Photon acceleration as a scattering process

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Outline

- Historical background;
- Photon acceleration models;
- Acceleration in a laser wakefields;
- Ionization fronts and particle beams;
- Scattering by relativistic plasma bubbles;
- Photon acceleration in gravitational fields;
- Generalized Sachs-Wolfe effect;
- Conclusions.

Historical background

- Relativistic mirror (Einstein, 1905)
- Moving ionization fronts:(Semenova, 1967; Lampe et al., 1978).
- Moving nonlinear perturbation: adiabatic frequency shift (Mendonça, 1979).
- Photon acceleration in a laser wakefield (Wilks et al., 1989).
- Time refraction (Mendonça, 2000).

Experimental evidence

- Laser self blue shift: flash ionization (Yablonovich, 1974, Wood et al., 1993).

- Microwave experiments: ionization fronts (Savage et al., 1992).

-2D optical experiments (Dias et al., 1997).

- Photon trapping in a wakefield (Murphy et al., 2006).

Related optical phenomena:

self and cross-phase modulation, super-continuum (70's); Unruh radiation!! (2010)

Theoretical models

- Classical model:
Geometric optics of space and time varying media

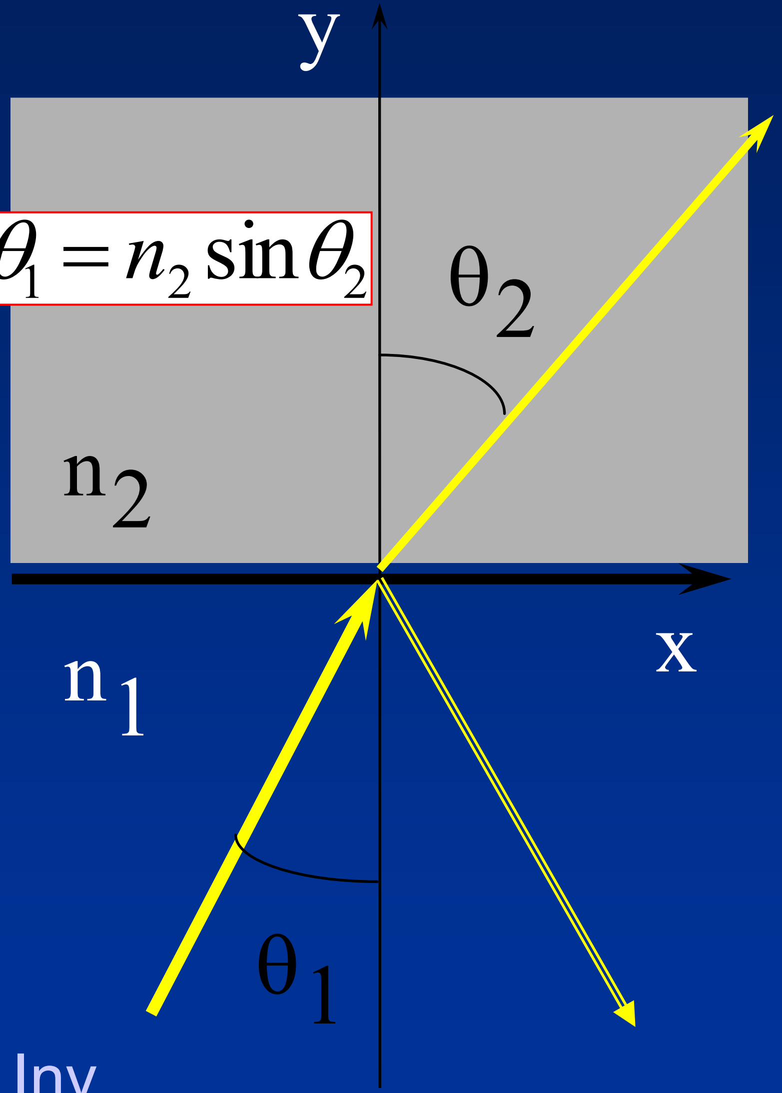
- Kinetic model
Photon kinetic theory (laser as a photon gas, photon Landau damping);

- Quantum model
Full wave theory (similar to scattering theory in Quantum Mechanics);

- Second-Quantization model
Quantum optics approach (theory of time refraction and temporal beam splitters);

-Extension to other types of interaction
neutrino-plasma physics, gravitational waves.

