第19回金茶会
KEK
June 2008/7/4

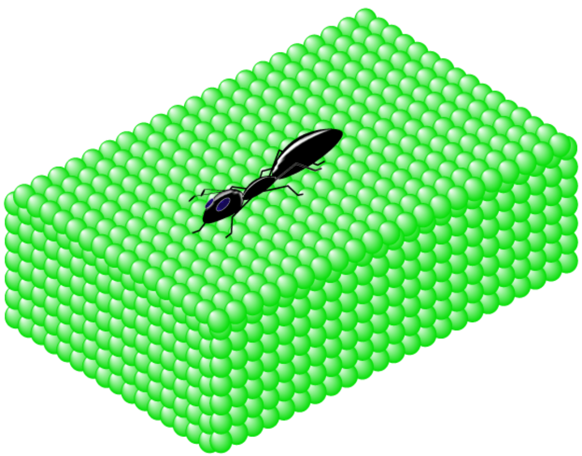
レーザーで何ができるの？

KEK
Toshiki Tajima
(also at JAEA)

Acknowledgment of collaborators: T. Takahashi, K.Homma, T.Tauchi, K.Kondo, T,Omori, J. Urakawa, K.Fujii, M. Nozaki, S.Bulanov, M. Fujiwara, P.Chen, T.Nomura, G. Mourou, D. Habs, Q. Niu, Y.Kato, K.Ueda, M.Kando, A.Pirozhkov, Y.Fukuda, F.Takasaki, K.Nakajima, R.Hajima, T.Hayakawa, Q.Niu, K.Nasu, A.Suzuki,Y.Takahashi, T.Ebisuzaki

- Quantum mechanics -- Relativity
- Particle physics in infinitesimally small distance (such as Planck distance) vs. ‘macroscopic’ structure of vacuum?
- Warping of vacuum, Structure and property of vacuum
- Extreme Field Science; Laser and Accelerator
- Single particle vs Collective effects
- Special vs General Relativity

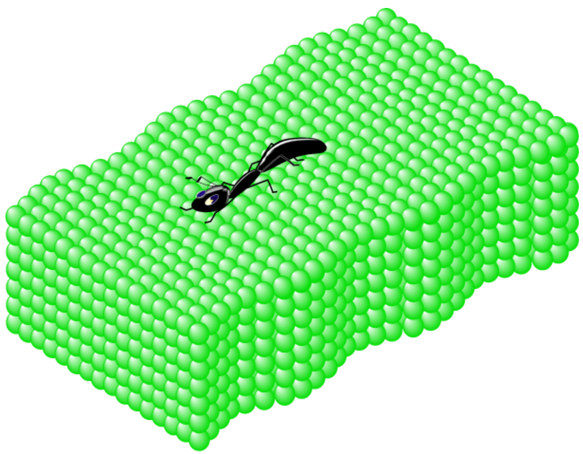
What is vacuum?
What is relativity?



An observer in a crystal as vacuum

↓

「（真）空」

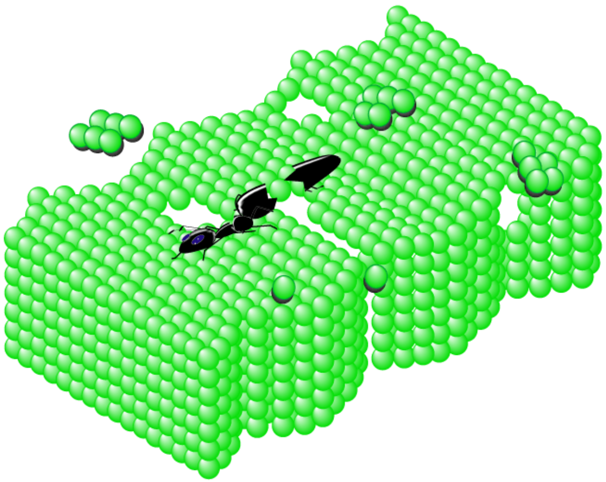


Phonon is an excitation of vacuum

↓

Photon is a distortion of vacuum

「色即是
空」



Strong field breaks vacuum

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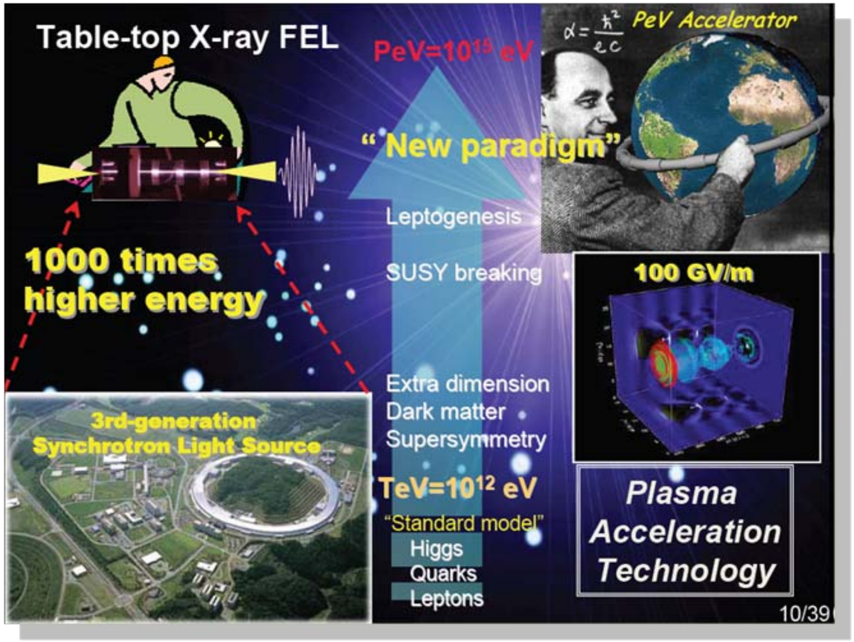
e+e- pair production
out of vacuum

「空即是色」

Lasers



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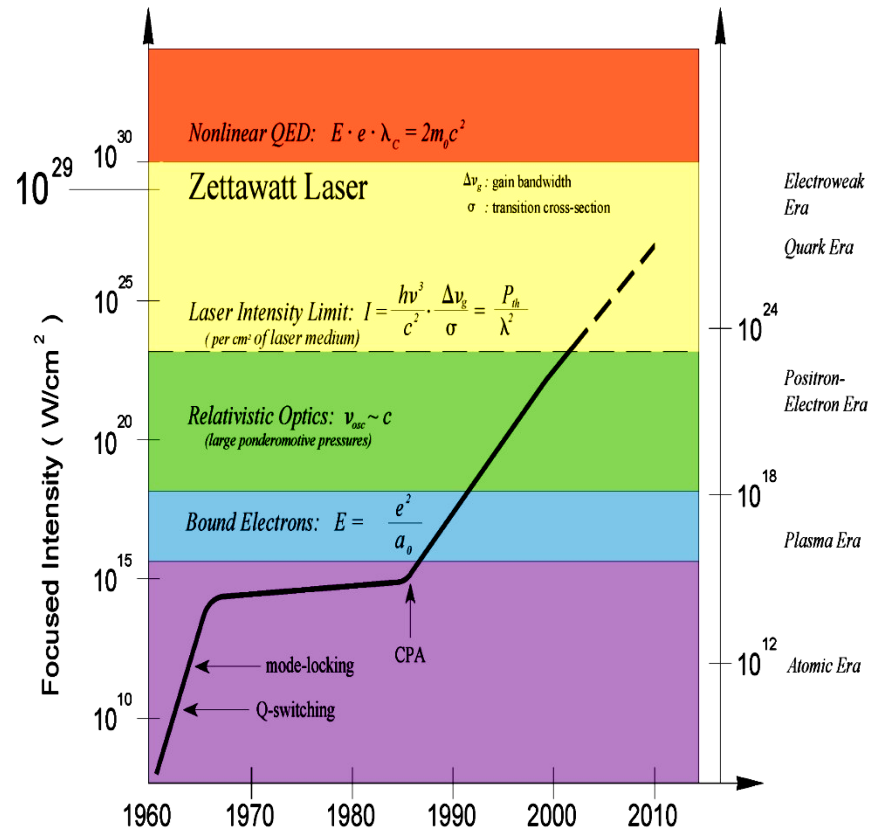
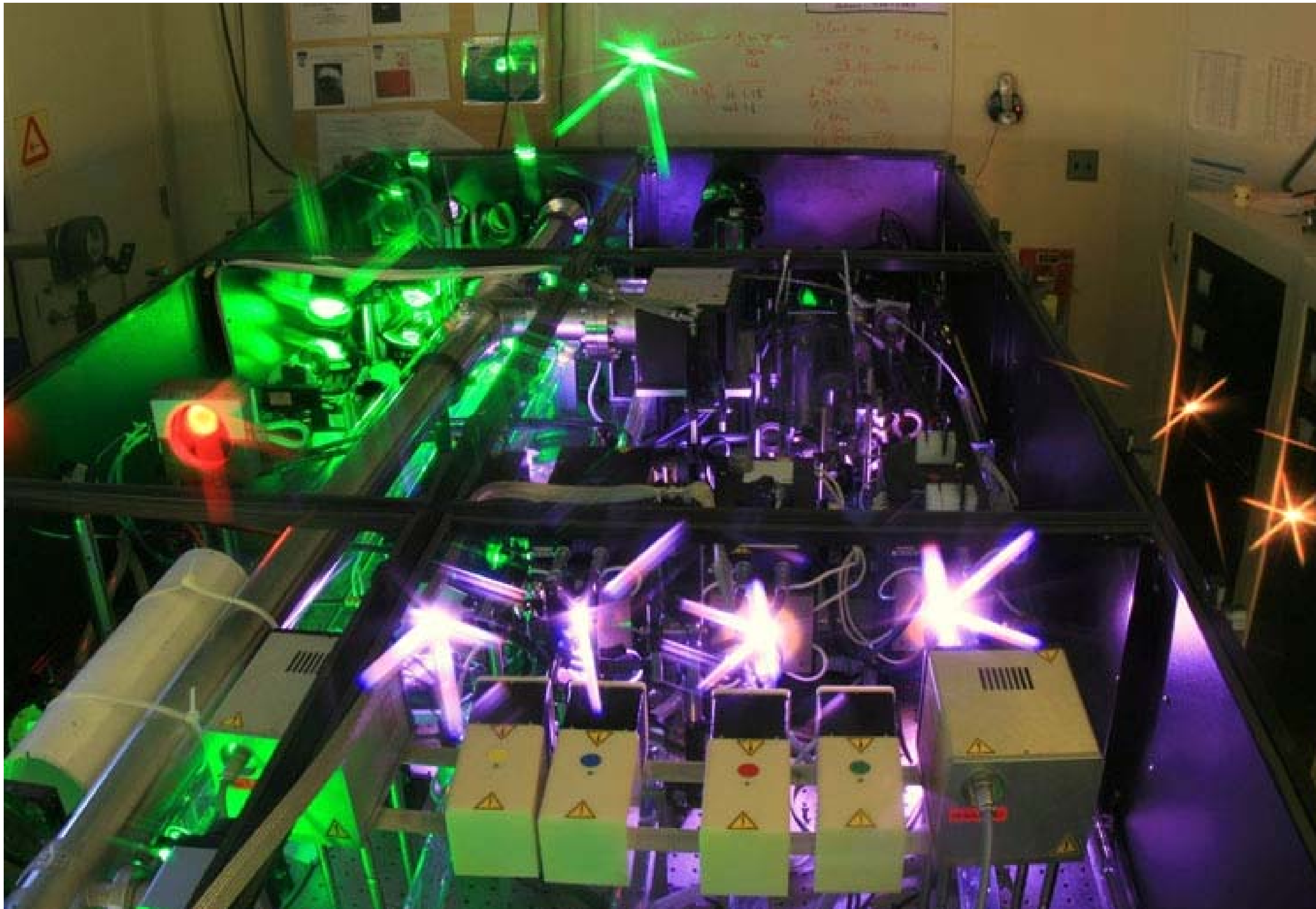


