Physics OSAKA UNIVERSITY

科研費 KAKENHI

量子コヒーレンスによる 素粒子微弱過程の増幅に向けた理論研究

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新学術領域「ニュートリノで拓く素粒子と宇宙」公募研究紹介セミナー，2021/11/16

これまでの研究

原子集団におけるコヒーレント過程

R.H. Dicke, Phys. Rev. 93, 99 (1954)

An ensemble of N atoms in a small volume L^3

$$L \ll \text{wave length} \implies e^{-ikx} \sim 1$$

Density matrix $\rho = \rho_{gg}|g\rangle\langle g| + \rho_{ee}|e\rangle\langle e| + \rho_{eg}|e\rangle\langle g| + \rho_{ge}|g\rangle\langle e|$

Fully excited state: $|e\rangle^N = |e\rangle \cdots |e\rangle\,,\ \rho_{eg} = 0$

deexcitation: $\left(\sum |g\rangle\langle e|\right)\prod |e\rangle = |g\rangle|e\rangle\cdots|e\rangle + |e\rangle|g\rangle\cdots|e\rangle + \cdots + |e\rangle|e\rangle\cdots|g\rangle$

→ $\Gamma = N\Gamma_0$ incoherent

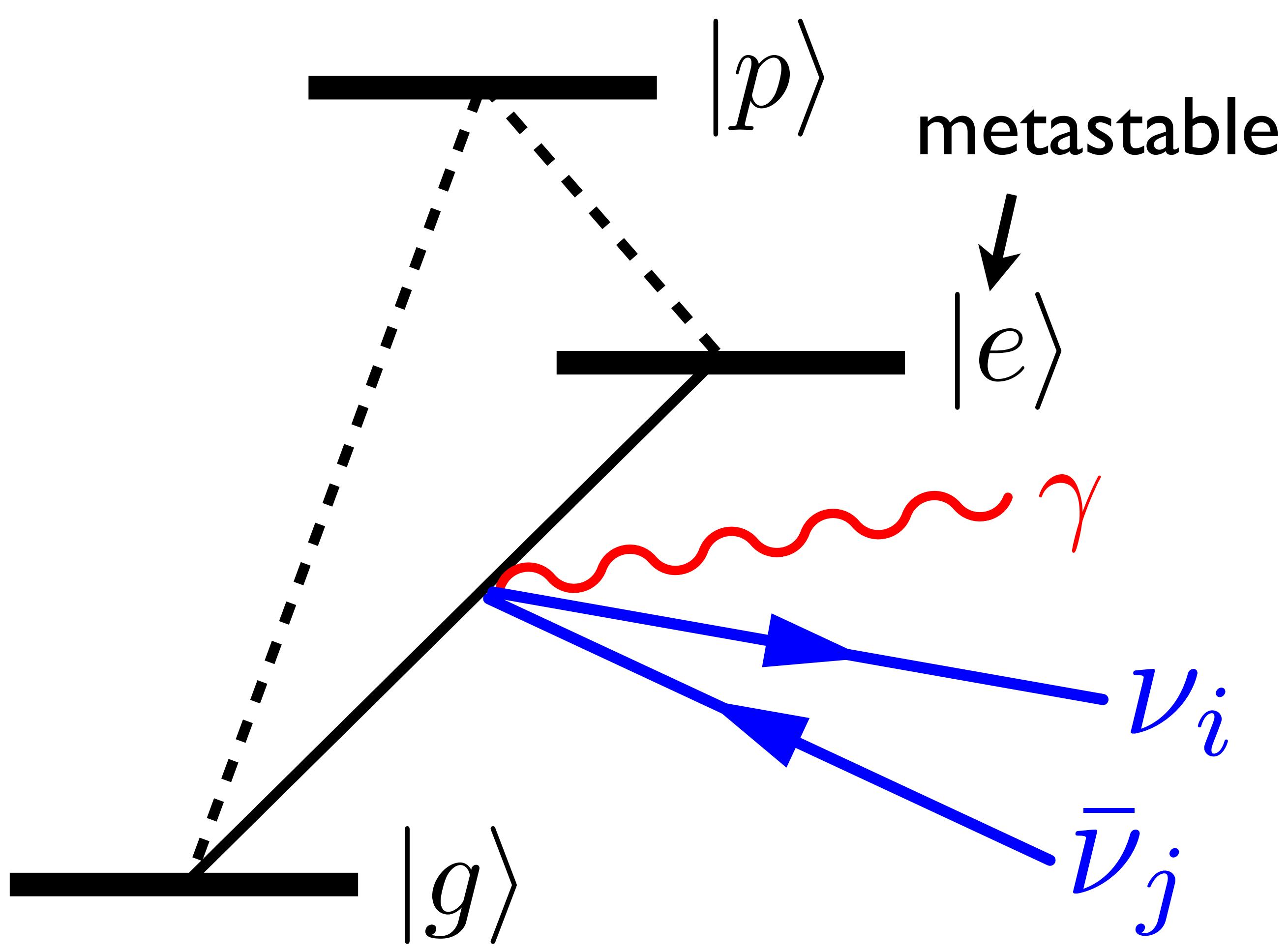
Fully coherent state: $\left[(|g\rangle + |e\rangle)/\sqrt{2}\right]^N\,,\ \rho_{eg} = 1/2$