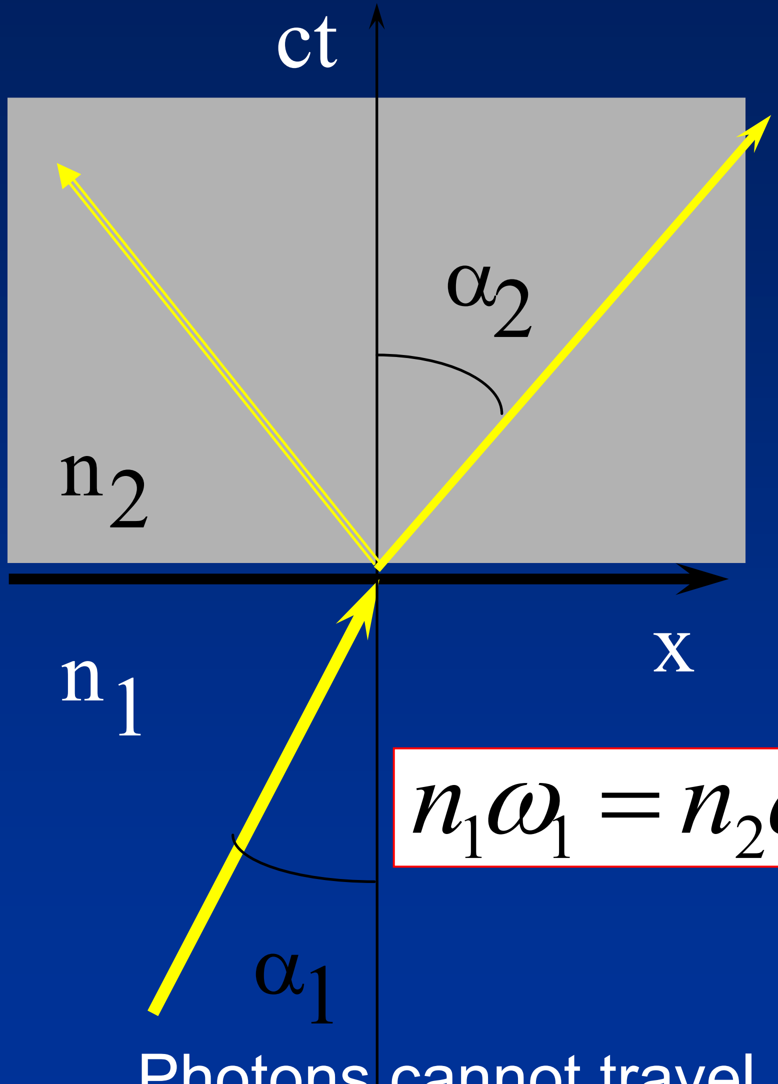
Refraction



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

W = Inv

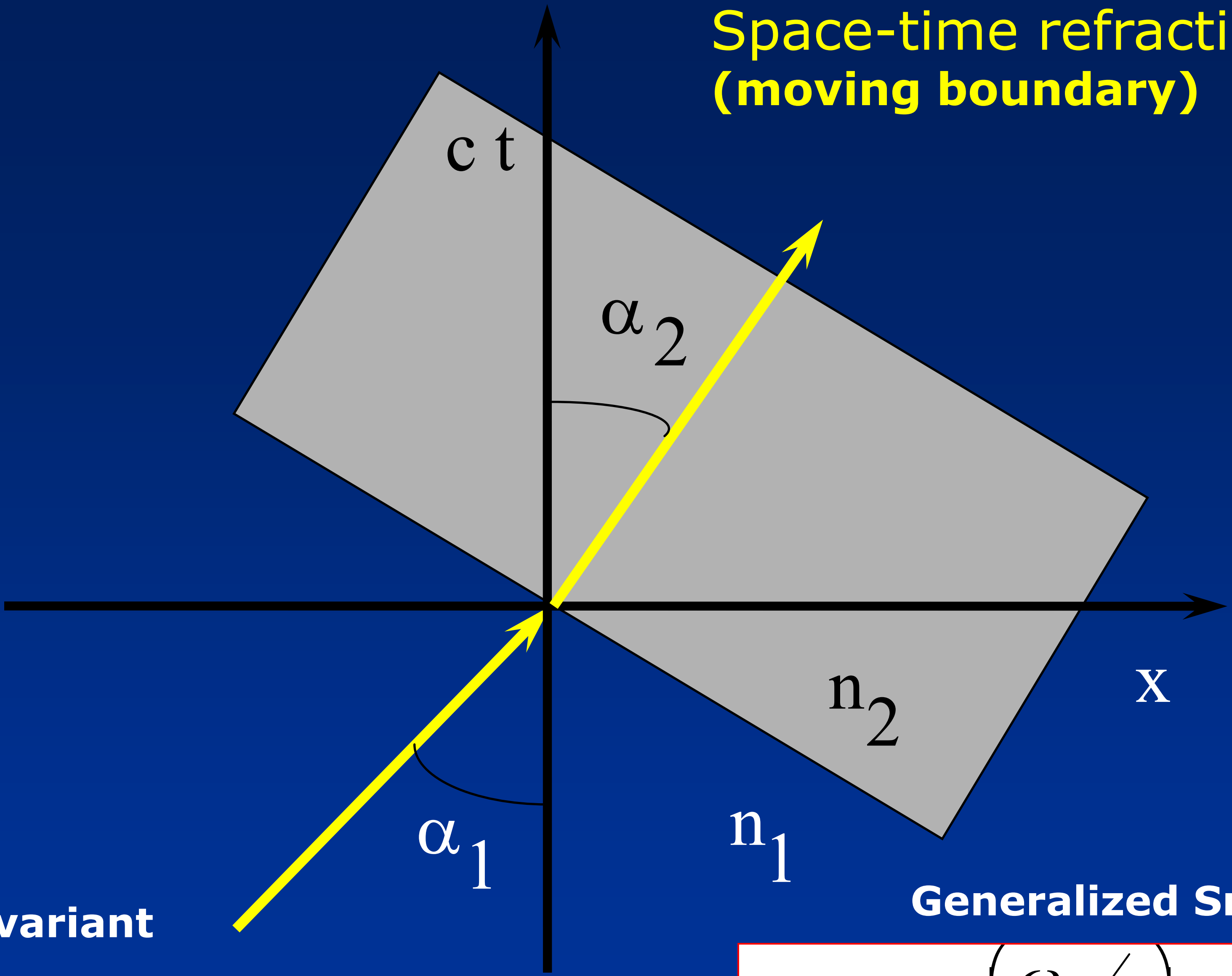
Time refraction



$$n_1 \omega_1 = n_2 \omega_2$$

Photons cannot travel back in the past

Space-time refraction
(moving boundary)



Invariant

$$\omega_j(1-\beta n_j\cos\theta_j)=Inv.$$

Generalized Snell's law

$$n_1\sin\theta_1=\left(\omega_2/\omega_1\right)n_2\sin\theta_2$$

Photon ray equations

- Photons ≡ relativistic particles with effective mass
- Photon Dynamics ≡ canonical equations of motion

$$\frac{d\mathbf{r}}{dt} = \frac{\partial \omega}{\partial \mathbf{k}} = \frac{\mathbf{k}}{\omega} c^2$$

$$\frac{d\mathbf{k}}{dt} = -\frac{\partial \omega}{\partial \mathbf{r}} = -\frac{1}{2\omega} \nabla \omega_p^2$$

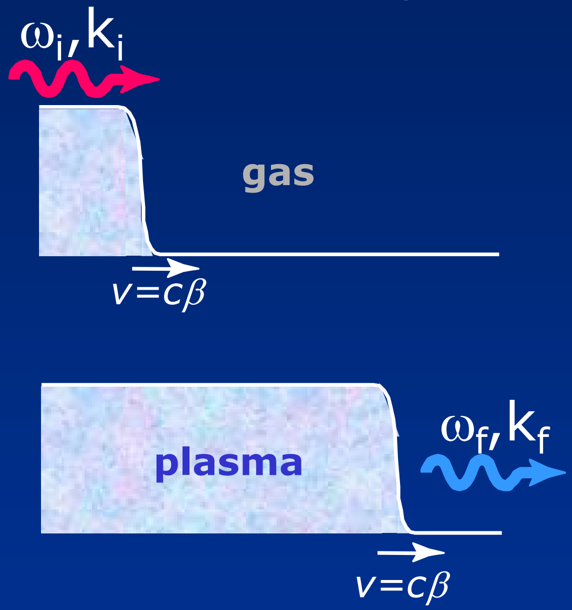
Hamiltonian

$$\omega = \sqrt{\mathbf{k}^2 c^2 + \omega_p^2}$$

<u>Force acting on the photon</u>: refraction (inhomogeneous plasma) and photon acceleration (non-stationary plasma).

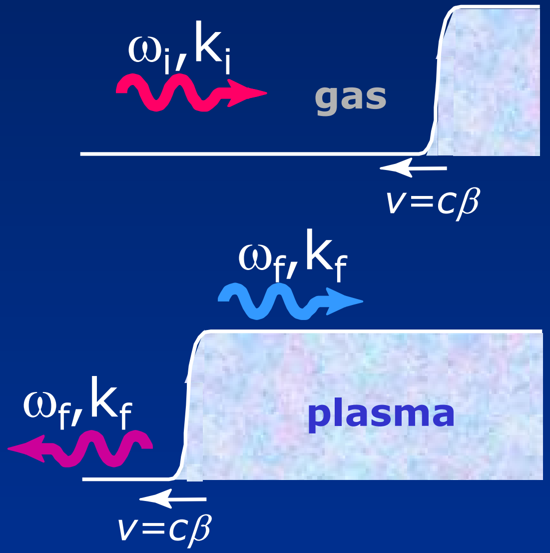
Photon interraction wit ionization fronts

Co-propagation (-)



$$\Delta\omega \approx \frac{\omega_{po}^2}{2\omega_0}\,\frac{\beta}{1\pm\beta}$$

Counter-propagation (+)