(Tajima,Mourou,2002)

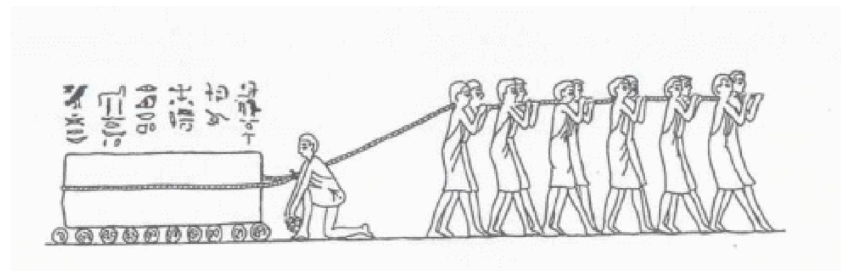
V. Yanovsky, et al., Opt. Express 16 2109 (2008)



Here we report the upgrade of the HERCULES laser to 300 TW output power at 0.1 Hz repetition rate. To our knowledge, this is the first multi-100TW-scale laser at high repetition rate. By using adaptive optics and f/1 parabola we focused the output beam into a 1.3 μ focal spot corresponding to unprecedented intensity of ~ 2 10^{22} W/cm^2 .

What is *collective force*？

How can a Pyramid have been built?



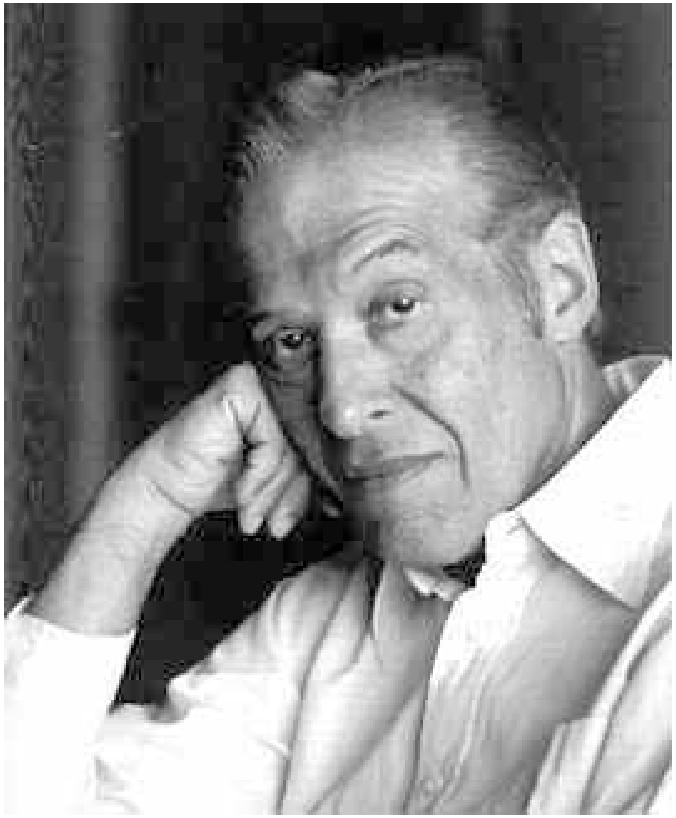
Individual particle dynamics vs. Coherent movement

Collective acceleration

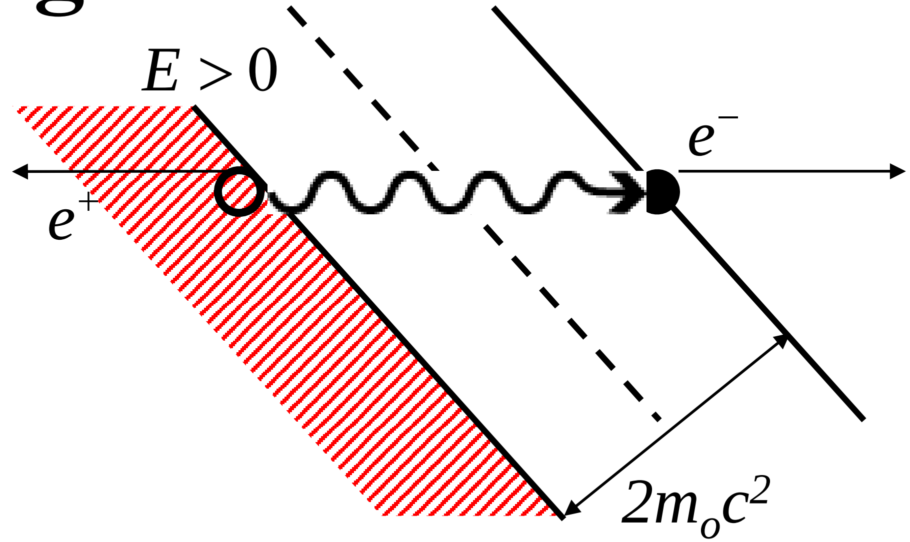
Collective radiation (N^2 radiation)

Collective ionization (N^2 ionization)

Vacuum Breakdown at Schwinger Field



Julian Schwinger



$$w = \frac{1}{\pi^2}\frac{\alpha c}{\bar{\lambda}^4}\left(\frac{E}{E_s}\right)^2 \exp\left(-\frac{\pi E_s}{E}\right)$$

Pair Creation: Vacuum boiling

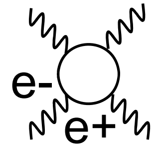
Note the similarity of Schwinger expression to the Keldysh atom ionization ⇐ from the 'structure' of vacuum / atom

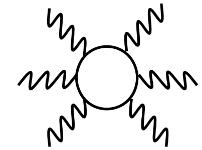
Higher order QED and QCD

hep-ph/9806389

Euler-Heisenberg effective action in constant Abelian field U(1) can be expressed as

$$L^{1-loop}{}_{LO+NLO}(A_\mu) = -\frac{1}{90}\frac{\pi^2}{m^4}\left[(\frac{\alpha}{\pi}F^2)^2 + \frac{7}{4}(\frac{\alpha}{\pi}F\widetilde{F})^2\right] + \frac{1}{315}\frac{\pi^4}{m^8}\left[4(\frac{\alpha}{\pi}F^2)^3 + \frac{13}{2}\frac{\alpha}{\pi}F^2(\frac{\alpha}{\pi}F\widetilde{F})^2\right] +$$





If U(1)→U(1) + condensed SU(3) due to self-interacting attractive force of gluons

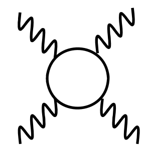
$$\frac{\alpha}{\pi}F^2 \rightarrow \left\langle \frac{\alpha_s}{\pi}G^2 \right\rangle + \frac{\alpha}{\pi}q^2F^2$$

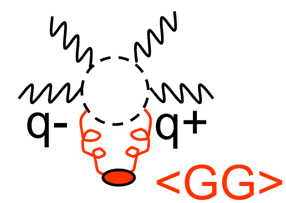
$$\langle 0|\frac{\alpha_s}{\pi}G^2|0\rangle \approx (2.3 \pm 0.3)10^{-2}GeV^4$$

Focus on only light-light scattering amplitude after the substitution

$$L^{1-loop}{}_{LO+NLO}(A_\mu + G^a{}_{\mu\nu}) = -\frac{1}{90}\frac{\pi^2}{m^4}\left[(\frac{\alpha}{\pi}F^2)^2 + \frac{7}{4}(\frac{\alpha}{\pi}F\widetilde{F})^2\right]$$

$$+\sum_{i=u,d}\frac{1}{315}\frac{q_i{}^2\pi^4}{m_i{}^8}\left[12(\frac{\alpha}{\pi}F^2)^2\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle + \frac{13}{2}(\frac{\alpha}{\pi}F\widetilde{F})^2\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle\right]$$





QCD effect dominates pure QED 1-loop vacuum polarization to light-light scattering

