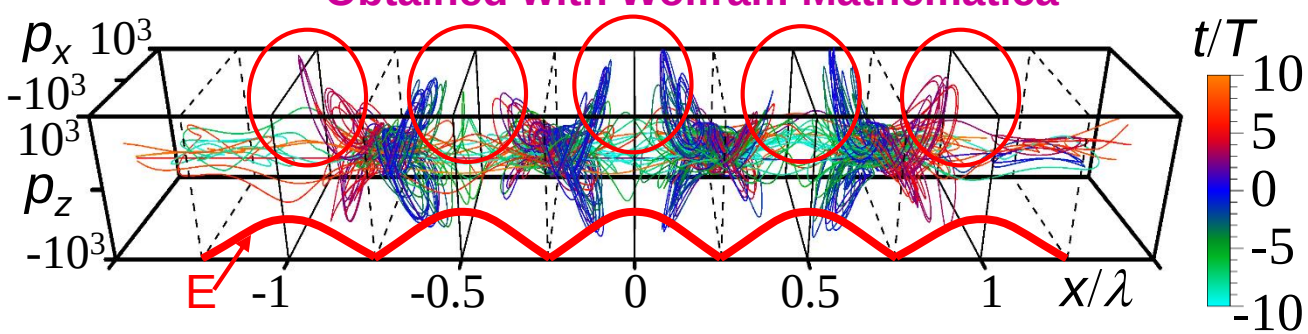


Attractors and chaos of electron dynamics in electromagnetic standing waves

T.Zh. Esirkepov, et al., Phys. Lett. A 379 (2015) 2044



Obtained with Wolfram Mathematica

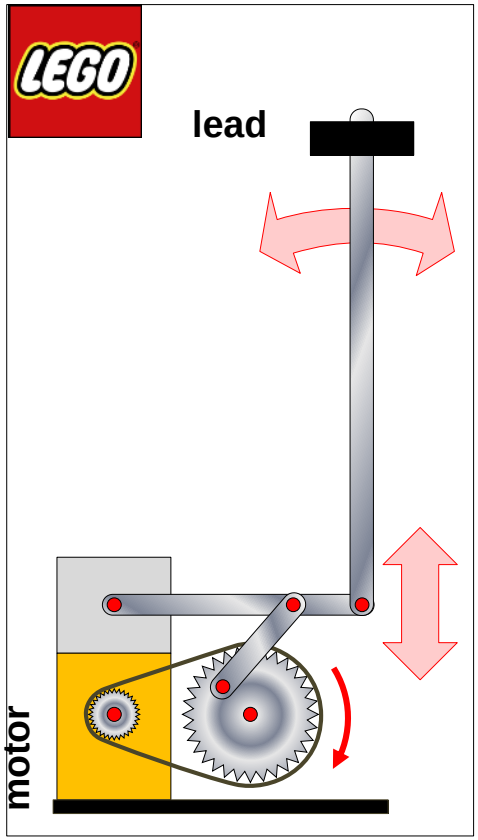


Paradoxical Stabilization of Forced Oscillations by Friction

Kapitza pendulum

(also called Stephenson-Kapitza pendulum, inverted pendulum)

Statically unstable equilibrium position of a rigid pendulum is stabilized by small fast vertical oscillations of the pivot point.



www.youtube.com/watch?v=PfvKA4WdZIY

A. Stephenson, "On an induced stability." Philos. Mag., Ser. 6, 15, (1908) 233.
P. L. Kapitza, "Pendulum with a vibrating suspension." Usp. Fiz. Nauk 44, (1951) 7.

Kapitza method

Simple but fundamental model

Constant potential + high-frequency force

$$\ddot{x} = -\frac{dU(x)}{dx} + F(x,t)$$

slowly varying

Assume $x = X(t) + \xi(t)$

fast oscillating

(*) Series expansion for $|\xi| \ll F/\partial_x F$:

$$F(X+\xi,t) \approx F(X,t) + \xi\frac{dF(X,t)}{dX}$$

$$\ddot{X} + \ddot{\xi} = -\frac{dU(X)}{dX} - \xi\frac{d^2U(X)}{dX^2} + F(X,t) + \xi\frac{dF(X,t)}{dX} \quad (*)$$

Greatest terms: $\ddot{\xi} = F(X,t)$ (1)
(fast oscillating)

Slowly varying terms: $\ddot{X} = -\frac{dU}{dX} + \left\langle \xi\frac{dF}{dX} \right\rangle$ (2)

Slowly varying and fast oscillating terms should cancel out separately.