- **Reflection in counter-propagation (relativistic mirror)**

$$\Delta\omega = \omega_0 \frac{2\beta}{1-\beta}$$

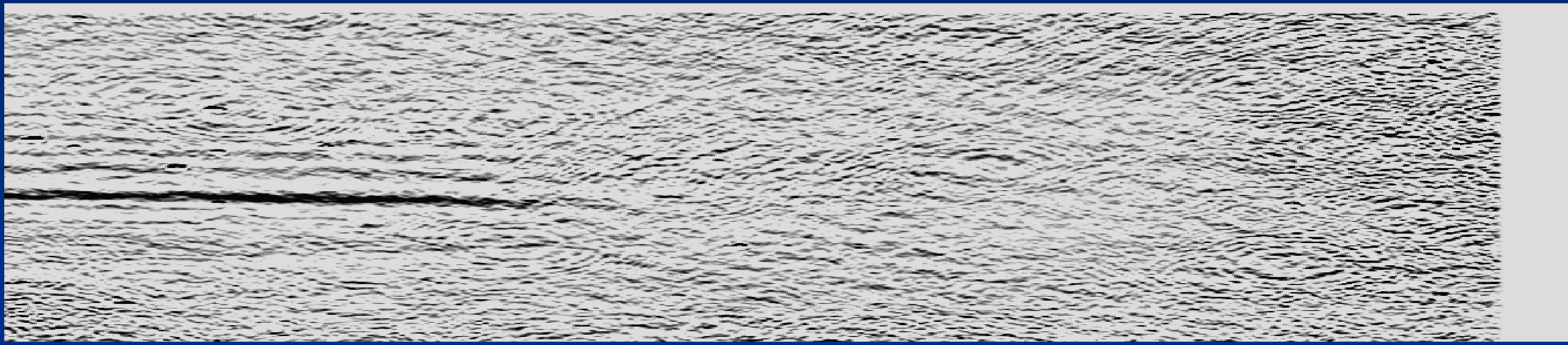
- **Plasma formation (flash ionization) $\beta \to \infty$** ⇒

$$\Delta\omega \approx \frac{\omega_{po}^2}{2\omega_0}$$

Intense laser pulse in a gas jet
Relativistic ionization fronts

Shadow images of a relativistic front

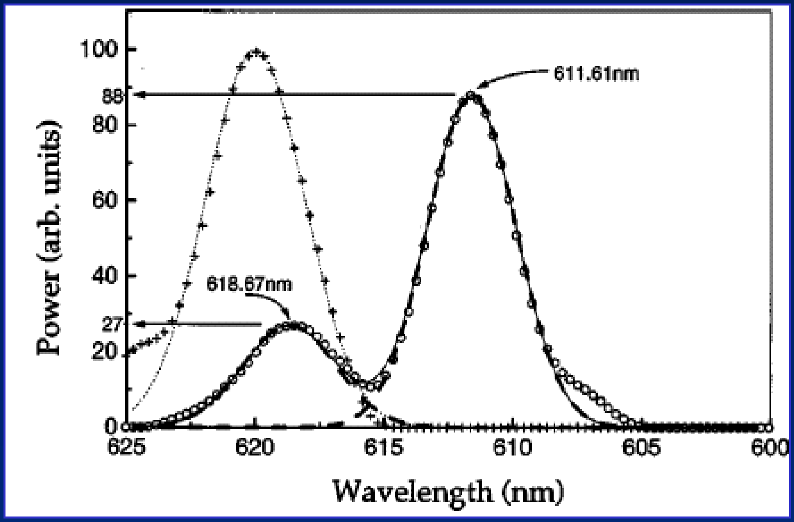
t_0



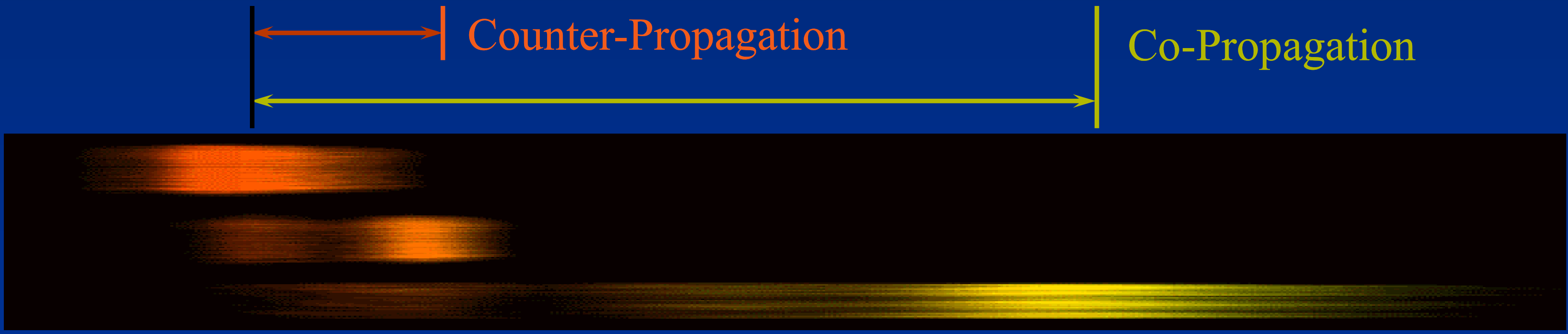
t_1

(Experiments done in collaboration with LOA, France)

Photon acceleration



Laser pulse
65 fs, 2.5 mJ @ 620 nm


Counter-Propagation

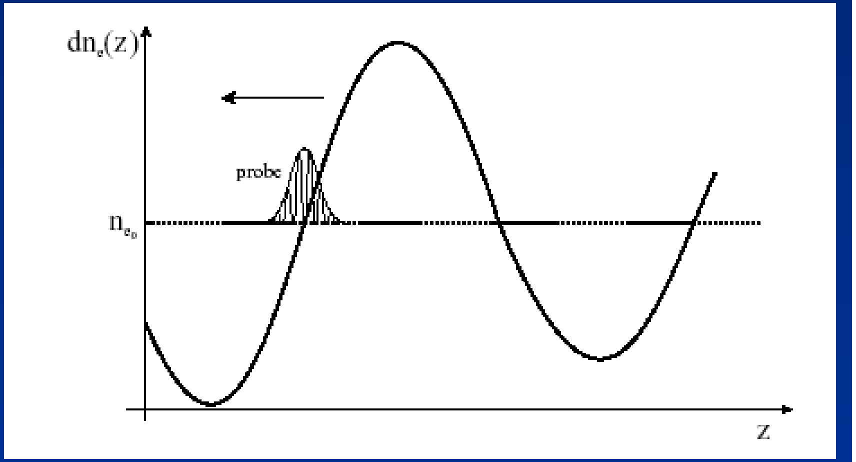
Co-Propagation

Simultaneous measurement:
β=0.942, n=4.26 x 10^{19} cm^{-3}

Dias et al. PRL (1997)