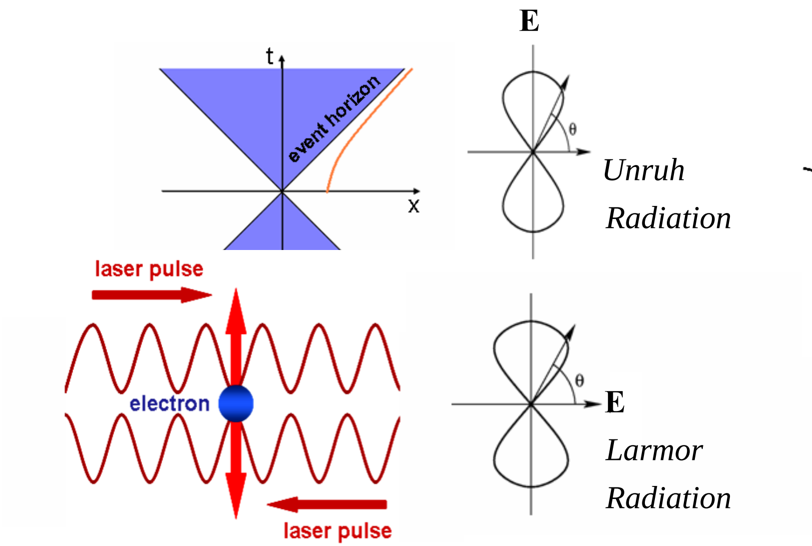
$$\frac{2nd-term}{1st-term} = \sum_{i=u,d}\frac{24}{7}\frac{q_i{}^2\pi^4}{m_i{}^8}m^4{}_e\left\langle\frac{\alpha}{\pi}G^2\right\rangle \approx e^{9\pm2.5}$$

$$m_u \approx \frac{1}{2}m_d \approx 5 \pm 1.5MeV, q_u{}^2 = 4q_d{}^2 = \frac{4}{9}$$

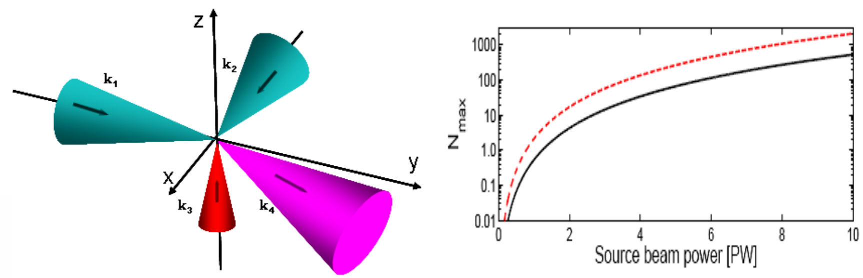
Check of Euler-Heisenberg yet to come. Any deviation from it?

→ axion field?; extended fields(such as dark energy, Tajima-Niu, 1997, etc.)?

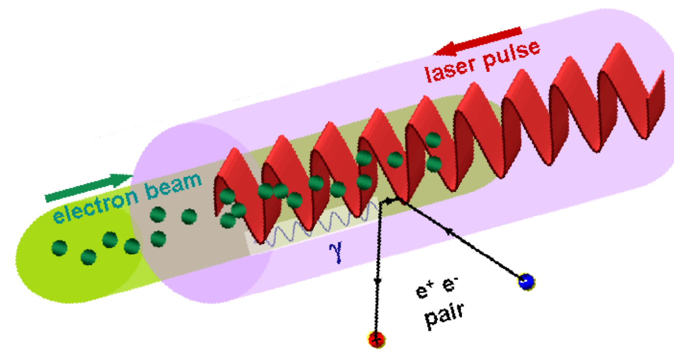
Some Examples of Vacuum Nonlinearities



Unruh radiation (Chen&Tajima (1999))



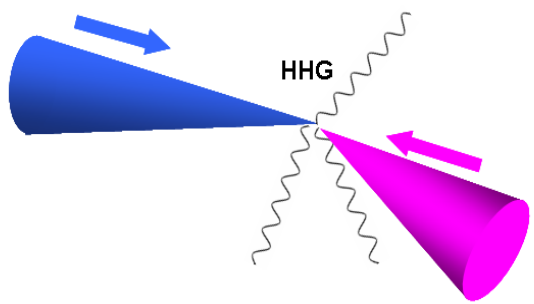
4-wave mixing (Lundström et al (2006))



Electron-positron pair production
in the laser interaction with the electron beam

$e^+ + n\gamma \longrightarrow \gamma,\ \gamma + n\gamma' \longrightarrow e^+ + e^-$

(Bula et al (1996); Burke et al (1997))



Higher harmonic generation
through quantum vacuum interaction
(Fedotov & Narozhny (2006))

Extra dimensional effect based on Kaluza-Klein theory

PRD 68(2003)106005, A. Ganguly et al.

$$S = \frac{1}{16\pi G_{4+n}} \int d^{4+n}x \sqrt{|\gamma|} R$$

$$\gamma_{\mathrm{mn}} = \phi^{-1/3} \begin{bmatrix} g_{\mu\nu} + \kappa^2 \phi A_\mu A_\nu & \kappa\phi A_\mu \\ \kappa\phi A_\nu & \phi \end{bmatrix}$$

$$S = \frac{1}{16\pi G_4} \int d^4x \sqrt{-g} \left[R^{(4)} + \frac{1}{4}\phi F_{\mu\nu}F^{\mu\nu} + \frac{1}{6}\frac{\partial_\mu \phi \partial^\mu \phi}{\phi^2} \right]$$

g_{55} couples electromagnetic field

$$v_{(1)}^2 = 1 + \sqrt{32}\lambda |\mathcal{B}| \frac{|k_\perp|}{\vec{k}^2}$$

$$v_{(2)}^2 = 1 - \sqrt{32}\lambda |\mathcal{B}| \frac{|k_\perp|}{\vec{k}^2}$$

$$\lambda \propto 1/\sqrt{G_4}$$

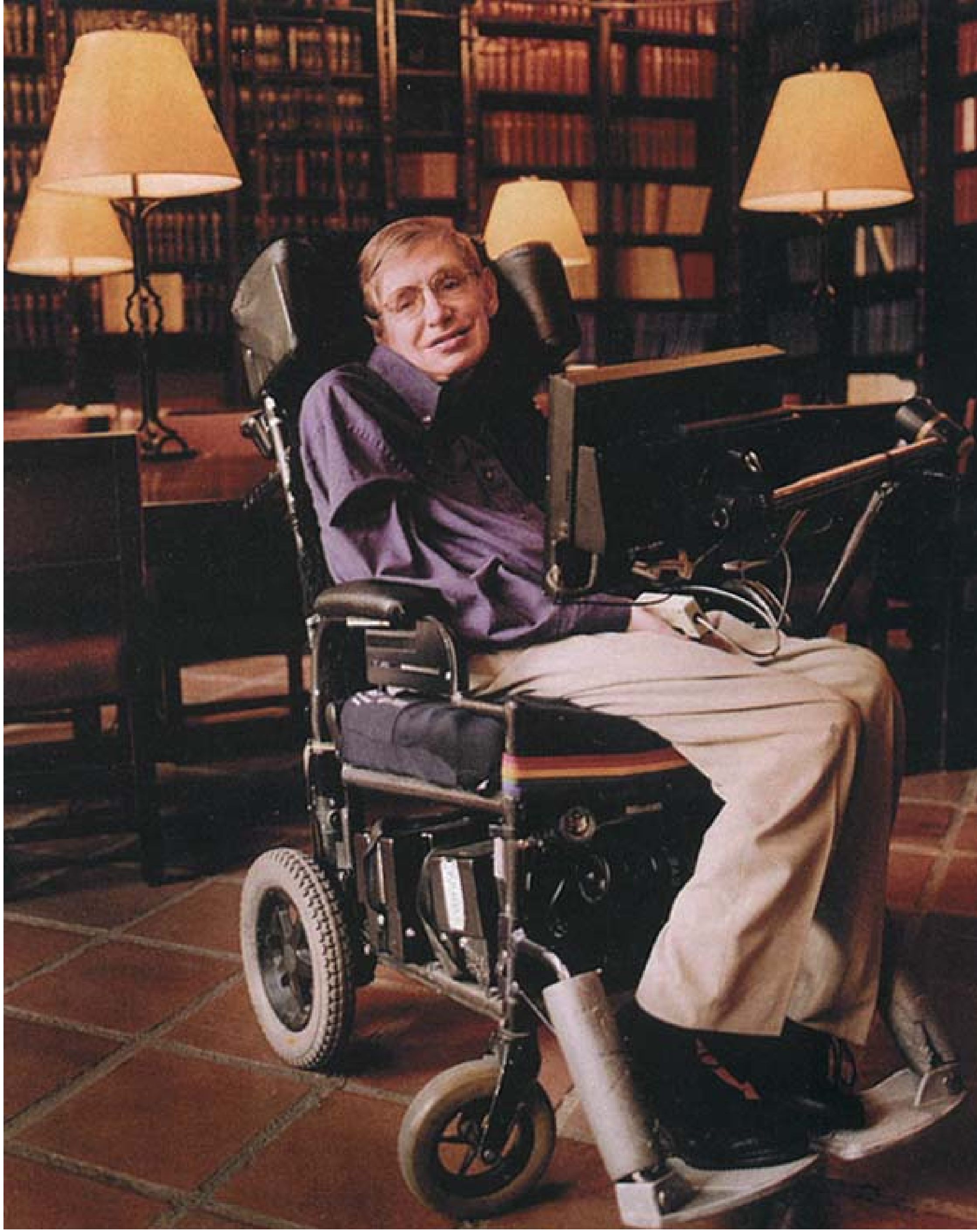
Extreeeemely small,
unless B is extreeeemly large

(K.Homma's slide,2007)

