Optical Manipulation of Matter Waves

Kamran Akbari

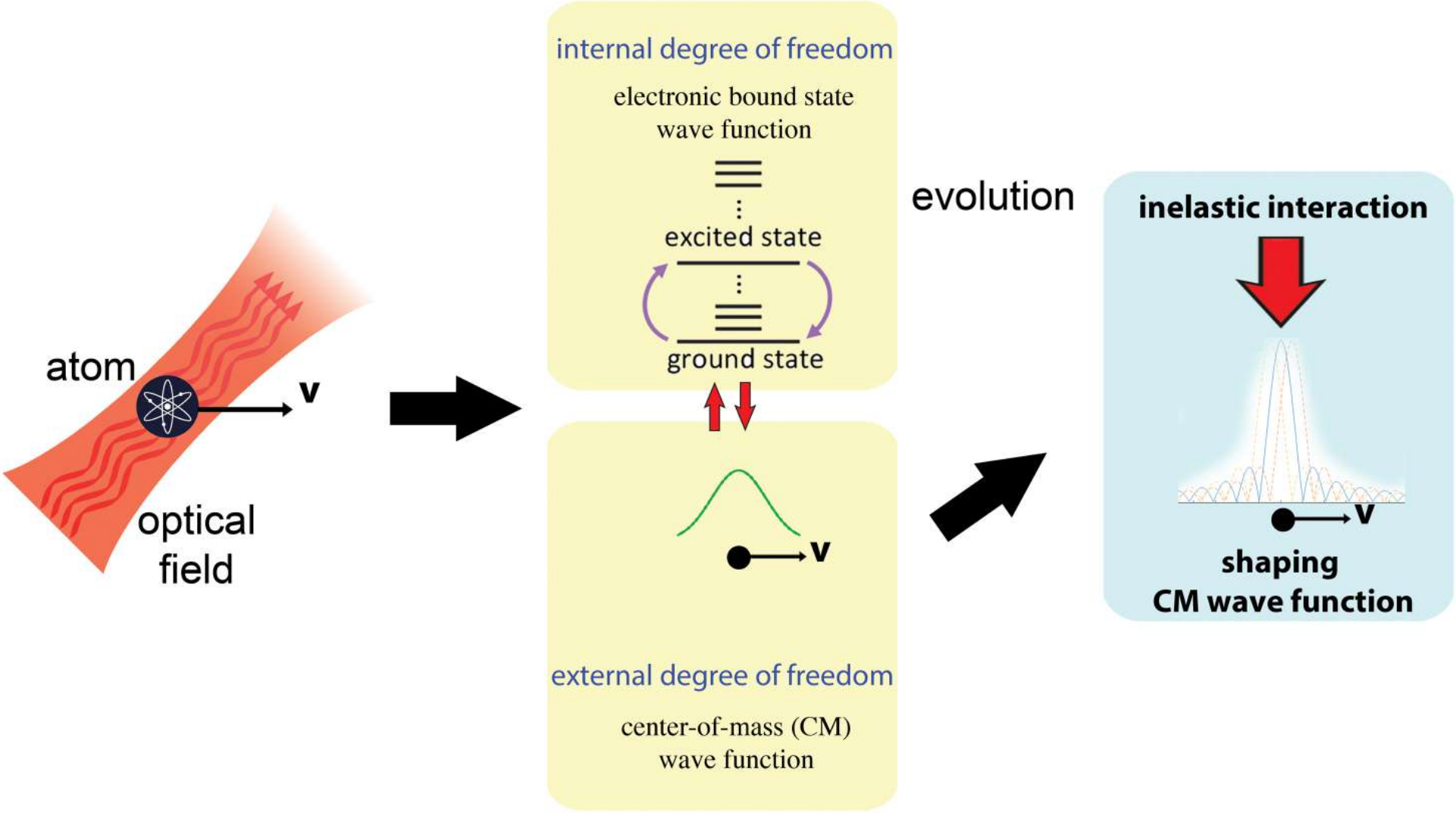
Valerio Di Giulio *and* **Javier García de Abajo**

ICFO-The Institute of Photonic Sciences, Barcelona, Spain

Benasque – Nanolight
March 11, 2022

What is meant to say ...

Optical Manipulation of Matter Waves



Outline

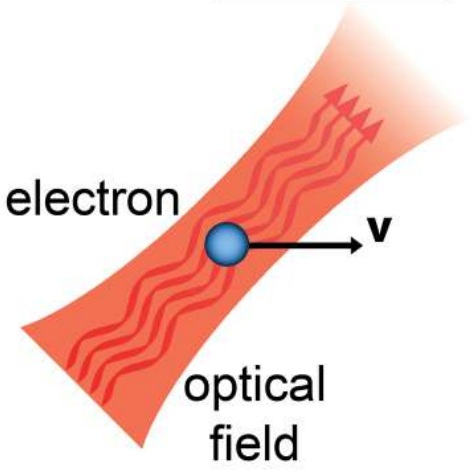
Introduction
- Electron world
- Atom world

What We Are Doing ...
- A bit on the technical side
- PINAM
- Stimulated Compton scattering

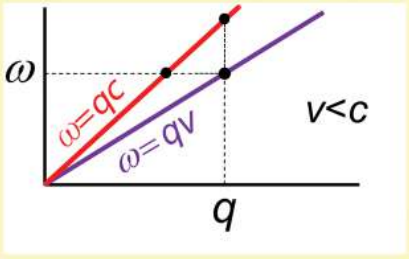
Wrap-up

Phase-matching

free space



energy-momentun mismatch



elastic interaction

pondermotive interaction: H ~ A²

steering
diffraction

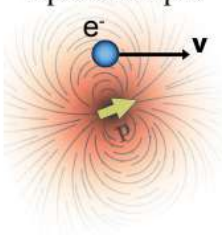
inelastic interaction

direct coupling: H ~ A · v

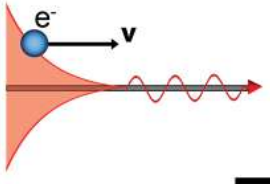
not possible!

