Physics
OSAKA UNIVERSITY

科研費
KAKENHI

Quantum coherent amplification of dark matter interaction with atoms

Minoru Tanaka (Osaka U)

in collaboration with
H. Hara, Y. Miyamoto, N. Sasao, J. Wang（Okayama U）

ICNAAM 2023, Quantum Science symposium, Sep. 15, 2023

Light dark matter candidates

Axion (and axion-like particles)

Proposed solution of the strong CP problem

$$\mathcal{L}_{\rm int} \supset g_{a\gamma\gamma}\, aF^{\mu\nu}\tilde{F}_{\mu\nu} \propto a\boldsymbol{E}\cdot\boldsymbol{B}$$

2 parameters : $m_a,\ g_{a\gamma\gamma}$

Dark photon

Minimal extension of the SM gauge sector $U_X(1)$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \boxed{\frac{\chi}{2}F_{\mu\nu}X^{\mu\nu}} + \frac{1}{2}m_X^2 X_\mu X^\mu - j^\mu_{\rm em}A_\mu$$

2 parameters : $m_X,\ \chi$ kinetic mixing

Standard model + inflation + dark photon

Graham, Mardon, Rajendran, PRD93, 103520 (2016)

→ Dark photon dark matter

$$\Omega_X = \Omega_{\rm CDM}\left(\frac{m_X}{6\times10^{-6}\ {\rm eV}}\right)^{1/2}\left(\frac{H_I}{10^{14}\ {\rm GeV}}\right)^2$$