→ (deexcitation) $\left[|g\rangle(|g\rangle + |e\rangle)\cdots(|g\rangle + |e\rangle) + (|g\rangle + |e\rangle)|g\rangle\cdots(|g\rangle + |e\rangle) + \cdots\right]/\sqrt{2^N}$

→ $\Gamma = N(N+1)\Gamma_0/4 \sim O(N^2)$ coherent

Radiative Emission of Neutrino Pair (RENP)

A.Fukumi et al. PTEP (2012) 04D002, arXiv:1211.4904



$$|e\rangle \to |g\rangle + \gamma + \nu_i \bar{\nu}_j$$

Λ-type level structure

Ba, Xe, Ca^+, Yb,...

H2, O2, I2, ...

Atomic/molecular energy scale ~ eV or less

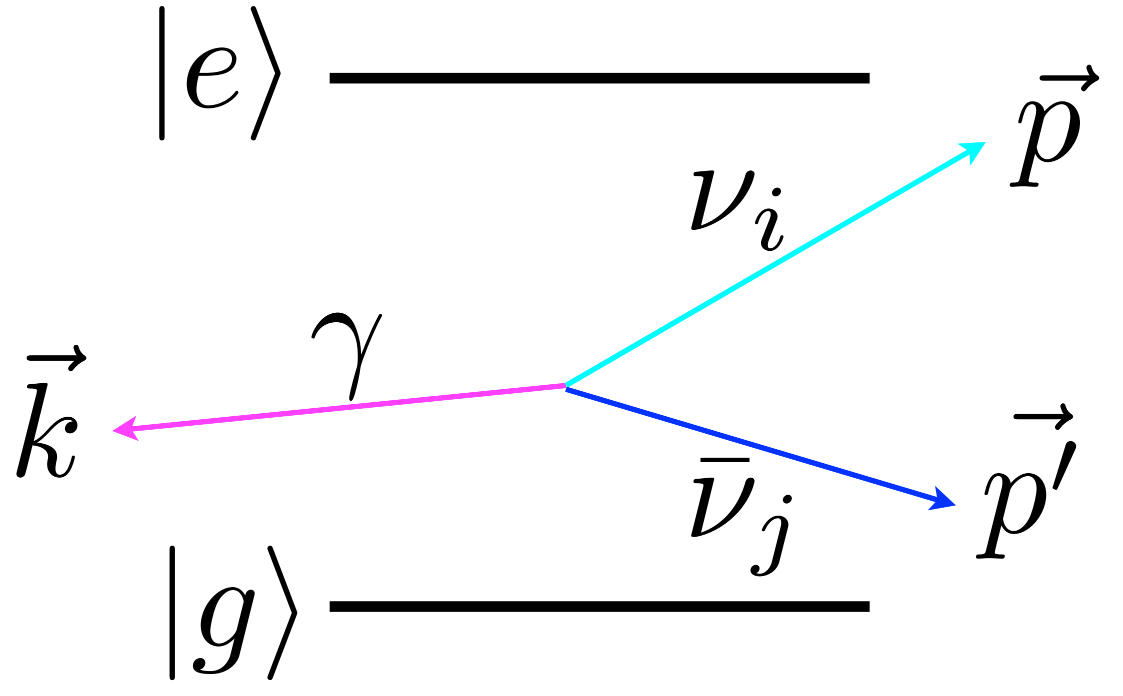
close to the neutrino mass scale   cf. nuclear processes ~ MeV

Rate $\sim \alpha G_F^2 E^5 \sim 1/(10^{33}\,\mathrm{s})$

Enhancement by coherence

Macrocoherence

Yoshimura et al. (2008)



position of atom

$$\propto e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a}(2\pi)\delta(\epsilon_{eg}-\omega-E_p-E_{p'})$$

$$(\epsilon_{eg}=\epsilon_e-\epsilon_g,\ \omega=|\vec{k}|)$$

Macroscopic target of N atoms, volume V (n=N/V)

$$\text{total amp.} \propto \sum_a e^{-i(\vec{k}+\vec{p}+\vec{p}')\cdot\vec{x}_a} \simeq \frac{N}{V}(2\pi)^3\delta^3(\vec{k}+\vec{p}+\vec{p}')$$