(1) collect the greatest terms:

$$\ddot{\xi} \propto \omega^2, \qquad \omega \gg \dot{X}/X$$

(2) collect the slowest terms:

Time-averaging: $\langle\xi\rangle = \frac{1}{T}\int_0^T \xi dt$

$$\langle\xi\rangle = \langle\dot{\xi}\rangle = \langle\ddot{\xi}\rangle = 0,$$

$$\langle x\rangle = \langle X\rangle \approx X.$$

Let's assume $F(x,t) = f(x)\sin(\omega t)$.

Then we can solve (1) and do time-averaging in (2).

Fast oscillating solution: $\xi = -\frac{f(X)\sin(\omega t)}{\omega^2}$

Slowly varying term: $\ddot{X} = -\frac{dU}{dX} - \frac{d}{dX}\frac{f^2}{4\omega^2}$

ponderomotive force

Landau & Lifshitz, Mechanics

Friction tug vs ponderomotive force

Simple but fundamental model $\ddot{x} + \underbrace{K\big(F(x,t)\big)\dot{x}}_{\text{Strong high-frequency friction}} = \underbrace{F(x,t)}_{\text{High-frequency driving force}}.$

Assume $x = X(t) + \xi(t)$

Expand in powers of ξ: $\ddot{X} + \ddot{\xi} + \left(K + \xi K' \frac{dF}{dX}\right)(\dot{X} + \dot{\xi}) = F(X,t) + \xi \frac{dF}{dX}$ $(*)$

Greatest fast oscillating terms: $\ddot{\xi} + K\dot{\xi} = F(X,t)$ (1)

Slowly varying terms: $\ddot{X} + \left(\langle K\rangle + \left\langle \xi K' \frac{dF}{dX}\right\rangle\right)\dot{X} = \left\langle \xi \frac{dF}{dX}\right\rangle - \left\langle \xi\dot{\xi} K' \frac{dF}{dX}\right\rangle - \langle K\dot{\xi}\rangle$ (2)

Let's assume $F(x,t) = f(x)\sin(\omega t)$, $K(F) = \nu F^{2n}$.

Then we can solve (1) and do time-averaging in (2).

If K is even function of F, then $\langle K\rangle > 0$.

Fast oscillating solution: $\xi \approx \dfrac{\kappa f(\sin(\omega t) - \cos(\omega t))}{\omega(\kappa^2 + \omega^2)}$, $\kappa = \langle K\rangle = \dfrac{\nu}{2^{2n}}\binom{2n}{n} f^{2n}$.

Slowly varying term:

$$\ddot{X} + \kappa\dot{X} = -\frac{d}{dX}\frac{f^2}{4(\kappa^2+\omega^2)} + \frac{d}{dX}\frac{n^2\kappa^2 f^2}{(n+1)(\kappa^2+\omega^2)^2}$$

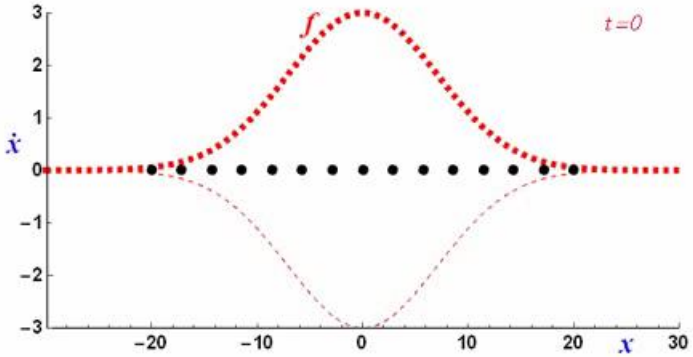
ponderomotive force $<$ friction tug for $\nu > \dfrac{2^{2n}(n!)^2(n+1)^{1/2}}{(2n)!\,(4n^2-n-1)^{1/2}}\dfrac{\omega}{f^{2n}}$