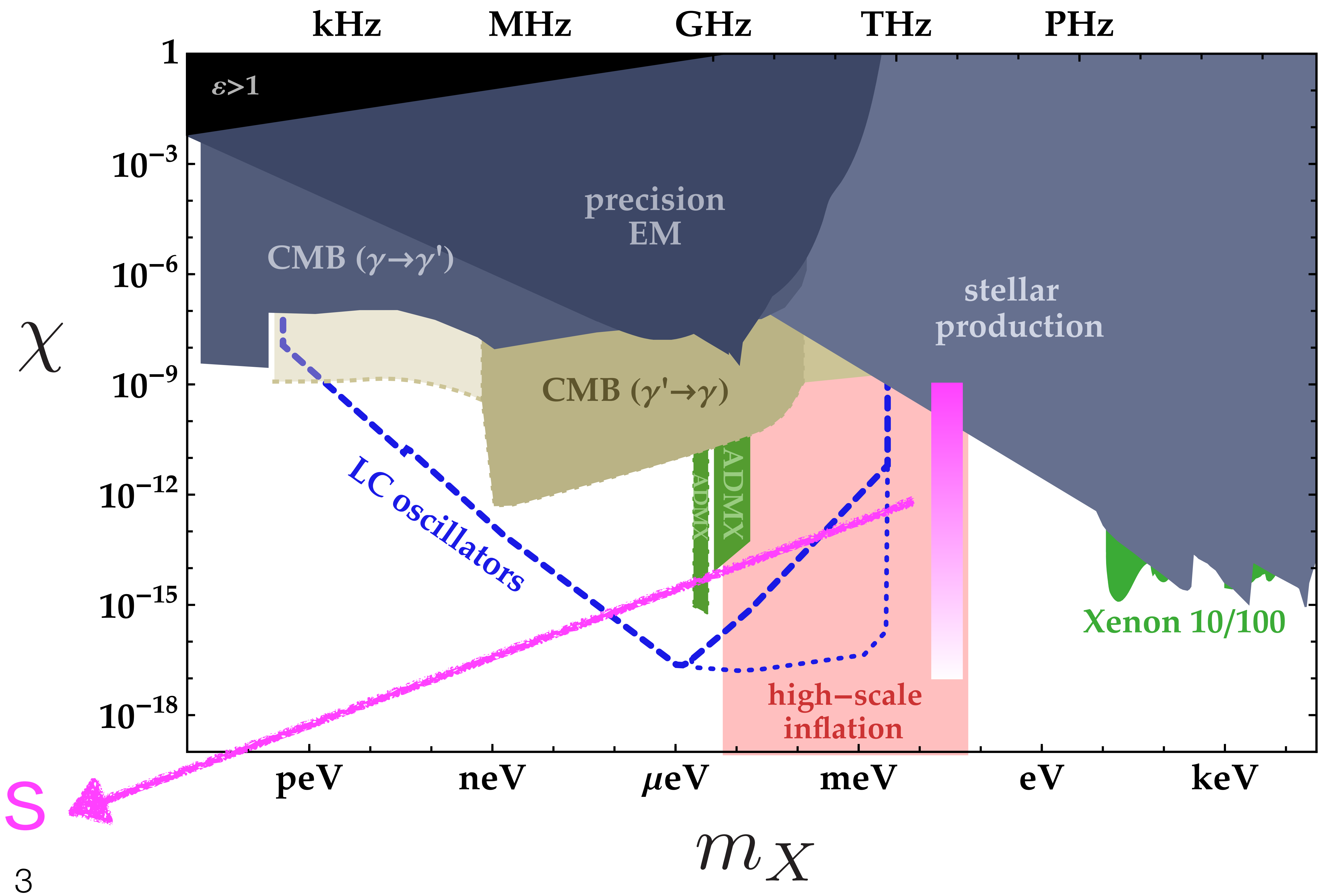
H_I : Hubble scale of inflation

$$H_I \lesssim 10^{14}\ {\rm GeV}$$

$$\longrightarrow \quad m \gtrsim 10^{-5}\ {\rm eV}$$

coherently oscillating

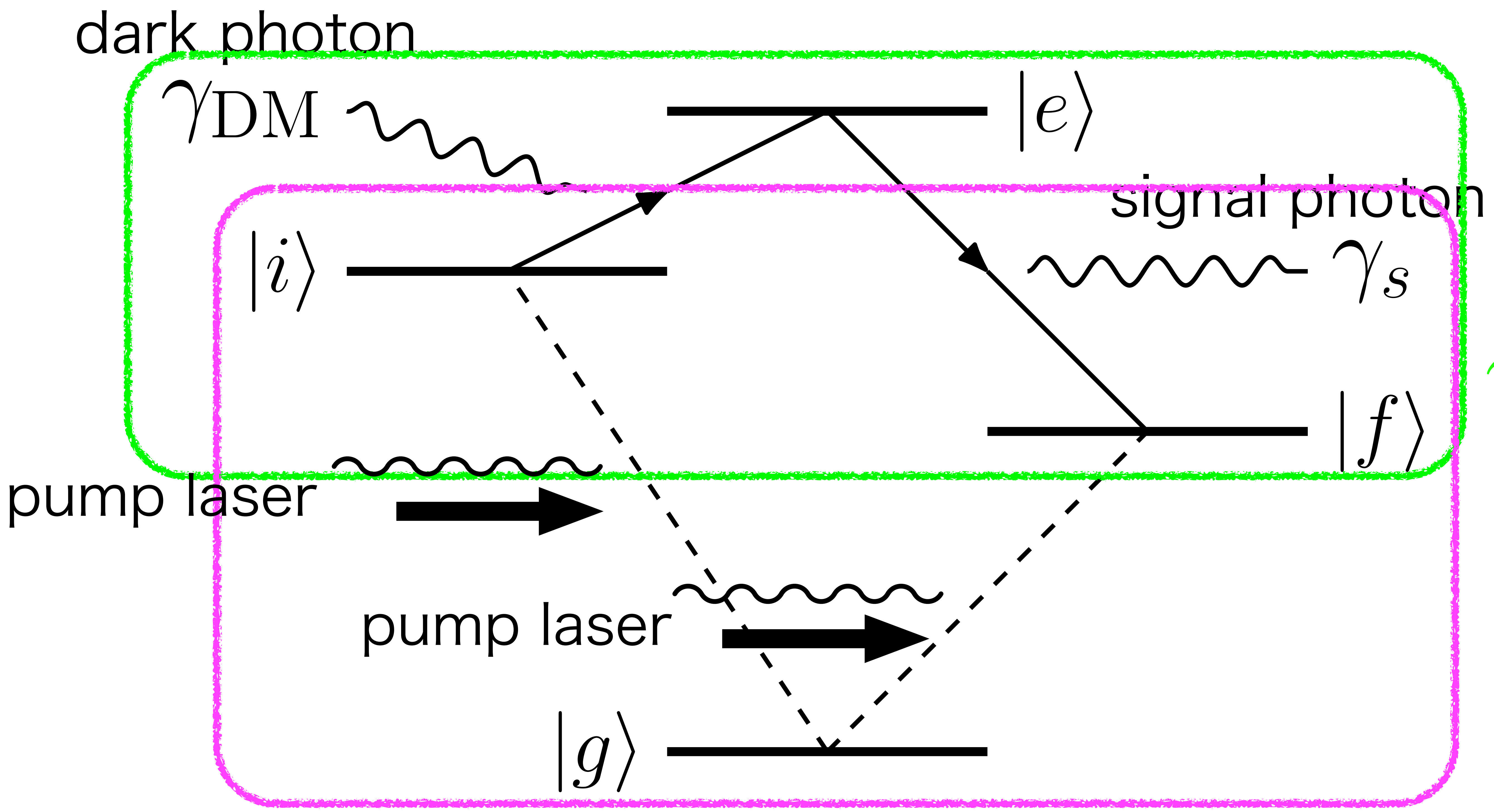
$$X^\mu \propto e^{im_X t}$$



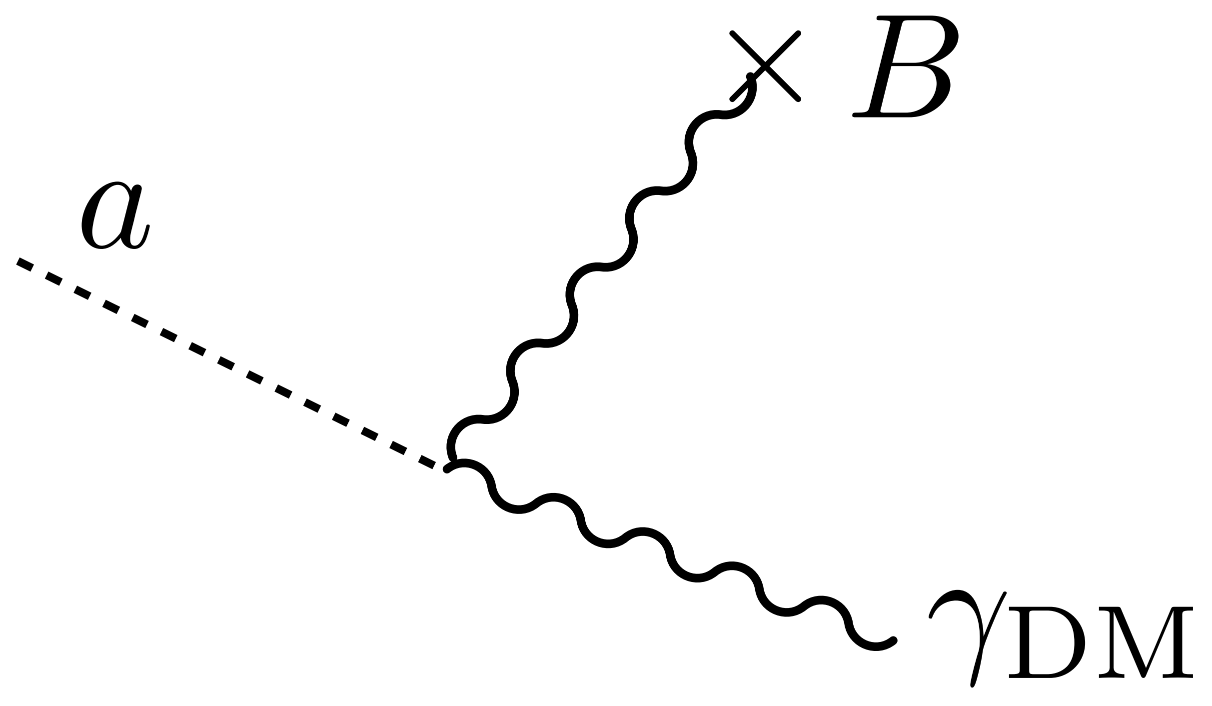
Search with atomic process

Search principle with quantum coherence

Excitation by dark photon absorption



axion case



$$\gamma_{\rm DM} + |i\rangle \to |e\rangle \to |f\rangle + \gamma_s$$

coherence generation

Macrocoherence

momentum conservation of DM, pump and signal photons

Macrocoherence

Yoshimura et al. (2008)

Initial state of N atoms