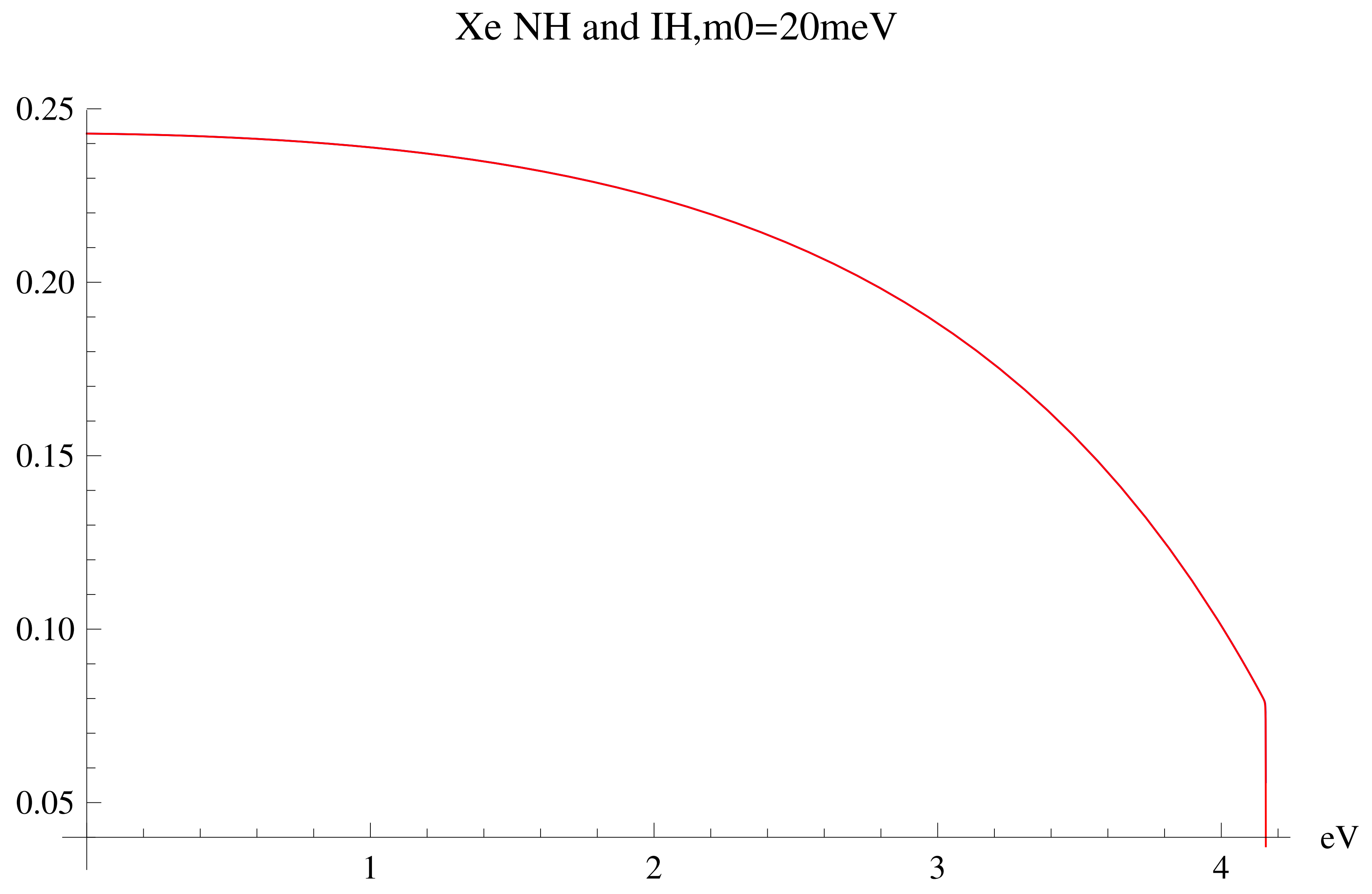
momentum conservation

$$d\Gamma \propto n^2V(2\pi)^4\delta^4(q-p-p') \qquad (q^\mu)=(\epsilon_{eg}-\omega,-\vec{k})$$

