NANYANG TECHNOLOGICAL UNIVERSITY

UNIVERSITÉ CÔTE D'AZUR

Forward Scattering of Light: Cooperativity, Superflash, and More

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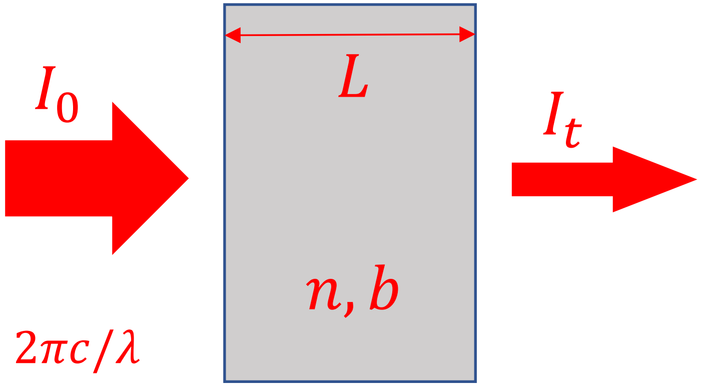
Centre for Quantum Technologies

MajuLab

GdR Complexe Annual Workshop: Dec 7th 2022

Coherent Transmission



Beer-Lambert's law: $I_t(\omega) = I_0(\omega)e^{-b(\omega)}$

Optical frequency: $\omega = kc = 2\pi c/\lambda$

For the electric field:

$$E_t(\omega) = E_0(\omega)\exp[in(\omega)kL] = E_0(\omega)\exp\left[-\frac{b(\omega)}{2} + i\phi(\omega)\right]\exp(ikL)$$

With a two-level atom (RWA): $n(\omega) = 1 + \rho\alpha(\omega)/2$

In a dilute medium $\rho\lambda^3 \ll 1$

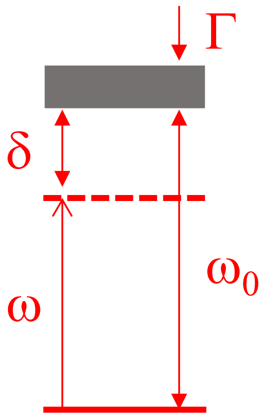
Atomic polarizability

$$\alpha(\omega) = -\frac{3\pi}{k^3}\frac{\Gamma}{\delta + i\Gamma/2}$$

$$b = \mathrm{Im}\{\alpha\}\rho kL$$

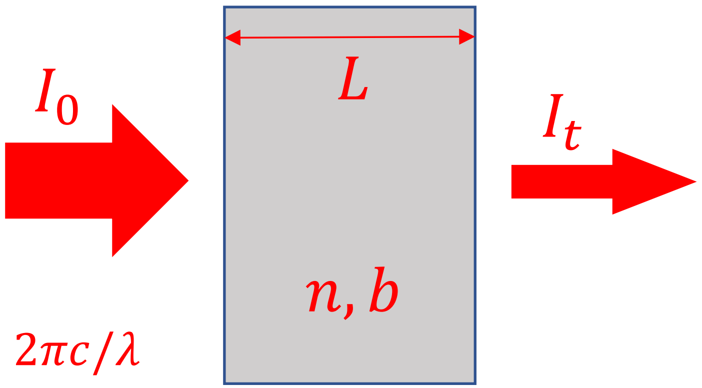
$$\phi = \frac{\mathrm{Re}\{\alpha\}}{2}\rho kL$$

Optical theorem → Scattering cross section



$\delta = \omega - \omega_0$

Forward Scattering Field



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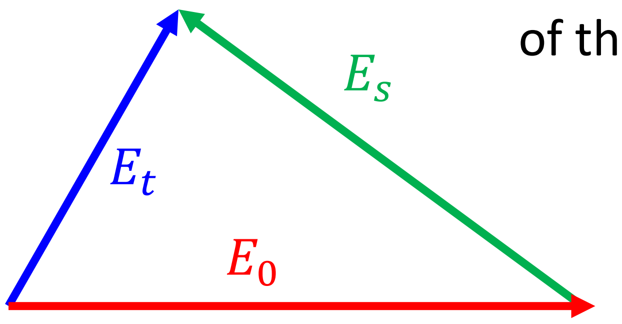
Coherent superposition of scalar fields:

$$E_t(t) = E_0(t) + E_s(t)$$

E_t: the transmitted field

E_0: the incident field

E_s: the forward scattering field



Geometrical representation of the fields in the complex plane

Content

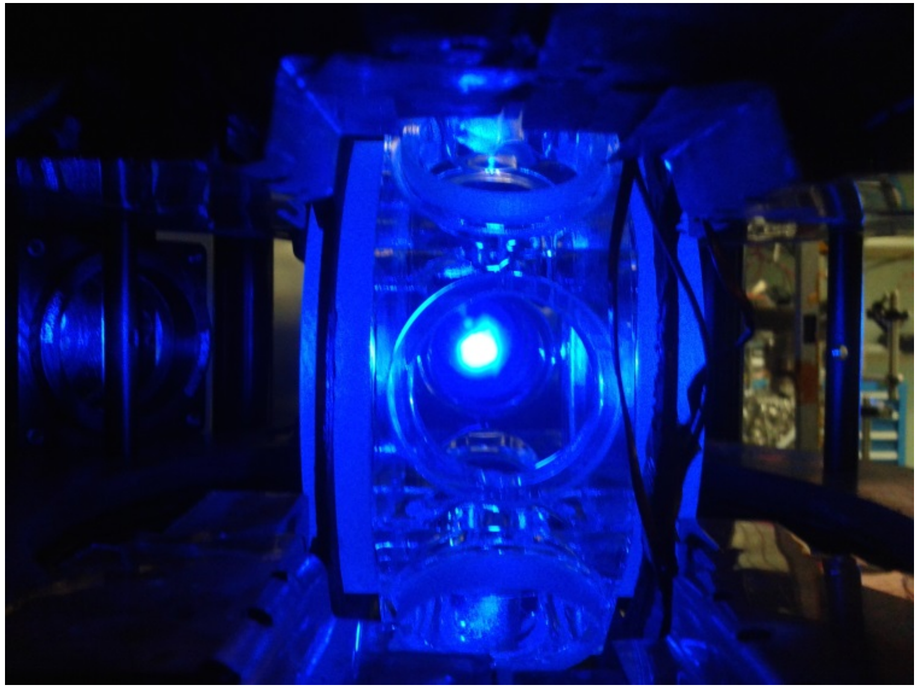
Direct Observation of the Forward Scattering Field: Flash Effect

Superflash Effect: $\left. I_s \right|_{\mathrm{sta}} > \left. I_0 \right|_{\mathrm{sta}}$

Cooperative Pulse Train

Flash in Λ–Scheme

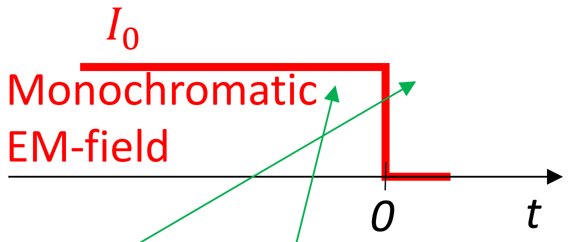
Outlook

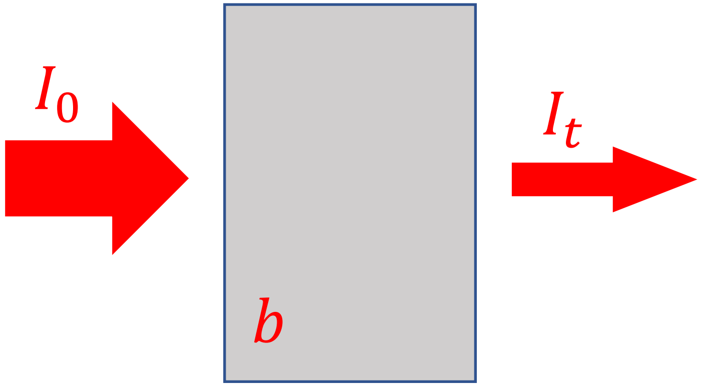


Magneto-optical trap: 10^9 strontium atoms

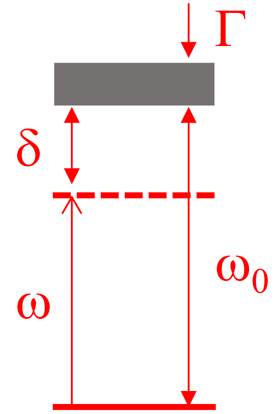
Direct Observation of the Forward Scattering Field

$$E_t(t) = E_0(t) + E_s(t) \Rightarrow E_t(t) = \xcancel{E_0(t)} + E_s(t)$$





$$E_s(0^+) = E_s\Big|_{\text{sta}} \equiv E_s = E_t - E_0 = E_0\left[\exp\left(-\frac{b}{2} + i\phi\right) - 1\right]$$

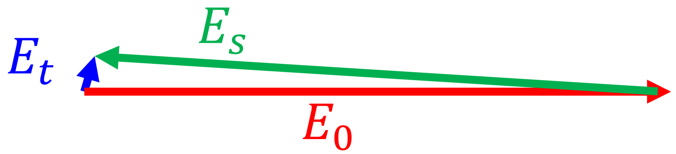


Medium response time has to be not “too fast”!