$$|\Psi\rangle := \Pi_a |a,\psi\rangle \ , \ |a,\psi\rangle := c_i e^{i\boldsymbol{k}_0\cdot\boldsymbol{x}_a} |a,i\rangle + c_f |a,f\rangle + c_g |a,g\rangle$$ a-th atom

Final state

$$|\Psi\rangle \to M_{fi} c_i c_f \sum_a |1,\psi\rangle \cdots e^{i(\boldsymbol{k}_0-\boldsymbol{k}_s)\cdot\boldsymbol{x}_a} |a,f\rangle \cdots |N,\psi\rangle$$

M_{fi} : transition matrix element

Coherent rate

$$d\Gamma = 2\pi\delta(m_{\rm DM} - E_{ei} + E_{ef} - E_s)|M_{fi}|^2|c_i c_f|^2 \left[N + \sum_{a\neq a'} e^{i(\boldsymbol{k}_0-\boldsymbol{k}_s)\cdot(\boldsymbol{x}_a-\boldsymbol{x}_{a'})}\right]\frac{d^3\boldsymbol{k}_s}{(2\pi)^3}$$

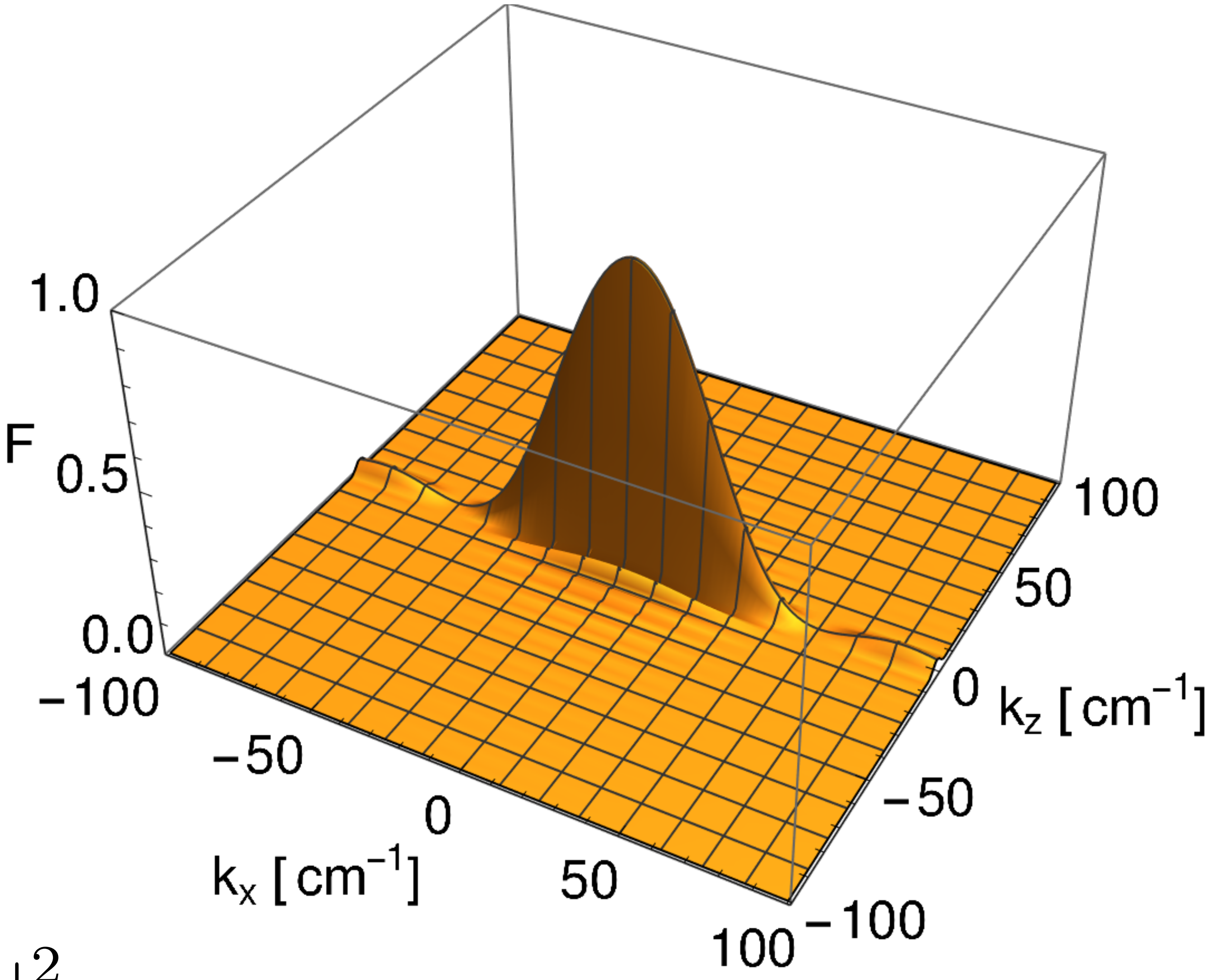
$V\to\infty\,,\ N/V$ fixed $\quad V$: target volume