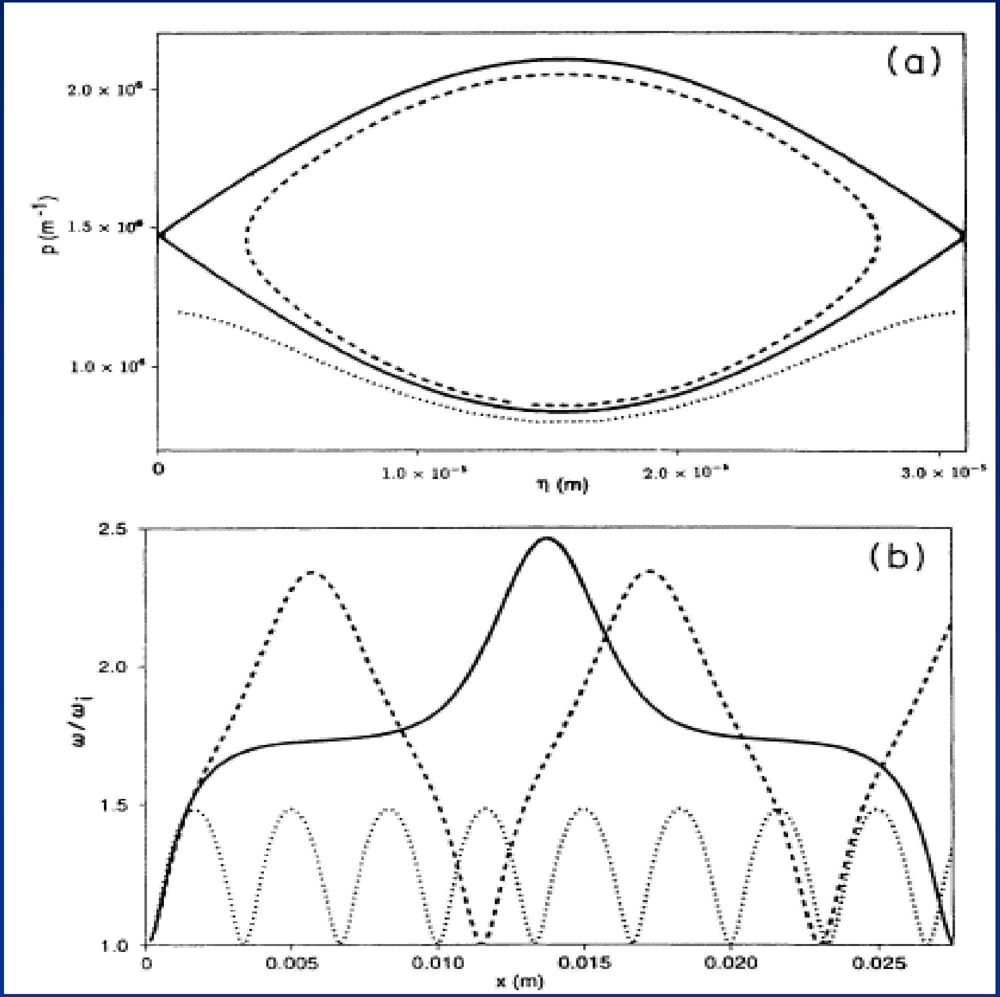
Photon dynamics in a wake field

Laser probe diagnostic for laser accelerators



Wakefield = relativistic electron plasma wave produced by a pump laser pulse

Phase space plot



frequency shift

Photon trapping in laser wakefield

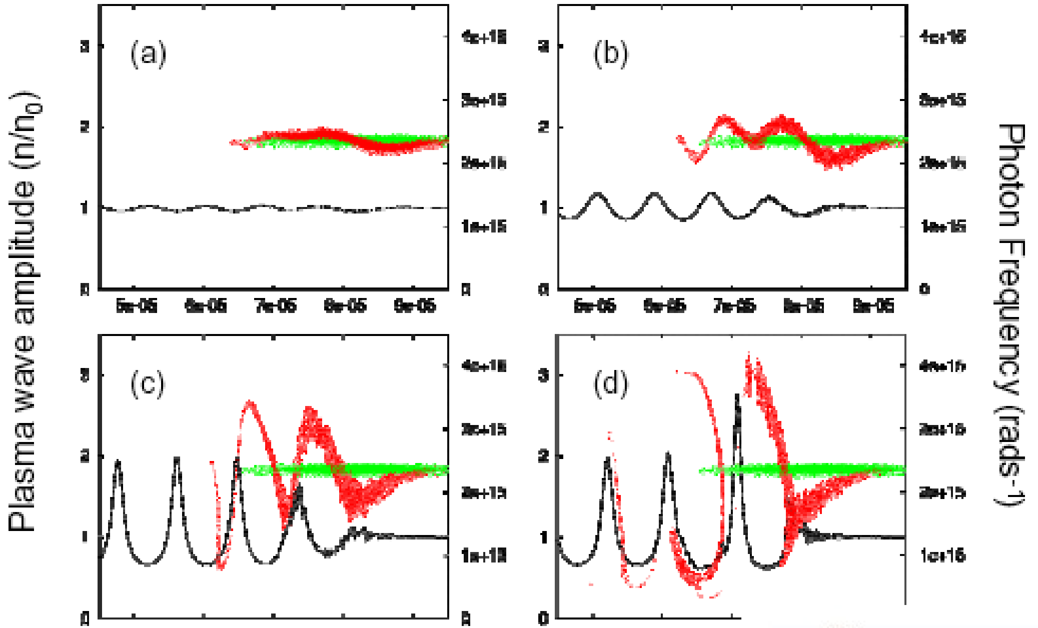
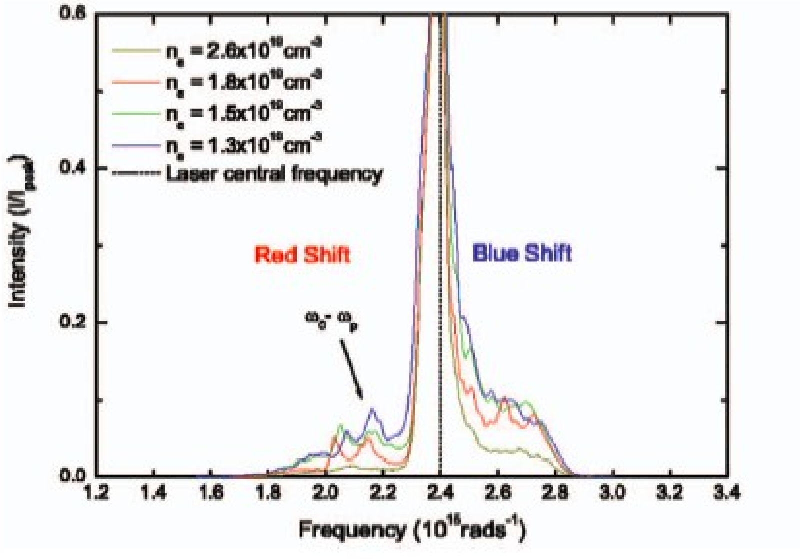


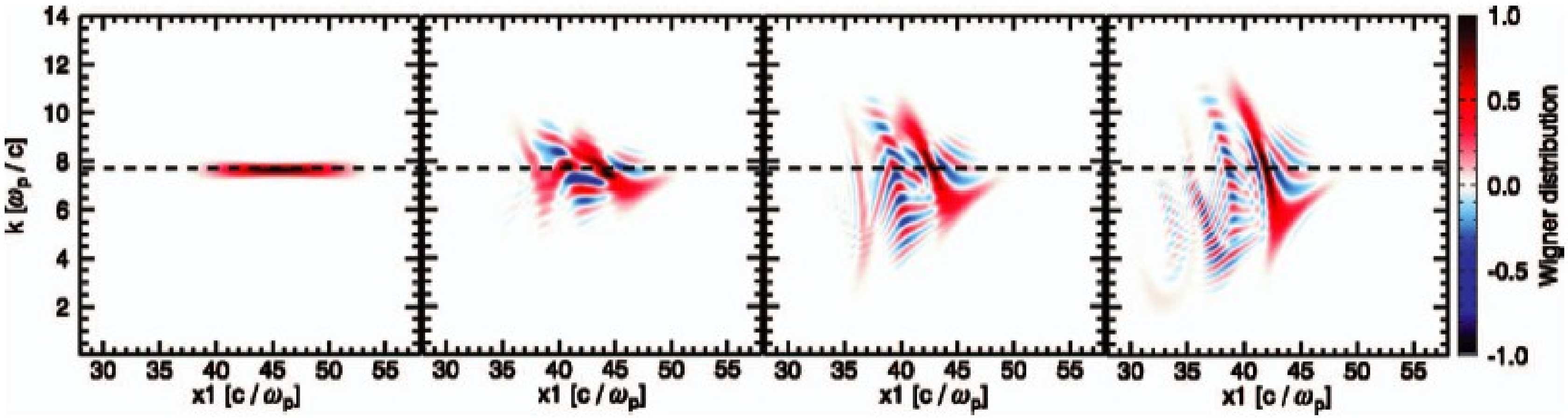
FIG. 2: Phase space plot when the laser puls
a) 200 b) 500 c) 750 and d) 1000 μm in a
3.6×10^{19} cm^{-3}