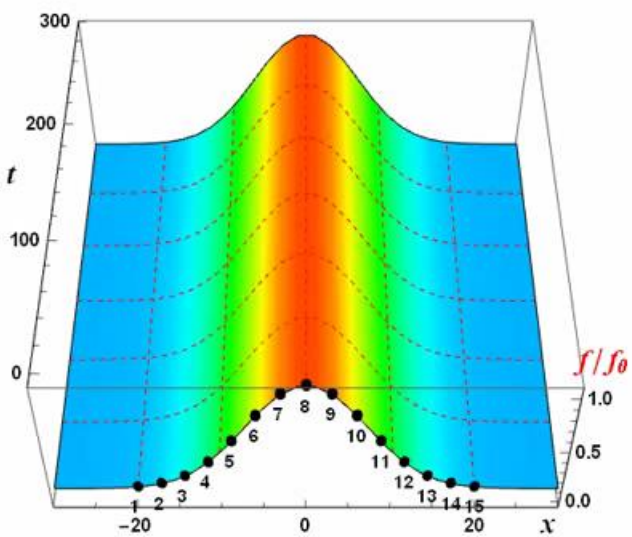
Friction tug vs ponderomotive force

$$\ddot{x} + \underbrace{\nu[f(x)\cos(\omega t)]^4\dot{x}}_{\text{nonlinear friction}} = \underbrace{f(x)\cos(\omega t)}_{\text{driving force}}.$$

$f(x) = f_0 \exp(-x^2/l_0^2)$, $l_0 = 10$, $\omega = 1$, $f_0 = 3$.

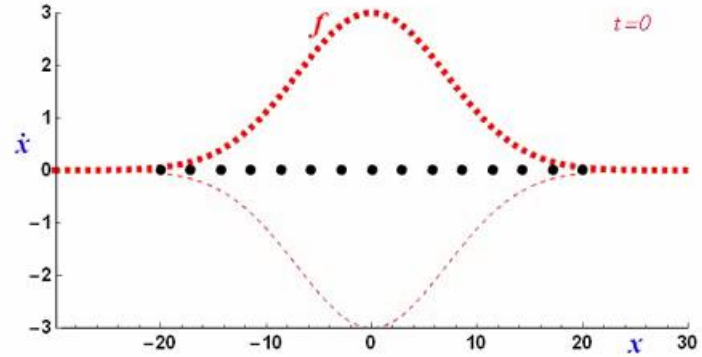
$\nu = 0$ (no friction)