near-field

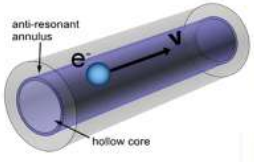
dipolar sample



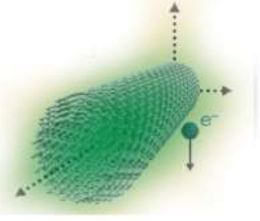
surface polariton



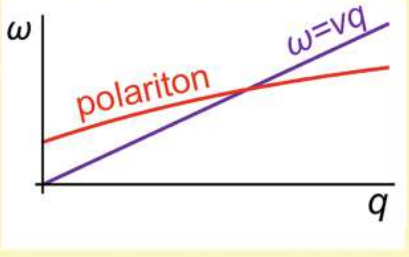
optical hollow fiber



carbon nanotube



phase matching



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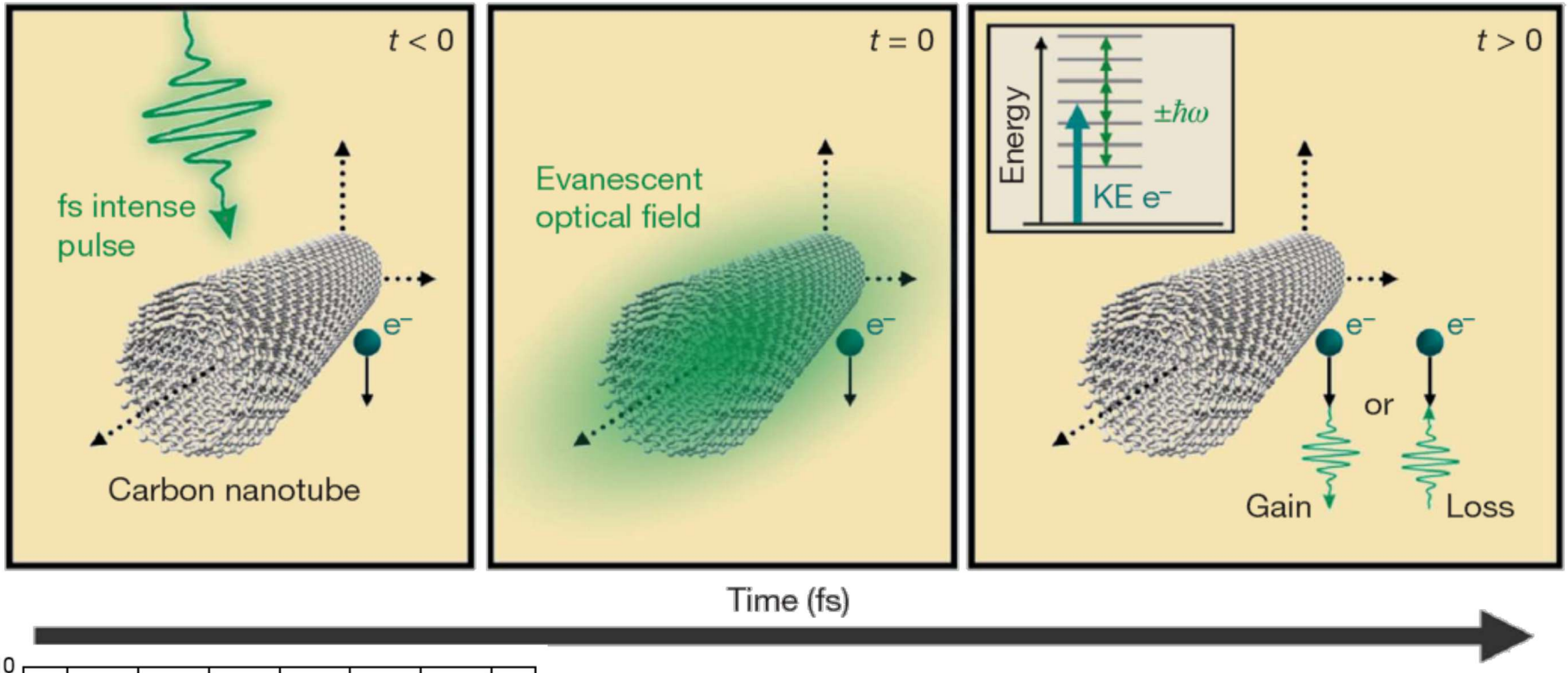
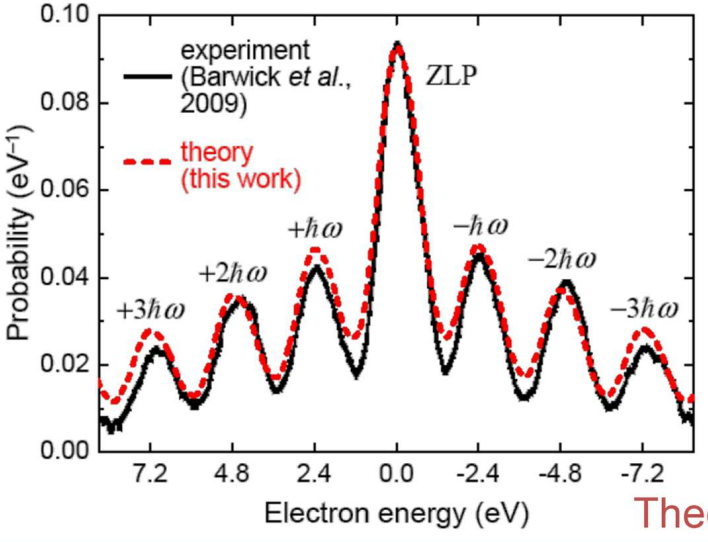
possible
PINEM

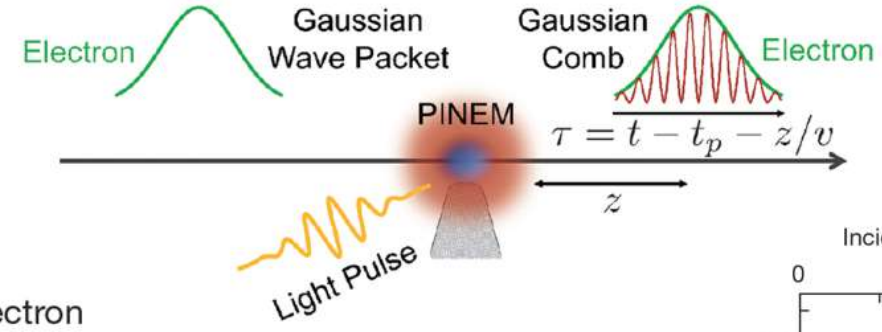
PINEM

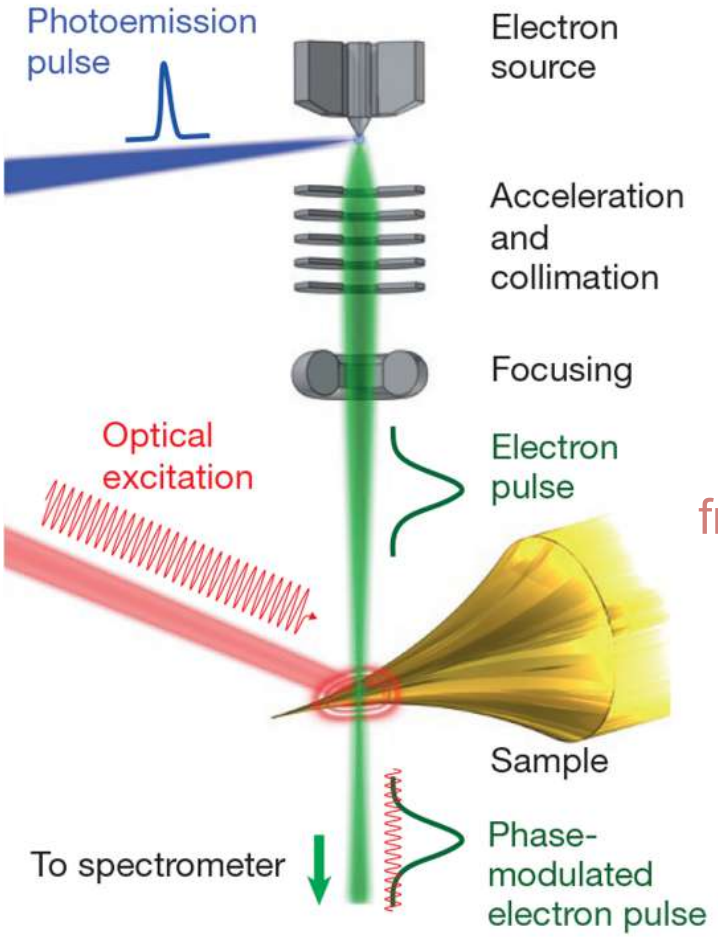


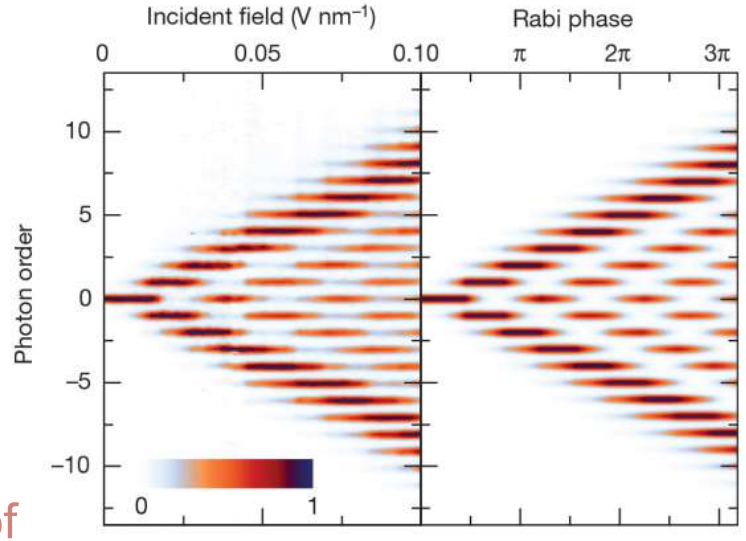


Experiment: Barwick, Flannigan, Zewail, Nature (2009)
Theory: García de Abajo, Asenjo-Garcia, and Kociak, Nano Lett. (2010)