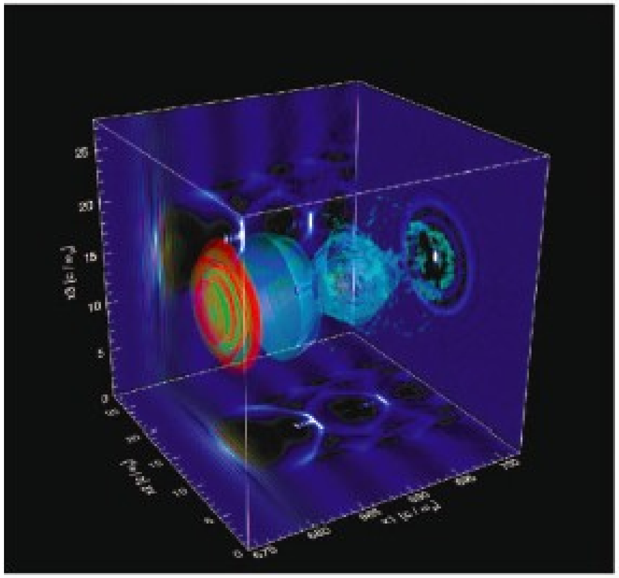


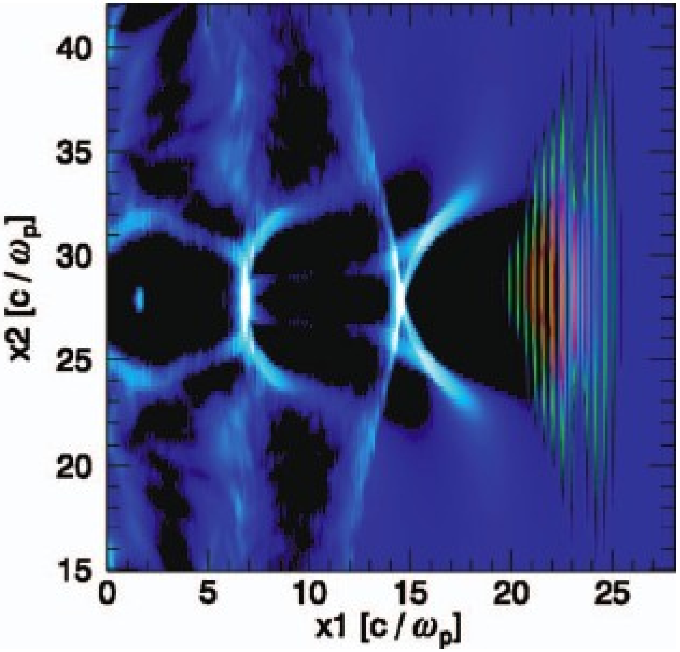
R. Trines (simulations)