$$d\Gamma \to 2\pi\delta(m_{\rm DM} - E_{ei} + E_{ef} - E_s)|M_{fi}|^2|\rho_{fi}|^2 \frac{N^2}{V}(2\pi)^3\delta^3(\boldsymbol{k}_0-\boldsymbol{k}_s)\frac{d^3\boldsymbol{k}_s}{(2\pi)^3}$$

macrocoherent amplification

$$\Gamma = 2\pi\delta(m_{\rm DM} - E_{ei} + E_{ef} - E_s)|M_{fi}|^2|\rho_{fi}|^2 n^2 V$$ $n := N/V$

Finite width and volume



Width

$$2\pi\delta(m_{\rm DM} - E_{ei} + E_{ef} - E_s)$$

$$\Rightarrow L(E_s) := \frac{\Gamma_i + \Gamma_f}{(m_{\rm DM} + E_i - E_f - E_s)^2 + (\Gamma_i + \Gamma_f)^2/4}\,.$$

Volume

$$\frac{(2\pi)^3}{V}\delta^3(\boldsymbol{k}) \Rightarrow F(\boldsymbol{k}) := \frac{1}{N^2}\sum_{a,a'} e^{i\boldsymbol{k}\cdot(\boldsymbol{x}_a - \boldsymbol{x}_{a'})} = \frac{1}{N^2}\left|\sum_a e^{i\boldsymbol{k}\cdot\boldsymbol{x}_a}\right|^2$$

