Surface Plasmons in Ordered and Disordered Chains of Metal Nanoparticles

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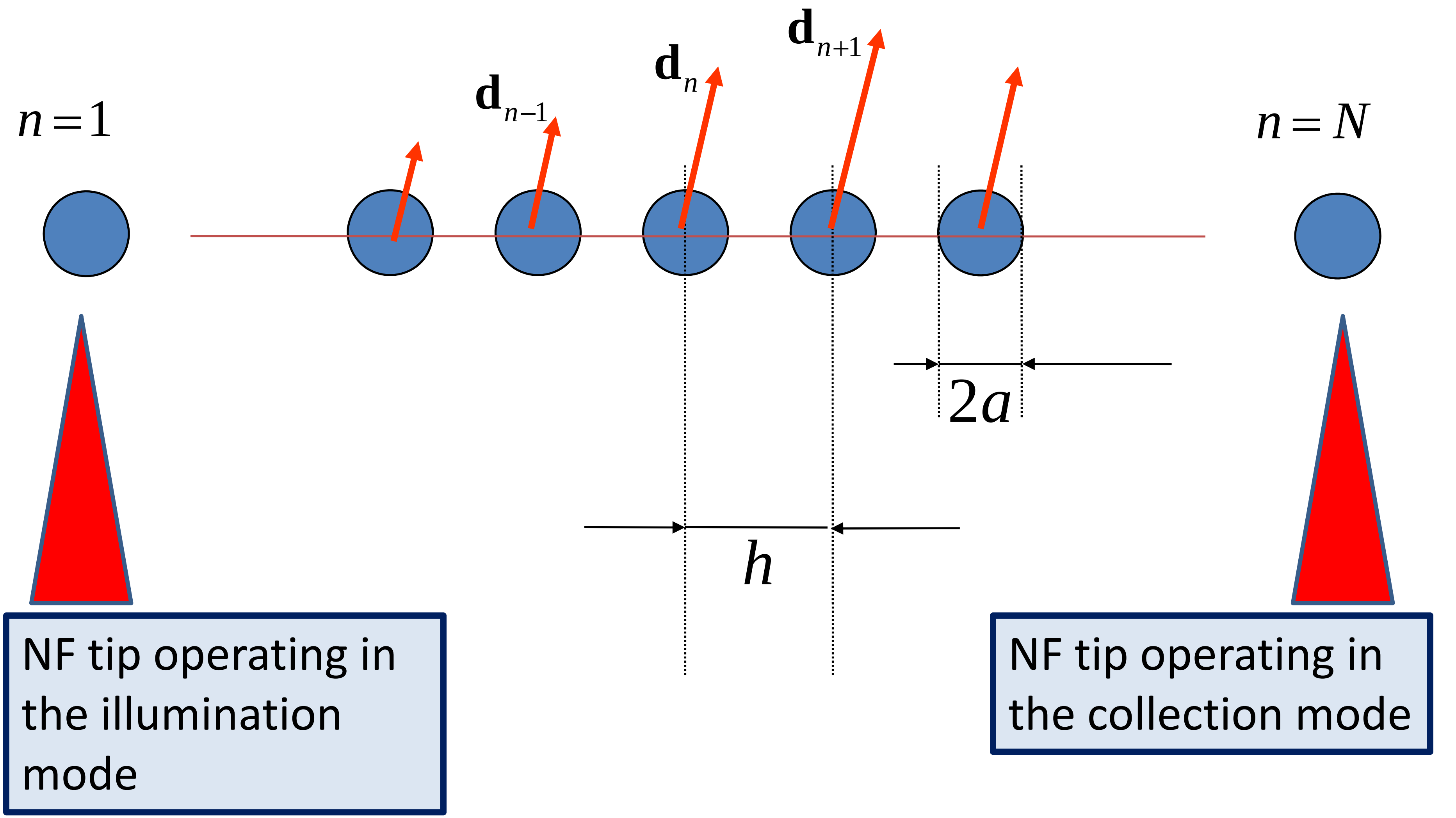
Physical Model



The Dipole Approximation

$$\mathbf{d}_n = \alpha_n \left[\mathbf{E}_n + \sum_{m \neq n} \hat{G}_k(x_n, x_m)\mathbf{d}_\mathbf{m} \right]$$

The coupled-dipole equation in the frequency domain

$$k = \frac{\omega}{c} = \text{const}$$

α_n - Polarizability of the *n*-th particle

$\hat{G}_k(x_n, x_m)$ - Green's function for the electric field in vacuum

$\mathbf{E}_n \propto \delta_{n1}$ - Electric field produced by the firsrt tip (the incidentb field)

Model for the Polarizability, α

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$ [Drude model for the dielectric function]

$$\mathrm{Re}\left(\frac{1}{\alpha}\right) = \frac{1}{a^3}\left[1 - \left(\frac{\omega}{\omega_F}\right)^2\right]; \quad \mathrm{Im}\left(\frac{1}{\alpha}\right) = -i\left(\frac{2k^3}{3} + \frac{1}{a^3}\frac{\omega\gamma}{\omega_F^2}\right)$$