C. Murphy (experiments)

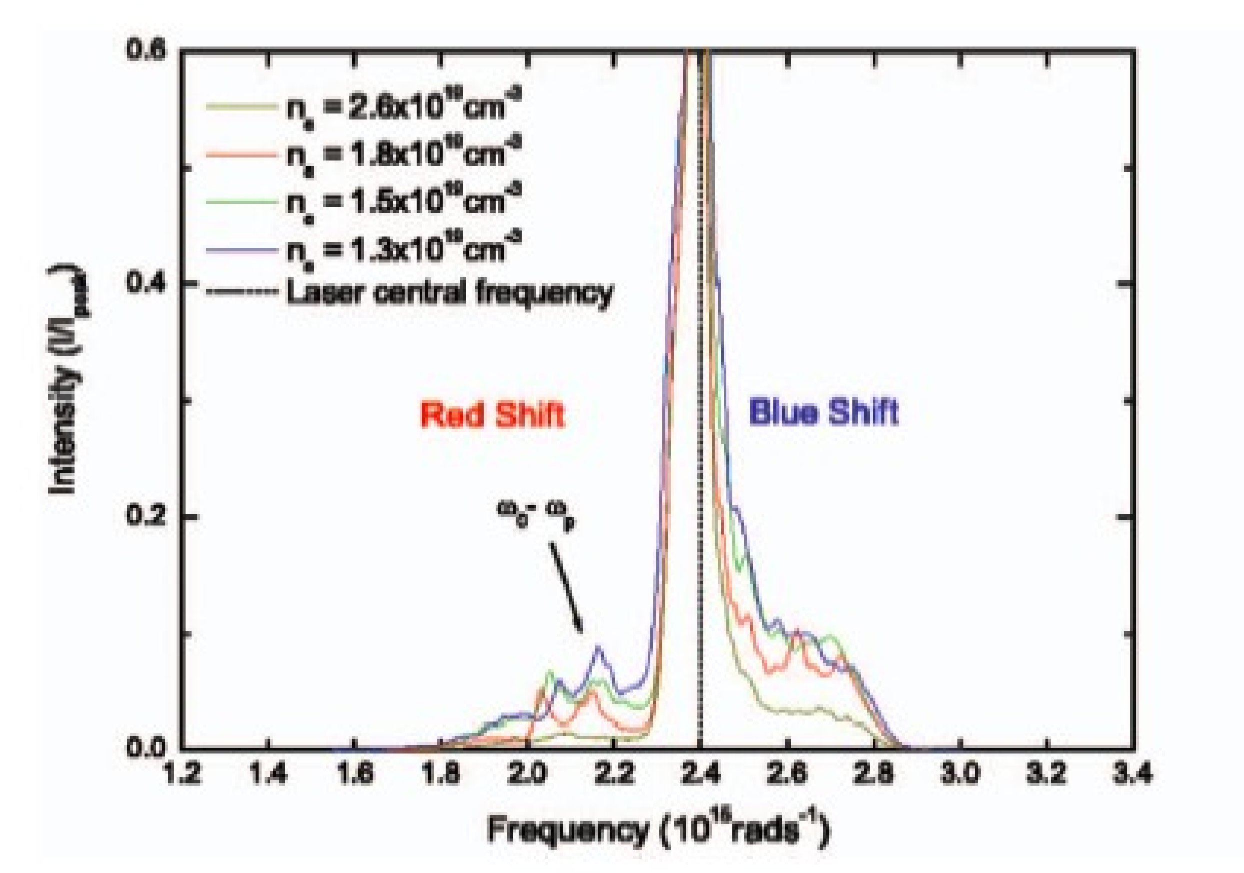
Confirmed by PIC code simulations







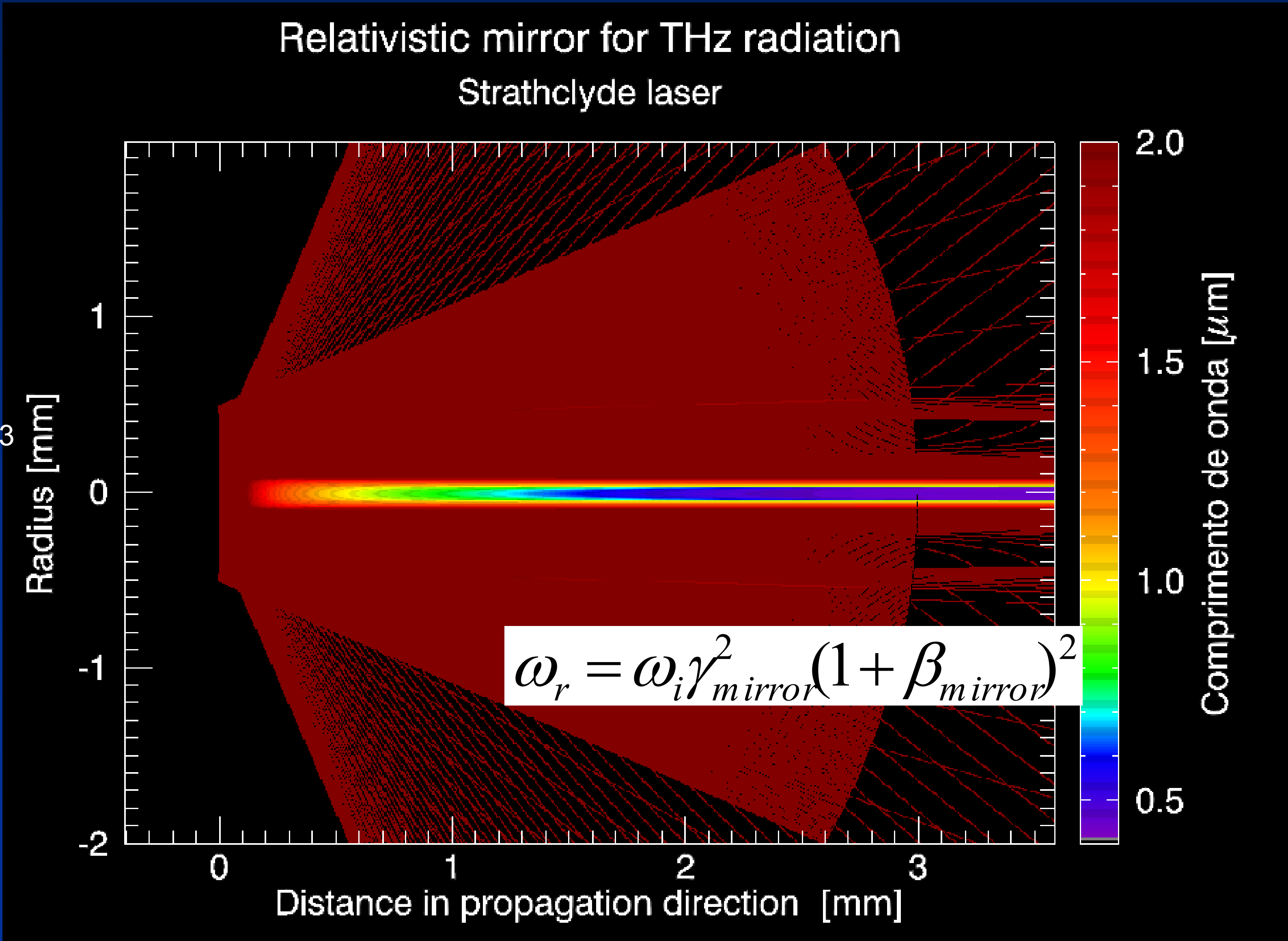
Laser wake field experiments at RAL



C. Murphy et al. PoP (2006)

Photon scattering by a ionization front

- Beta 0.997
- n_{Ar} 1×10^{19} cm^{-3}

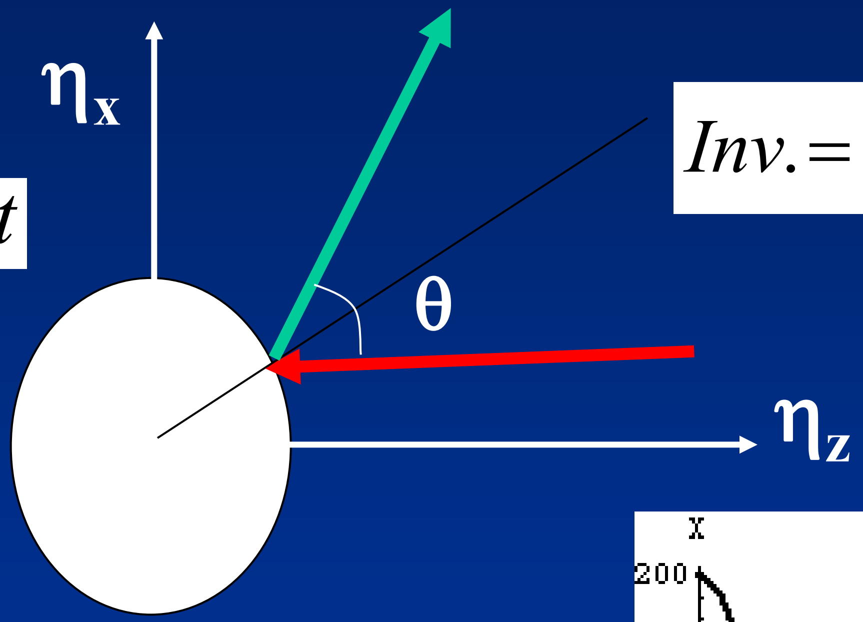


Relativistic mirror for THz radiation

Strathclyde laser

$$\omega_r = \omega_i \gamma_{mirror}^2 (1+\beta_{mirror})^2$$

Photon Scattering by a relativistic plasma bubble

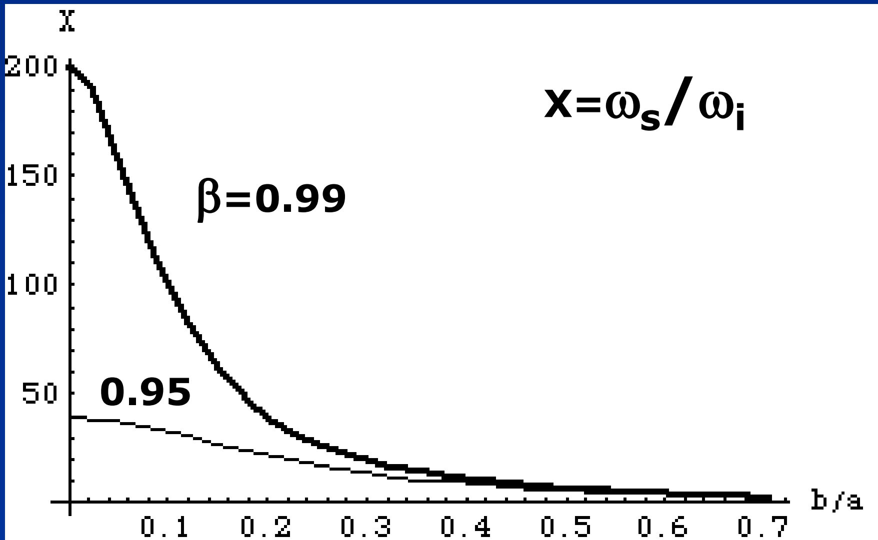


$$\vec{\eta} = \vec{r} - \vec{v}t$$

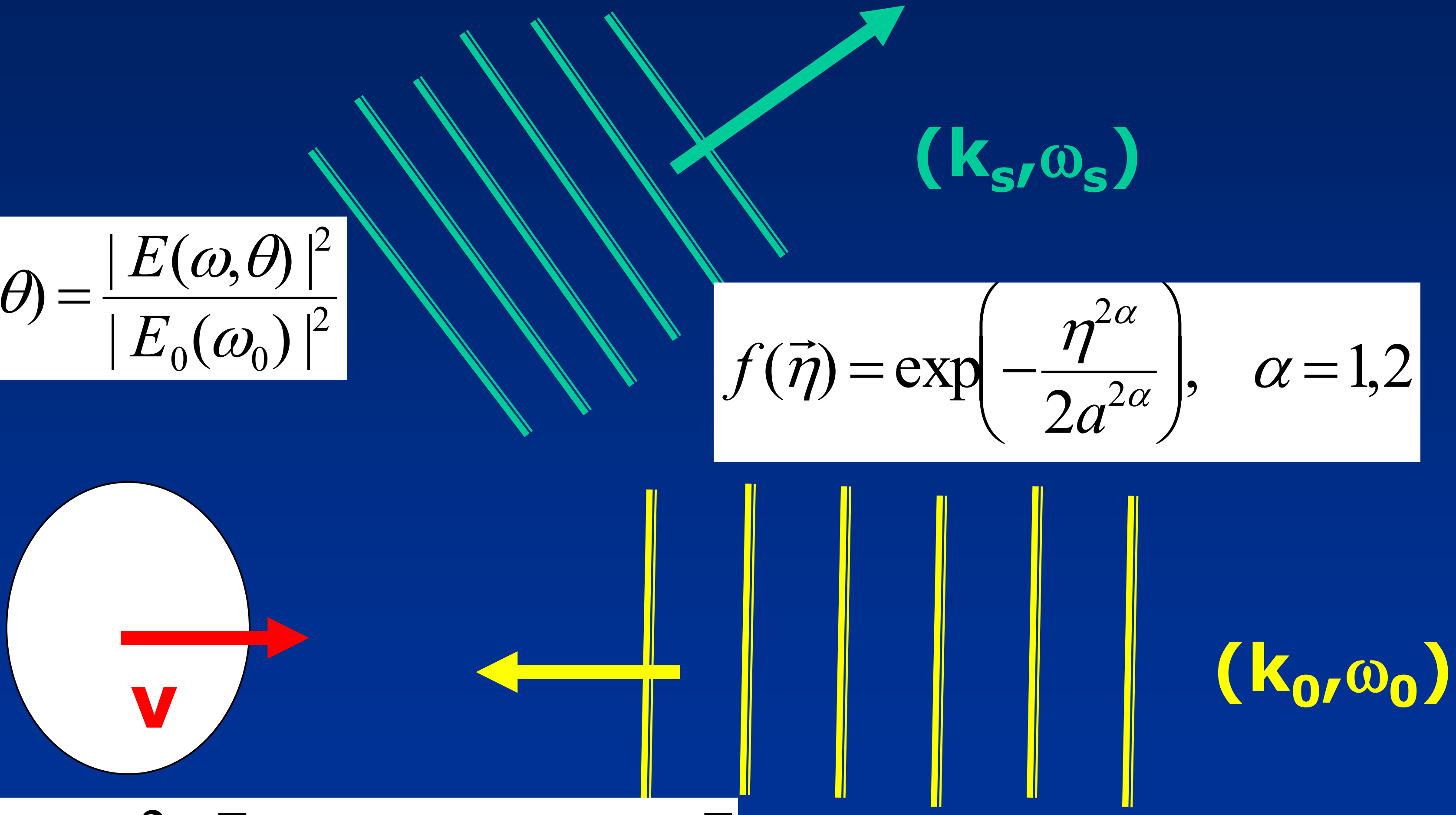
$$Inv. = \sqrt{k^2c^2 + \omega_p^2(\vec{\eta})} - \vec{v}\cdot\vec{k}$$

Scattered frequency

$$\omega_s = \omega_0 \frac{1 + \beta\sqrt{1 + \omega_{p0}^2/\omega_0^2}}{1 - \beta\cos\theta\sqrt{1 + \omega_{p0}^2/\omega_s^2}}$$



Photon-bubble scattering problem



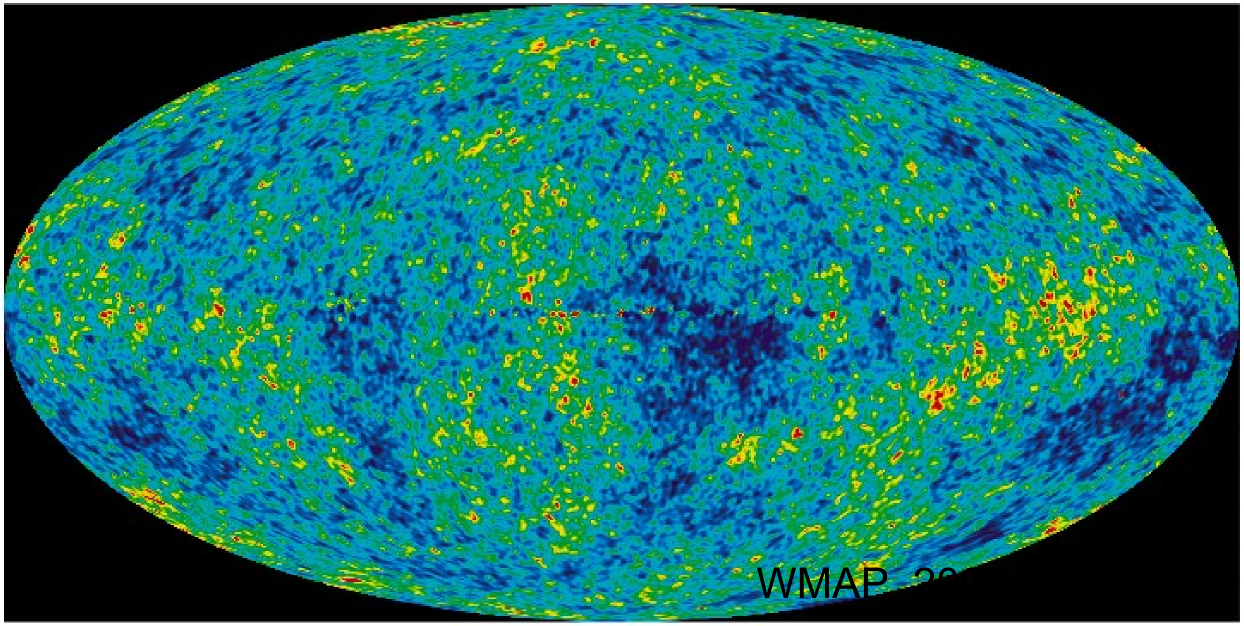
$$S(\omega_0,\omega,\theta)=\frac{|E(\omega,\theta)|^2}{|E_0(\omega_0)|^2}$$

$$f(\vec{\eta})=\exp\left(-\frac{\eta^{2\alpha}}{2a^{2\alpha}}\right), \quad \alpha=1,2$$

$$\omega_p^2=\omega_{p0}^2\left[1-\varepsilon f(\vec{r}-\vec{v}t)\right]$$

Photon acceleration in a gravitational field scenario

Cosmic Temperature map



WMAP 20

Sachs-Wolfe effect is photon acceleration

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Low plasma density limit

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Low frequency shift limit

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TIFF (Uncompressed) decompressor
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Mendonça, Bingham and Wang, CQG (2008)

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Moving perturbations

Dynamical invariant

Generalized Sachs-Wolfe

Purely vacuum perturbations

This is not a Doppler correction!