form factor

$F(0) = 1$

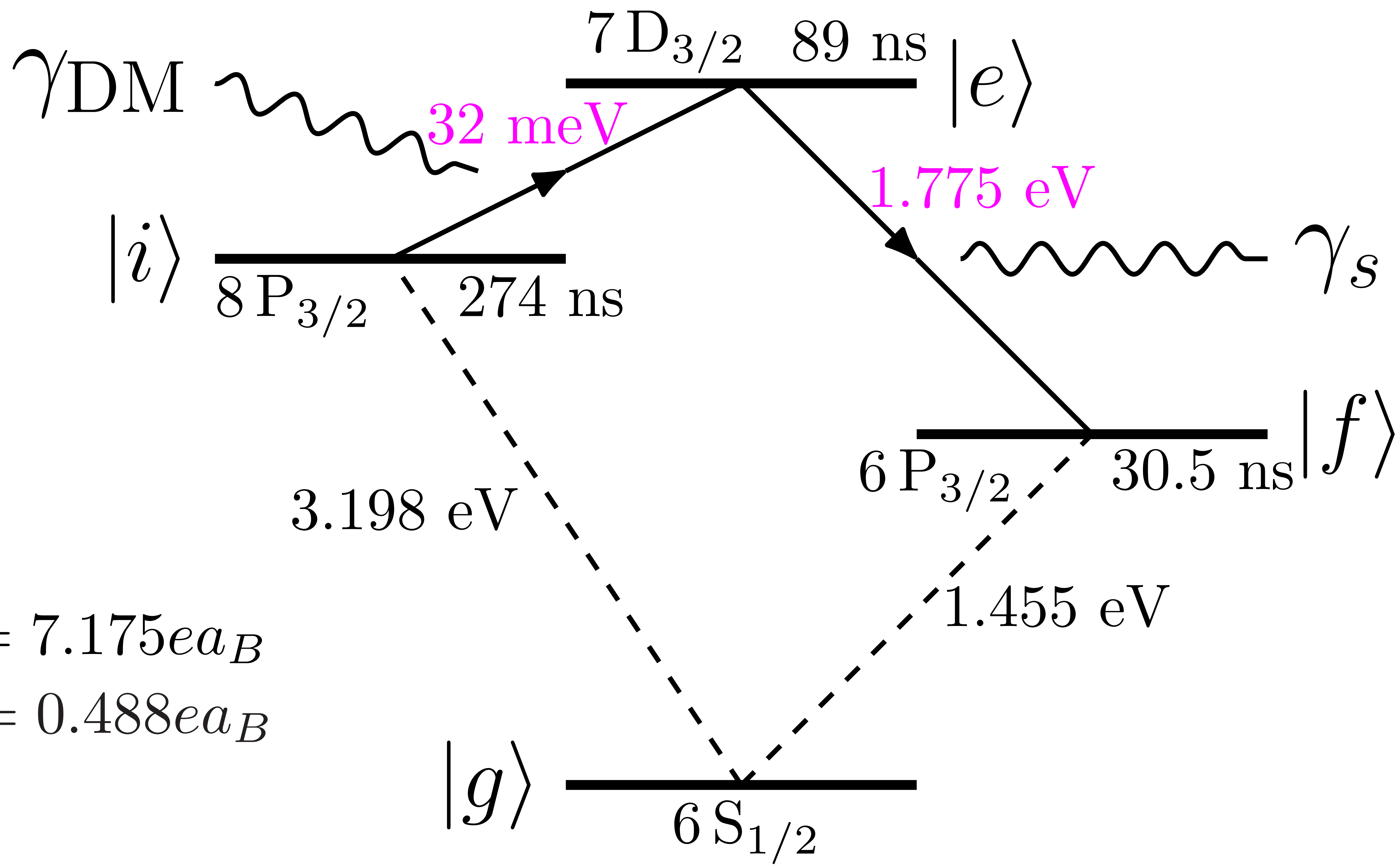
Rate

$$\Gamma \simeq n^2 V |\rho_{fi}|^2 |M_{fi}|^2 \frac{1}{\Gamma_{\rm eff}} \qquad \frac{1}{\Gamma_{\rm eff}} := \int \frac{V d^3\boldsymbol{k}_s}{(2\pi)^3} L(E_s) F(\boldsymbol{k}_0 - \boldsymbol{k}_s)$$

effective (inverse) width

Minoru TANAKA

Cs pilot experiment



$d_{ei} = 7.175 e a_B$

$d_{fe} = 0.488 e a_B$

target spec.

$n = 1 \times 10^{12}\ \mathrm{cm}^{-3}$

$V = 0.1 \times 0.1 \times 1\ \mathrm{cm}^3$

$\Gamma_{\mathrm{eff}} \simeq 2.2 \times 10^{-5}\ \mathrm{eV}$

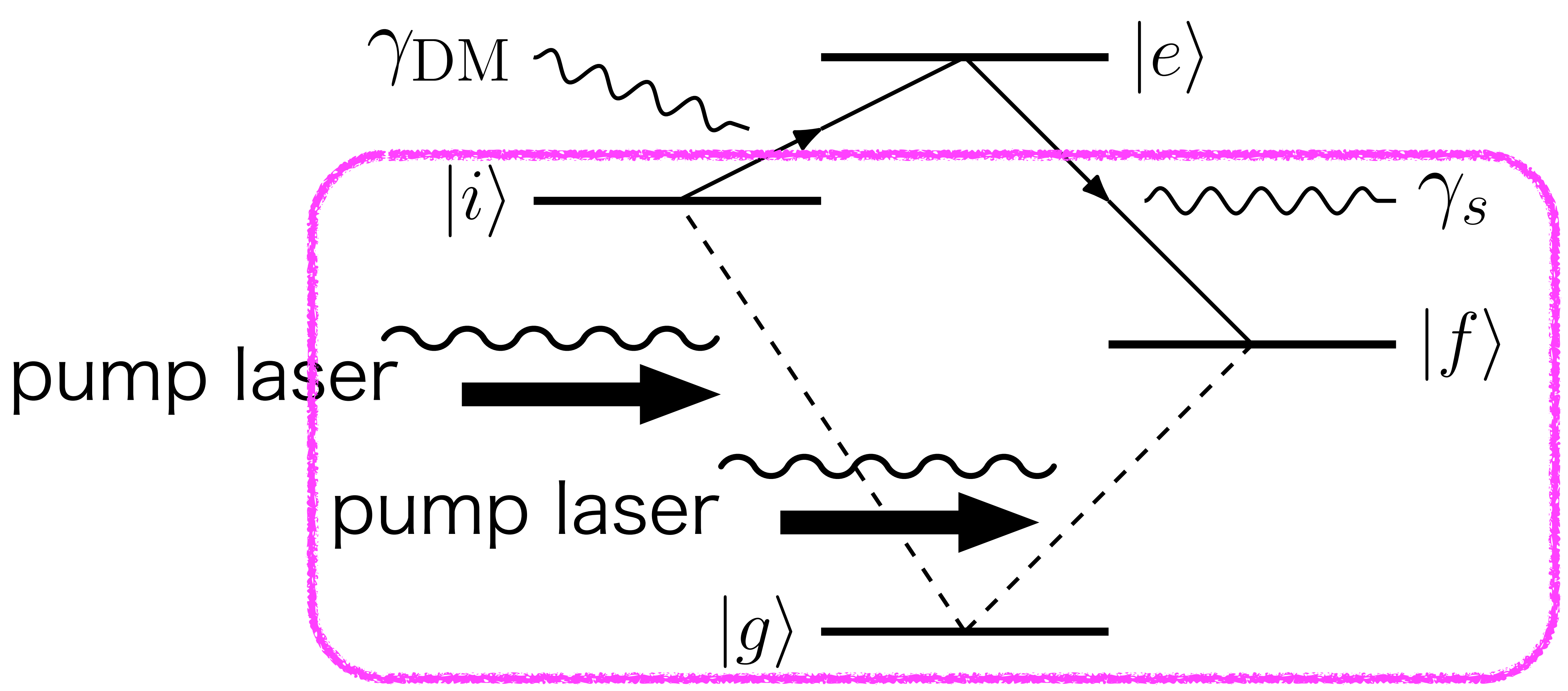
(>> natural width)

$$\Gamma = 1.6 \times 10^3 \left(\frac{\chi}{10^{-9}}\right)^2 \left(\frac{n}{10^{12}\ \mathrm{cm}^3}\right)^2 \left(\frac{\rho_{fi}}{0.25}\right)^2\ \mathrm{Hz}$$

cf. single atom rate: $\Gamma_0 = 3.7 \times 10^{-9} \left(\frac{\chi}{10^{-9}}\right)^2\ \mathrm{Hz}$