Atoms with large resonance quality factor: $\frac{\Gamma}{\omega_0} \sim 10^{-11}$

If $\delta \gg \Gamma \;\rightarrow (\phi, b) \sim 0 \rightarrow E_s \sim 0$

If $\delta \ll \Gamma$ and $b \gg 1 \rightarrow E_t = 0, E_s \sim -E_0$



$$\delta = \omega - \omega_0$$

$$b = \mathrm{Im}\{\alpha\}\rho k L$$

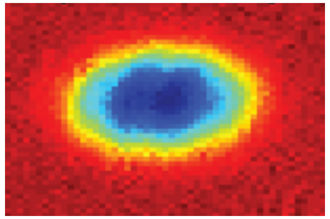
$$\phi = \frac{\mathrm{Re}\{\alpha\}}{2}\rho k L$$

$$\alpha(\omega) = -\frac{3\pi}{k^3}\frac{\Gamma}{\delta + i\Gamma/2}$$

Flash Effect

Ultracold Strontium gas

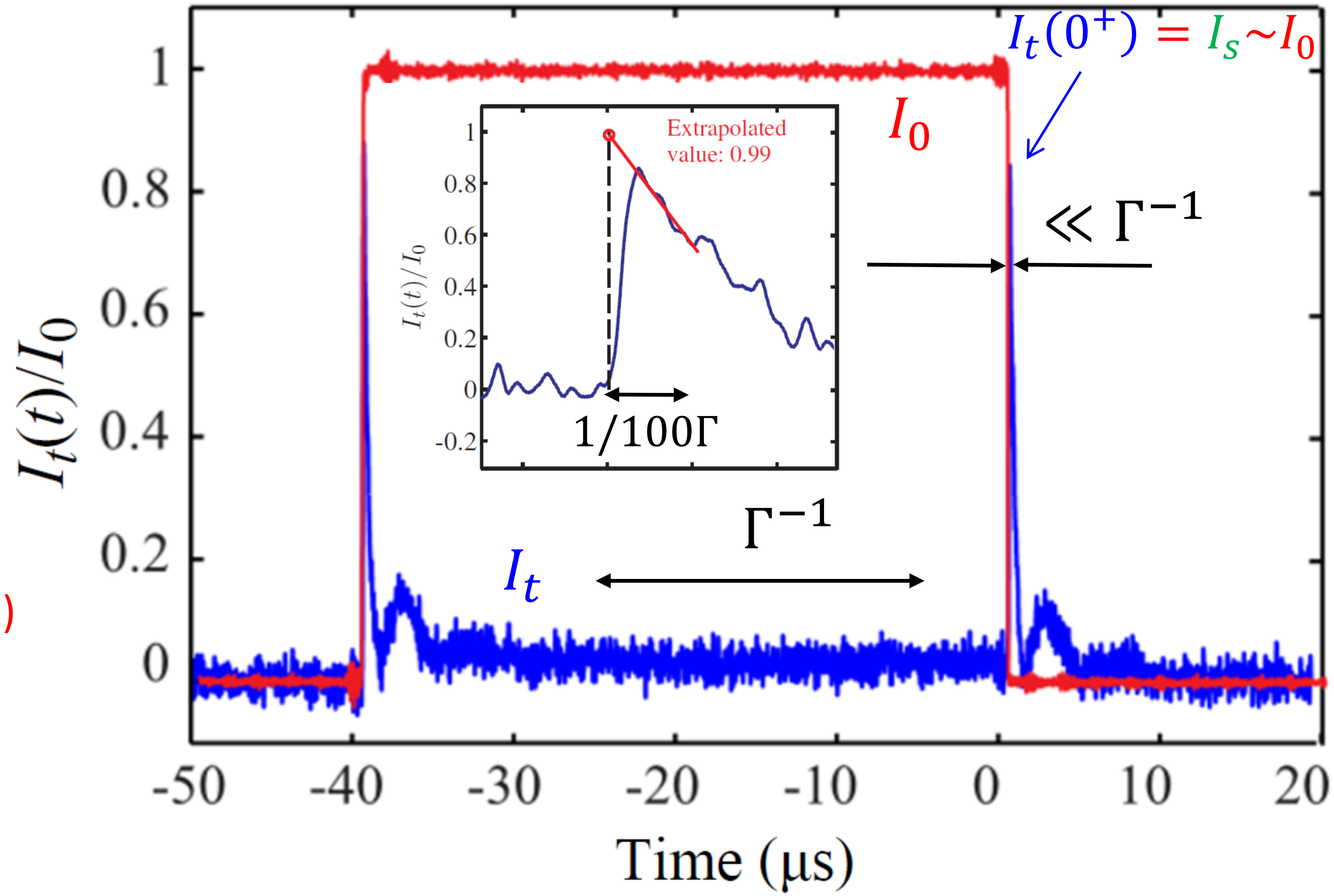
380 μm



240 μm

Atoms number: $N = 3\ 10^8$
Density: $\rho \sim 5\ 10^{11}$ atoms/cm^3
Dilute medium: $\rho\lambda^3 \sim 0.1$
Temperature: 3 μK -> $k\bar{v} = 3.4\ \Gamma$
Optical thickness: $b_0(\bar{v}) = 19$ ($\frac{\Gamma}{2\pi} \sim 7.5$ kHz)
$b_0(0) = 120$
$\delta = 0$ $T = 0$

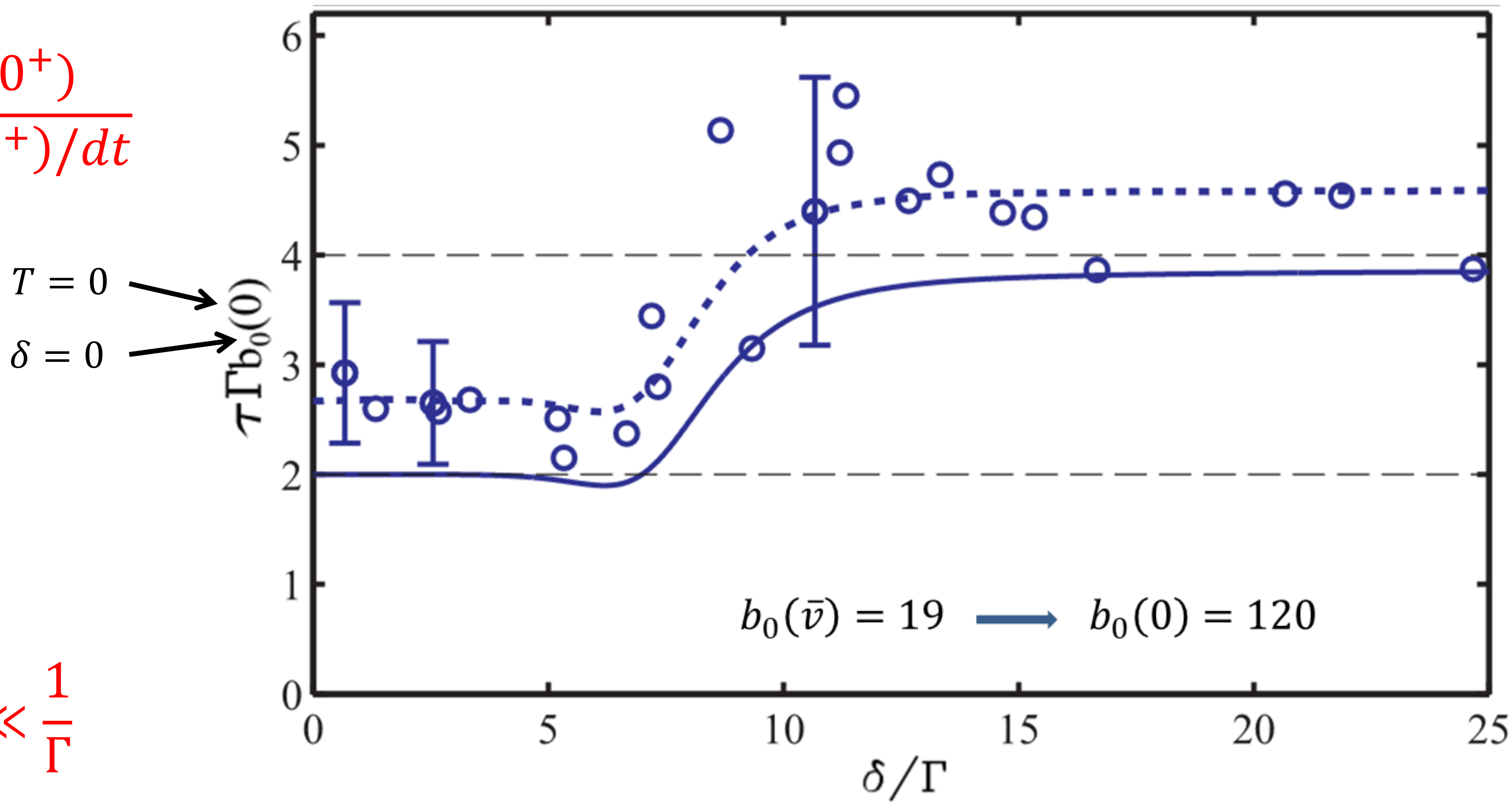
$\delta = 0$



M. Chalony et *al.*, PRA **84**, 011401(R) (2011)
C. C. Kwong, et *al.* PRL **114**, 223601 (2015)

Flash Effect: Time Scale

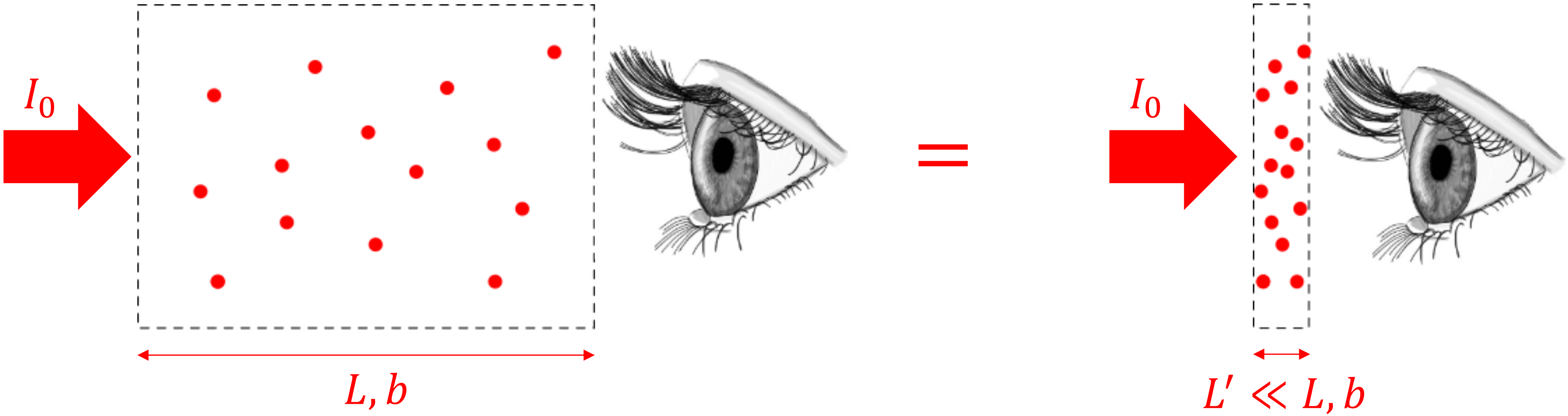
$$\tau = \frac{I(0^+)}{dI(0^+)/dt}$$



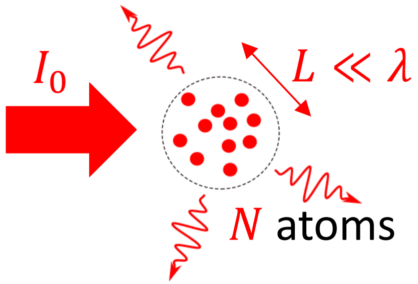
$$\tau \sim \frac{1}{b\Gamma} \ll \frac{1}{\Gamma}$$