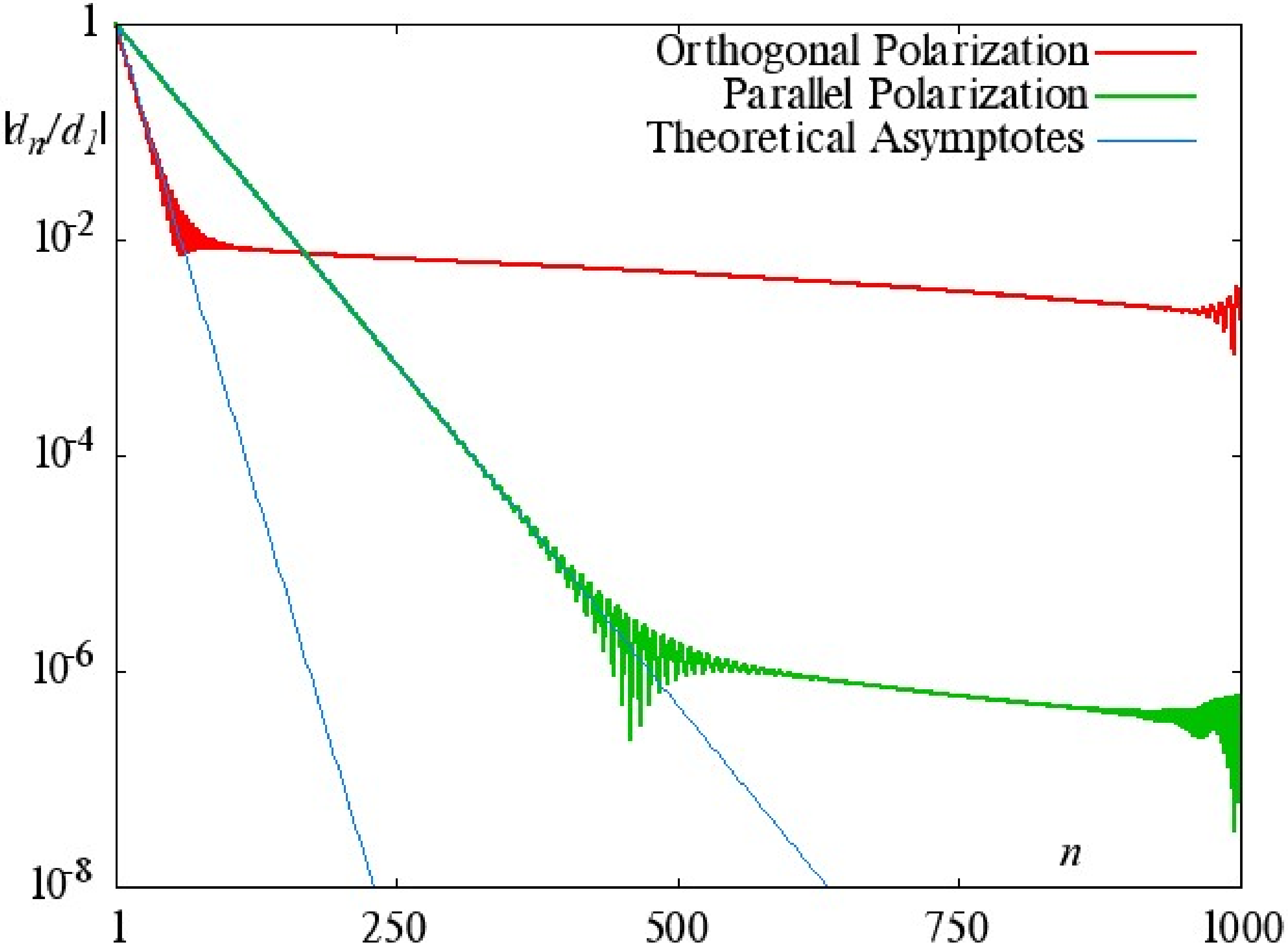
[Quasistatic approximation + the first radiative correcton]

a - Nanosphere radius

$\omega_F = \omega_p/\sqrt{3}$ - Frohlich frequency

$k = \omega / c$

Simulation in a Finite Chain of N=1000 Identical Nanospheres



Parameters:

$\omega = \omega_F$

$\frac{\gamma}{\omega_F} = 0.002$

$\lambda = \frac{2\pi c}{\omega} = 10h$

$h = 4a$

Analytical Solution in an Infinite Periodic Chain

$$d_n^{(\|,\perp)} = \int_{-\pi/h}^{\pi/h} \frac{E_n^{(\|,\perp)} e^{iqx_n}}{1/\alpha - S^{(\|,\perp)}(k,q)} \frac{dq}{2\pi}$$

$$S^{(\|,\perp)}(k,q) = 2\sum_{n>0} G_k^{(\|,\perp)}(0,x_n)\cos(qx_n) \quad \text{[The dipole sum]}$$

$$\text{If } q > k,\ \ \mathrm{Im}[S^{(\|,\perp)}(k,q)] = -\frac{2k^3}{3}$$

The dispersion equation:

$$Z(k,q) = 1/\alpha - S^{(\|,\perp)}(k,q) = 0 \quad \Rightarrow \quad \omega = f(q)$$

The Quasi-Particle Pole Approximation

Let, for a given value of k, $Z(k,q_0) \approx 0$ and $q_0 > k$

$$Z(k,q_0) = 1/\alpha - S(k,q_0) \approx 0$$

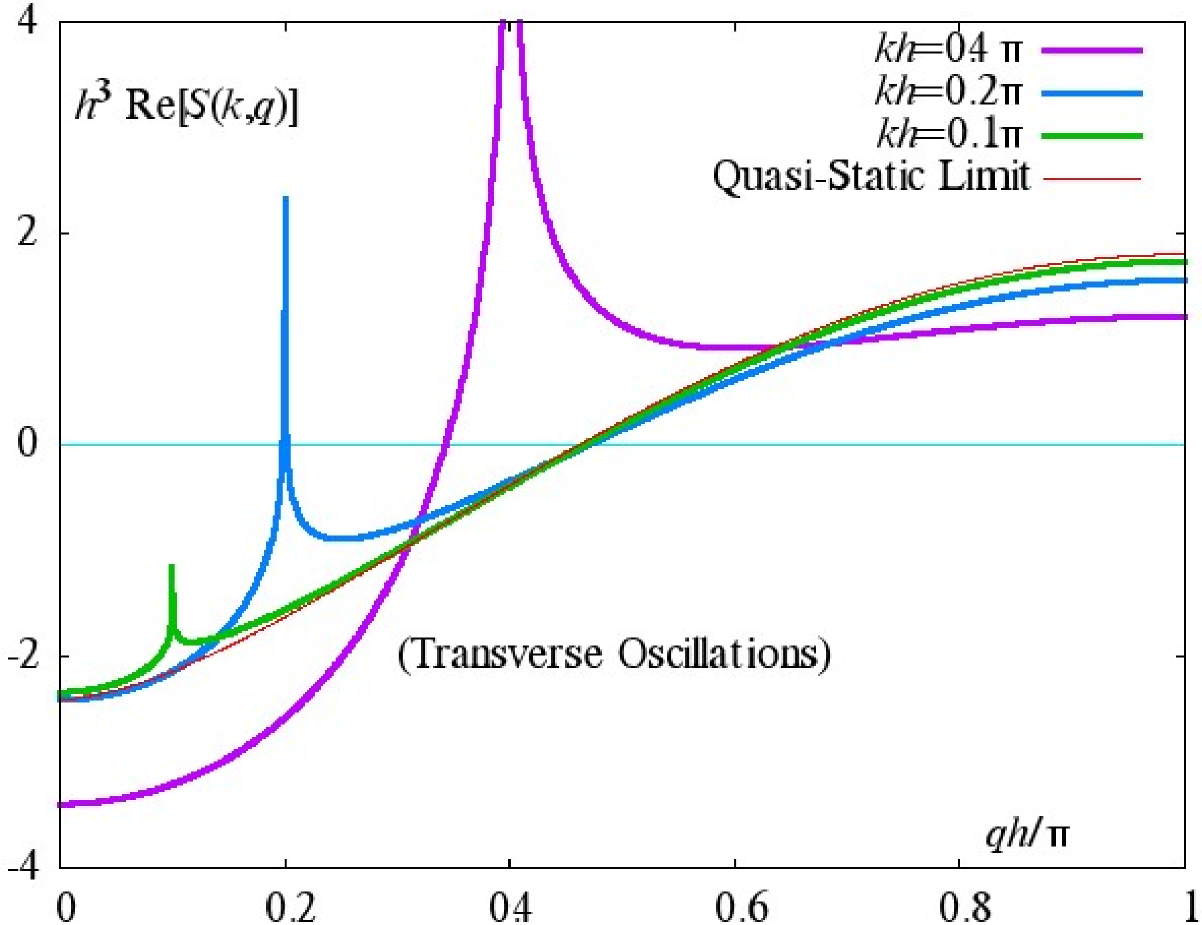
Then we write approximately:

$$S(k,q) \approx \mathrm{Re}\,S(k,q_0) + (q-q_0)\left.\frac{\partial\,\mathrm{Re}\,S(k,q)}{\partial q}\right|_{q=q_0} - i\,\frac{2k^3}{3}$$