Minoru TANAKA

Coherence generation



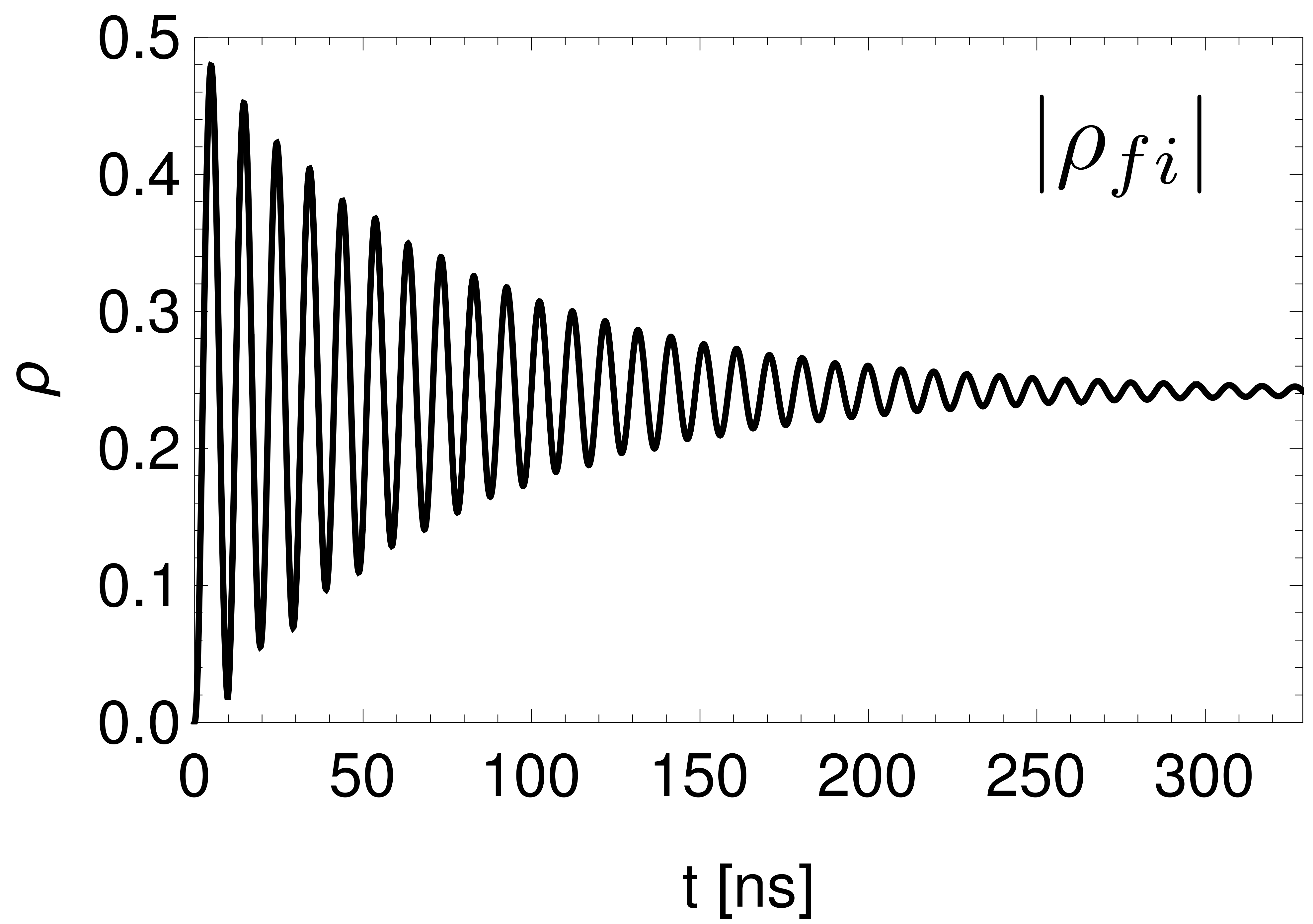
Liouville - von Neumann equation with relaxation

$$\partial_t \, \rho_{ij}(t) = -i[H(t), \rho(t)]_{ij} - \sum_{m,n} \Gamma_{ij,mn} \rho_{mn}$$