Photons in a Gravitational wave

Perturbed flat space time

$$g^{ij} = \eta^{ij} + h^{ij}$$

$$\eta^{\alpha\beta} = -\delta^{\alpha\beta}, \ \eta^{00} = 1$$

Weak gravitational wave

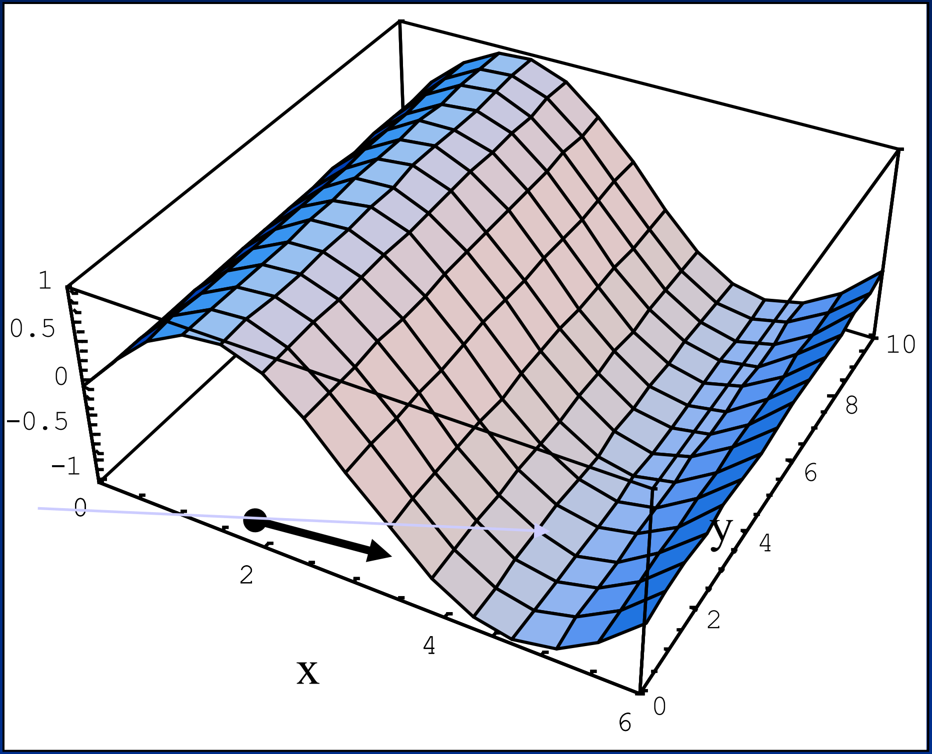
$$a = A\sin(k_0 x^0 + k_1 x^1 + \phi) = A\sin(qx - \Omega t + \phi)$$

$$h_{22} = -h_{33} = a$$

Photon dispersion relation

$$\omega = kc\left\{1 + \frac{a}{2}\left[\left(\frac{k_y}{k}\right)^2 - \left(\frac{k_z}{k}\right)^2\right]\right\}$$

Nearly parallel photon propagation



Perpendicular photon motion

$$y(t) = ck_y \int^t \frac{1 + a(t')}{k(t')} dt'$$

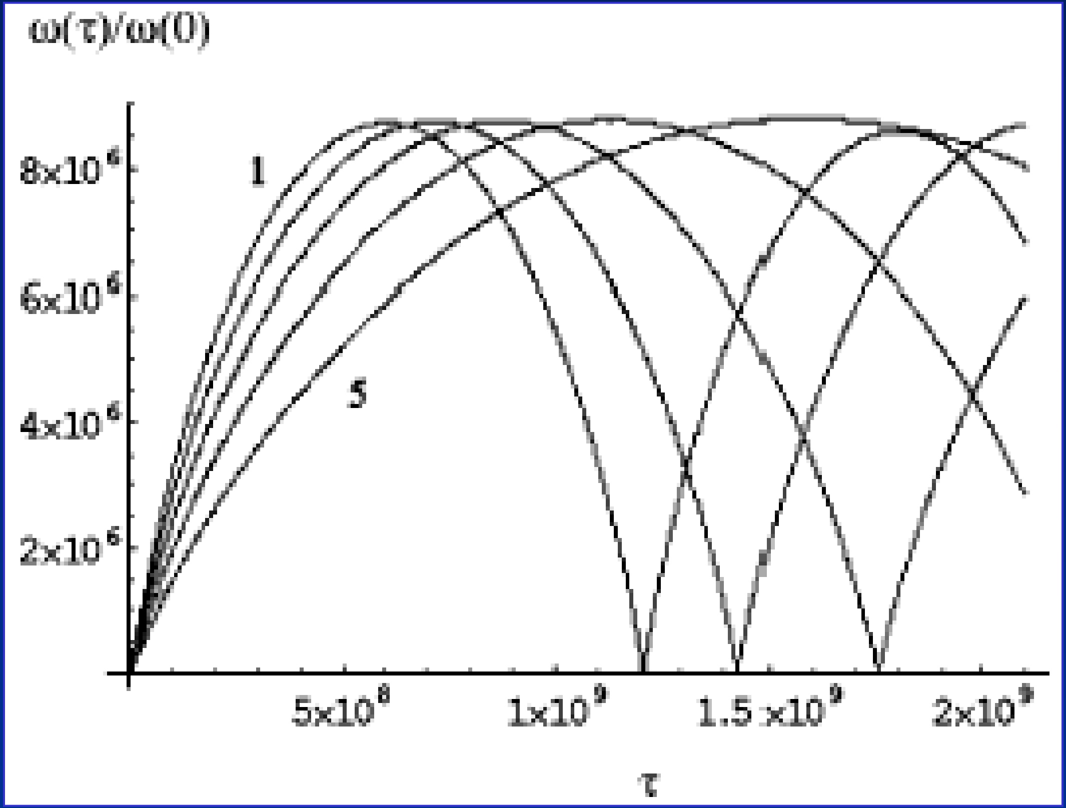
Parallel photon motion

$$\frac{dx}{dt} = c\frac{k_x}{k}$$

$$\frac{dk_x}{dt} = -\frac{1}{2}\left(\frac{k_y}{k}\right)^2 \frac{\partial a}{\partial t}$$

Typical photon trajectories

$$\frac{d\omega}{dt} = c\frac{dk_x}{dt}$$



- Photon acceleration by gravitational waves

Gravitational wave frequency: $\Omega=10^4$ s^{-1}

$\tau=Act/2$

and amplitude A $=10^{-4}$

Conclusions

- Photon acceleration is a first order effect;
- Experimental evidence: relativistic fronts, wakefields (plasmas), self and cross phase modulations (optics);
- It can be seen as space-time refraction;
- It can also be seen as a scattering process;
- Interaction with Gfields and Gwaves (γ ray bursts, Sachs-Wolfe effect);
- Applications: plasma diagnostics, ultra-short laser pulses, sub-cycle and attosecond optics, tunable radiation sources.