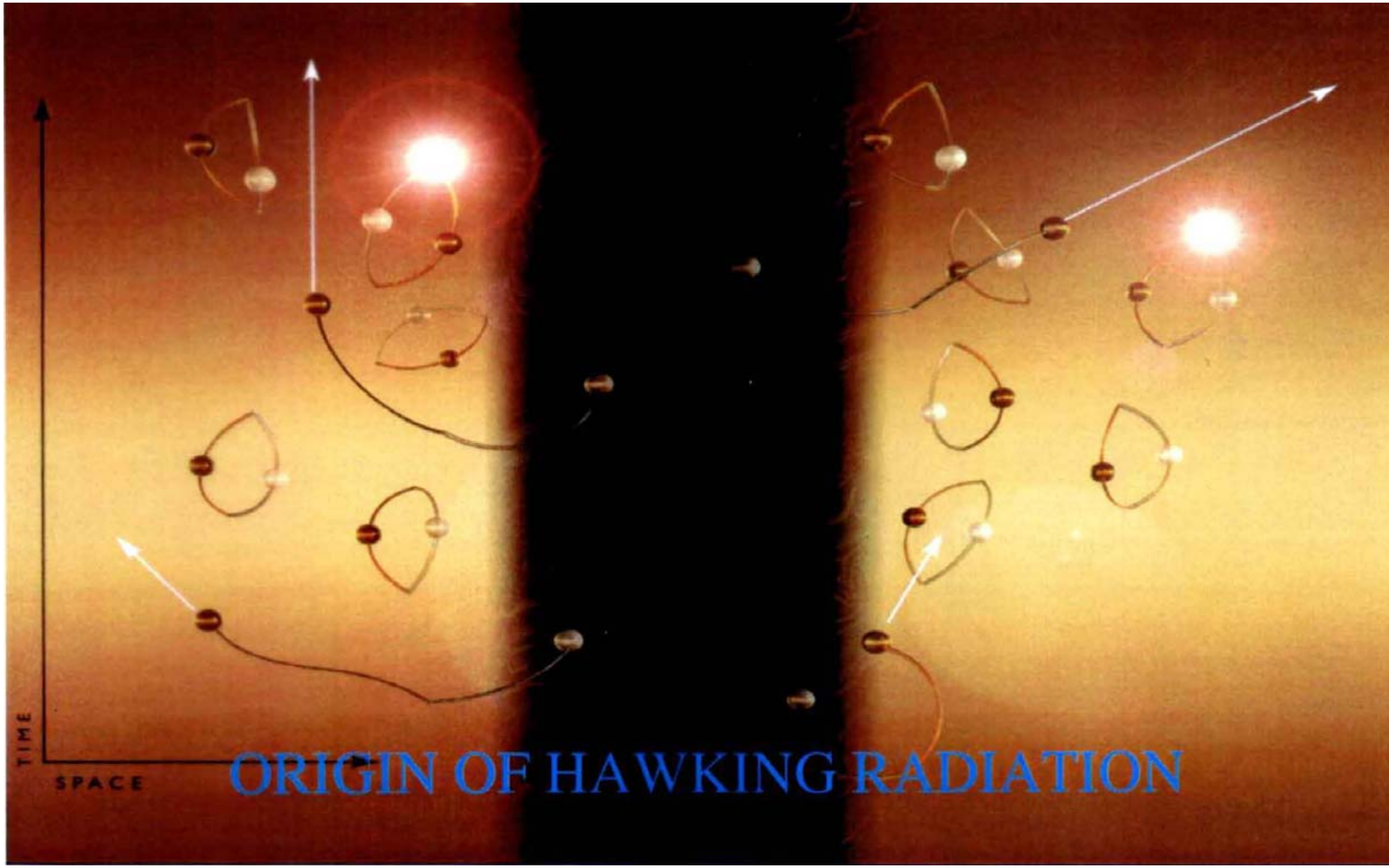
Vacuum Emission Under Gravity

General Relativity

and Black Holes



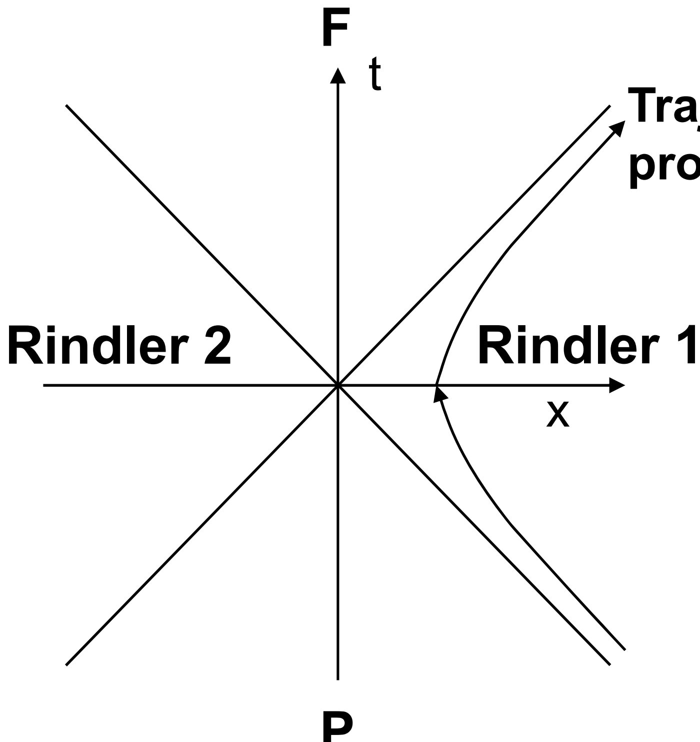
Hawking radiation



What is ‘vacuum’? Does ‘something’ emerge from ‘nothing’?

「空」＝「色」？　　「混沌」➔「秩序」？

Radiation via event horizon
-- access to zero-point energy --



Trajectory of observer with a constant proper acceleration α (Rindler observer)

Rindler 1 and 2 are causally disconnected (introduction of an event horizon)

$$\phi = \sum_{k=-\infty}^{+\infty} (a_k u_k + a^{+}{}_k u_k^{*})$$

$$\phi = \sum_{k=-\infty}^{+\infty} (b^{(1)}{}_k u_k^{(1)} + b^{(1)^{+}}{}_k u_k^{(1)*} + b^{(2)}{}_k u_k^{(2)} + b^{(2)^{+}}{}_k u_k^{(2)*})$$

Minkowski spacetime

Minkowski spacetime looks as if thermal bath to a Rindler observer via the Bogoliubov trans.

$$\left\langle 0_M \,|\, b^{+(1,2)} b^{(1,2)} \,|\, 0_M \right\rangle \propto \frac{1}{e^{-2\pi\omega/\alpha} - 1}$$

(K.Homma)

Optical laser as a source of acceleration
Electron as an Rindler particle

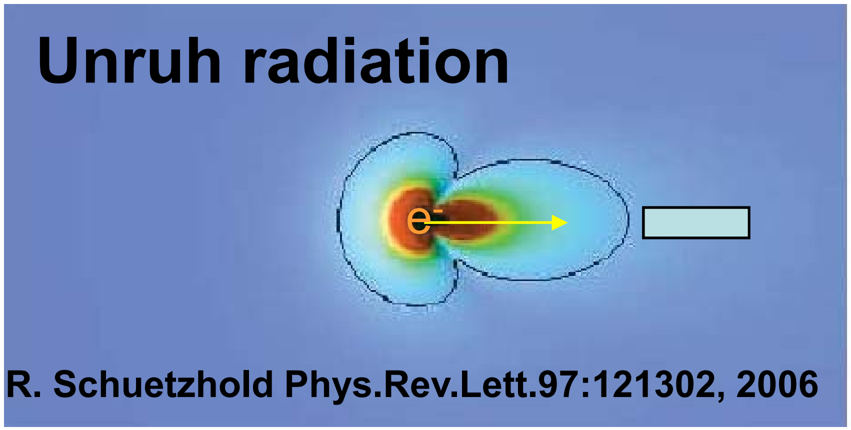
Unruh temp.⇔ Hawking temp.

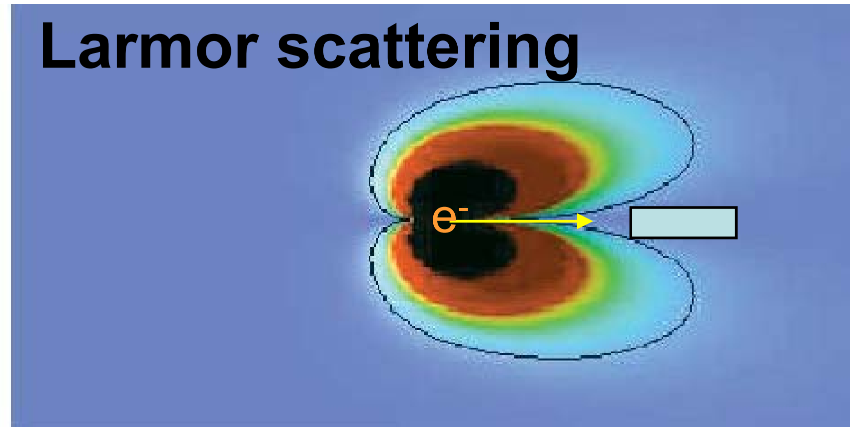
$$k_B T = \frac{\alpha}{2\pi} \Leftrightarrow k_B T = \frac{\kappa}{2\pi}$$

Unruh vs. Larmor radiation

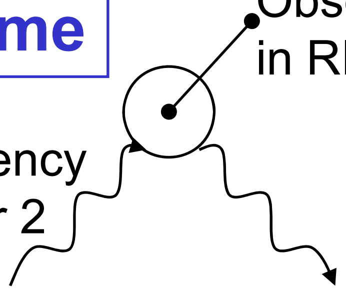
$I = 10^{17}[W/cm^2] \Rightarrow E \approx 10^{12}[V/m]$ (Chen, Tajima,1999)

$\Rightarrow k_B T = 0.06eV \Rightarrow$ **~10eV (blue shift in lab. frame)**





Rindler frame



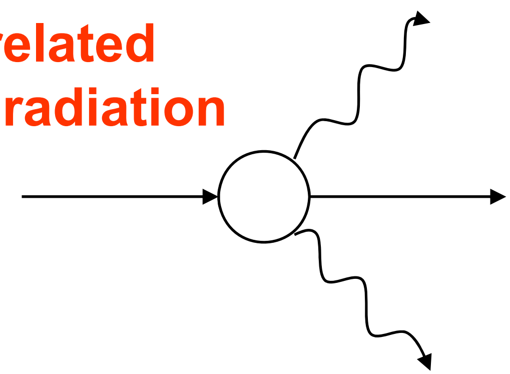
Observer
in RIndler 1

negative frequency
mode in Rinder 2

Strong correlation between absorption and emission despite of causal disconnection

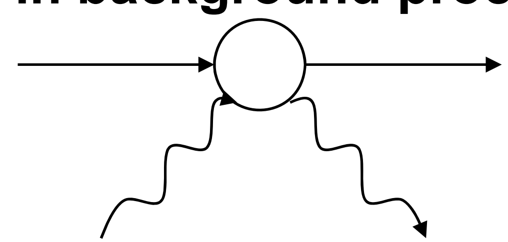
G. Unruh PRD 29 1047-1056, 1984

Correlated pair radiation



Inertial frame

No correlated pair in background process



Event Horizon Analog?,…..