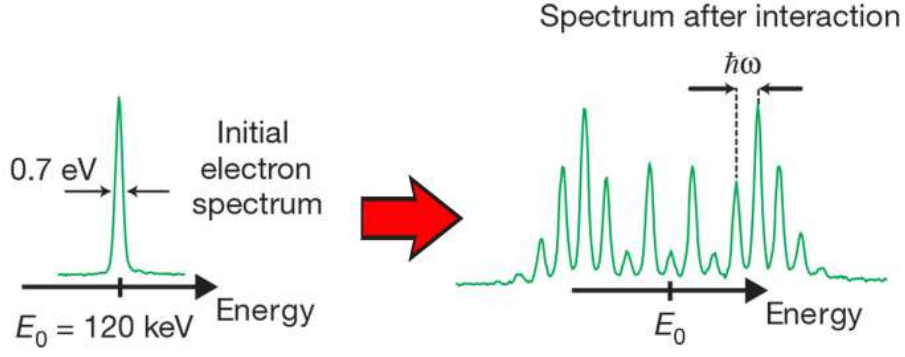
PINEM





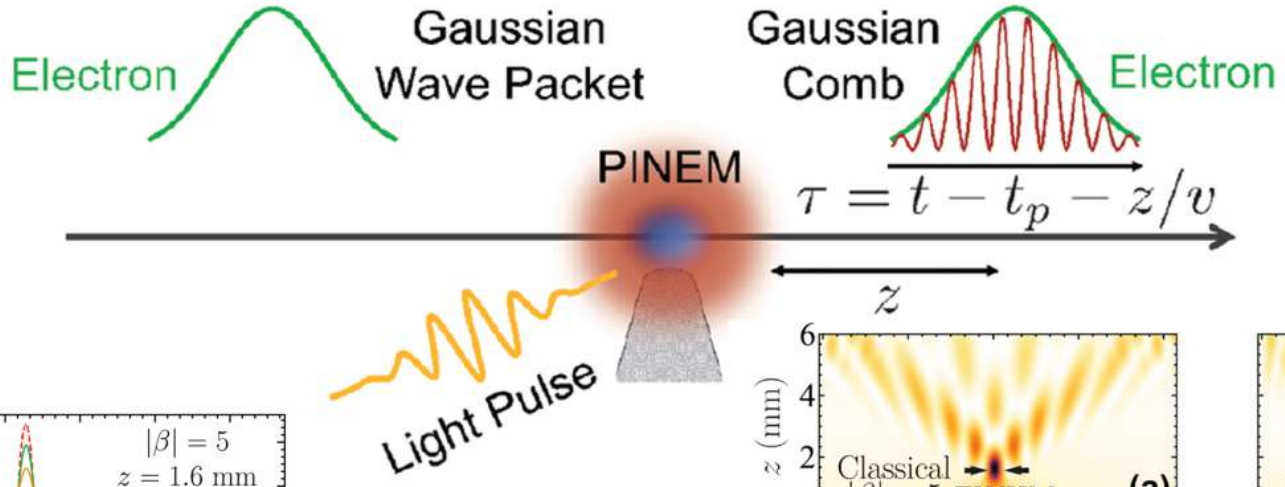


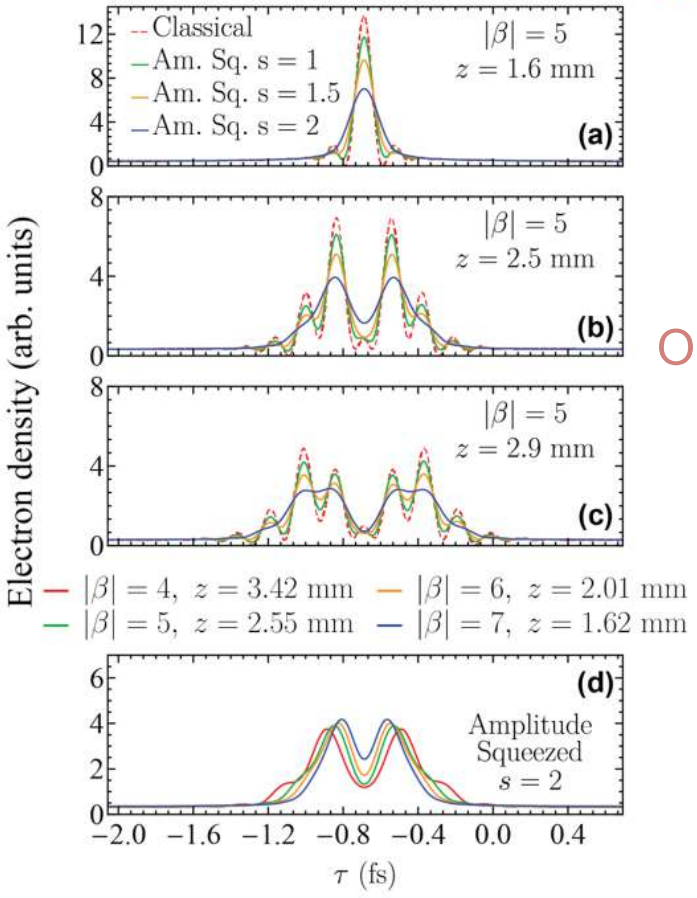
Experiment on
Optical manipulation of
free-electron wave function