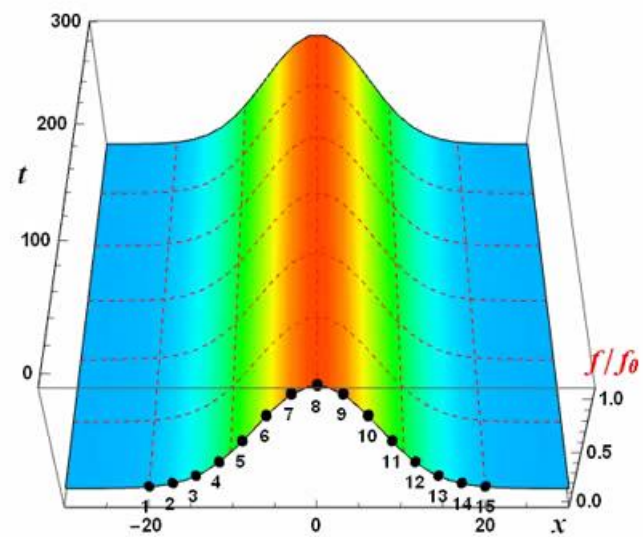




Ponderomotive force pushes particles out

$\nu = 0.2$

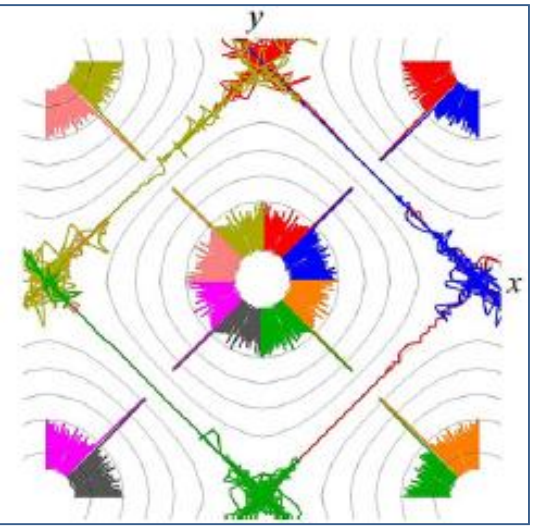




Friction tug overcomes ponderomotive force

T. Zh. Esirkepov

Paradoxical stabilization of forced oscillations by strong nonlinear friction



$$\ddot{x} + \underbrace{\nu[f(x)\cos(\omega t)]^4\dot{x}}_{\text{nonlinear friction}} = \underbrace{f(x)\cos(\omega t)}_{\text{driving force}}$$

$f(x) = f_0 \exp(-x^2/l_0^2)$

$f(x) = f_0 \cos^2(2\pi x/l_0)$

$l_0 = 10$

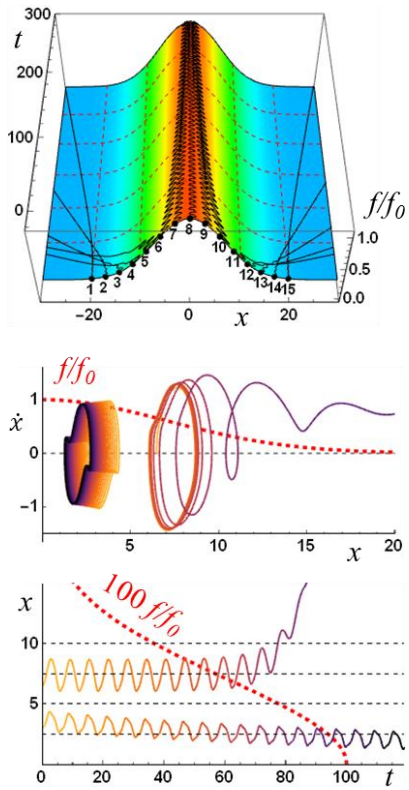
$\omega = 1$

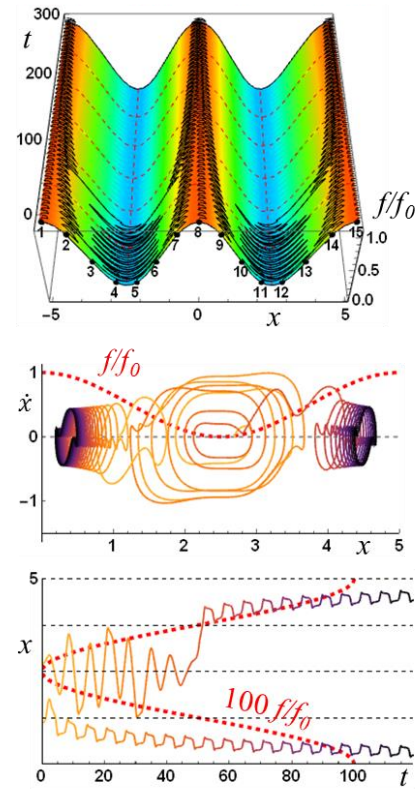
$f_0 = 3$

$\nu = 0.2$

$f_0 = 8$

$\nu = 0.25$





T. Zh. Esirkepov & SVB “Paradoxical stabilization of forced oscillations by strong nonlinear friction” Phys. Lett. A (2017)

William Thomson (Lord Kelvin):

“I never satisfy myself until I can make a mechanical model of a thing"

Thank you for your attention!