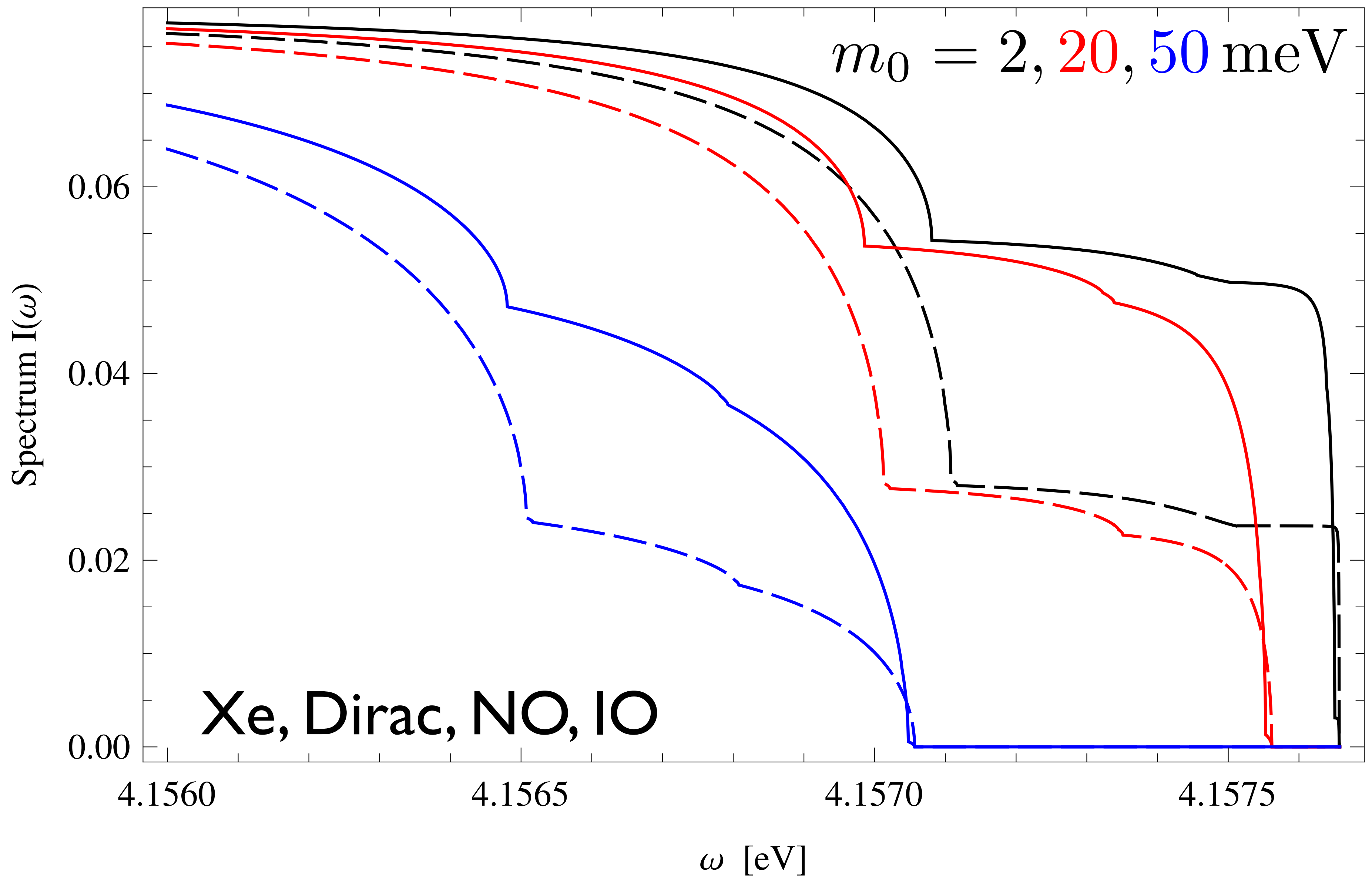
macrocoherent amplification

Photon spectrum (spin current)

Global shape



Threshold region



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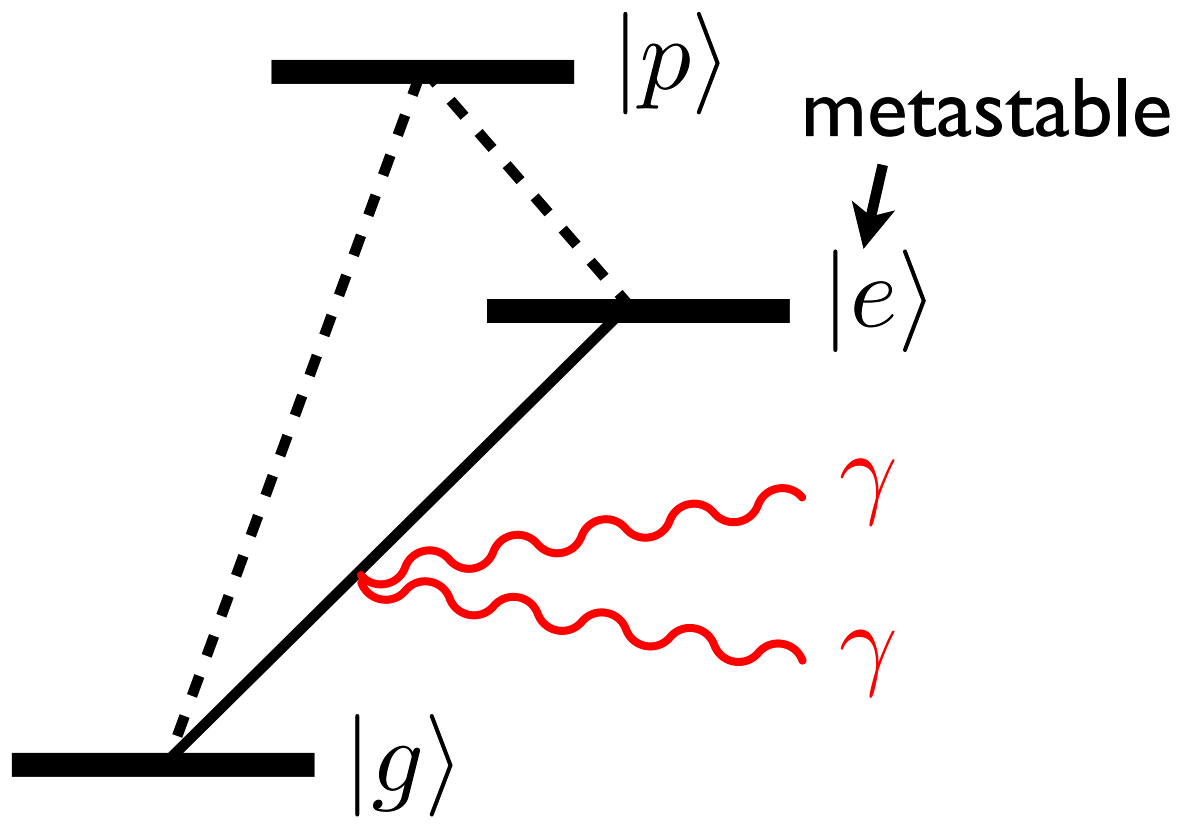
Paired Super-Radiance (PSR)