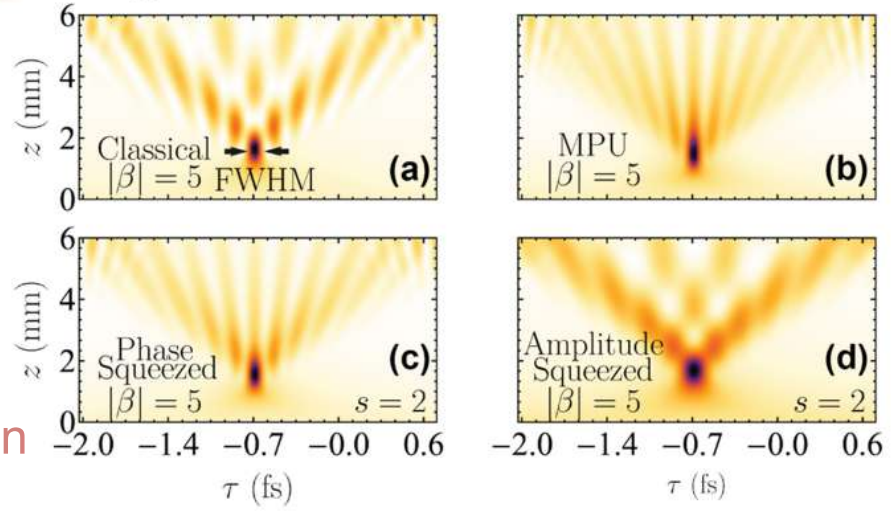


A. Feist, S. V. Yalunin, S. Schäfer, and C. Ropers, Nature (2015)

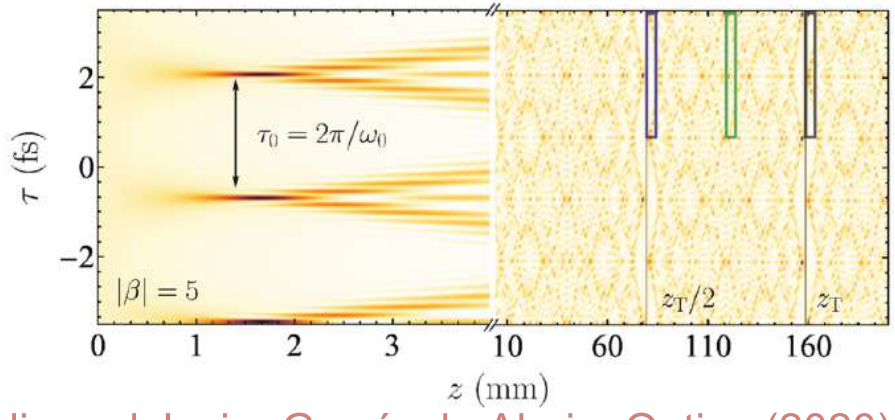
PINEM





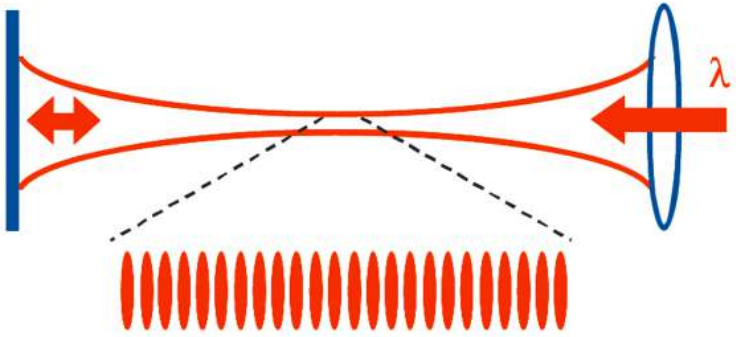


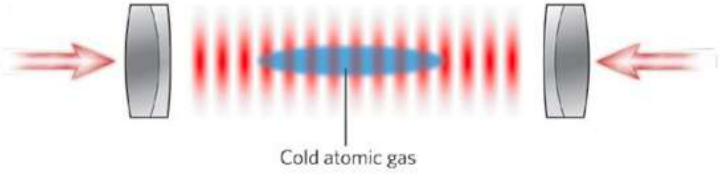
Theory on
Optical manipulation
of free-electron
wave function

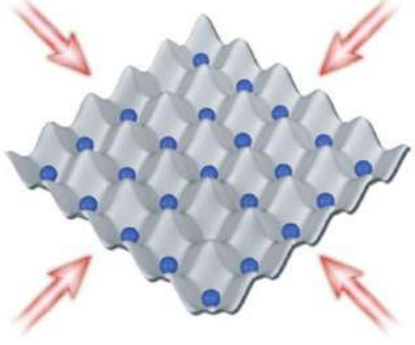


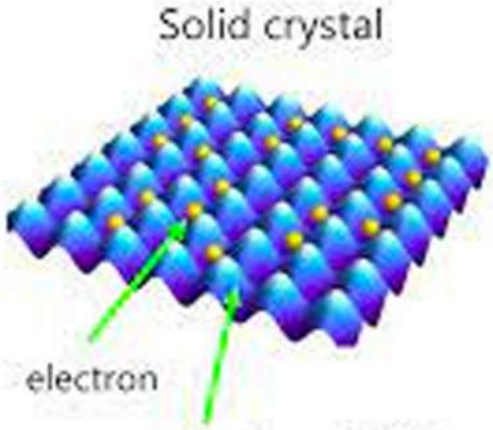
Valerio Di Giulio and Javier García de Abajo, Optica (2020)

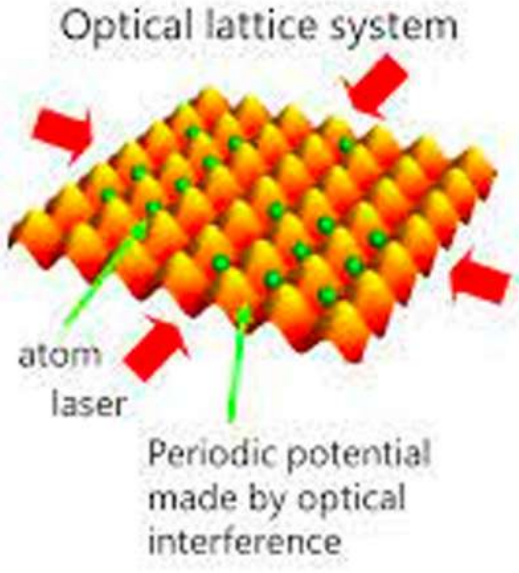
Atom-light interaction









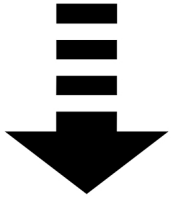


Theory

$$\hat{\mathcal{H}}(t) = \hat{\mathcal{H}}^{\mathrm{at}} + \hat{\mathcal{H}}'(t) + \hat{\mathcal{H}}''(t)$$

$$\hat{\mathcal{H}}'(t) = \frac{\mathrm{i}\hbar e Z}{m_{\mathrm{n}} c}\mathbf{A}(\mathbf{r}_{\mathrm{n}}, t)\cdot\nabla_{\mathbf{r}_{\mathrm{n}}} - \frac{\mathrm{i}\hbar e}{m_{\mathrm{e}} c}\sum_i \mathbf{A}(\mathbf{r}_i, t)\cdot\nabla_{\mathbf{r}_i}$$

$$\hat{\mathcal{H}}''(t) = \frac{e^2 Z^2}{2m_{\mathrm{n}} c^2} A^2(\mathbf{r}_{\mathrm{n}}, t) + \frac{e^2}{2m_{\mathrm{e}} c^2}\sum_i A^2(\mathbf{r}_i, t)$$



$$\mathrm{i}\hbar\,\dot{\psi}(\mathbf{r}, t) = \Big[E_0 - \hbar(\mathrm{i}\nabla_{\mathbf{r}} + \mathbf{q}_0)\cdot\mathbf{v} + H^{\mathrm{eff}}(\mathbf{r}, t)\Big]\psi(\mathbf{r}, t)$$

$$H^{\mathrm{eff}}(\mathbf{r}, t) = \frac{e^2}{\hbar c^2}\sum_{j\neq 0}\omega_{j0}\,|\hat{\mathbf{x}}\cdot\mathbf{d}_{j0}|^2\;\mathbf{A}(\mathbf{r}, t)\cdot\tilde{\mathbf{A}}_j(\mathbf{r}, t)$$

$$\tilde{\mathbf{A}}_j(\mathbf{r}, t) = -\mathrm{i}\omega_{j0}\int_{-\infty}^{t} \mathrm{e}^{-\mathrm{i}\omega_{j0}(t-t')}\,\mathbf{A}(\mathbf{r} - \mathbf{v}t + \mathbf{v}t', t')$$