C. C. Kwong, et *al*. PRL **114**, 223601 (2015)

Flash Effect vs Superradiance



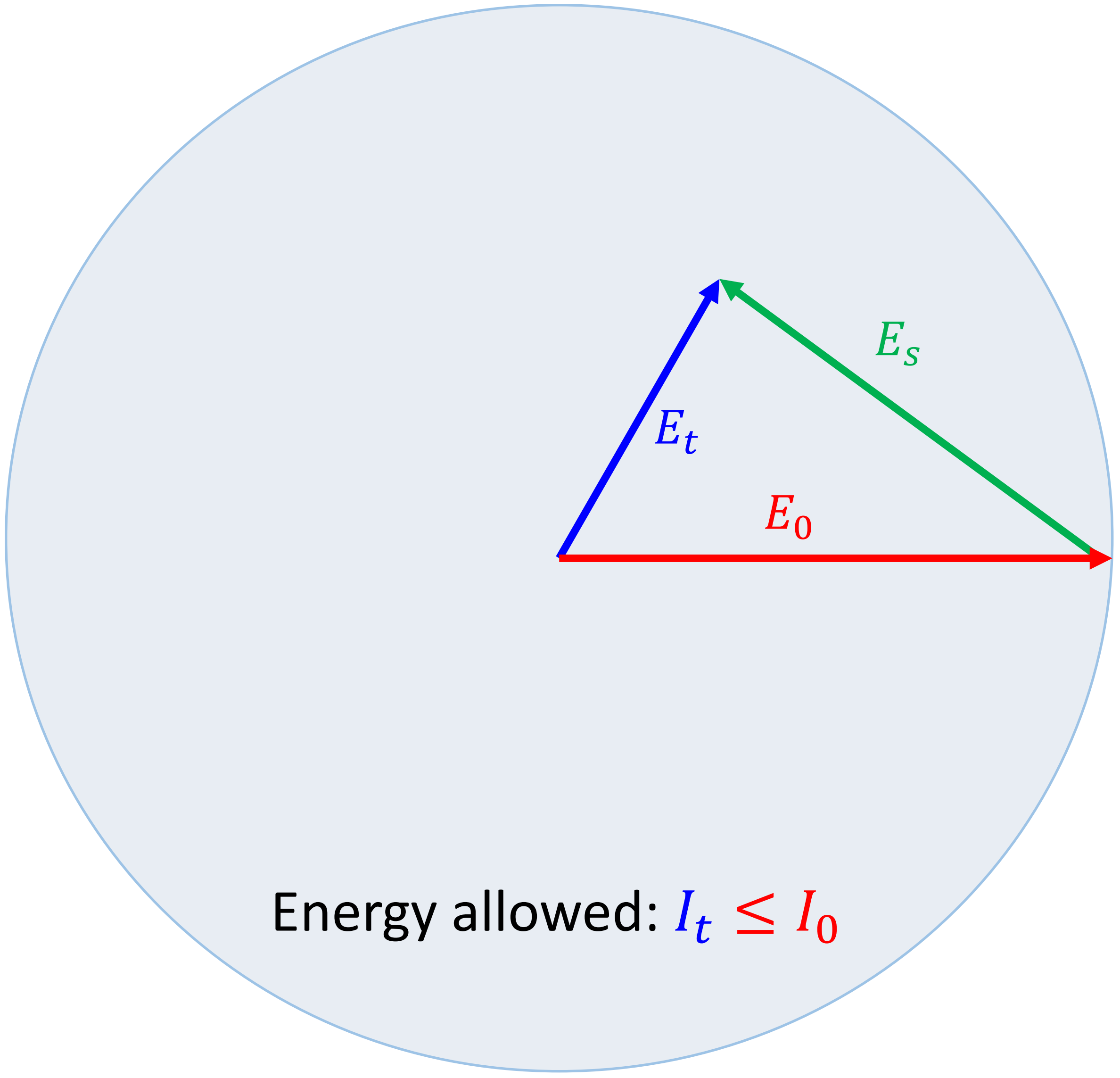
Optical thickness b ↔ Effective atoms number



Superradiance: $\tau \sim 1/N\Gamma$ ↔ Flash $\tau \sim 1/b\Gamma$

Flash is a cooperative emission in the forward direction

Flash (or Forward scattering) Amplitude



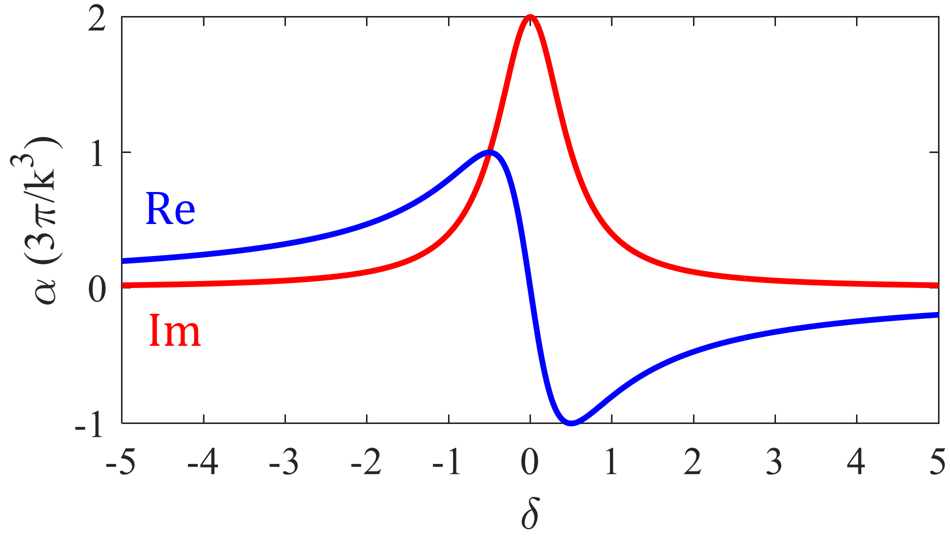
Energy allowed: $I_t \leq I_0$

$$E_s(\omega) = E_0(\omega)\left[\exp\left(-\frac{b}{2} + i\phi\right) - 1\right]$$

Max. value: $\exp\left(-\frac{b}{2} + i\phi\right) \rightarrow -1$

So we need: $b \rightarrow 0$ and $\phi \rightarrow \pm\pi$

$$b = \mathrm{Im}\{\alpha\}\rho k L \qquad \phi = \frac{\mathrm{Re}\{\alpha\}}{2}\rho k L$$



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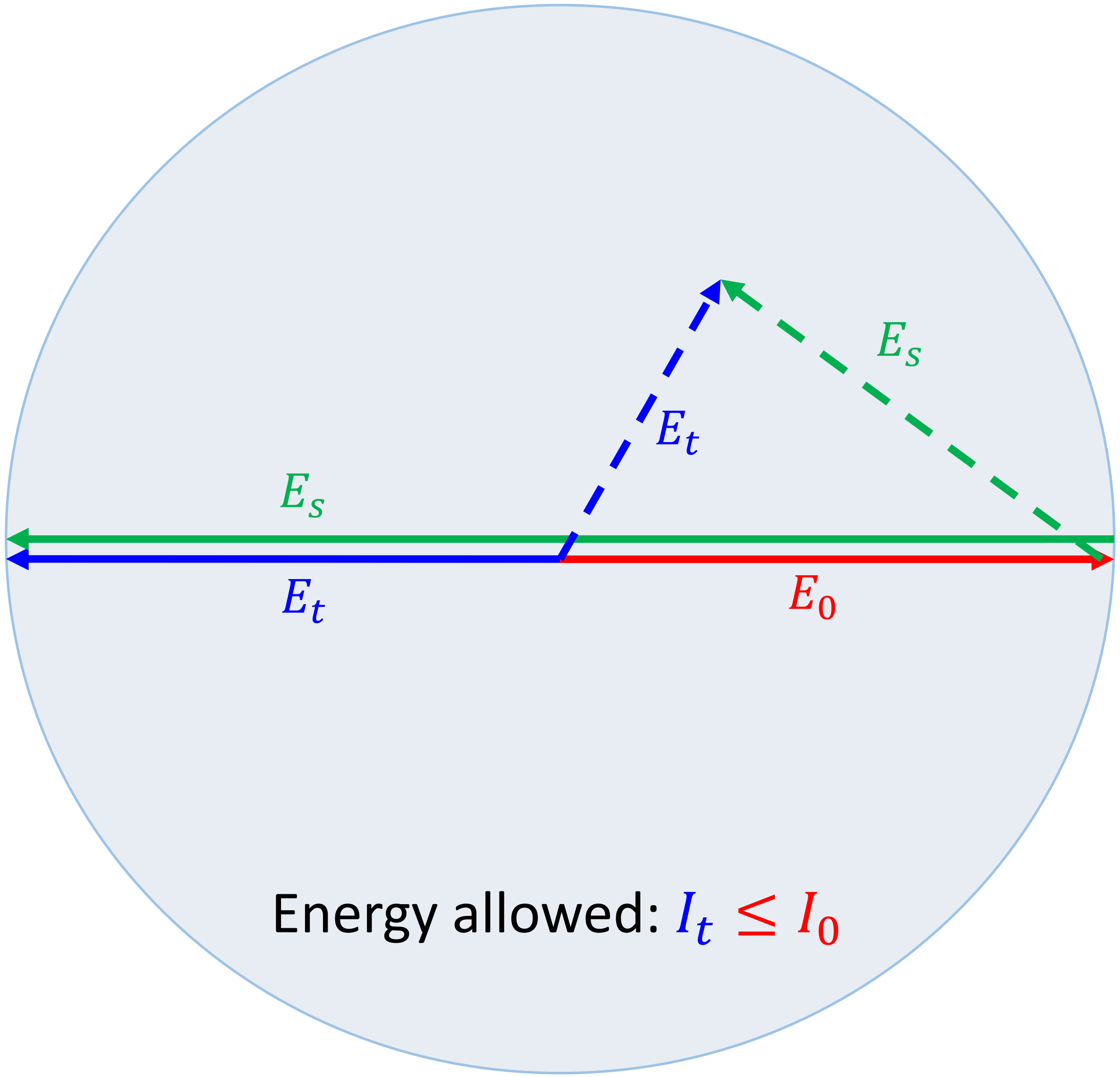