M. Yoshimura, N. Sasao, MT, PRA86, 013812 (2012)

$$|e\rangle \to |g\rangle + \gamma + \gamma$$



Prototype for RENP

proof-of-concept for the macrocoherence

Preparation of initial state for RENP

coherence generation ρ_{eg}

dynamical factor $\eta_\omega(t)$

Theoretical description to be tested

Maxwell-Bloch equation

Para-hydrogen gas PSR experiment

@ Okayama U

Y. Miyamoto et al. PTEP113C01(2014), PTEP081C01(2015)

vibrational transition of p-H2

$$|e\rangle = |Xv=1\rangle \longrightarrow |g\rangle = |Xv=0\rangle$$

two-photon decay: $\tau_{2\gamma} \sim 10^{11}$ s

p-H2: nuclear spin=singlet

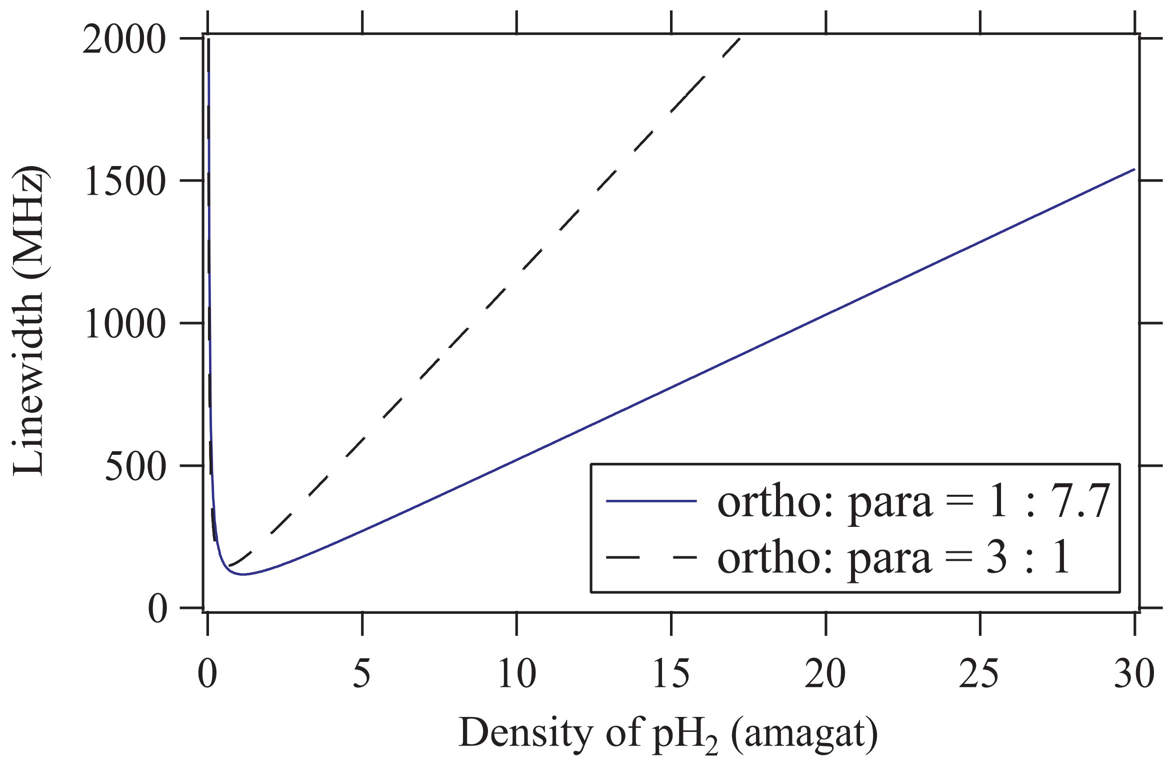
smaller decoherence $1/T_2 \sim 130$ MHz