Theory

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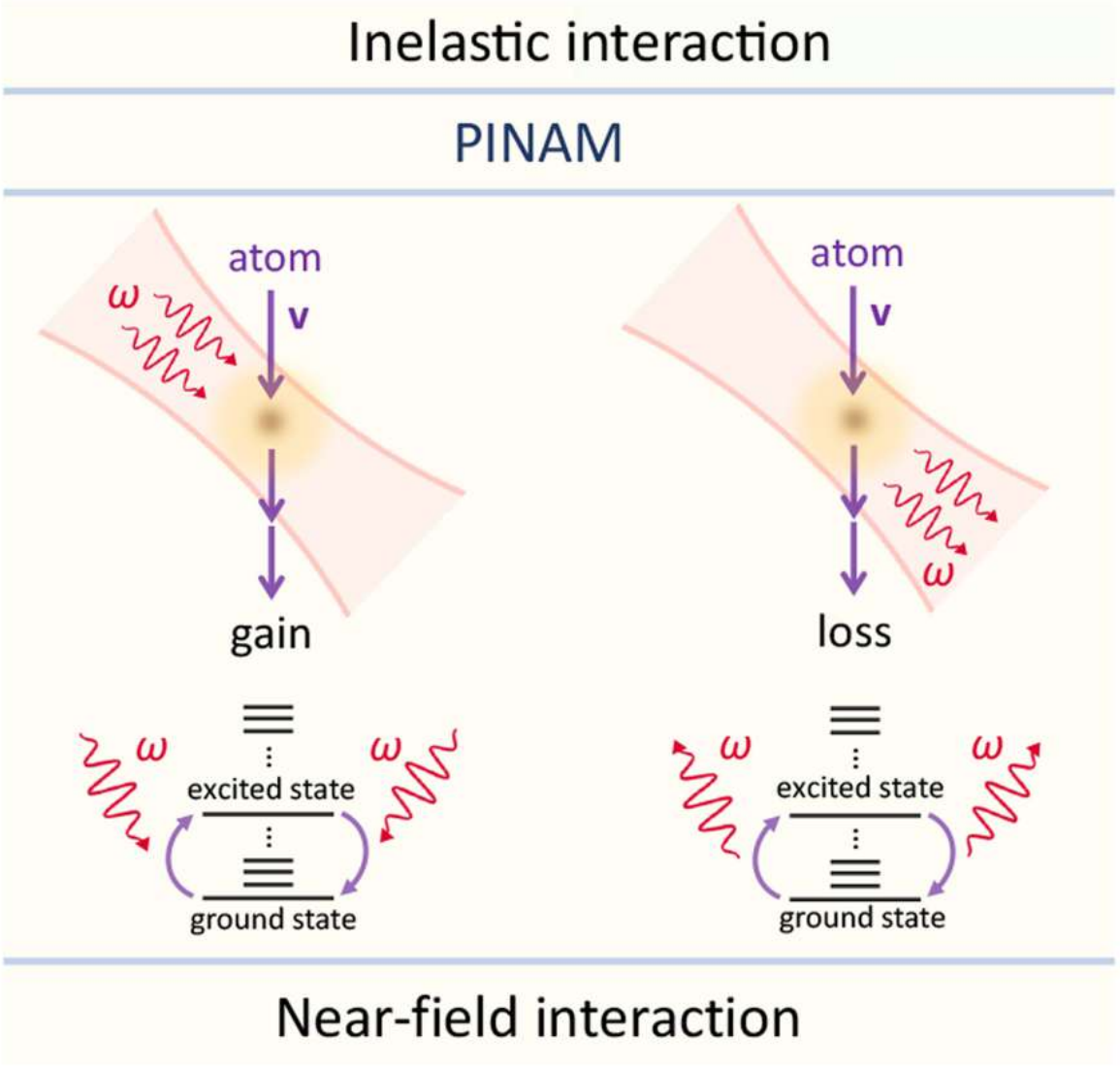
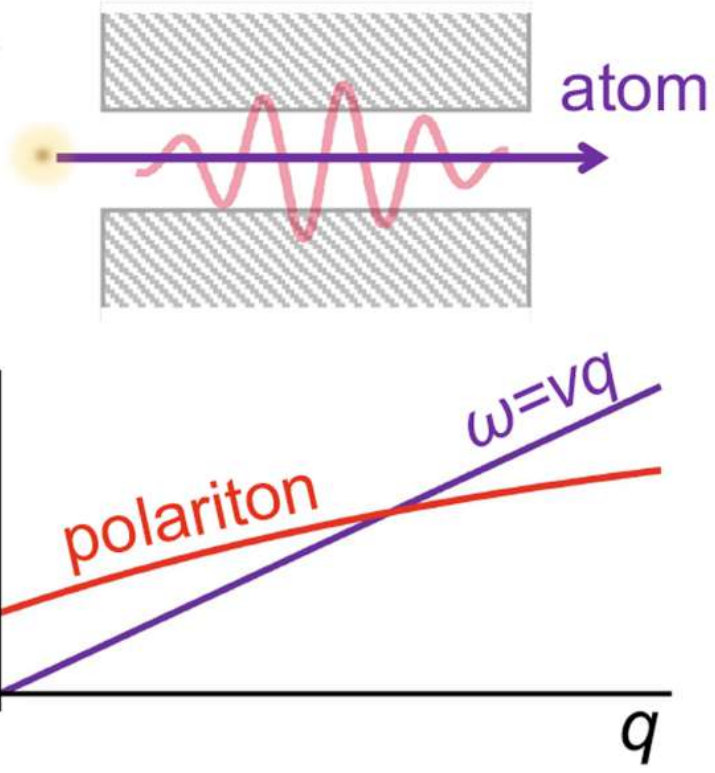
collimated beam (E_0,$\mathbf{p}_0$)

$$\psi(\mathbf{r},t) = \psi^{\mathrm{inc}}(\mathbf{r},t)\,\mathrm{e}^{-(\mathrm{i}/\hbar)\int_{-\infty}^{t}dt'\,H^{\mathrm{eff}}(\mathbf{r}-\mathbf{v}t+\mathbf{v}t',t')}$$