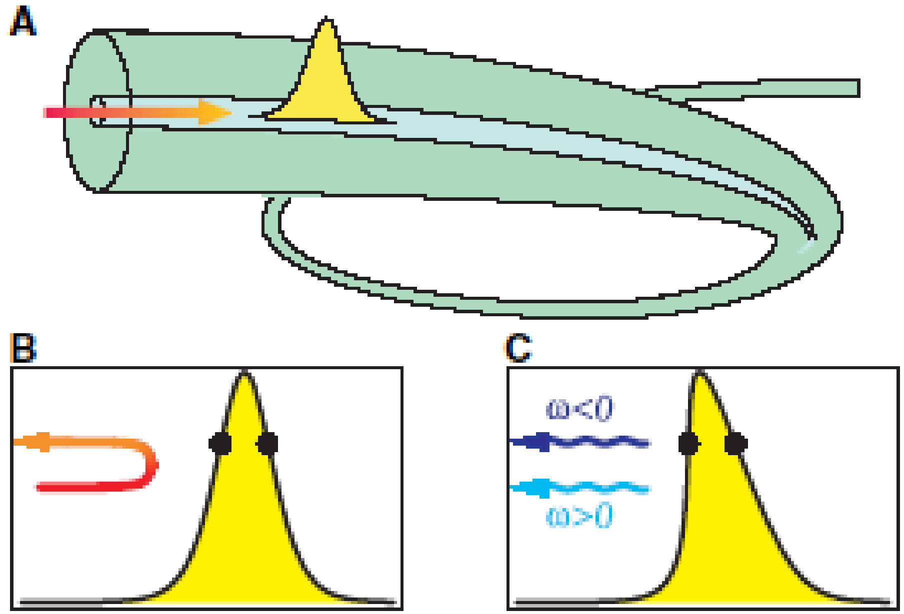
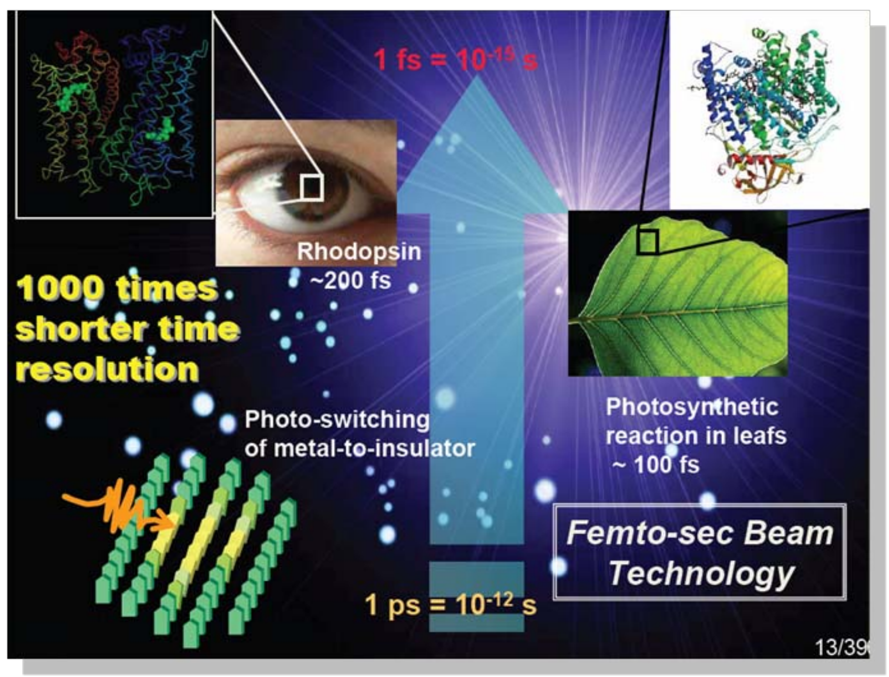


Fig. 1. Fiber-optical horizons. **(A)** A light pulse in a fiber slows down infrared probe light, attempting to overtake it. The diagrams below are in the co-moving frame of the pulse. **(B)** Classical horizons. The probe is slowed down by the pulse until its group velocity matches the pulse speed at the points indicated by black dots, establishing a white-hole horizon at the back and a black-hole horizon at the front of the pulse. The probe light is blue-shifted at the white hole until the optical dispersion releases it from the horizon. **(C)** Quantum pairs. Even if no probe light is incident, the horizon emits photon pairs corresponding to waves of positive frequencies from the outside of the horizon paired with waves at negative frequencies from beyond the horizon. An optical shock has steepened the pulse edge, increasing the luminosity of the white hole.

T.Philbin et al., Science **319**, 1367 (2008)

Flying Mirror for Femto-, Atto-, … Science



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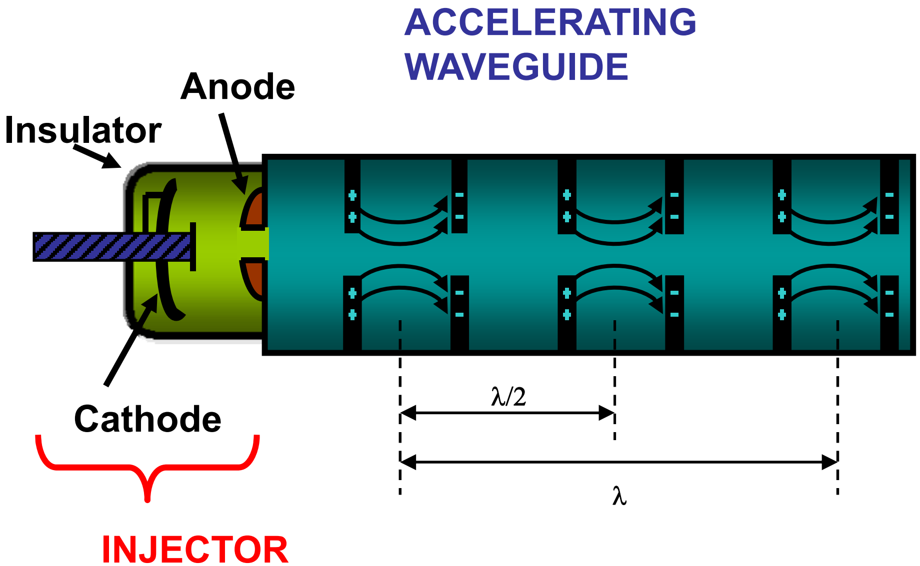
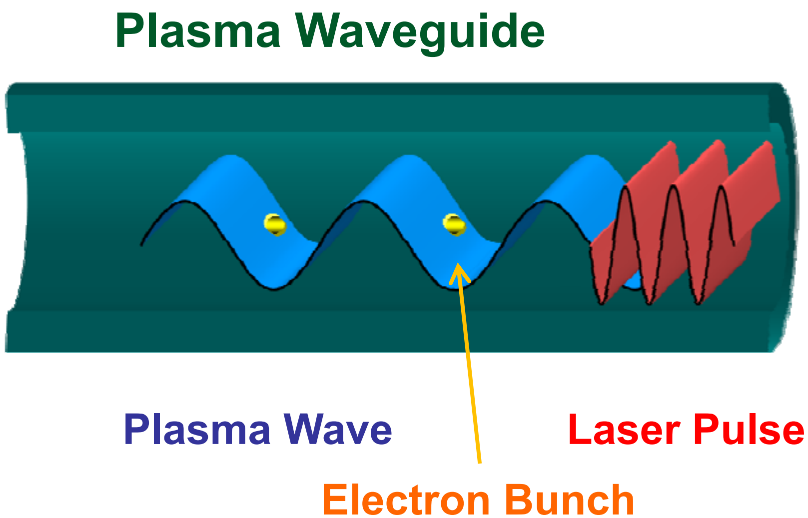
Classical and LWF Accelerators

E-field $_{max}$ ≈ 10 MV/m
R>R$_{min}$ Synchrotron radiation

Plasma cavity



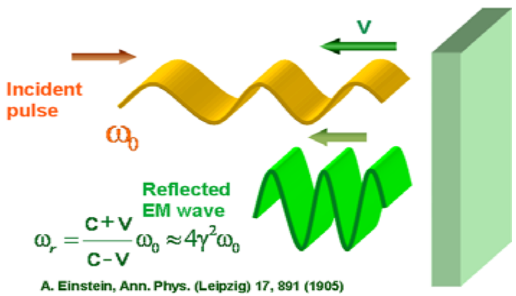


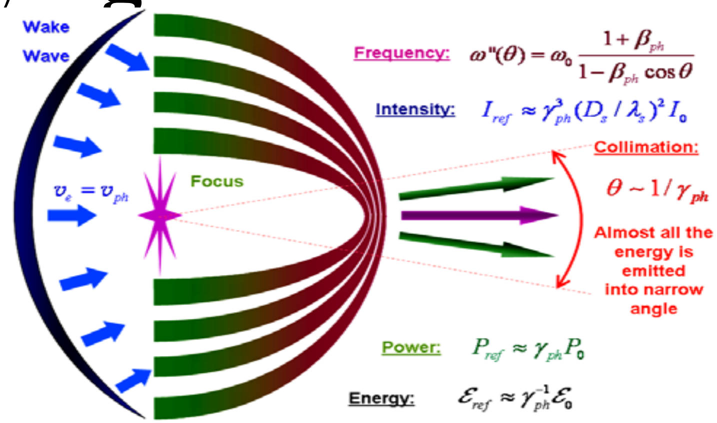
RF cavity

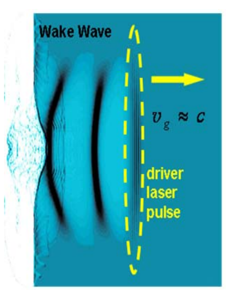
Ultrahigh axial electric fields
Compact electron accelerators
Plasma wakefields: *Tajima & Dawson (1979)*
E > 10 GV/m, fast waves
Plasma channel: Guides laser pulse and supports plasma wave

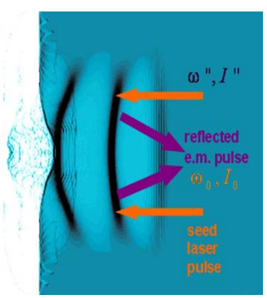
(Bulanov)