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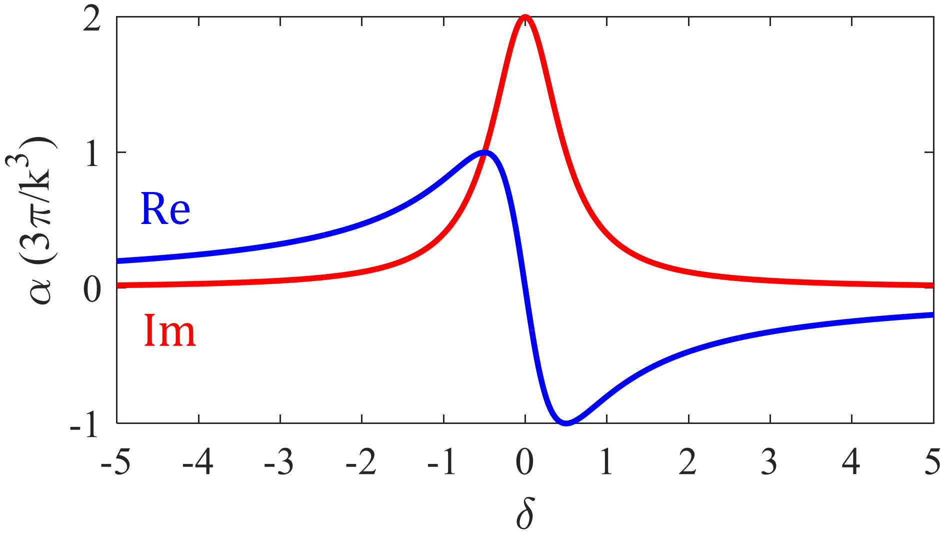
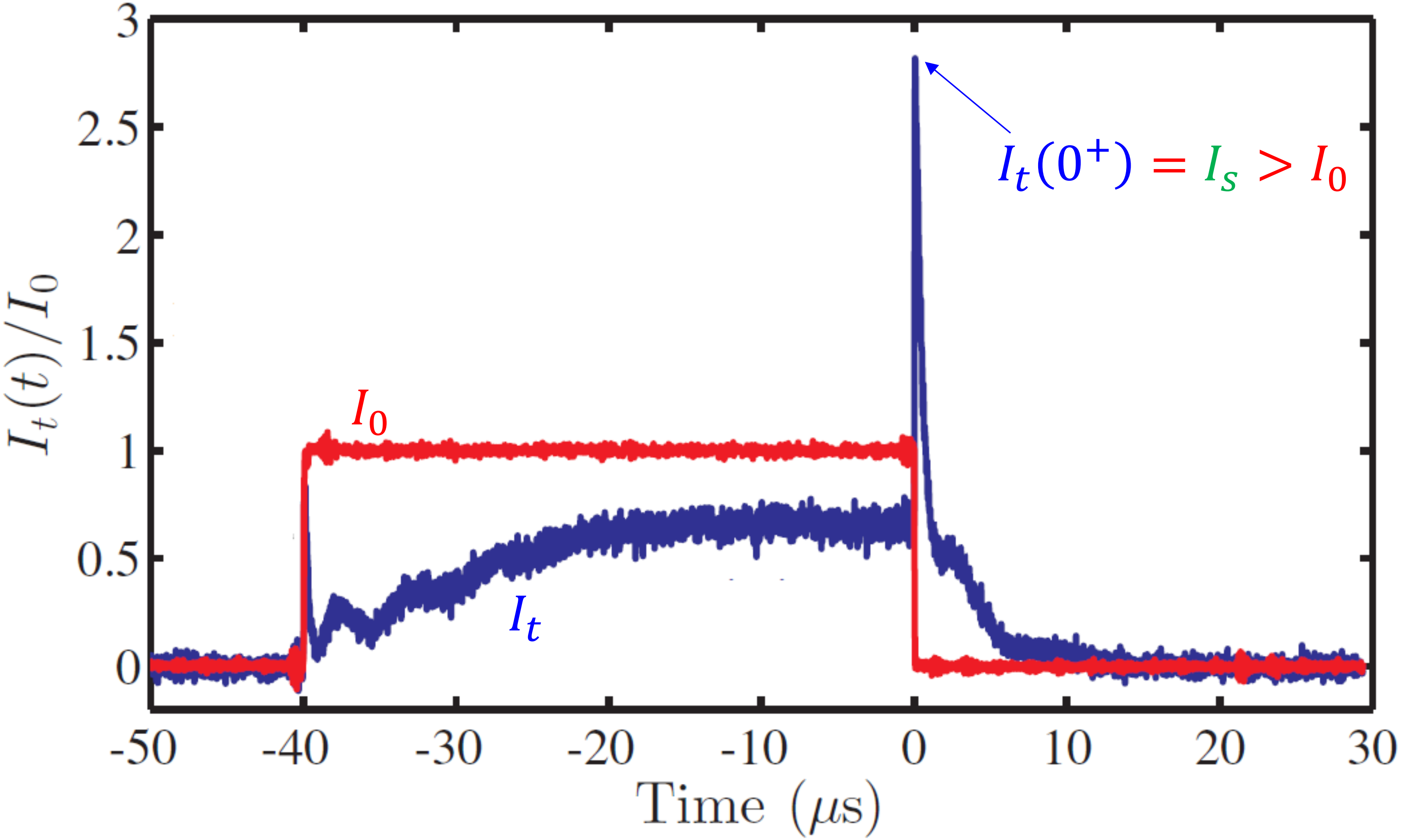


Superflash Effect

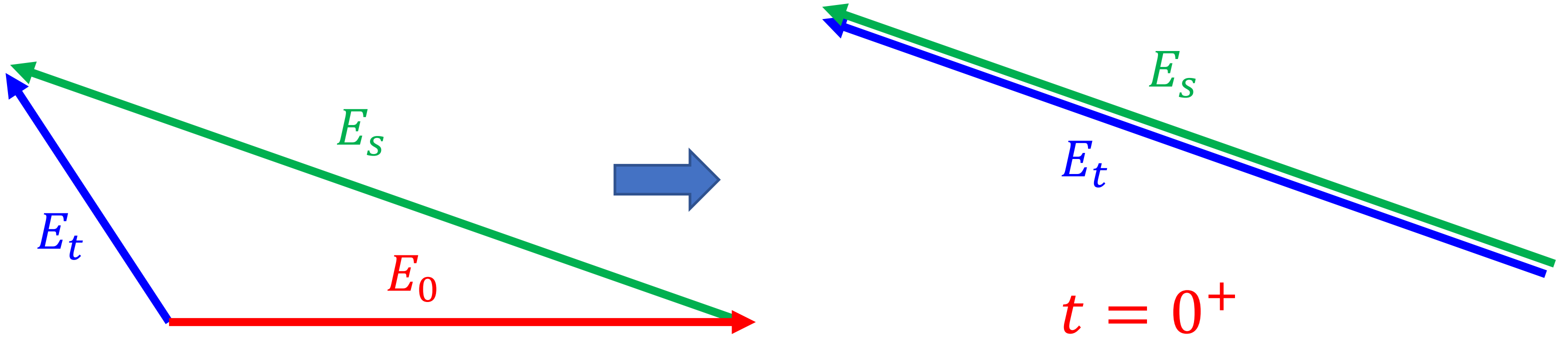
$\delta = -11\Gamma$



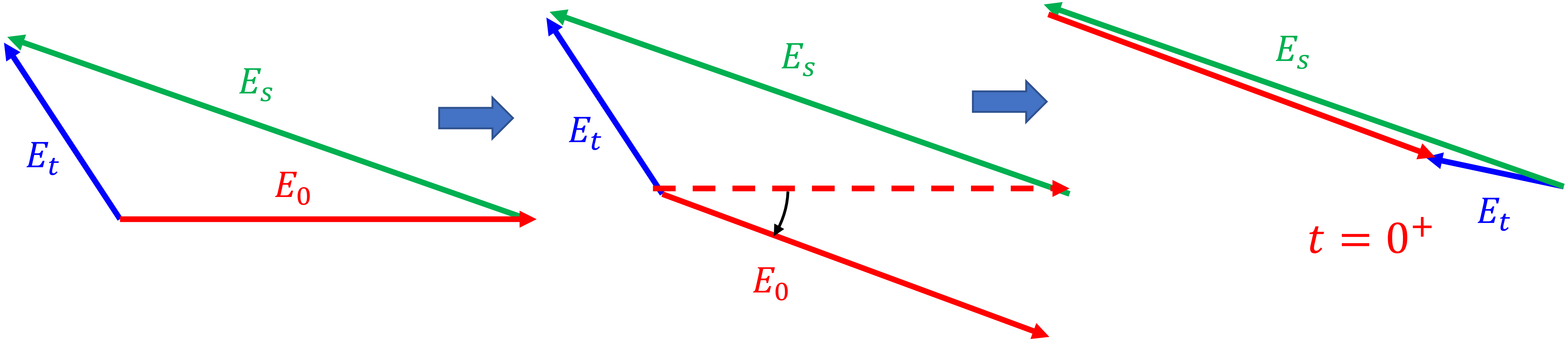
C. C. Kwong, et *al.*, PRL **113**, 223601 (2014)