static φ elastic interaction

dynamical inelastic interaction β



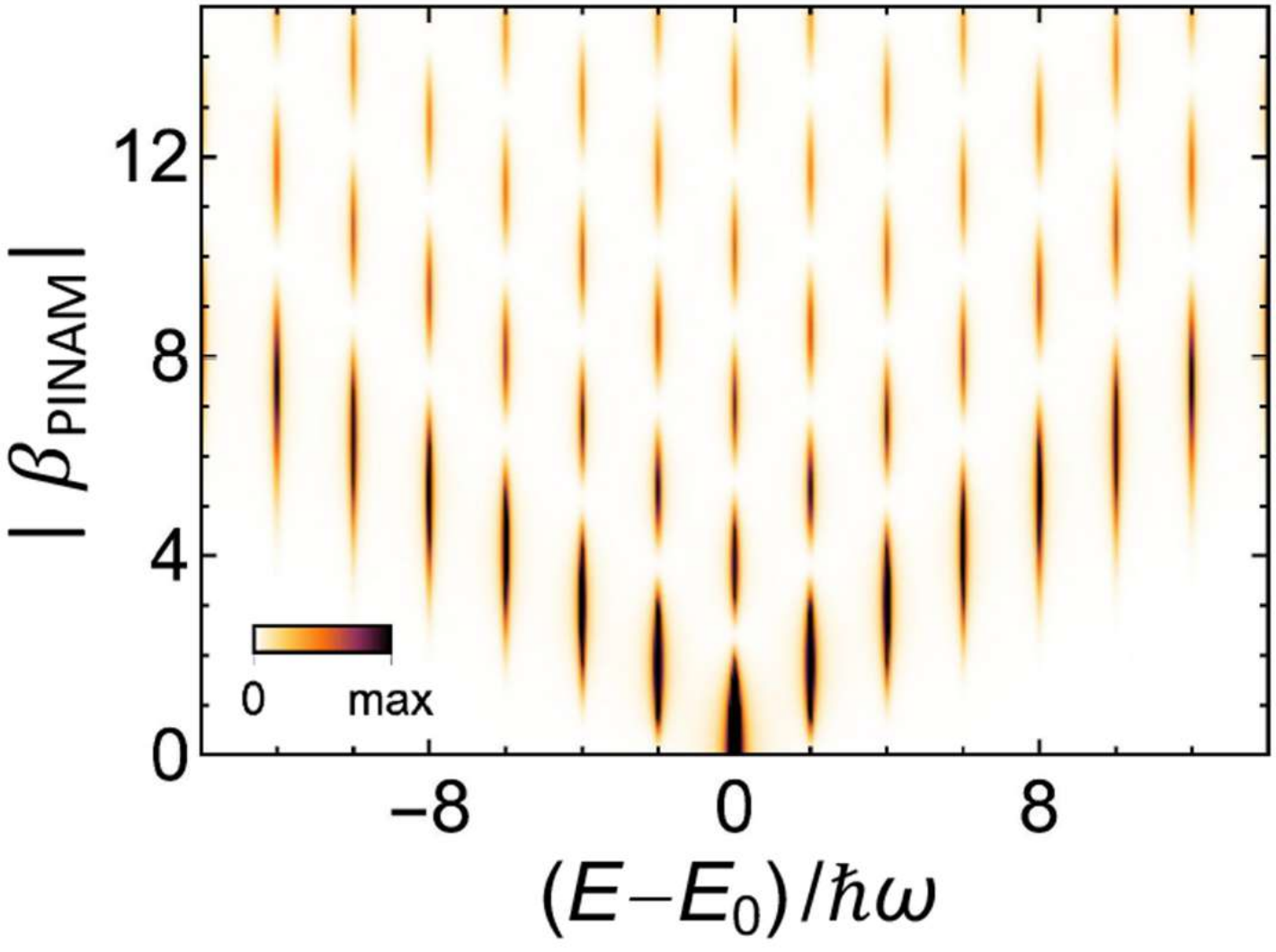


$$\mathbf{q} \cdot \mathbf{v} = \omega$$

PINAM

inelastic interaction: $\psi(\mathbf{r},t) = \psi^{\mathrm{inc}}(\mathbf{r},t)\,\mathrm{e}^{\mathrm{i}\varphi(\mathbf{R})}\exp\left\{-\beta(\mathbf{R})\,\mathrm{e}^{2\mathrm{i}\omega(z-vt)/v} + \beta^{*}(\mathbf{R})\,\mathrm{e}^{-2\mathrm{i}\omega(z-vt)/v}\right\}$

$$|\beta_{\mathrm{PINAM}}| \propto L\,\alpha_0\,|\mathcal{E}_0|^2 / v$$



atom

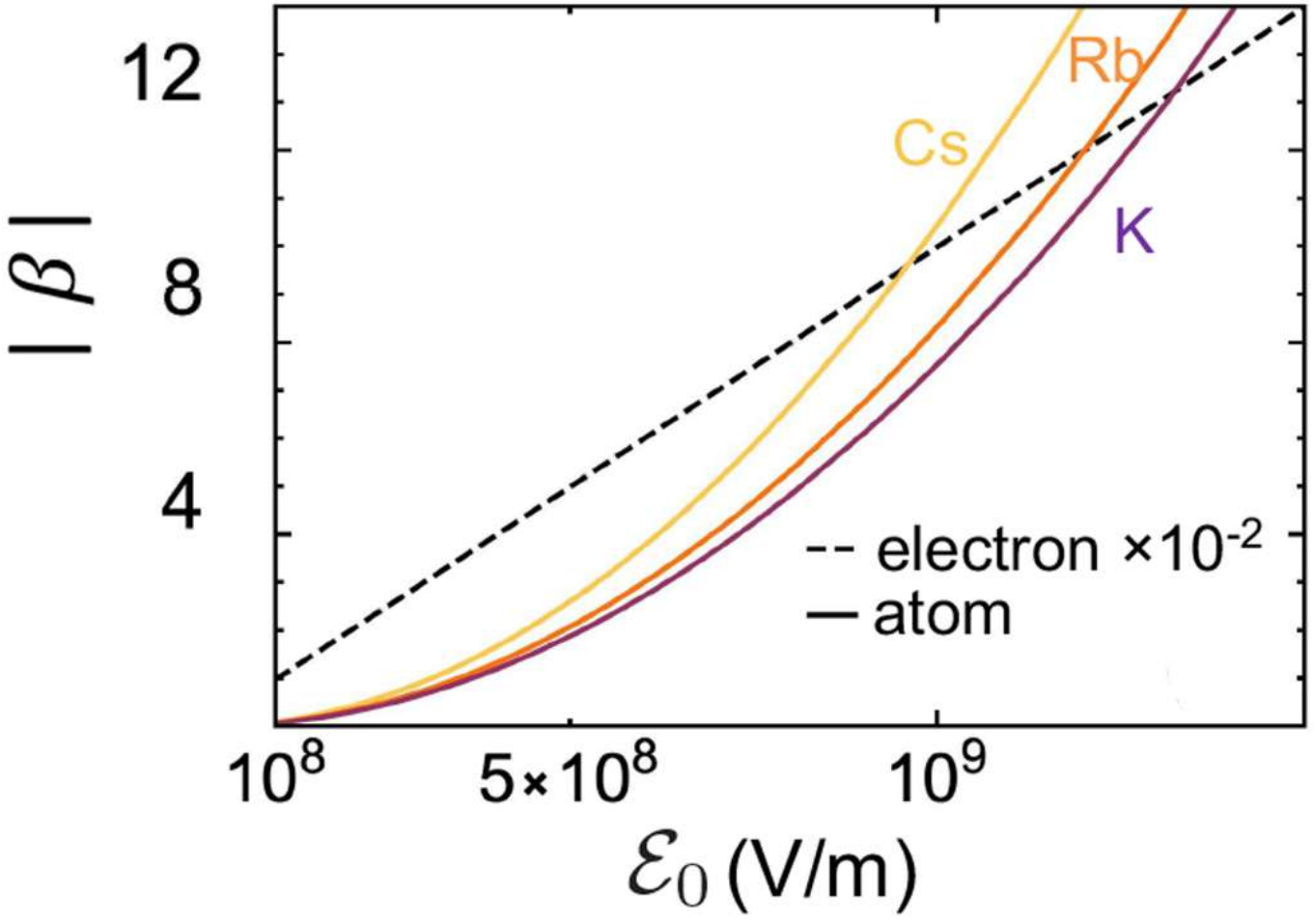
$$\exp\left\{-\beta(\mathbf{R})\,e^{2i\omega(z-vt)/v}+\beta^*(\mathbf{R})\,e^{-2i\omega(z-vt)/v}\right\}$$