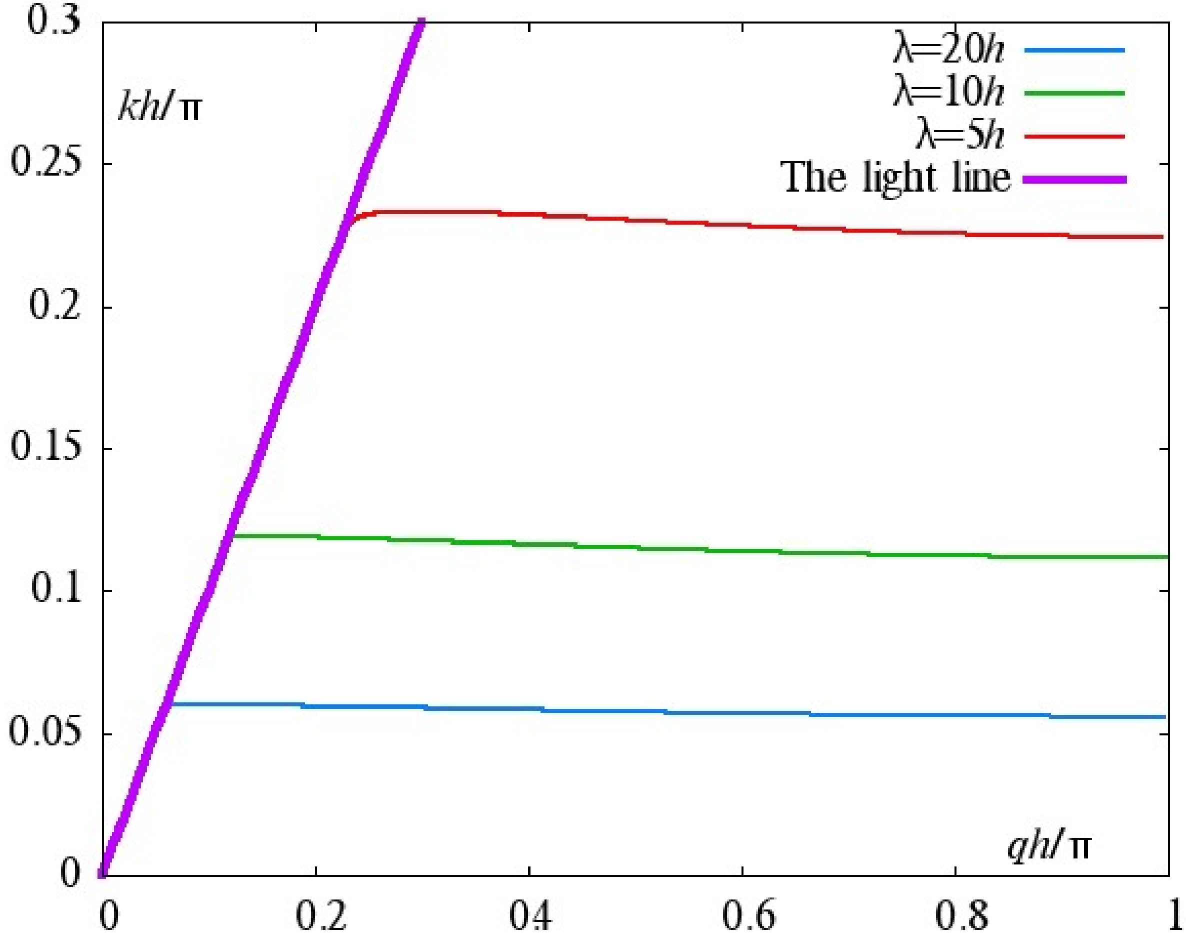
$$\ell = \frac{1}{\delta}\left|\frac{\partial\,\mathrm{Re}\,S(k,q)}{\partial q}\right|_{q=q_0} \qquad \text{[Decay length]}$$