Phase change

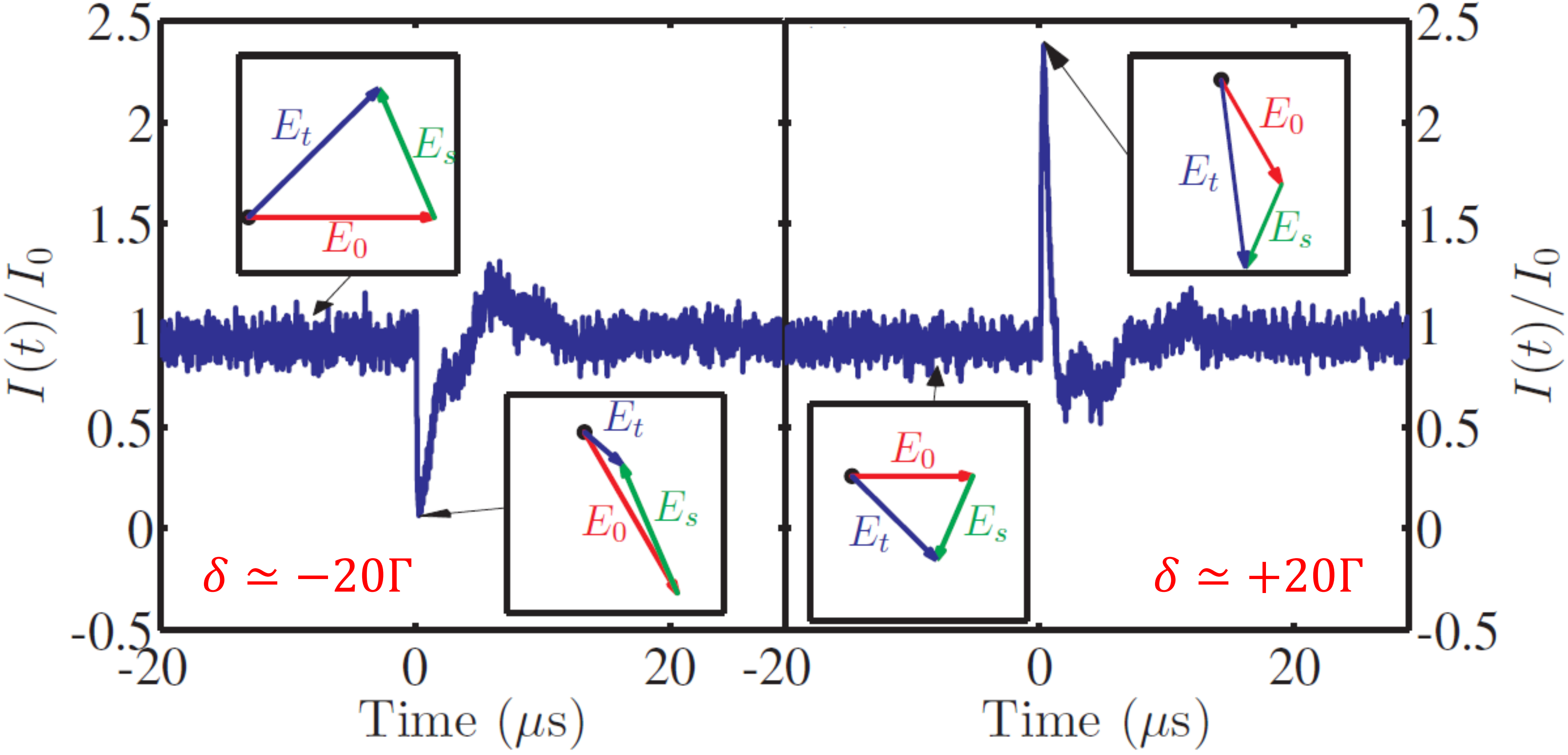
Switch off:



Phase change:



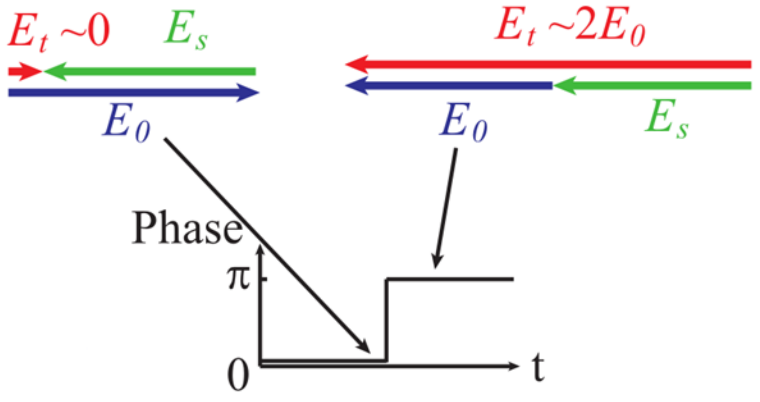
Phase change

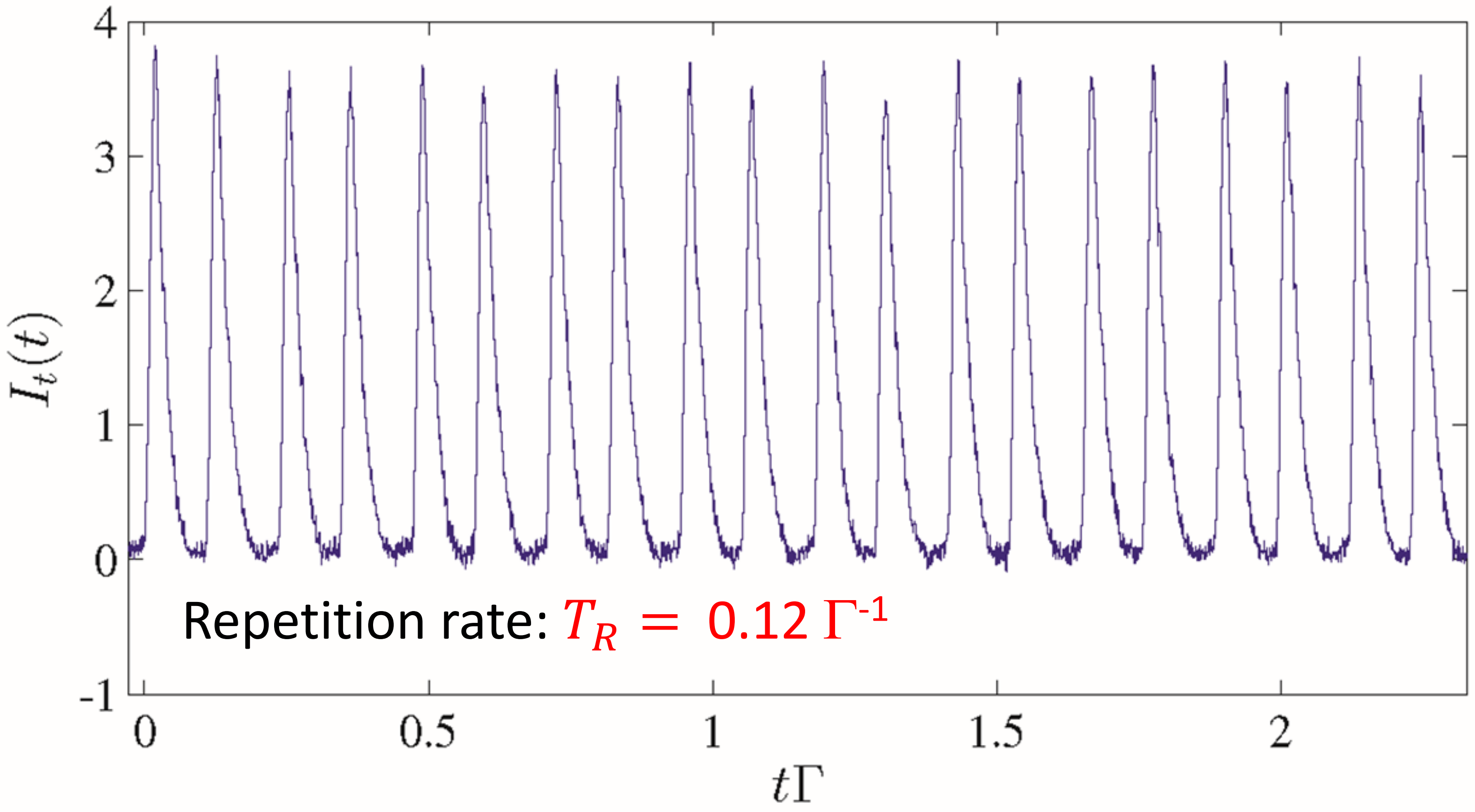


C. C. Kwong, et *al*. PRL **114**, 223601 (2015)

Cooperative Pulse Train

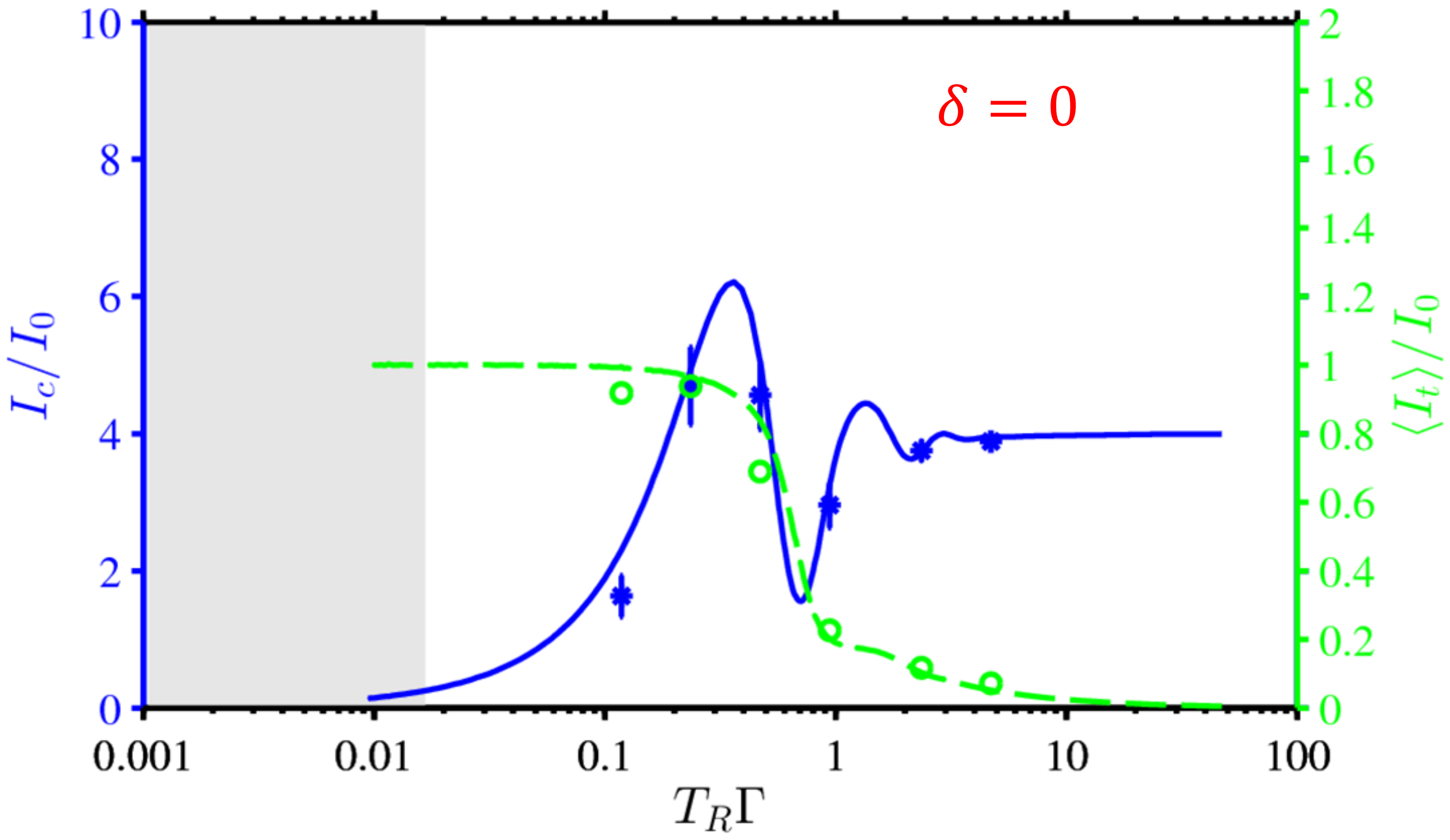
$\delta = 0$





C. C. Kwong, et *al*. PRL **114**, 223601 (2015)

Pulse Train: Figure of Merit



If the repetition rate $T_R < \Gamma^{-1}$ fluorescence is quenched

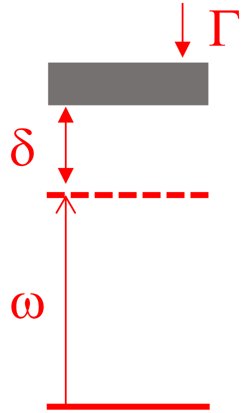
C. C. Kwong, et *al*. PRL **114**, 223601 (2015)

Two-level to Λ-scheme

Two-level: $E_t(t) = E_0(t) + E_s(t)$

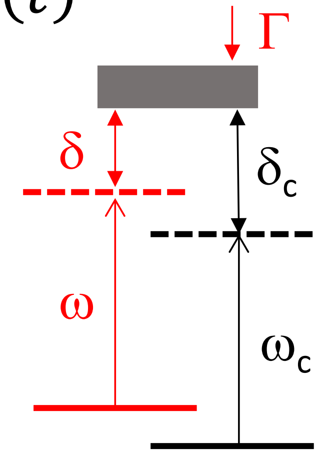
$$\alpha = -\frac{3\pi}{k^3}\frac{\Gamma}{\delta + i\Gamma/2}$$

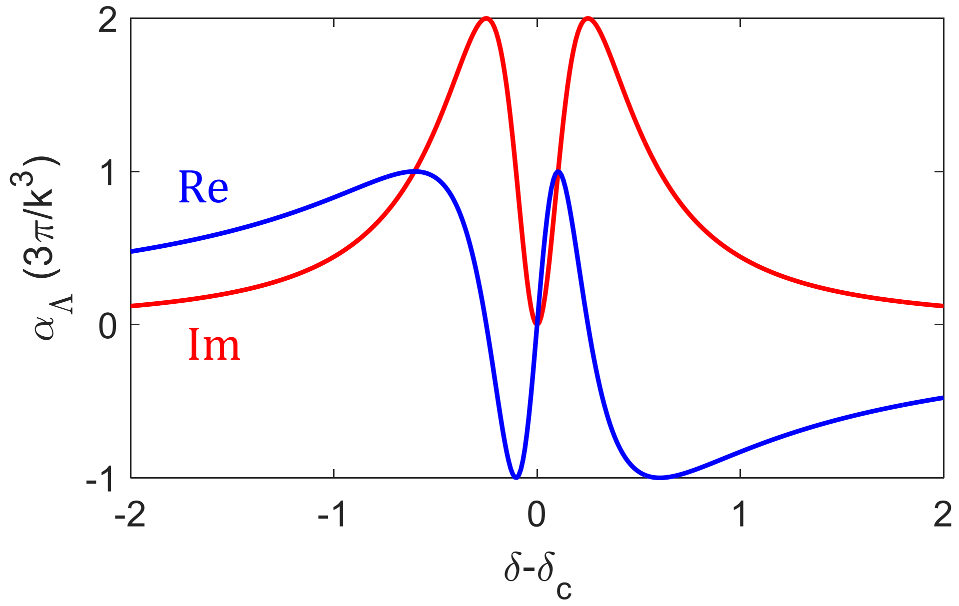
If $\delta = 0$ and $b \gg 1$ ($\phi \sim 0$), $E_s \sim -E_0$



Λ-scheme: $E_t(t) = E_0(t) + E_s(t) + E_{S/\Lambda}(t)$

$$\alpha_\Lambda = \alpha\left(1 - \frac{|\Omega_c|^2/4}{(\delta + i\Gamma/2)(\delta - \delta_c)}\right)^{-1}$$





Narrow dark resonance: $\Gamma_d = |\Omega_c|^2/\Gamma$

If b $\gg 1$, $\tau_{S/\Lambda} = b/\Gamma_d \gg \tau_S = 1/b\Gamma$

If $\delta = \delta_C = 0$ and $b \gg 1$ ($\phi = 0$), $E_s = -E_0$

and $E_t = E_0$, so $E_{S/\Lambda} = E_0$, and $I_t(0^+) = \left|E_s + E_{S/\Lambda}\right|^2_{sta} = 0$

C. Madasu, et *al.* PRA **105**, 013713 (2022)

Two-level to Λ-scheme

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If $\delta = 0$ and $b \gg 1$ ($\phi \sim 0$), $E_s \sim -E_0$

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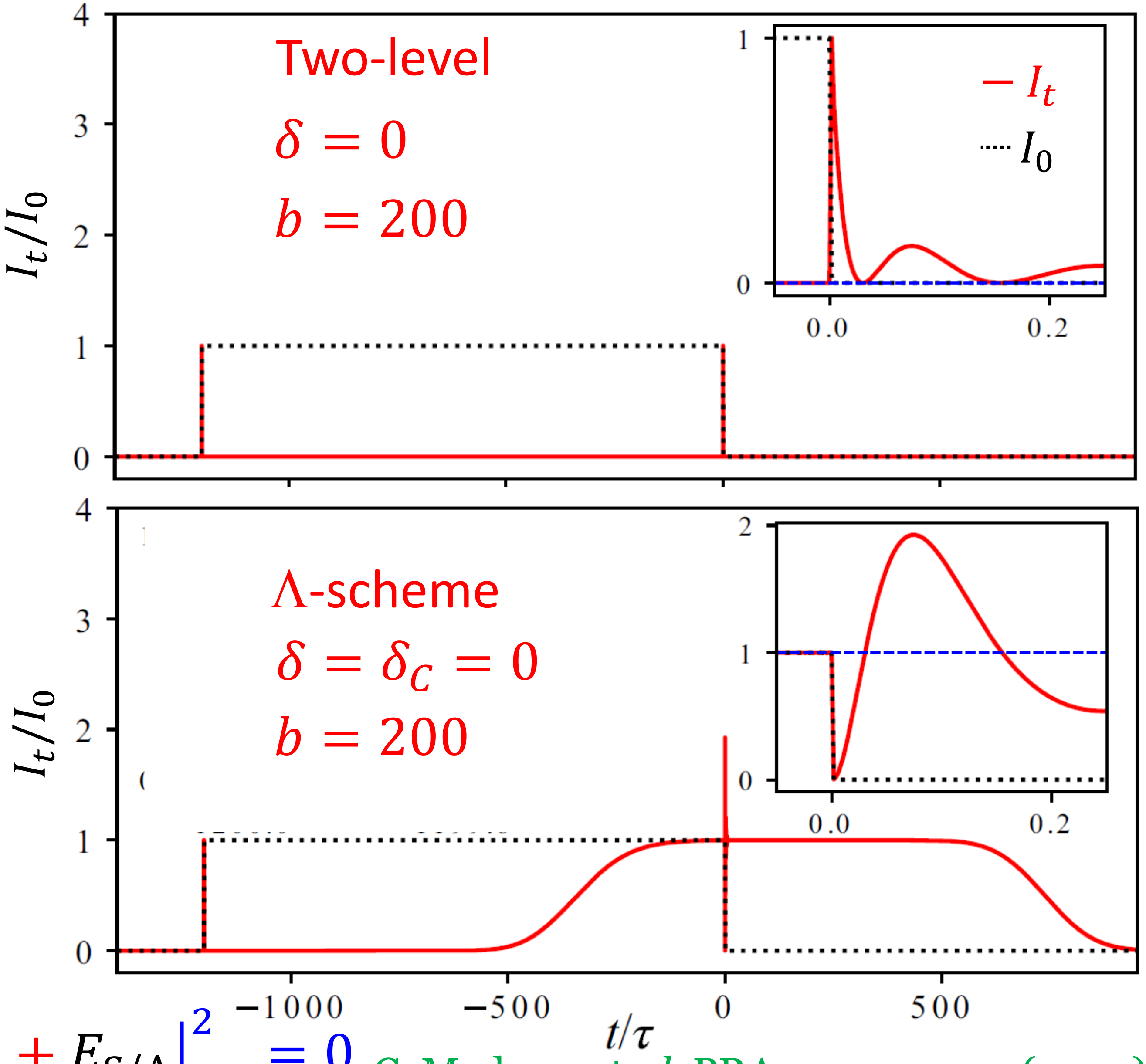