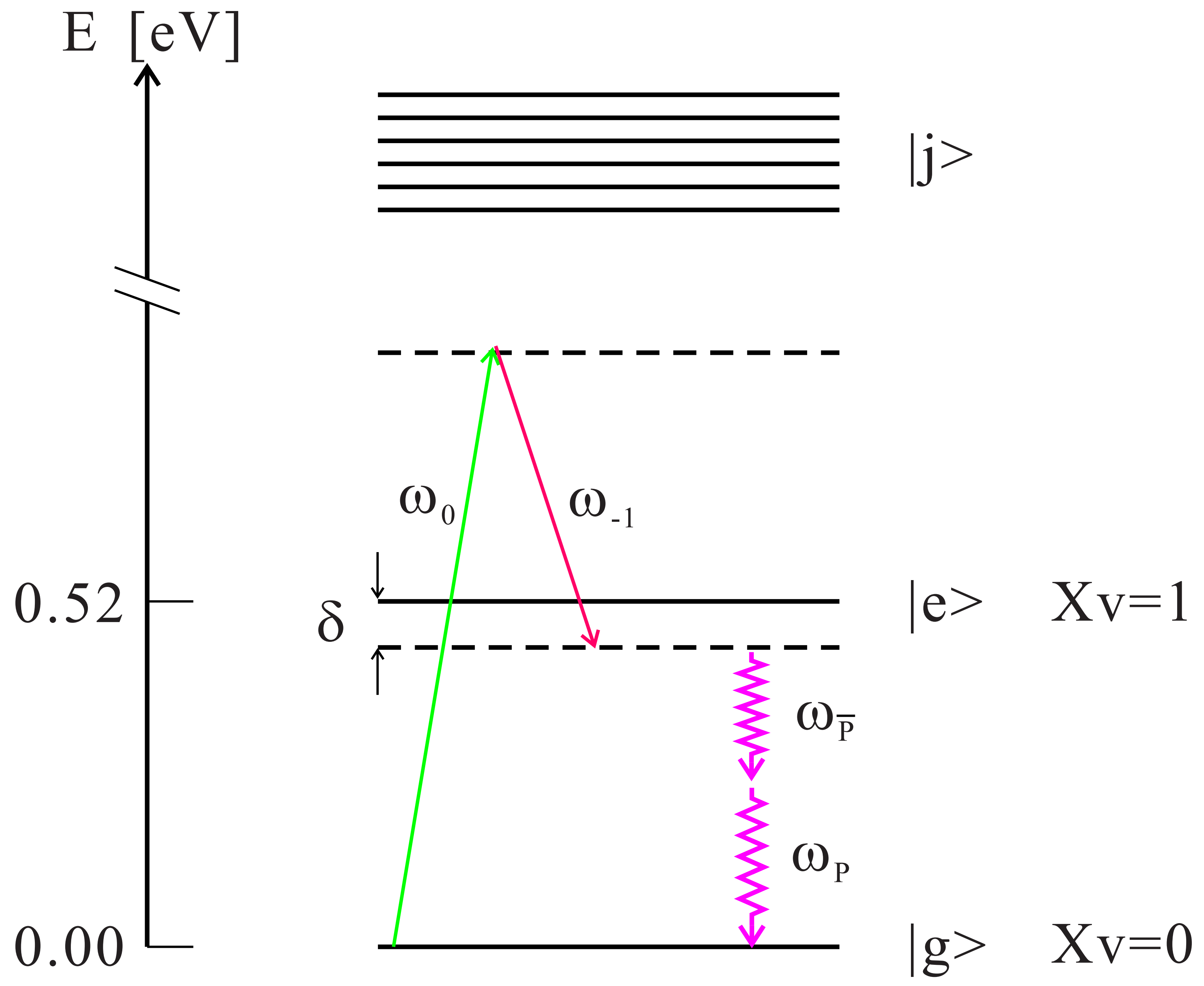
coherence production

adiabatic Raman process

$$\Delta\omega = \omega_0 - \omega_{-1} = \epsilon_{eg} - \delta = \omega_p + \omega_{\bar{p}}$$