$$\delta = -\mathrm{Im}(1/\alpha) - 2k^3/3 \qquad \text{[Absorption strength]}$$

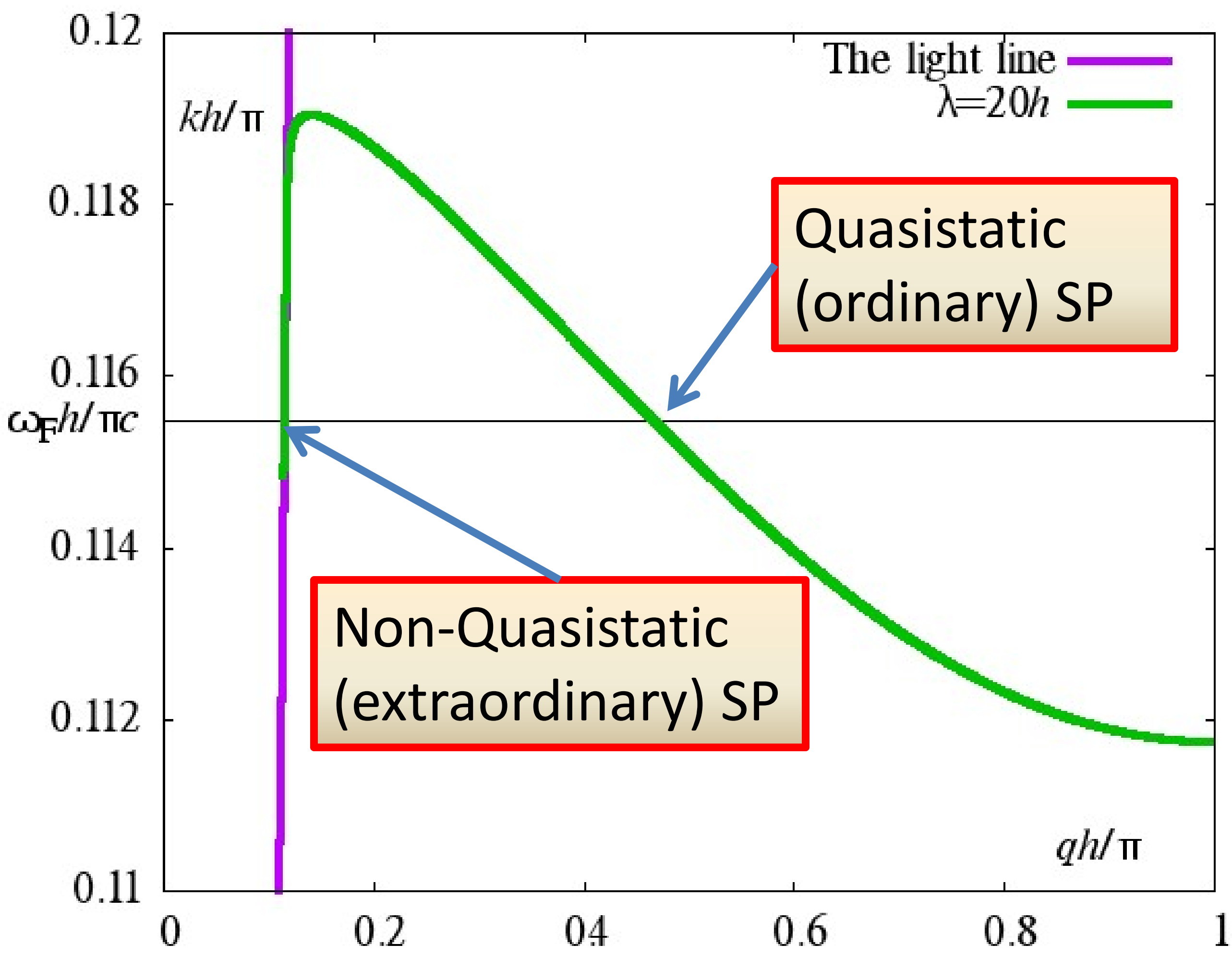
The Dipole Sum (Transverse Oscillations in an Infinite Periodic Chain



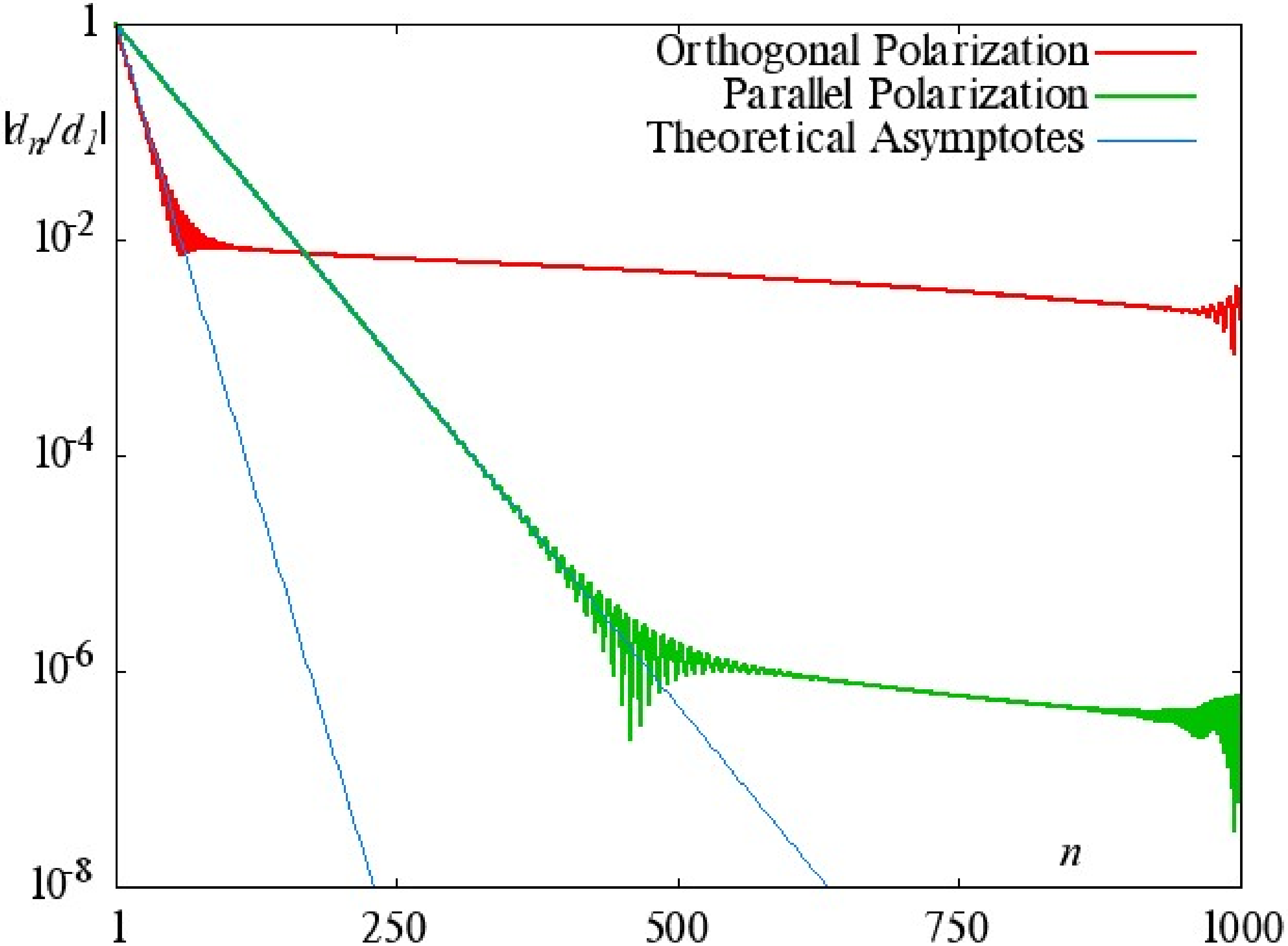
The Dispersion Curve (Transverse Oscillations in an Infinite Ordered Chain)



Dispersion Curves (continued)



Simulation in a Finite Chain of N=1000 Identical Nanospheres



Parameters:

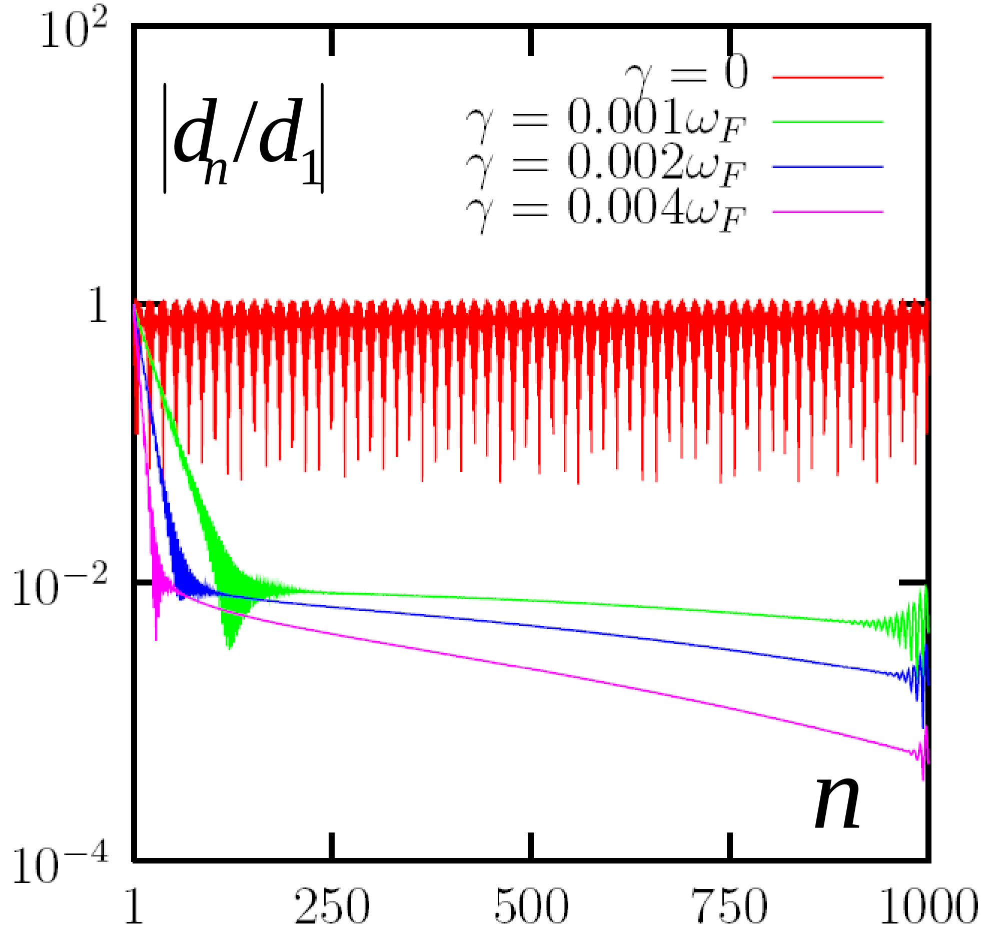
$\omega = \omega_F$

$\dfrac{\gamma}{\omega_F} = 0.002$

$\lambda = \dfrac{2\pi c}{\omega} = 10h$

$h = 4a$

Effect of Ohmic Losses



Parameters:

$\omega = \omega_F$

$\frac{\gamma}{\omega_F}$ varies

$\lambda = \frac{2\pi c}{\omega} = 10h$

$h = 4a$

Effects of Disorder

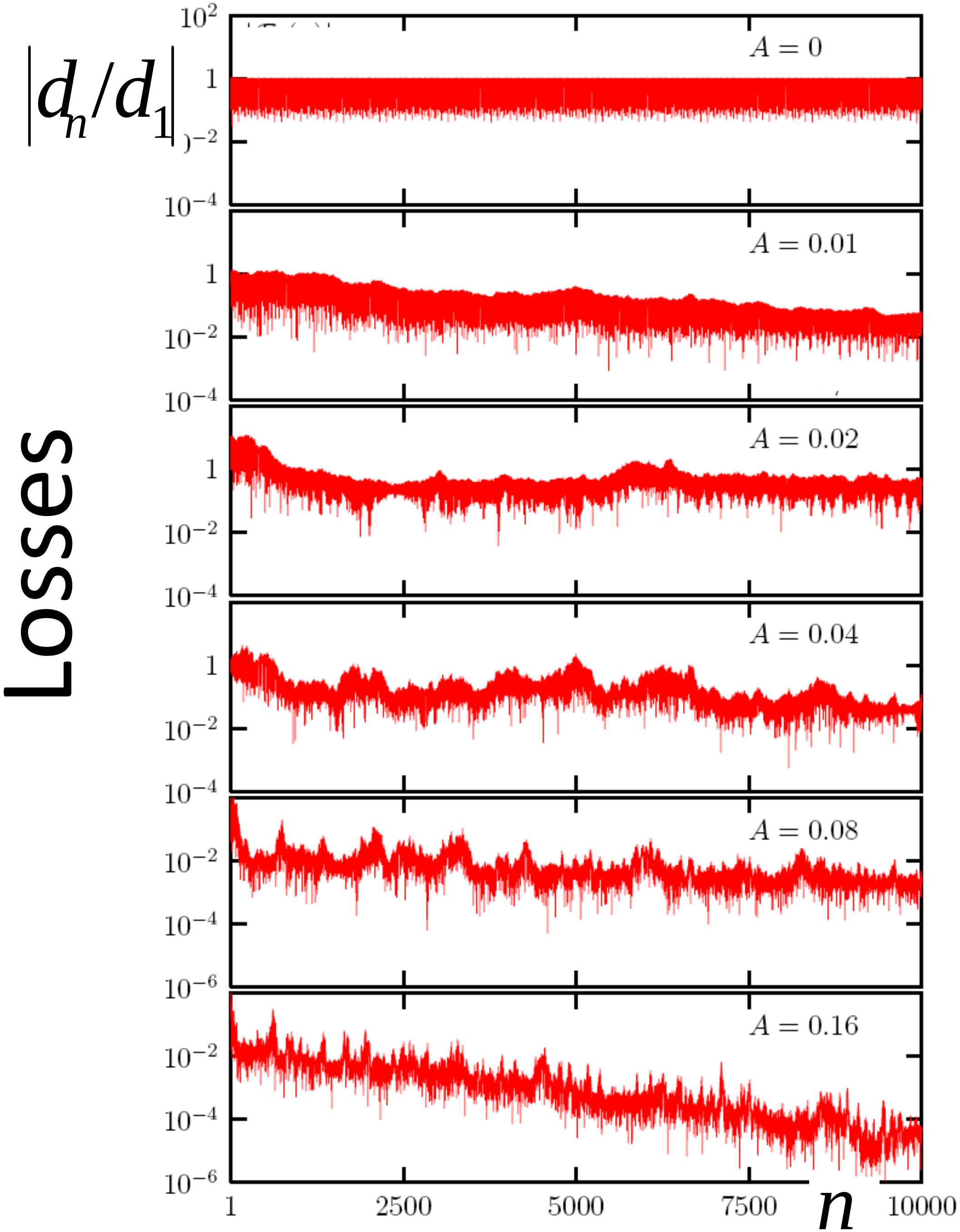
- Off-diagonal disorder (disorder in the nanoparticle positions)