C. Madasu, et *al.* PRA **105**, 013713 (2022)

Two-level to Λ-scheme: Experiment

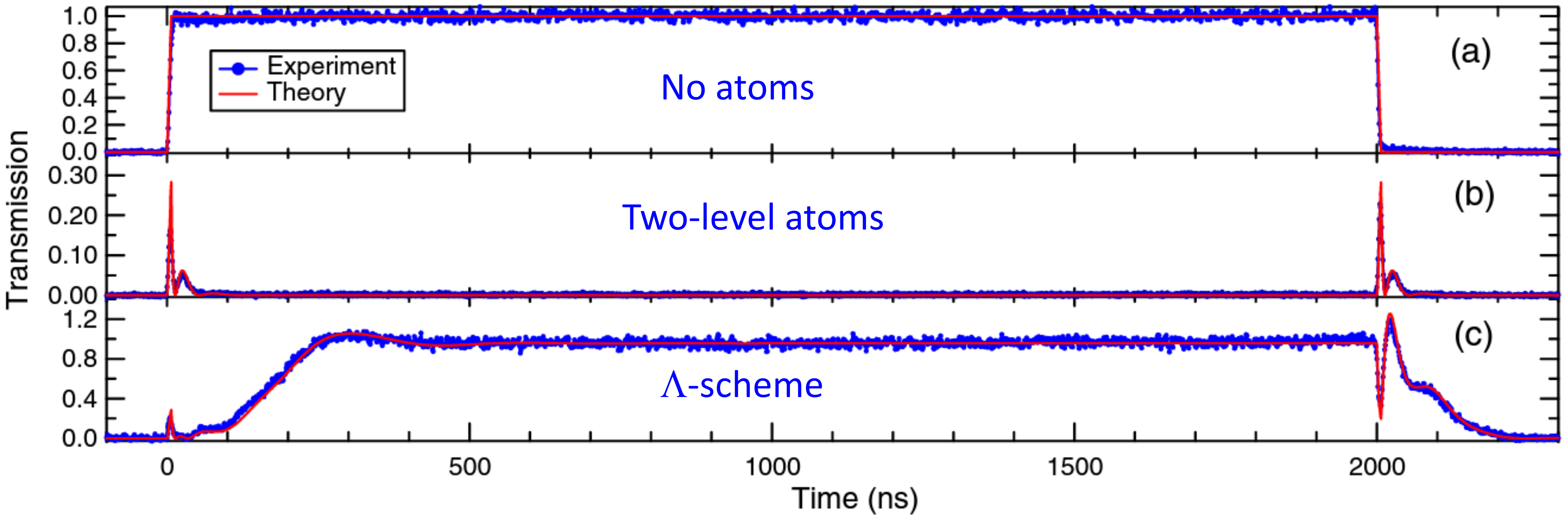
PRL **103,** 093602 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

Optical Precursors with Electromagnetically Induced Transparency in Cold Atoms

Dong Wei, J. F. Chen, M. M. T. Loy, G. K. L. Wong, and Shengwang Du*

Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

(Received 10 July 2009; published 28 August 2009)



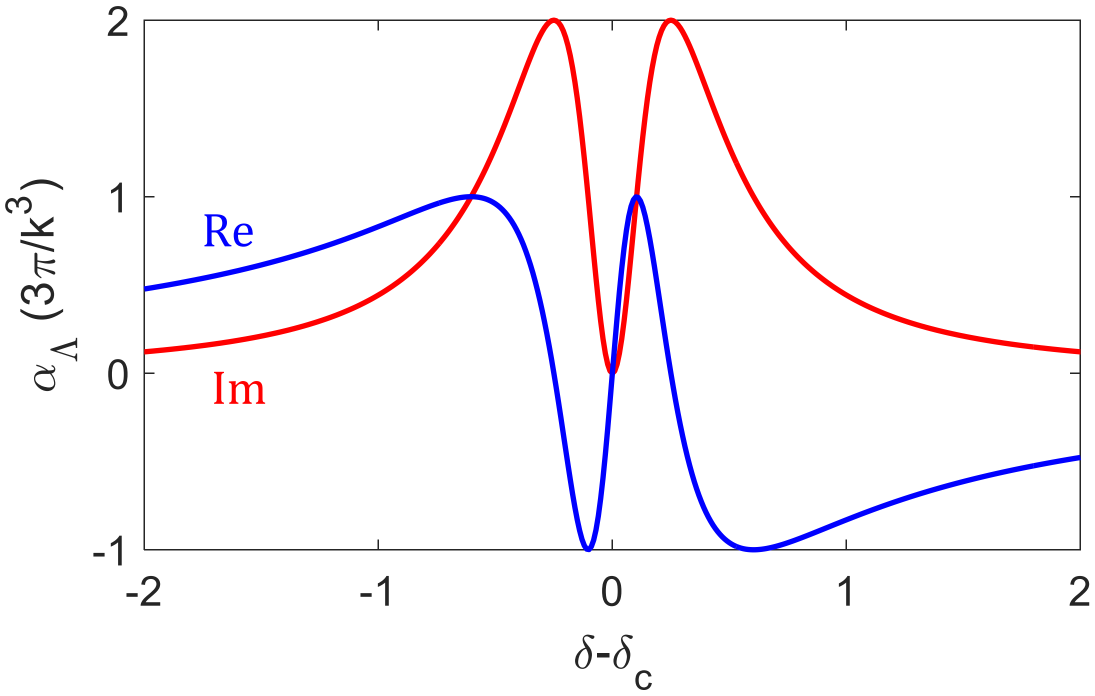
Phase Rotation in Λ-scheme

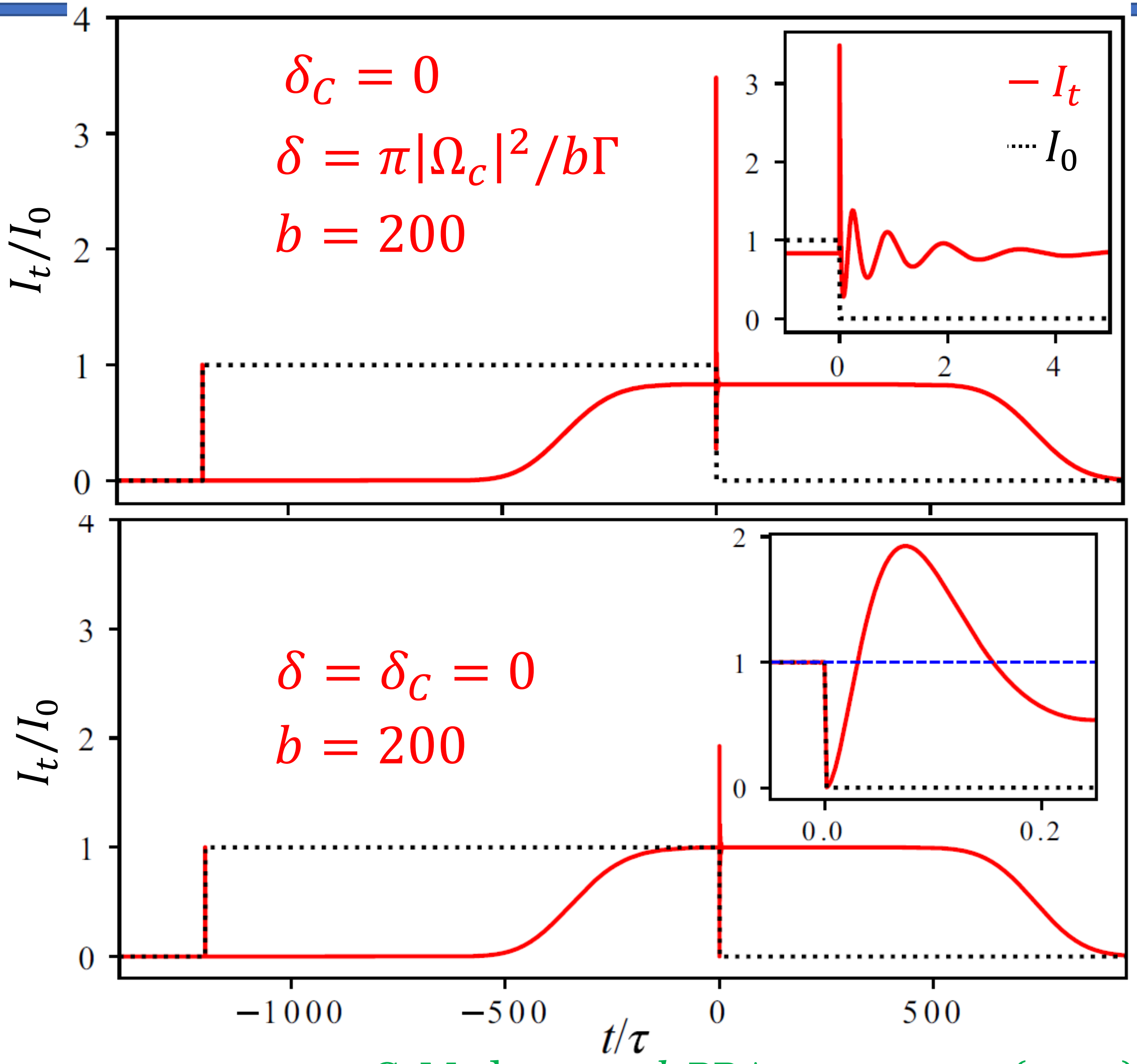
Λ-scheme: $E_t(t) = E_0(t) + E_s(t) + E_{S/\Lambda}(t)$