Laser x Laser: EM Pulse Intensification and Shortening by the Flying Mirror

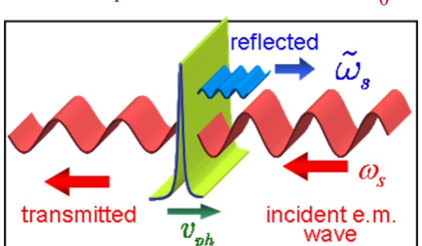






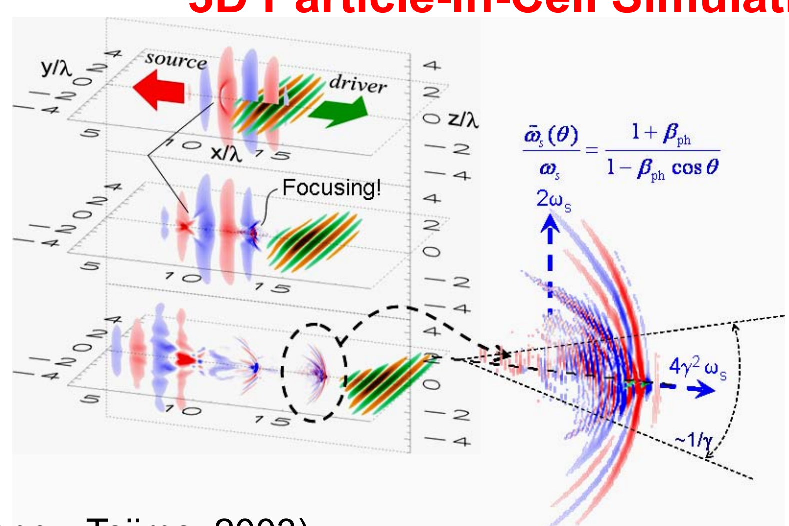


$$\omega'' = \frac{c+v_{ph}}{c-v_{ph}}\,\omega \approx 4\gamma_{ph}^2\omega_0 \qquad \frac{I''_{max}}{I_0} \approx \kappa\,\gamma_{ph}^6 \left(\frac{D}{\lambda}\right)^2$$



$$\kappa \sim \gamma_{ph}^{-3}$$

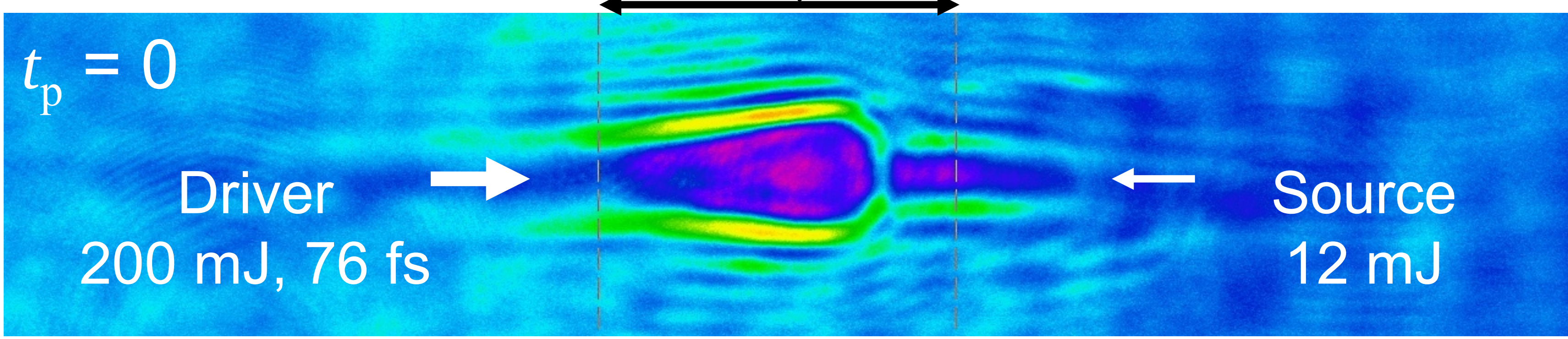
3D Particle-In-Cell Simulation



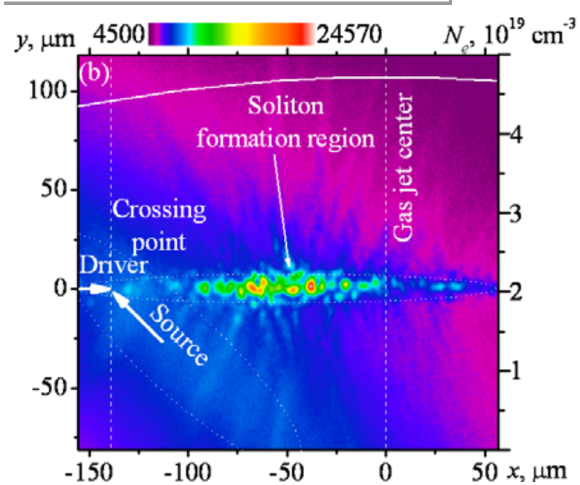
(Bulanov, Esirkepov, Tajima, 2003)

Colliding two lasers for the flying mirror experiment

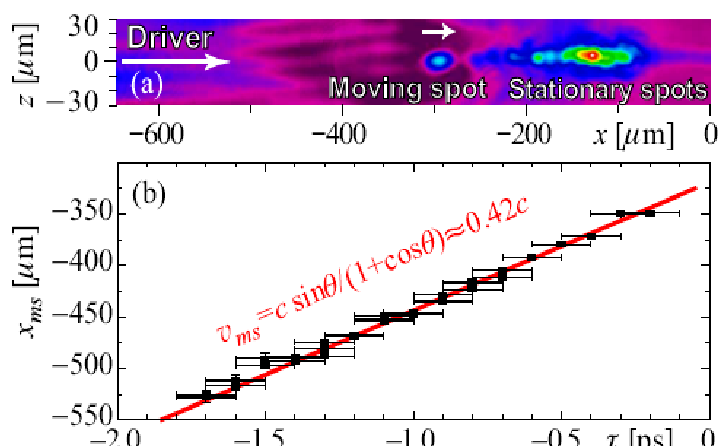
Side View

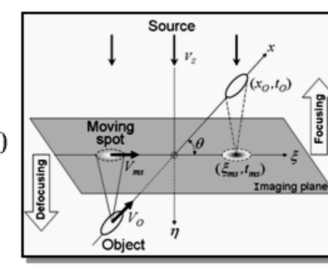


Top View



Relativistic Microlens





(Kando et al 2007)

➢ The interaction of two counter-propagating pulses is described by equations

$$\partial_t E_1 + \partial_z E_1 = i n_2 \omega_1 |E_2|^2 E_1$$

$$\partial_t E_2 - \partial_z E_2 = i n_2 \omega_2 |E_1|^2 E_2$$

with $n_2 = 7(e^4 / 45\pi m_e^4)$

These equations yield for $E_j = \sqrt{I_j}\exp(i\Phi_j) \quad j = 1,2$

$$I_1 = I_1(u), \quad I_2 = I_2(v), \quad u = z - t, \quad v = z + t$$

$$\Phi_1(u,v) = \Phi_1(u,v_0) + (n_2\omega_1/2)\int_{v_0}^{v} I_2(s)ds$$

$$\Phi_2(u,v) = \Phi_2(u_0,v) - (n_2\omega_2/2)\int_{u_0}^{u} I_1(s)ds$$

The pulse profiles transport without any distortion and the phases undergo nonlinear shifts!

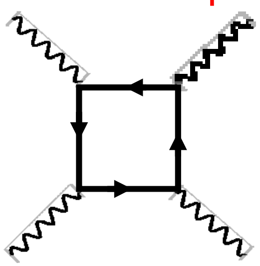
Laser Energy & Power Required to Achieve the Schwinger Field

The driver and source must carry **10 kJ** and **30 J**, respectively
(**Parameters on the order of ELI and HiPER Lasers**)

Reflected intensity can approach **the Schwinger limit**

$$E_{QED} = \frac{m_e^2 c^3}{e\text{h}}$$

It becomes possible to investigate such the fundamental problems of nowadays physics, as e.g. the electron-positron pair creation in vacuum and the photon-photon scattering



$$L = \frac{1}{16p} F_{ab} F^{ab} - \frac{k}{64p} \text{鵠} 5 \left(F_{ab} F^{ab} \right)^2 - 14 F_{ab} F^{bg} F_{gd} F^{dm}$$

The critical power for nonlinear vacuum effects is $P_{cr} = \frac{45 p^2}{a} \frac{c E_{QED}^2 l^2}{4p}$