$$|\beta_{\text{PINAM}}| \propto L\,\alpha_0\,|\mathcal{E}_0|^2 / v$$

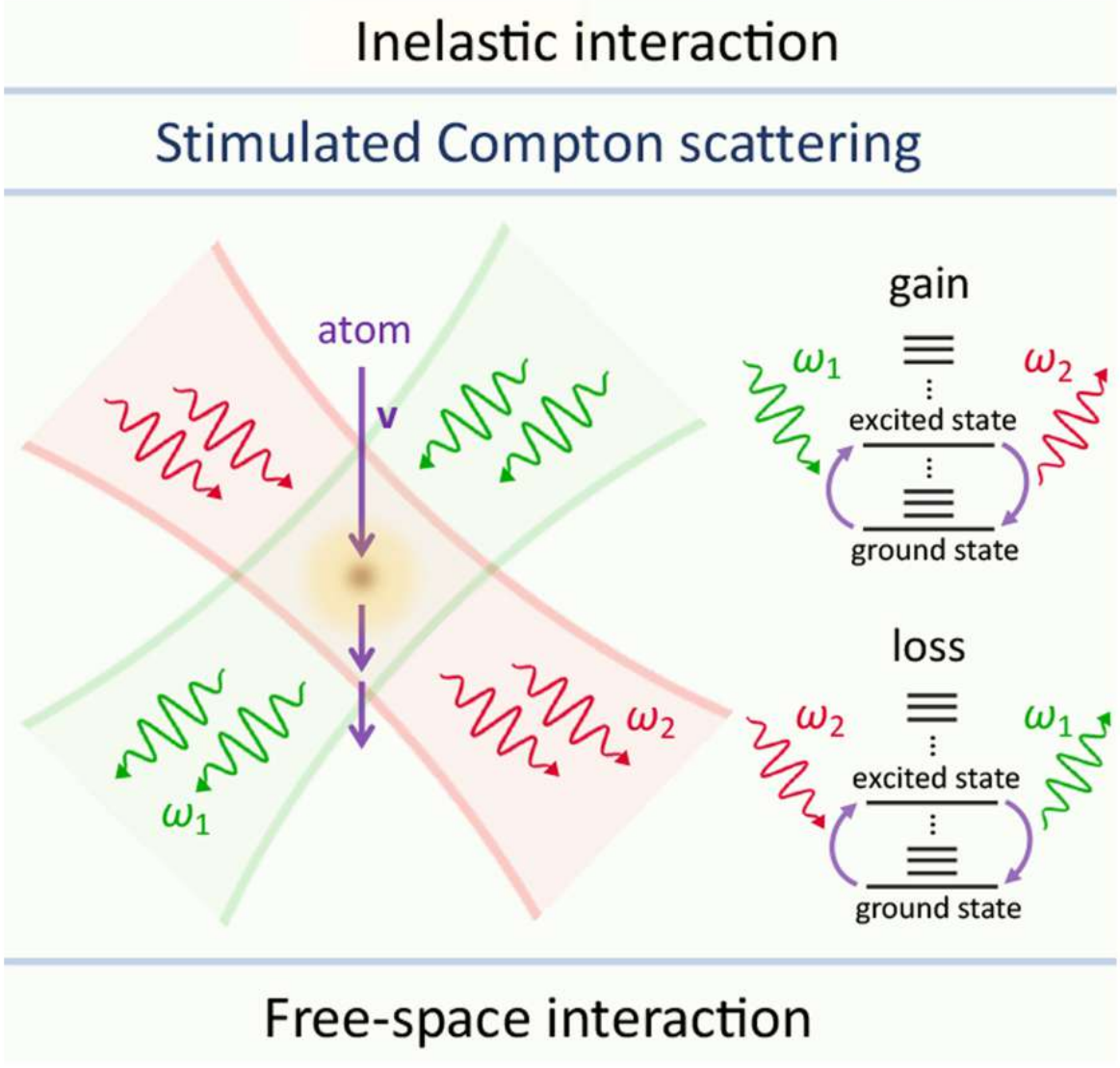
electron

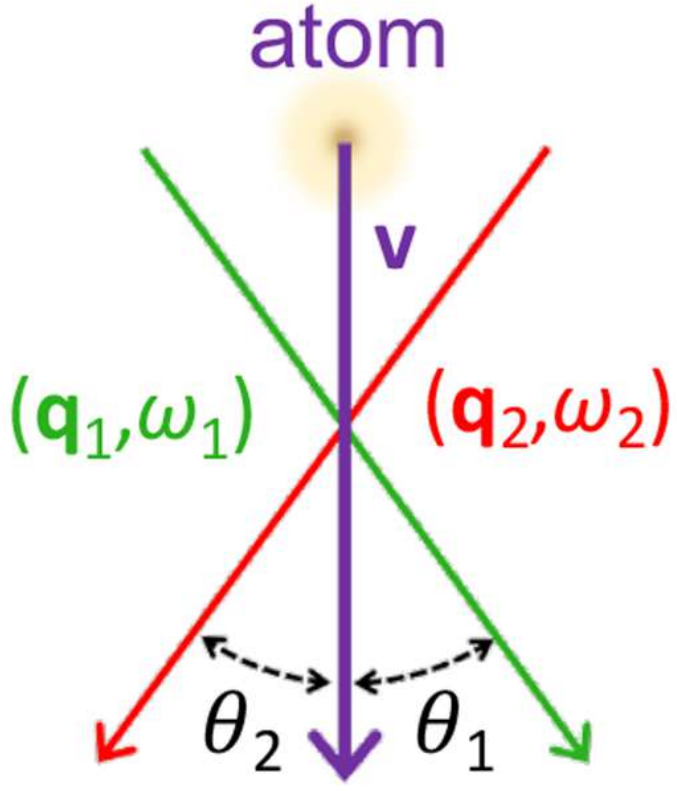
$$\exp\left\{-\beta(\mathbf{R})\,e^{i\omega(z-vt)/v}+\beta^*(\mathbf{R})\,e^{-i\omega(z-vt)/v}\right\}$$