If $\delta = \delta_C = 0$, then $E_{S/\Lambda} = E_0$

If $\delta = \pm\pi|\Omega_c|^2/b\Gamma \ll \Gamma$, then $E_{S/\Lambda} = -E_0$

$$I_t(0^+) = \left|E_s + E_{S/\Lambda}\right|^2_{\mathrm{sta}} = 4$$

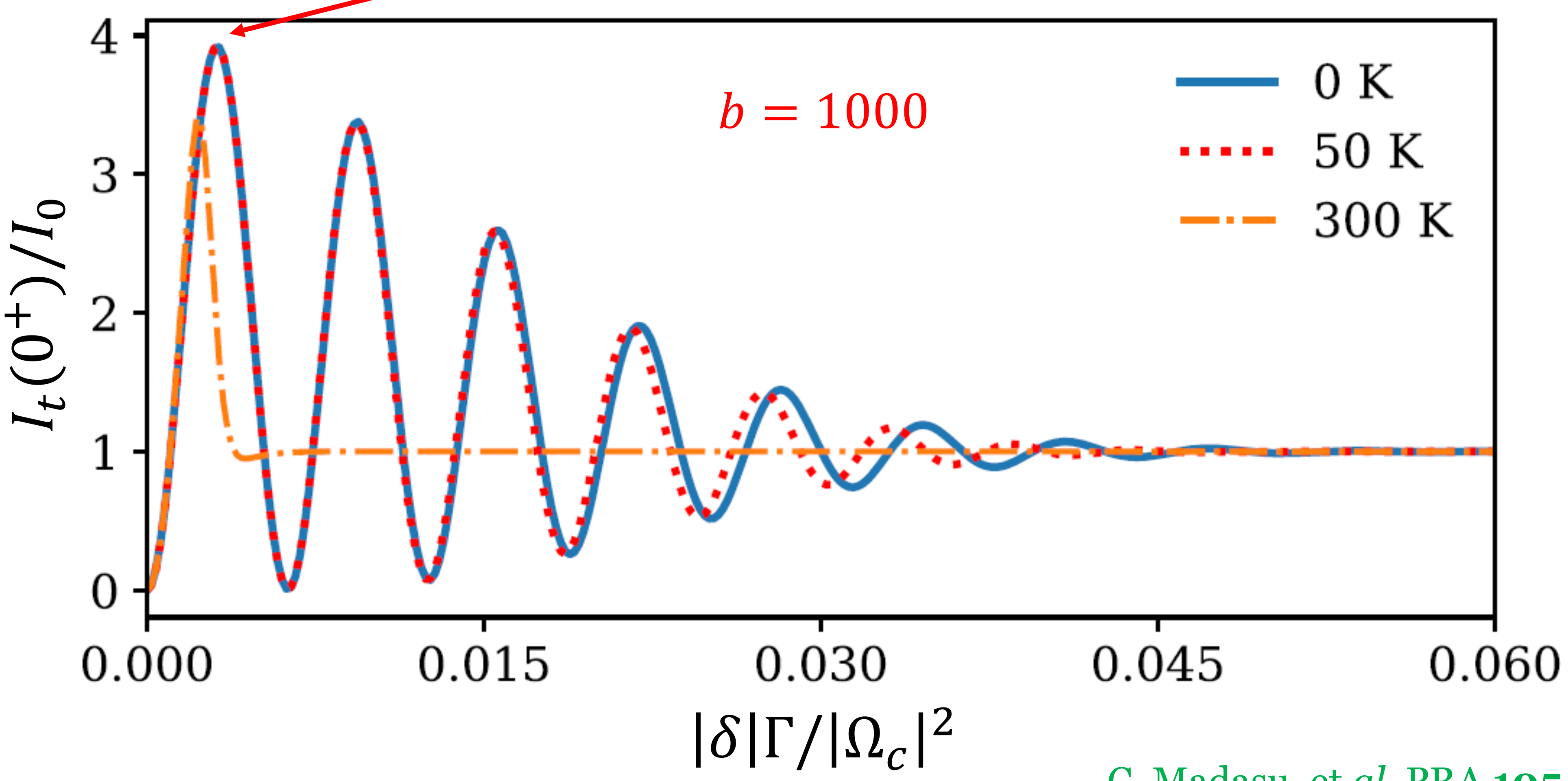




C. Madasu, et *al*. PRA **105**, 013713 (2022)

Λ-scheme: Thermal effect

For Rb atoms: $\Gamma/2\pi = 6\ \mathrm{MHz}$, $|\Omega_c| = \Gamma/10$, $|\delta|_\pi/2\pi \approx 300\ \mathrm{Hz}$ and $\frac{|\delta|_\pi}{\Delta\omega_{hf}} = 5\times10^{-8}$



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Conclusion and Outlook

Transient phenomena in the coherent transmission
of a optical thick medium with “slow” resonant response time.

Decomposition of the field as:

$$E_t(t) = E_0(t) + E_s(t) + E_{S/\Lambda}(t)$$

Transmission

Incident

Forward scattering

Λ-contribution

E_s is “fast” $\sim 1/b\Gamma$. Similar to superradiance

$E_{S/\Lambda}$ is very “slow” $\sim b/\Gamma$. Slow light

E_s, $E_{S/\Lambda}$ can be extracted using the (super)flash effect, *i.e.* measurement of $I_t(0^+)$

Applications: Cooperative pulse generator, frequency sensing

People

Flash Effect

Maryvonne Chalony
Dominique Delande
Romain Pierrat

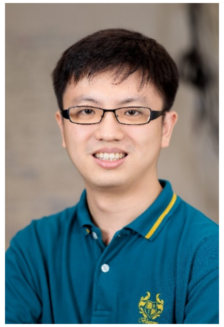
Romain Pierrat, IL ESPCI (Fr)

M. Chalony et *al.*, PRA **84**, 011401(R) (2011)

Dominique Delande, LKB SU (Fr)

Superflash and cooperative Pulse

Kwong Chang-Chi
Kanhaiya Pandey
Mysore Pramod
Tao Yang
Dominique Delande
Romain Pierrat



C. C. Kwong, et *al.*, PRL **113**, 223601 (2014)
C. C. Kwong, et *al.* PRL **114**, 223601 (2015)

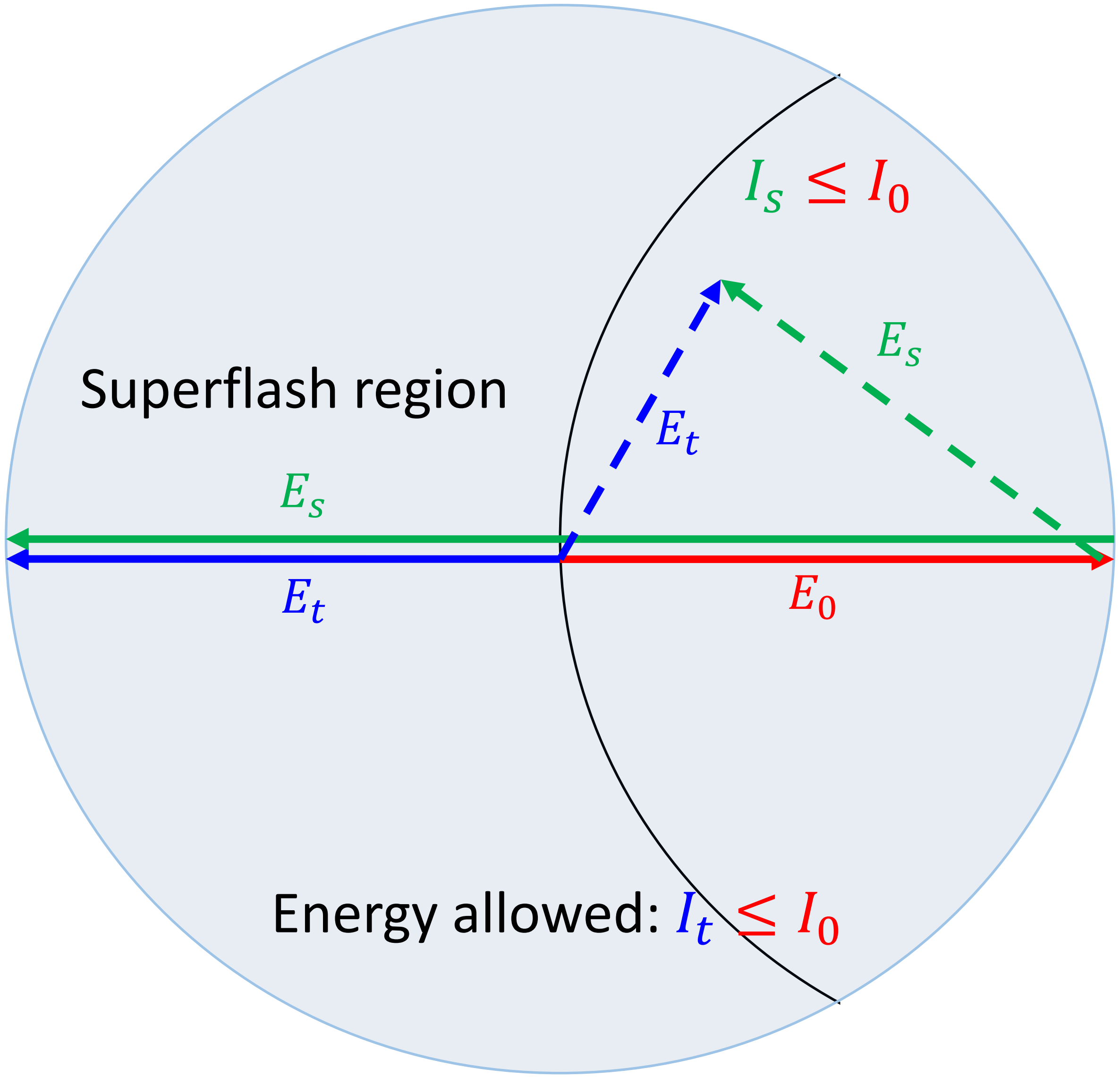
Kanhaiya Pandey, IIT Guwahati (In)

Flash with Λ-Scheme

Chetan S. Madasu
Kwong Chang-Chi
Kanhaiya Pandey

C. Madasu, et *al.* PRA **105**, 013713 (2022)

Flash (or Forward scattering) Amplitude



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