for $l = 1 mm$ it yields P_{cr} サ 2.5 エ $10^{24} W$

Light compression and focusing with the FLYING MIRRORS yields

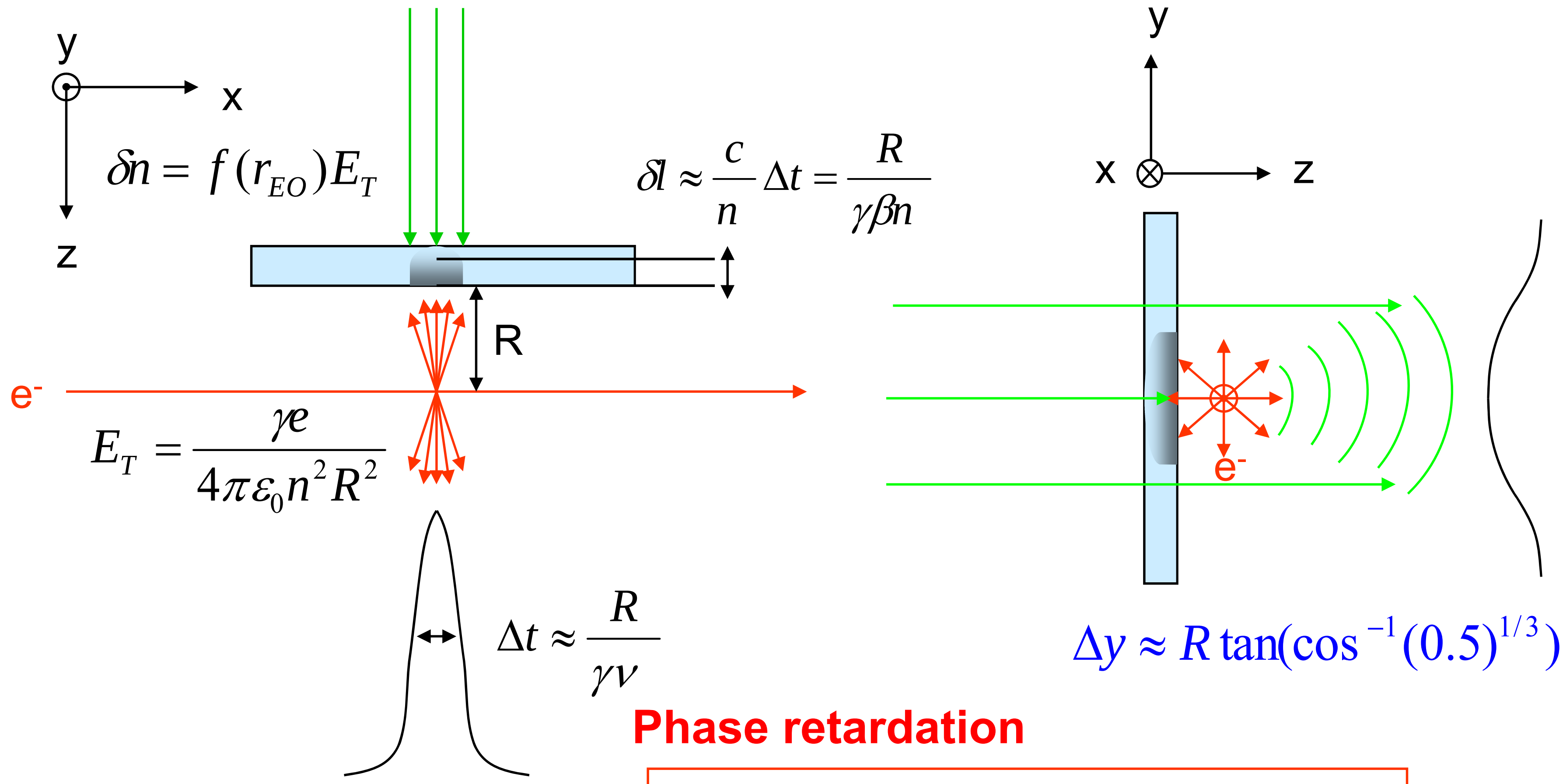
for $l = l_0 / 4 g_{ph}^2$ $P = P_0 g_{ph}$ with g_{ph} サ 30 the driver power P_{cr} サ $10 PW$

(Mourou, Tajima, Bulanov, 2006)

Laser self-focuses in vacuum with RE!

Homma proposes: experimental test

Measure instantaneous variation of refractive index
in Electro-Optical crystal by external electric fields.



$$\delta n = f(r_{EO}) E_T$$

$$\delta l \approx \frac{c}{n} \Delta t = \frac{R}{\gamma \beta n}$$

$$E_T = \frac{\gamma e}{4\pi\varepsilon_0 n^2 R^2}$$

$$\Delta t \approx \frac{R}{\gamma v}$$

$$\Delta y \approx R \tan\left(\cos^{-1}(0.5)^{1/3}\right)$$

$$\Delta x \approx \frac{R}{\gamma}$$

(Homma, 2007)

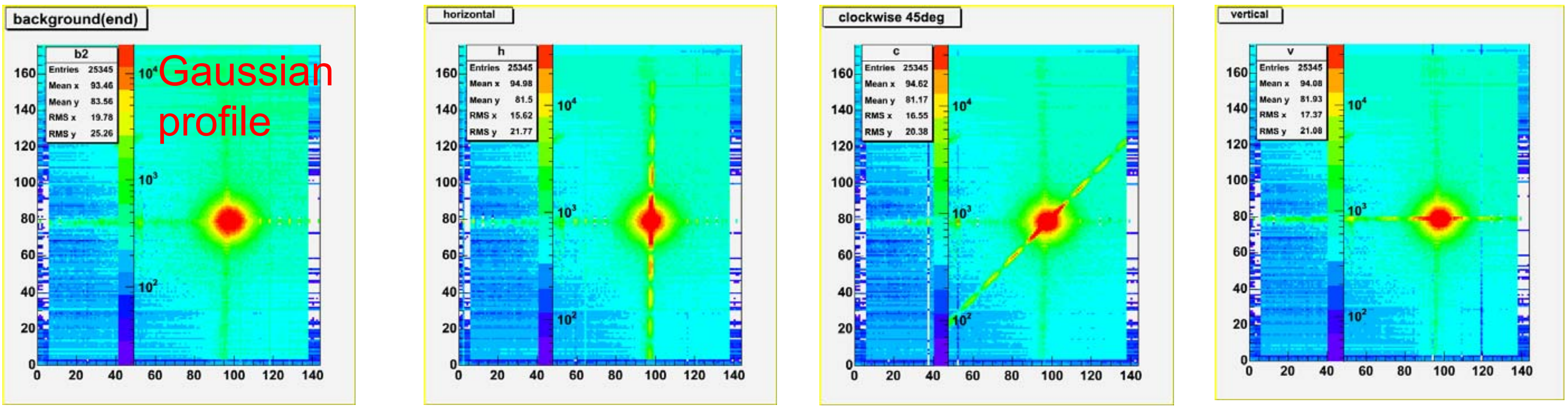
Phase retardation

$$\delta\Gamma = \frac{2\pi}{\lambda} \delta n \delta l = \frac{f(r_{EO})}{2\varepsilon_0 n^3} \frac{e}{\lambda \beta R}$$

Diffraction patterns with a thin wire of 50μm$^{\phi}$

Fourier transformation of Gaussian is Gaussian with smaller waist.

Pictures taken by wide dynamic range CMOS camera



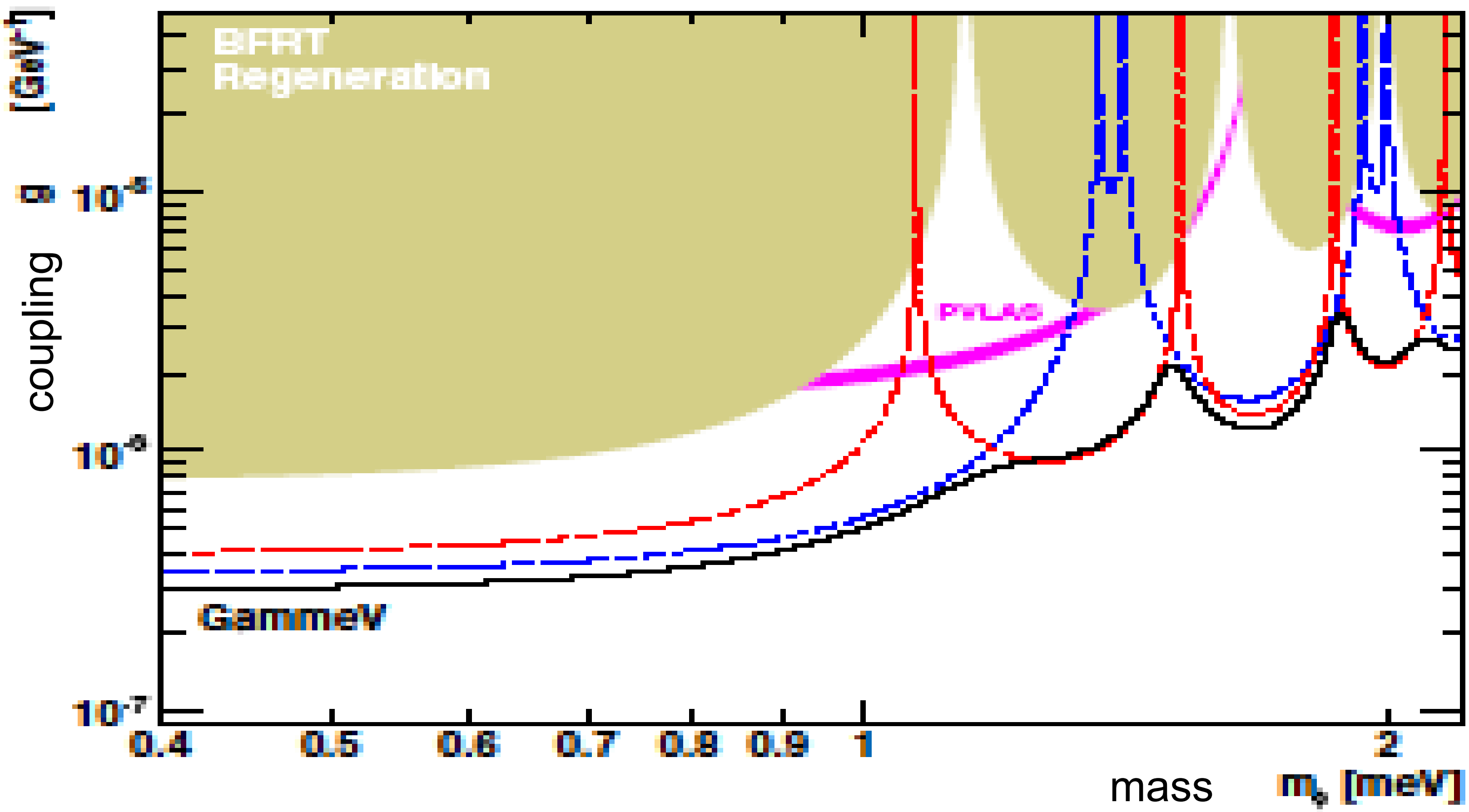
No wire **Horizontal wire** **Tilted wire** **Vertical wire**

Spatially homogenous interferometer:
Intensity modulation of $(A+\delta A)^2$ gives contrast ~ $\delta A/A$ in everywhere.

Outer diffraction sampling gives contrast close to infinity !