  We assume here that the position of the *n*-th particle is evenly distributed in the interval $[h(n-A), h(n+A)]$, $A \ll 1$

- Diagonal disorder

  [A more subtle effect, not considered in this talk; see Phys.Rev.B **75**, 085426 (2007)]

Off-Diagonal Disorder in the Absence of Ohmic Losses



Parameters:

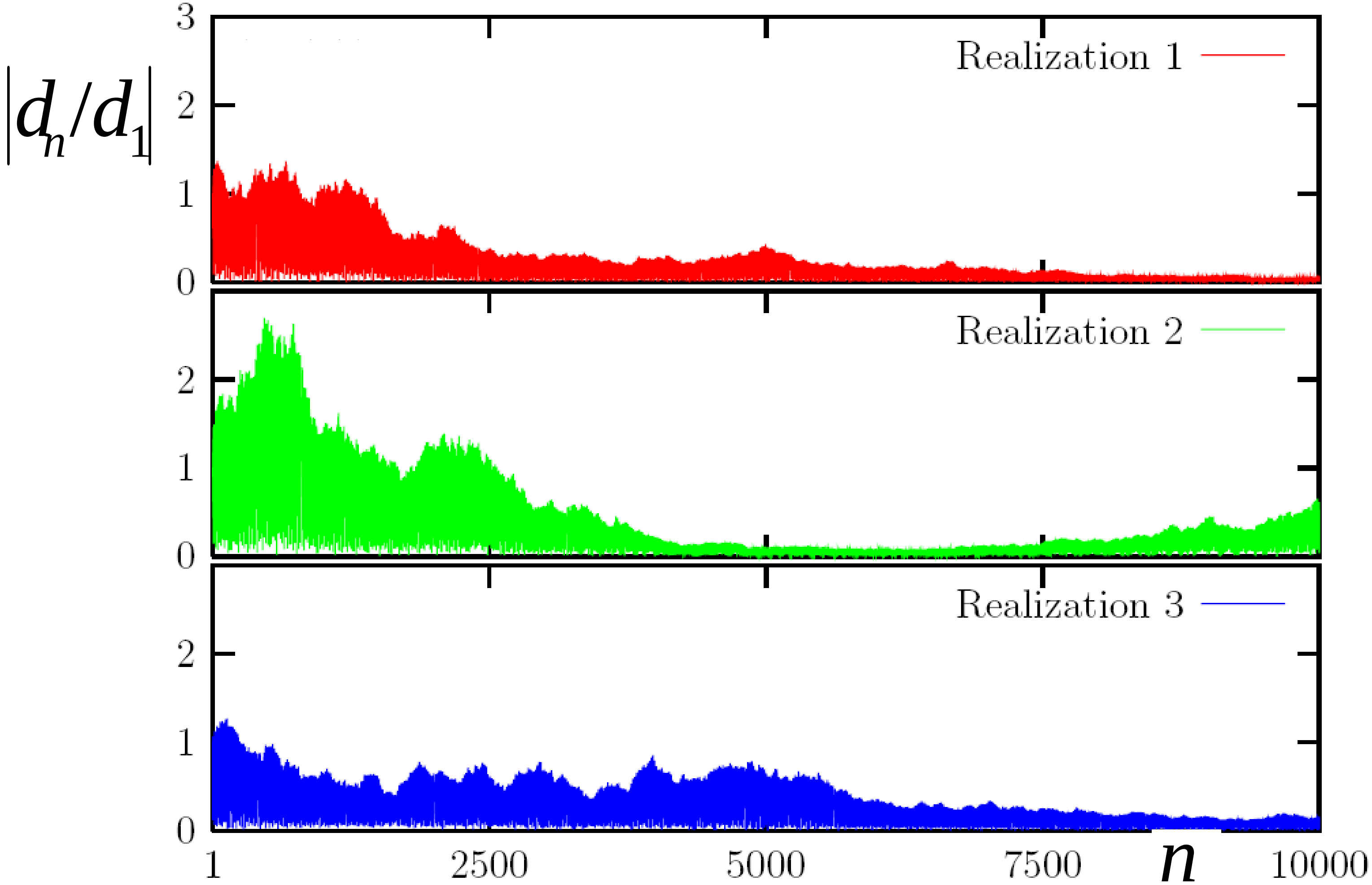
$\omega = \omega_F$

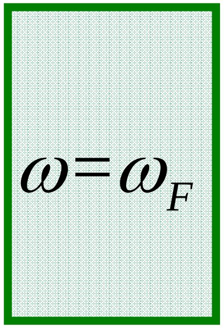
$\frac{\gamma}{\omega_F} = 0$

$\lambda = \frac{2\pi c}{\omega} = 10h$

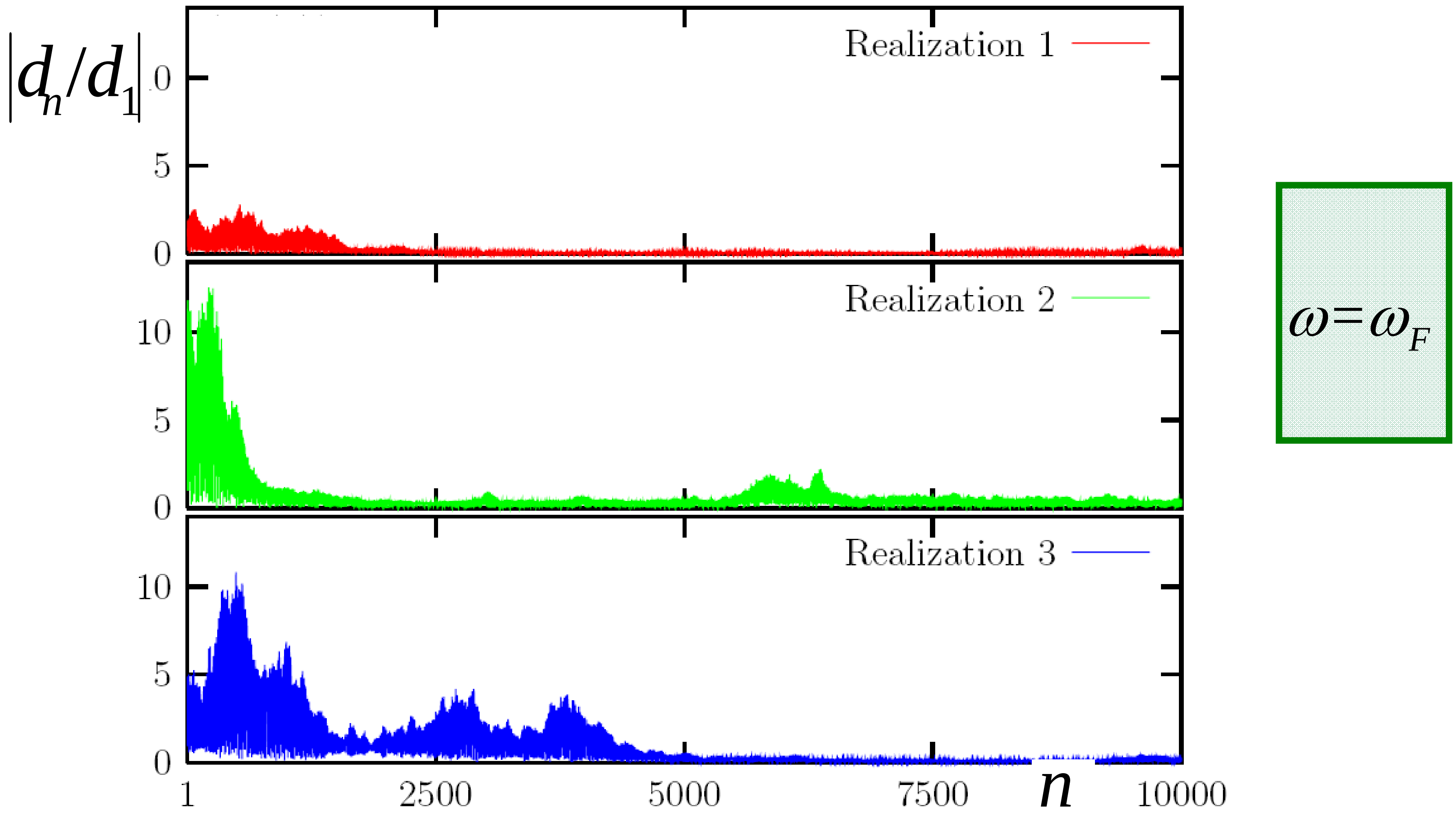