$$|\beta_{\text{PINEM}}| \propto L\,|\mathcal{E}_0| / \omega$$



Stimulated Compton Scattering

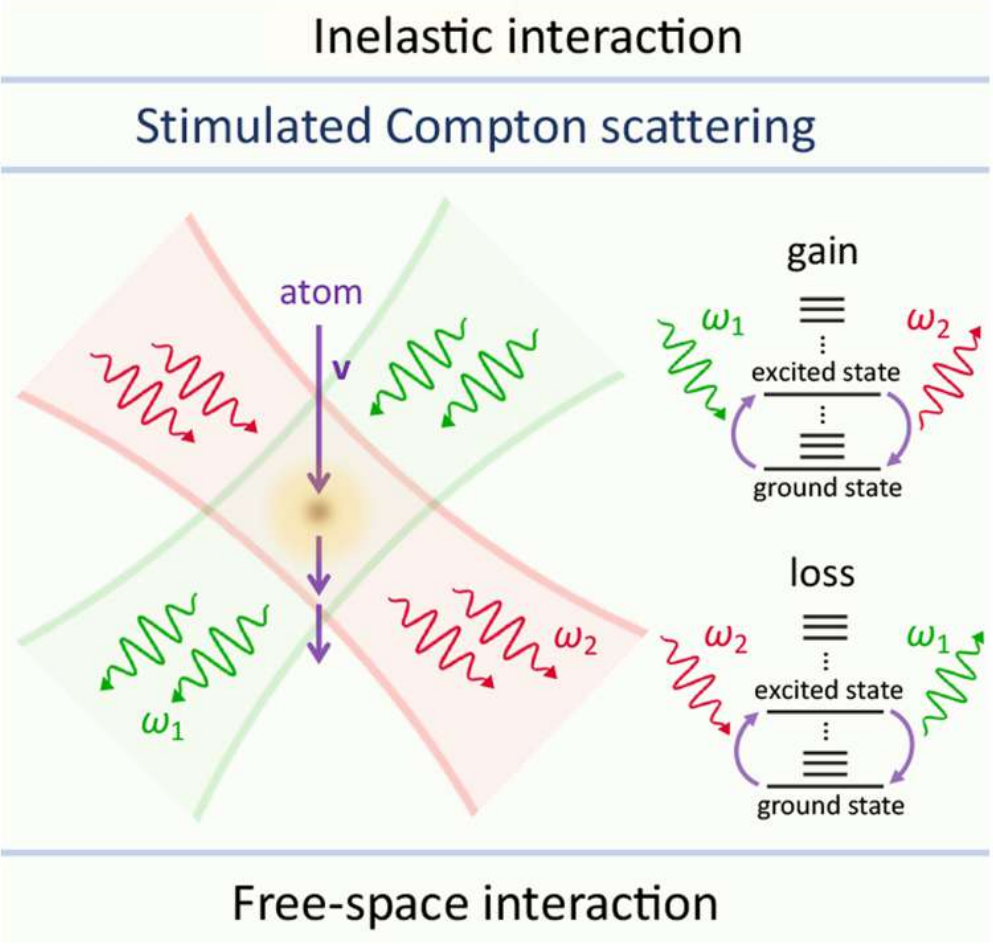


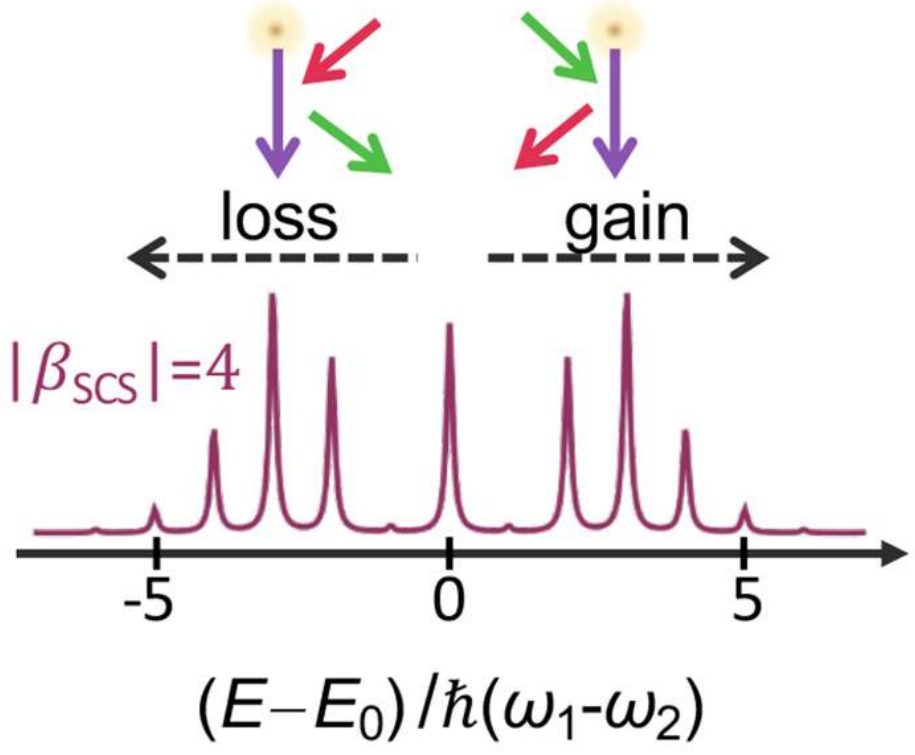


$$(\mathbf{q}_1 - \mathbf{q}_2) \cdot \mathbf{v} = \omega_1 - \omega_2$$

Stimulated Compton Scattering

$$\psi(\mathbf{r},t) = \psi^{\mathrm{inc}}(\mathbf{r},t)\,\mathrm{e}^{\mathrm{i}\varphi}\exp\left\{-\beta\,\mathrm{e}^{\mathrm{i}(\mathbf{q}_1-\mathbf{q}_2)\cdot(\mathbf{r}-\mathbf{v}t)} + \beta^*\,\mathrm{e}^{-\mathrm{i}(\mathbf{q}_1-\mathbf{q}_2)\cdot(\mathbf{r}-\mathbf{v}t)}\right\}$$





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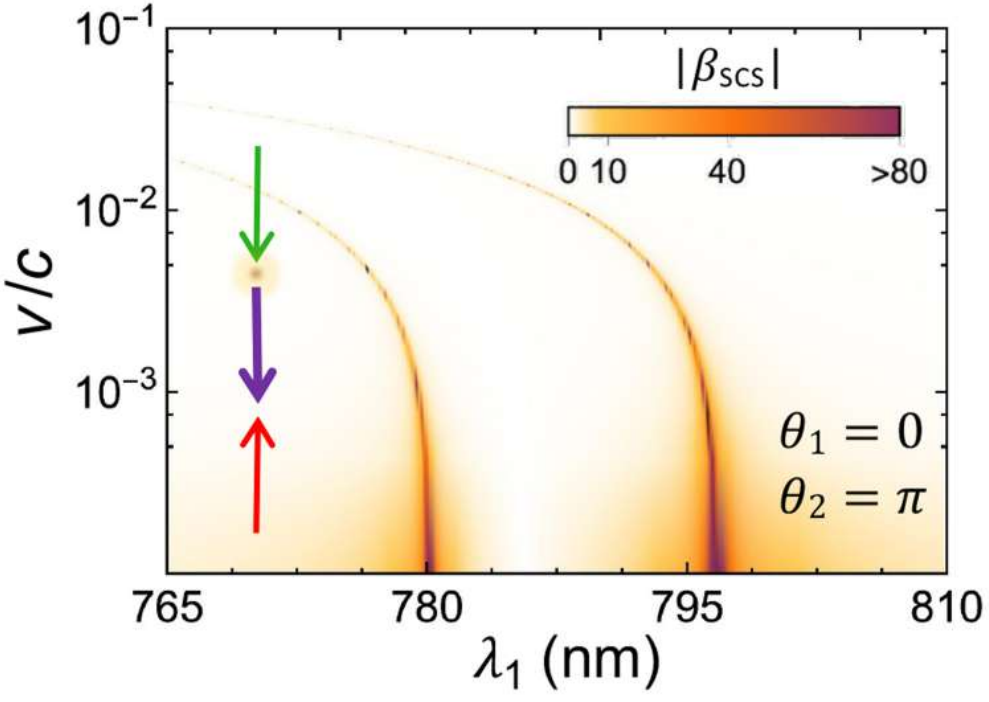
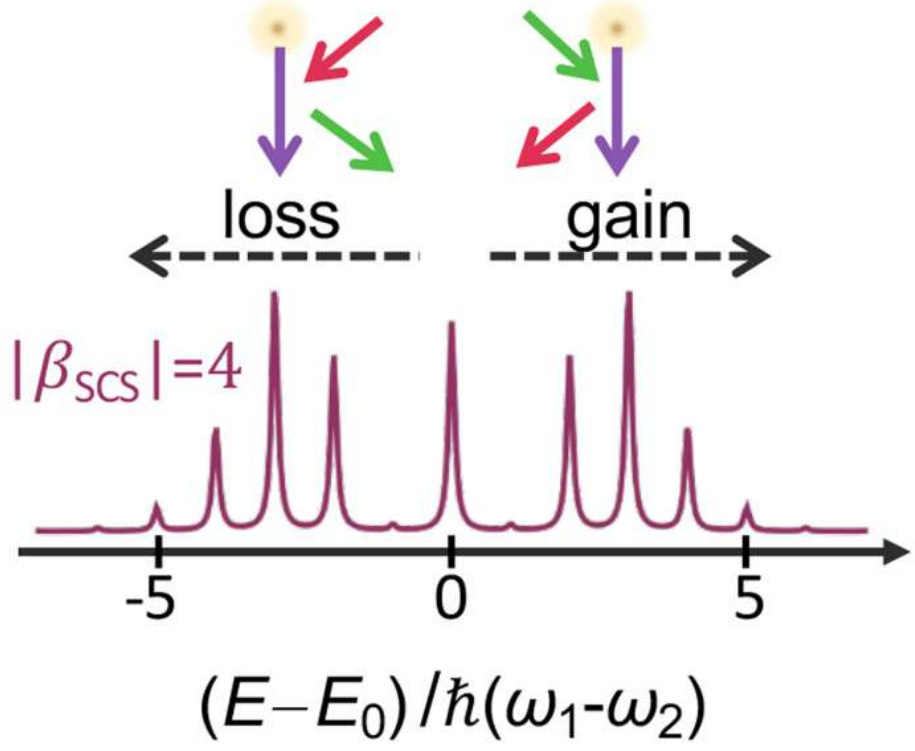
$$\beta = \beta_{\mathrm{SCS}} \equiv -\frac{2\mathrm{i}e^2\omega_1 L}{\hbar^2 v\,\omega_2}\mathbf{E}_1\cdot\mathbf{E}_2^*\sum_{j\neq 0}\frac{\omega_{j0}\,|\hat{\mathbf{x}}\cdot\mathbf{d}_{0j}|^2}{\omega_{j0}^2-(\omega_1-\mathbf{q}_1\cdot\mathbf{v})^2}$$





Wrap-up

- Light & atoms before
  steer the motion of atoms in free space
  - cooling and trapping of matter waves
  - ponderomotive interaction & Doppler-mediated photon scattering
- Light & free electrons
  modulation of the electron wave function
- Combination of these two worlds
  manipulation of matter waves by inelastic interactions with optical fields
- Realization of the modulation
  stimulated photon absorption and emission by an atomic beam
  - interaction with phase-matching evanescent optical fields
  - stimulated Compton scattering in free space
- Optical manipulation of matter waves
  powerful tool for application in atom-based microscopy & spectroscopy

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