(Homma, 2007)

Past attempts via non-collider method exploring new fields such as axion……



A.Chou et al.,PRL (2008) observed no signal so far (Note:claim of axion by PVLAS was withdrawn)

Example of Crossing of Laser and Beams

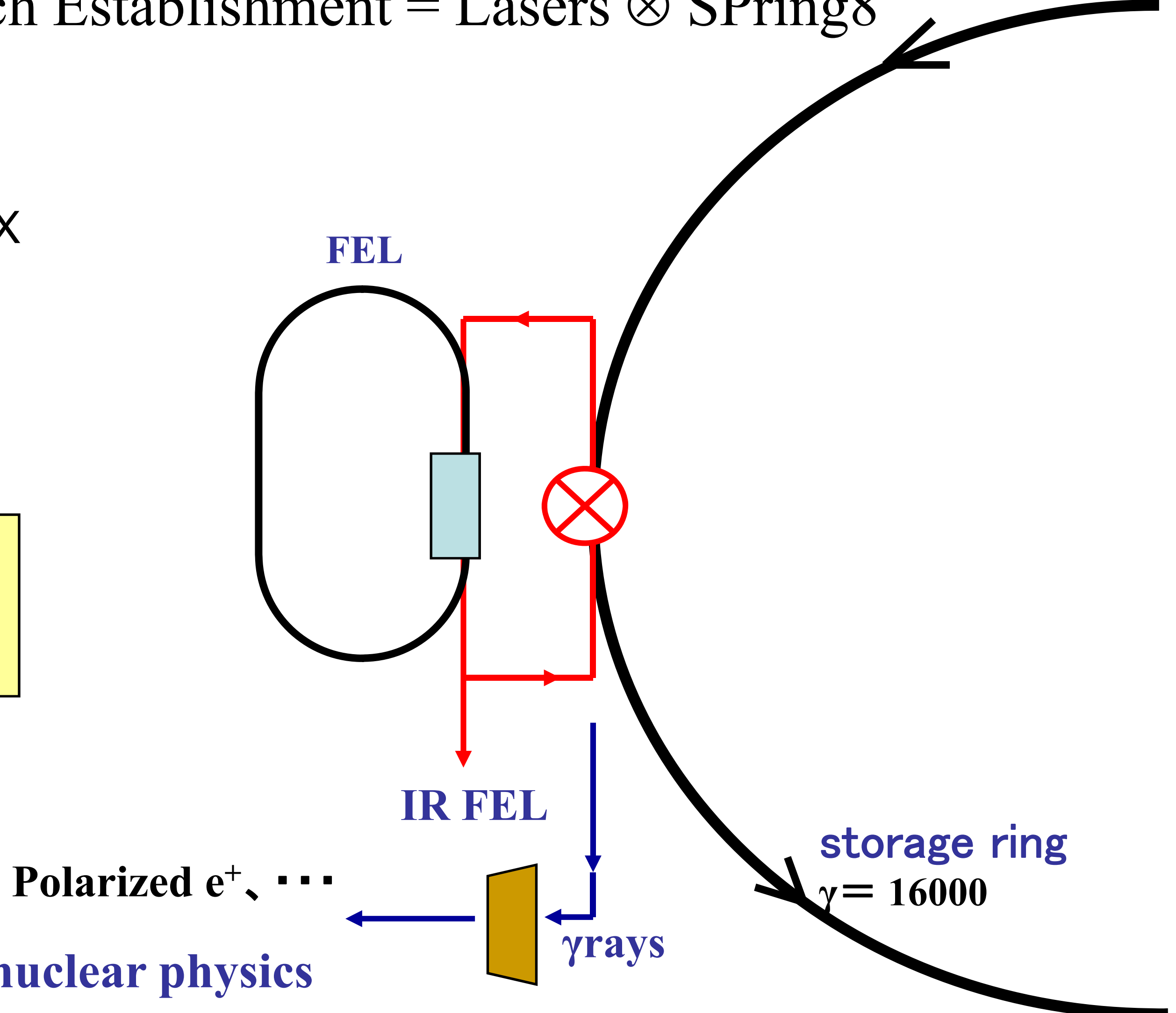
Kansai Research Establishment = Lasers ⊗ SPring8

SPring-88GeV e-beams X laser(FEL)

↓

New Paradigm for nuclear physics and nuclear energy

(Ejiri et al.)
(Omori et al.)



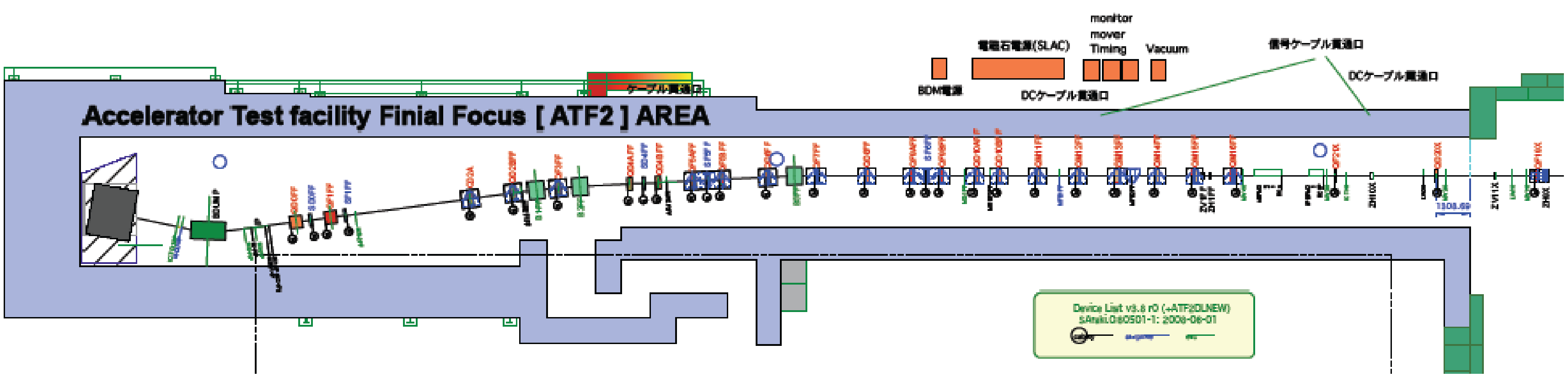
Photonuclear physics
Photonuclear transmutation
Polarized positrons for collider

Intense Laser at ATF2 Suggested laser x accelerator

- Laser Compton Gamma Rays
  nuclear resonance fluorescence,
  Moessbauer spectroscopy, detection of nuclear matter, EW/S coupled physics, gamma-gamma collider simulator
- High Y Physics
  QED nonperturbative regimes, near-
  Schwinger field physics, vacuum polarization and nonlinearities
- Quantum Control
  coincided modulation and scattering, beam
  manipulation, femtosecond diagnosis, zeptosecond spectroscopy

ATF2 Configuration @KEK

Electrons with γ 'see' the EM fields compactified and Intensified by a factor of γ (and intensity *I* by γ^2)



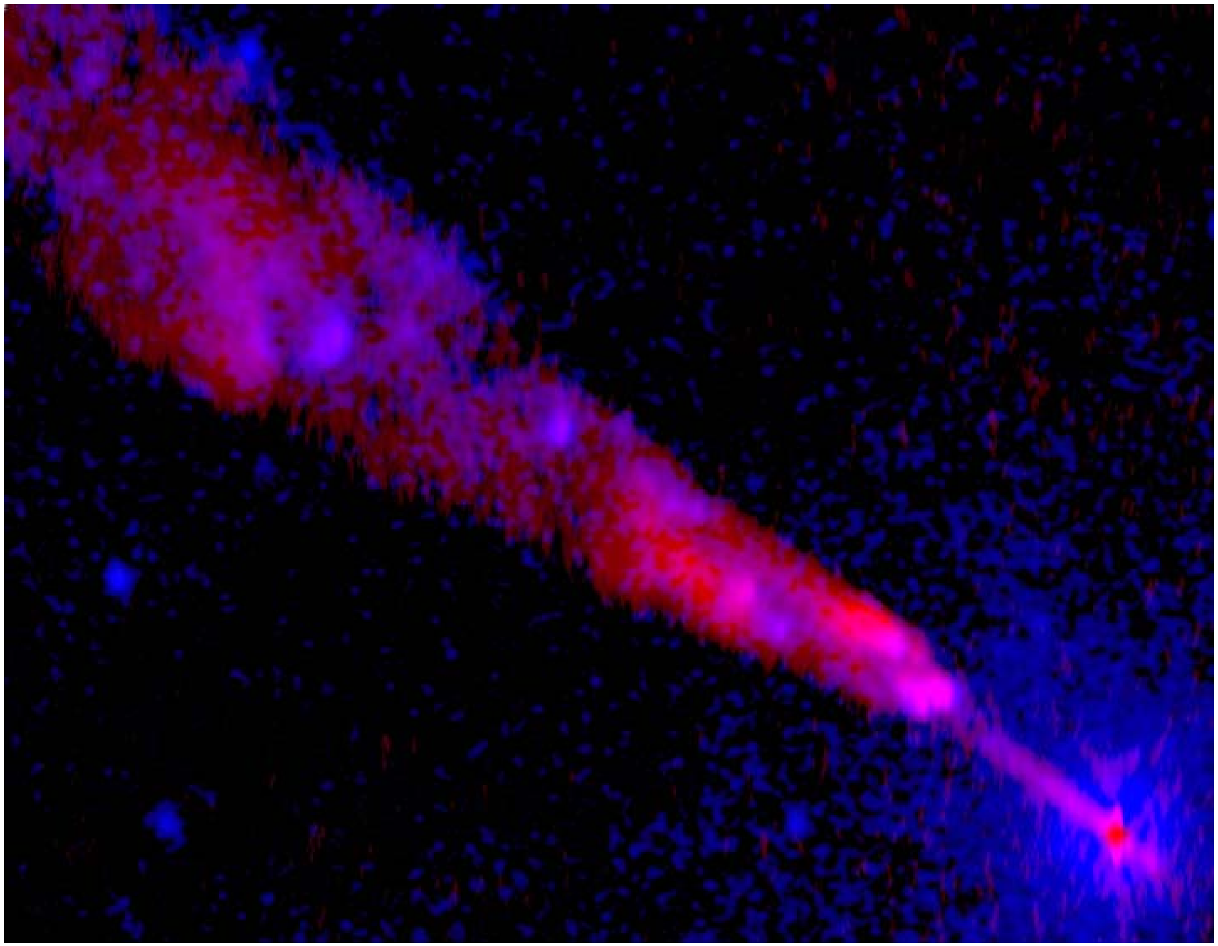
$\gamma \sim 2.5 \times 10^3$

$I = 10^{22}\ \mathrm{W/cm^2}$ -----→ $I = 10^{29}$ (~ Schwinger field)

Conclusions

- Extreme fields of laser: a new tool for particle and field physics
- Beyond collider paradigm?
- Laser x Accelerator: window into new regimes
- Is anything beyond standard theory? Verification of Euler-Heisenberg theory, axions, dark energy,…?
- Is *c* constant?
- Collective effects important for laser acceleration, vacuum study, …
- More study of relativity expected, needed

宇宙のプラズマ線型加速器(beyond 10^{20} eV)？



ケンタウルス座A

ご清聴有難うございました。