$h = 4a$

Different Realization of Disorder at the Level *A*=0.01

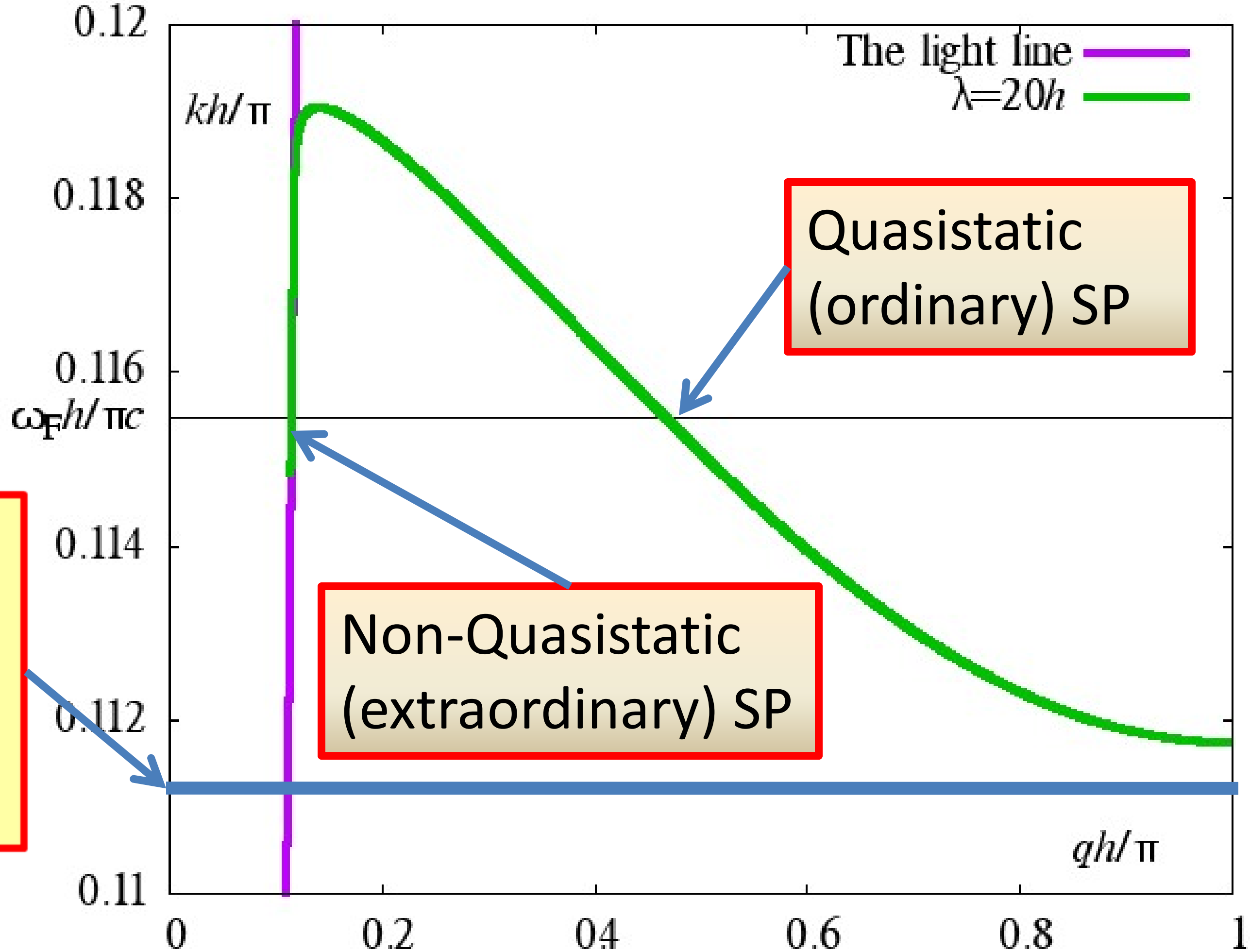




Different Realization of Disorder at the Level A=0.02

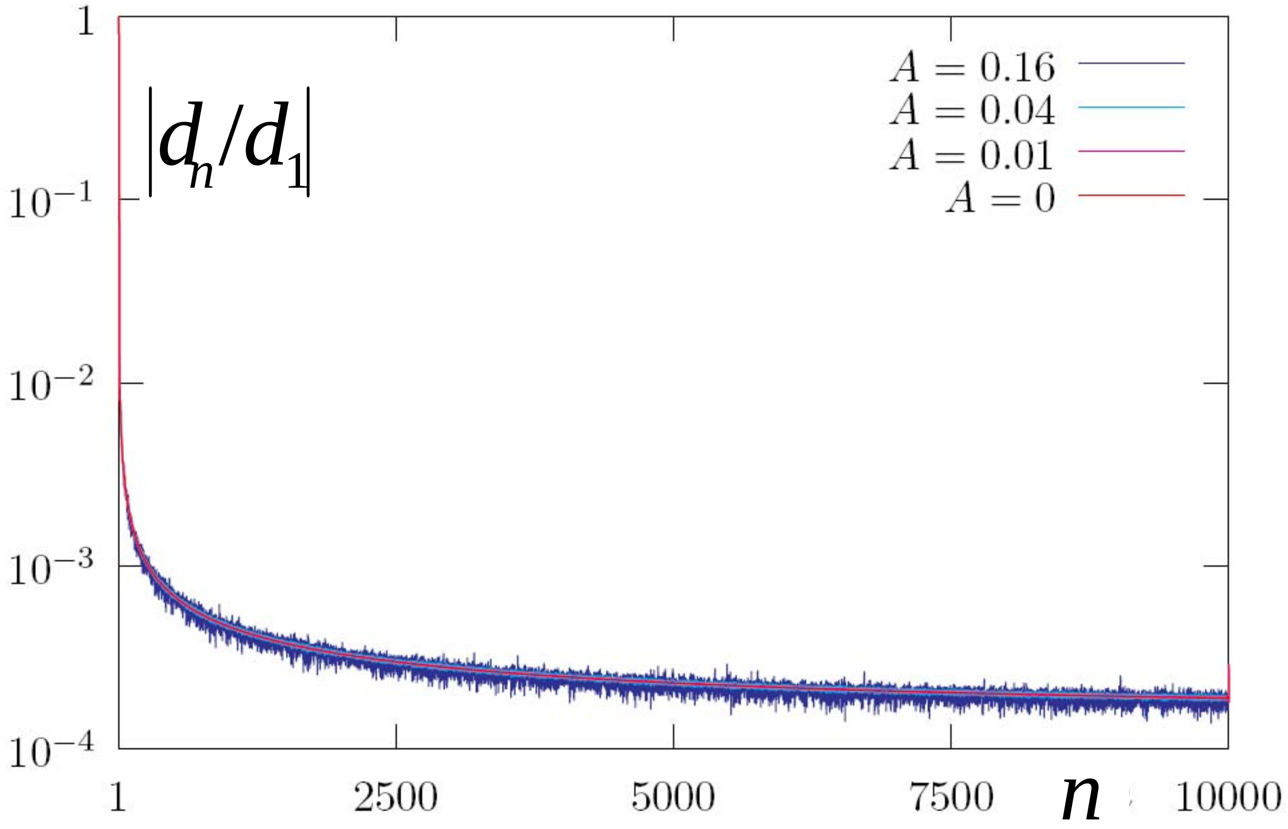


Non-Quasistatic SP at Different Levels of Disorder



Let the frequesncy be small enough so that the ordinary SP is not excited

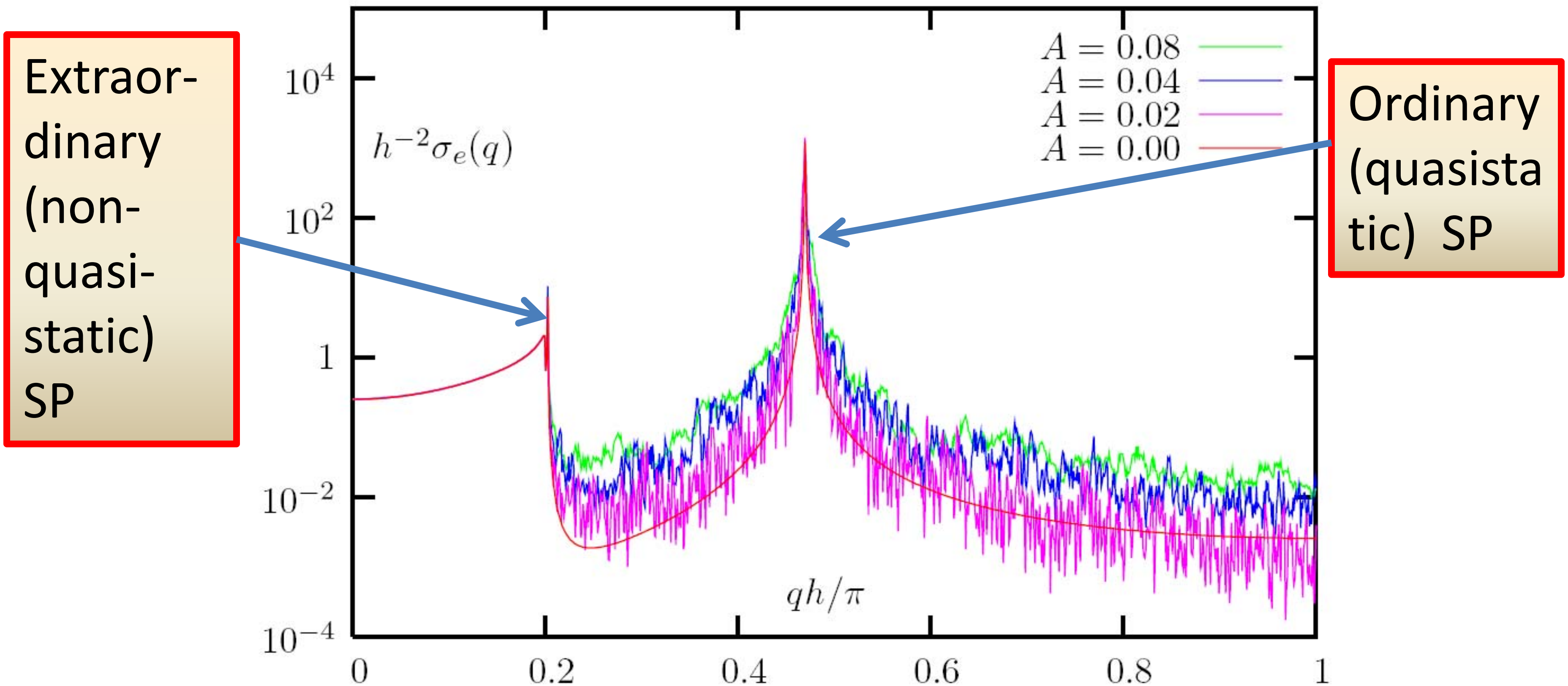
Non-Quasistatic SP at Different Levels of Disorder (continued)



$\frac{\omega}{\omega_F}$=0.984

(small enough so that the ordinary SP is not excited)

Specific Extinction for Excitation by a Plane Wave exp(*iqx*)
(e.g., created by the TIR, *q* can be larger than *k*)



CONCLUSIONS

- Extraordinary SP can propagate to remarkable distances and is affected by the off-diagonal disorder only weakly
- This is in contrast to the ordinary SP which is dramatically affected by Ohmic losses and disorder
- Numerical evidence indicates that the ordinary SP becomes strongly localized in the presence of disorder while the extraoirdinary SP does not.