Cs parameters with radiation damping only

CW laser power: 1W(g-i), 1mW(g-f)
Laser cross section: 1mm^2

$|\rho_{fi}| \simeq 1/4$ possible



Minoru TANAKA

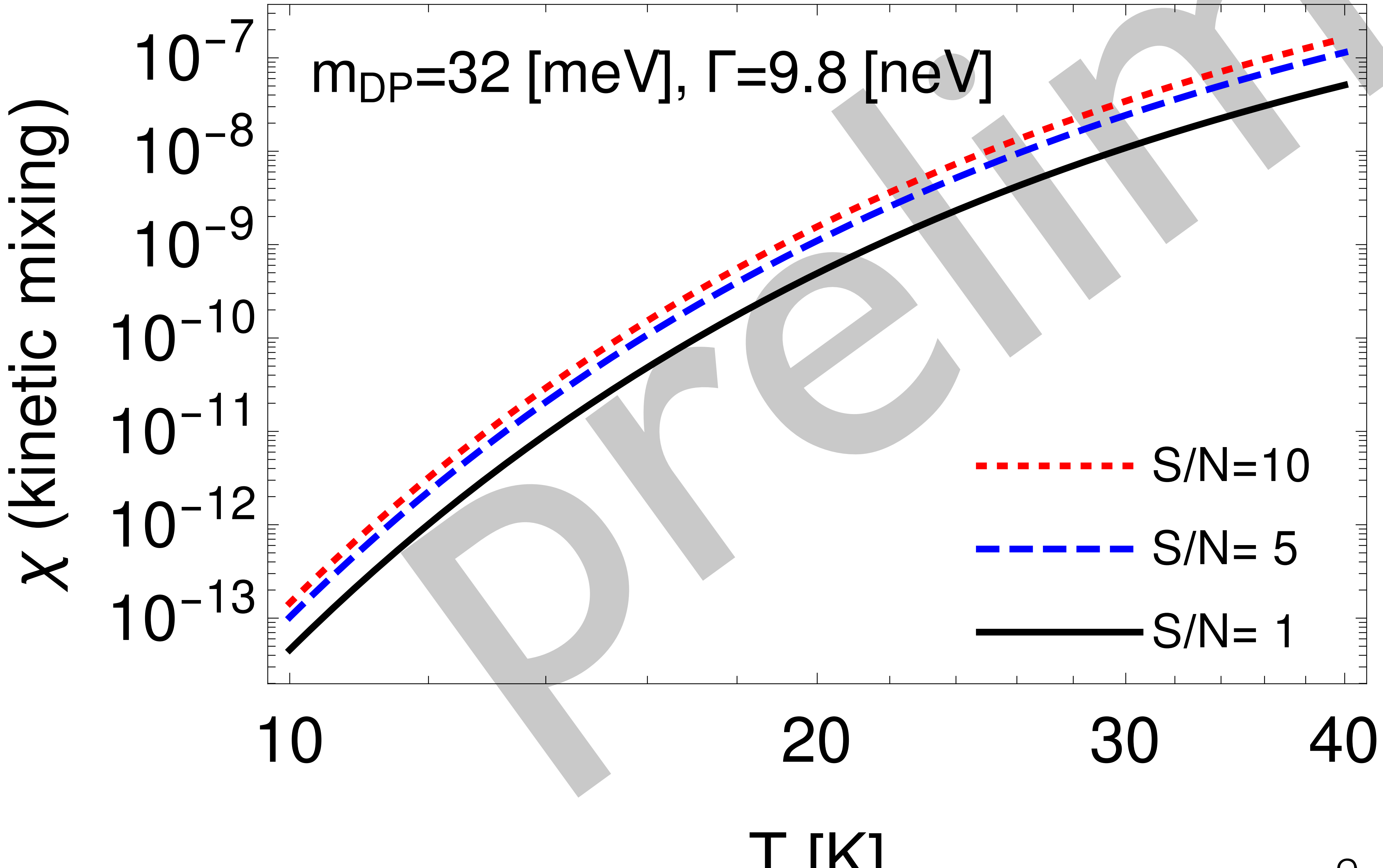
Background

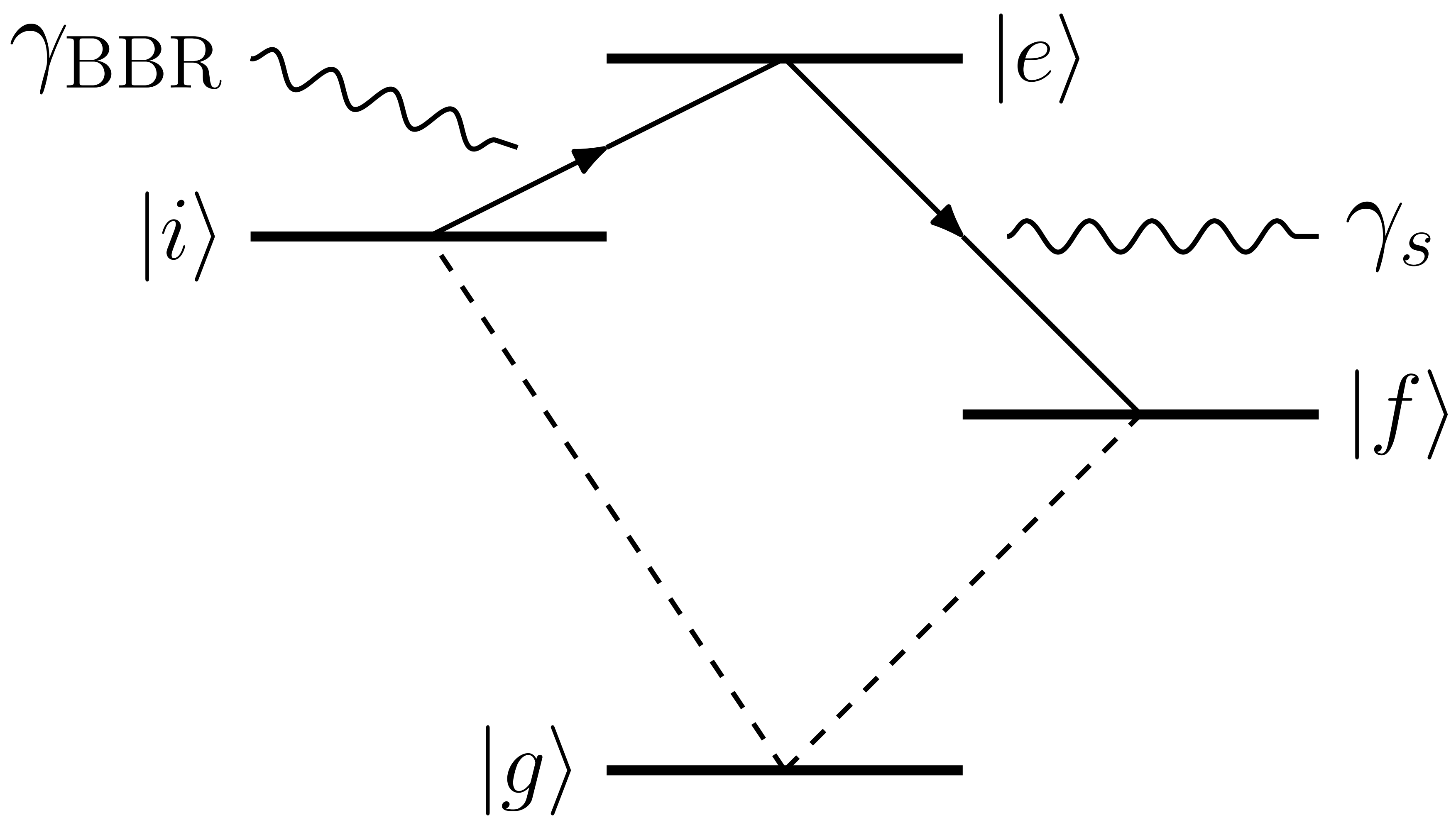
Black-body radiation

dark photon → BBR photon

not macrocoherent in the limit of $N, V \to \infty$ (N/V fixed)

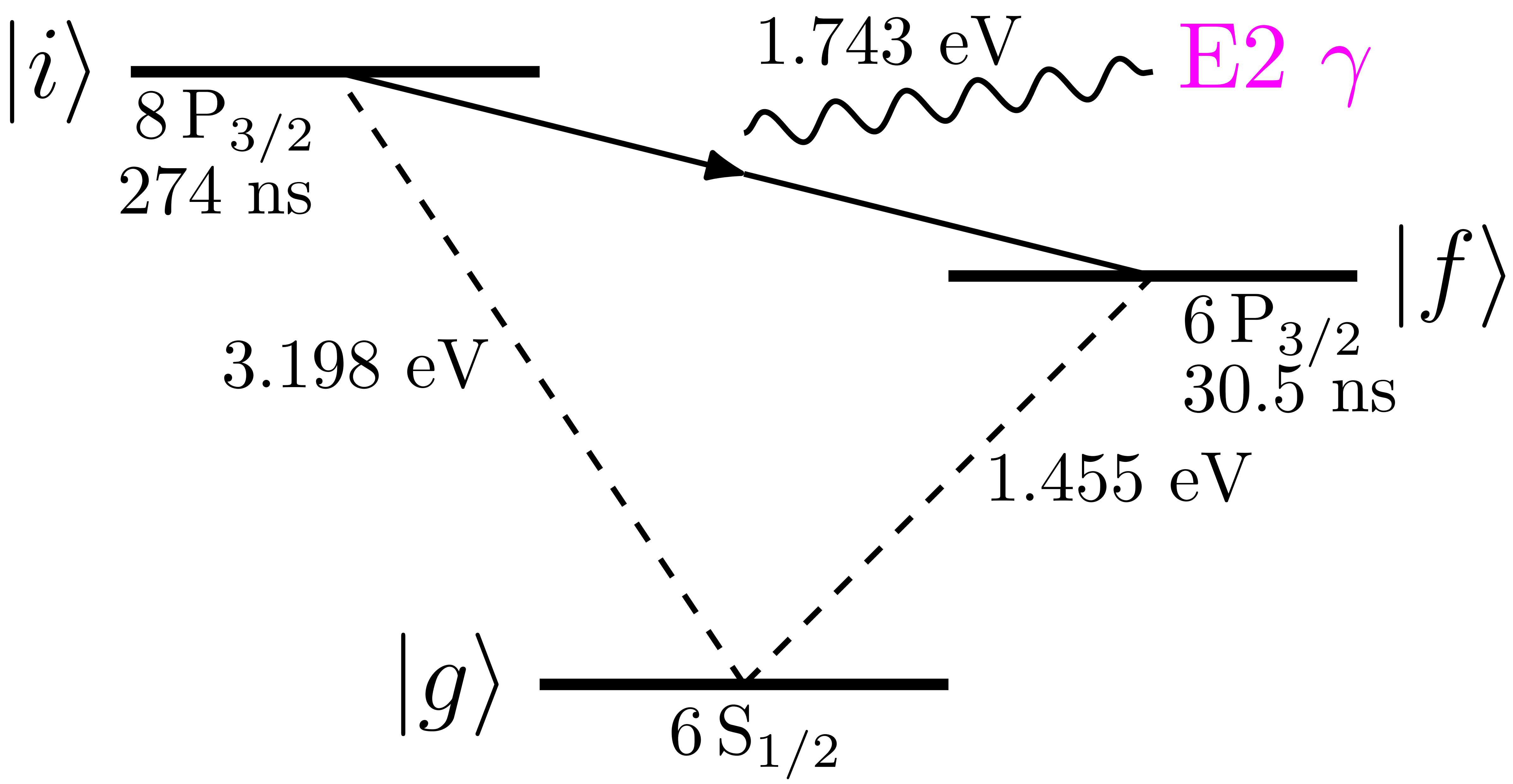
potentially dangerous for finite volume





Minoru TANAKA

Coherence measurement



E2 transition

$$\Gamma(i \to f) \sim O(1)\ \text{Hz}$$

Observed w/o coherence

Rate measurement with coherence → ρ_{fi}

Summary

- Rate amplification by coherence in ensemble of atoms

  macrocoherence and momentum conservation

  significance of ρ_{fi}

- Halo dark photon/axion search experiment

  Cs pilot experiment at Okayama U

  coherence generation and ρ_{fi} measurement ongoing

- Theoretical issues

  more realistic simulation of signal and background

  dark photon polarization and its detection

  temporal signal variation, high-density (solid) target