detuning





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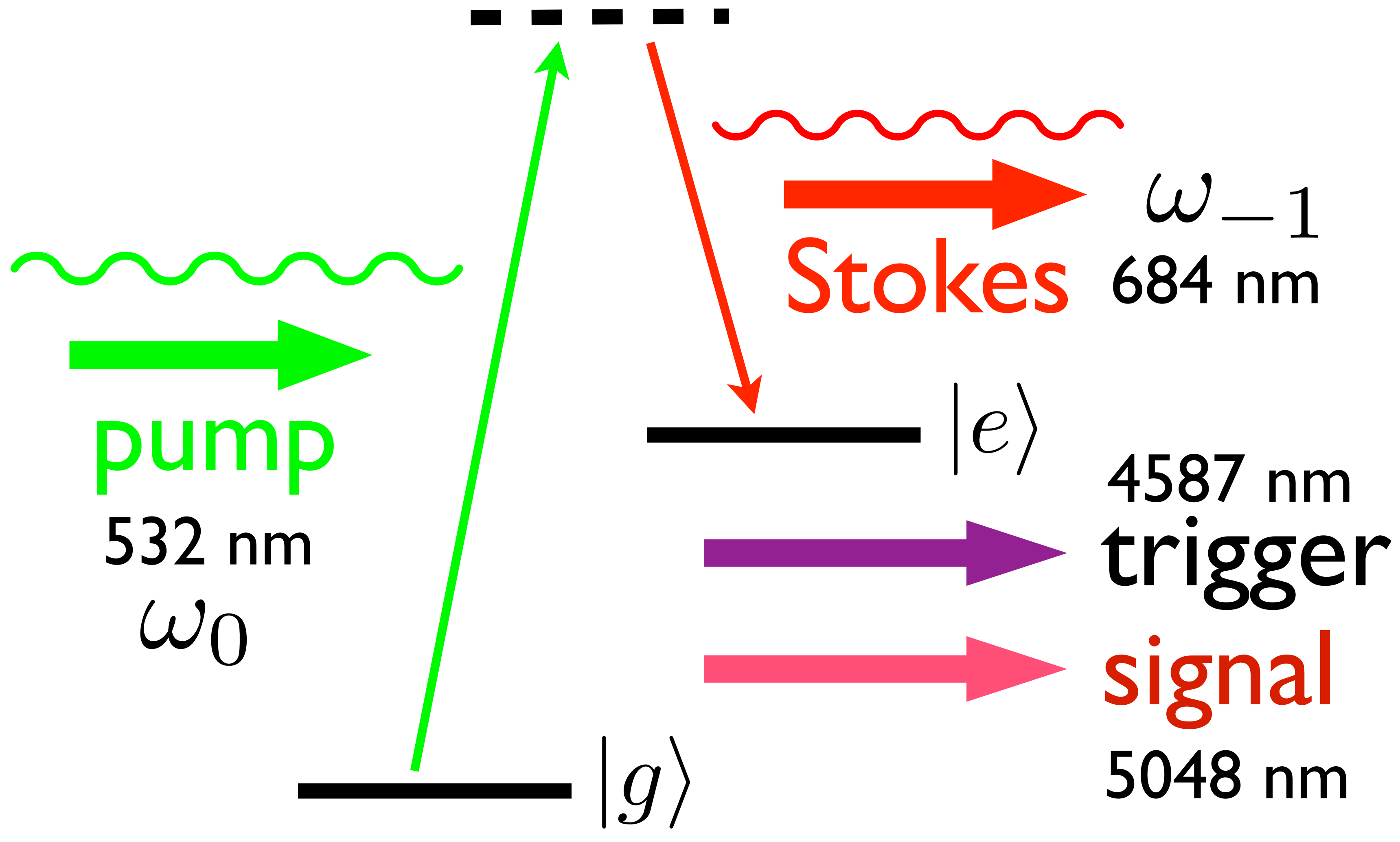
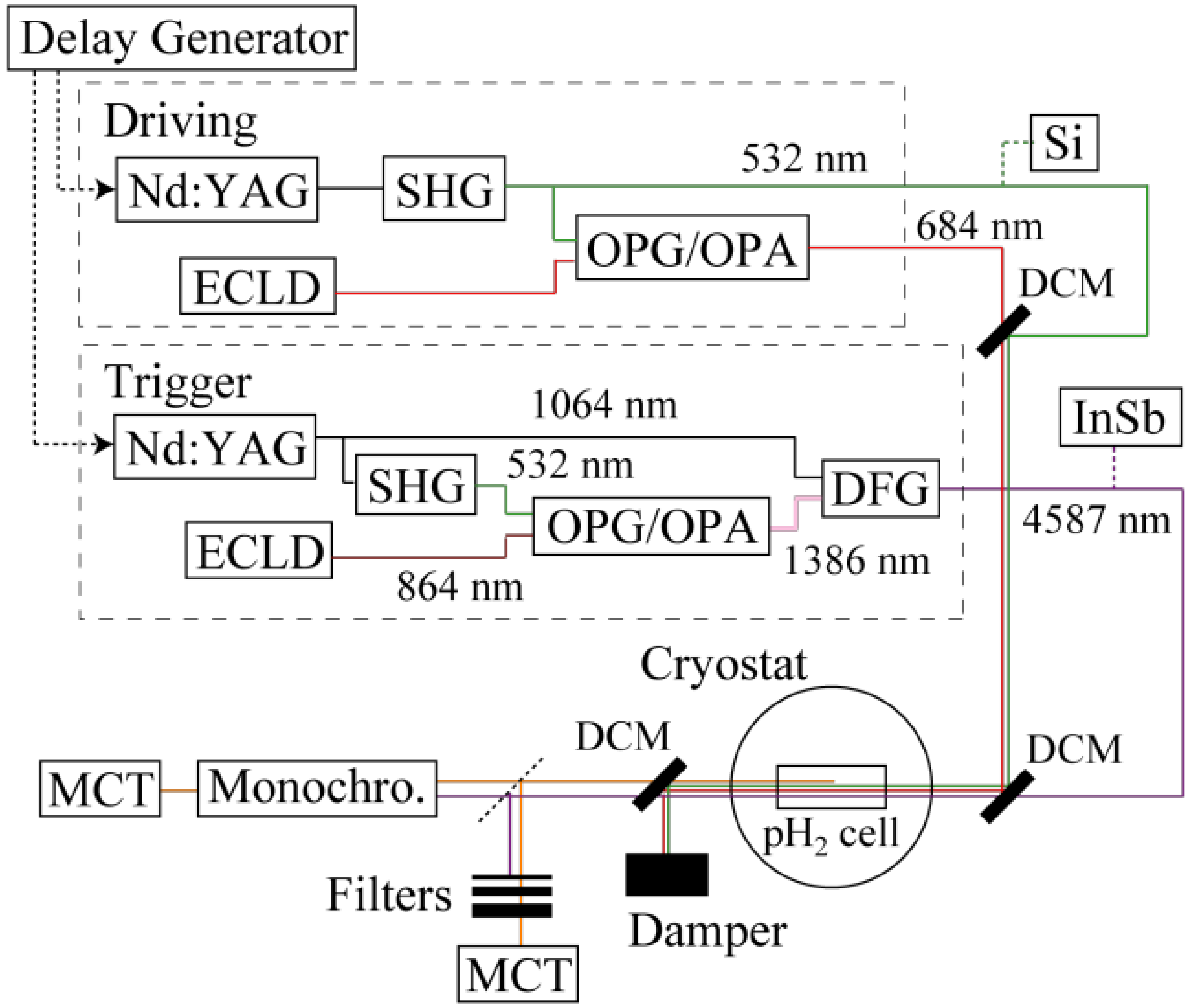
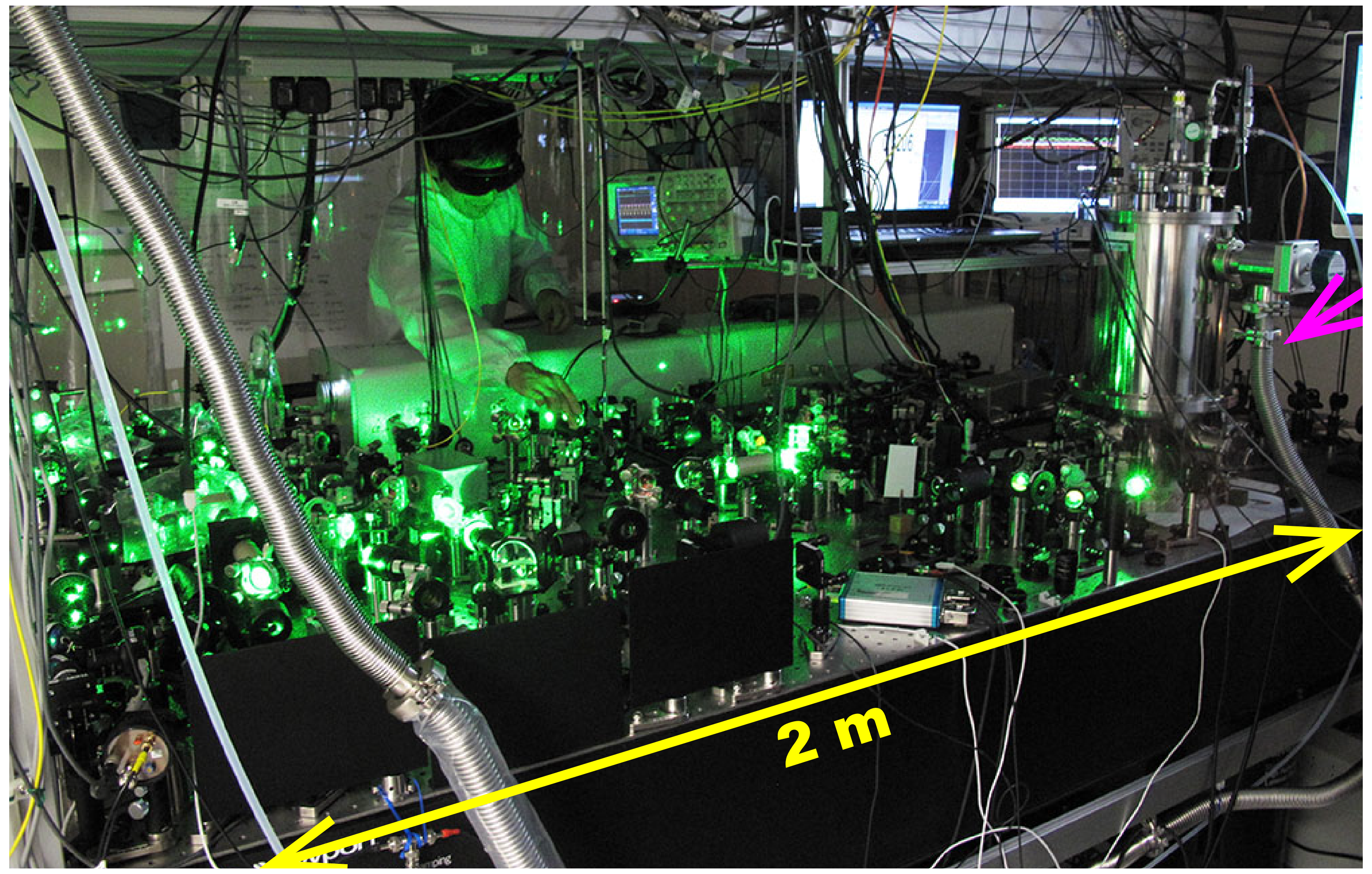
Experimental setup







Target cell: L=15 cm, Φ=2 cm, 78 K, 60 kPa

$$n = 5.6 \times 10^{19}\ \mathrm{cm}^{-3} \quad 1/T_2 \sim 130\ \mathrm{MHz}$$

Driving lasers: 532, 684 nm

$$5\ \mathrm{mJ},\ \ 9, 6\ \mathrm{ns},\ \ w_0 = 100\ \mu\mathrm{m}\ (5\ \mathrm{GW/cm^2})$$

Trigger: 4587 nm

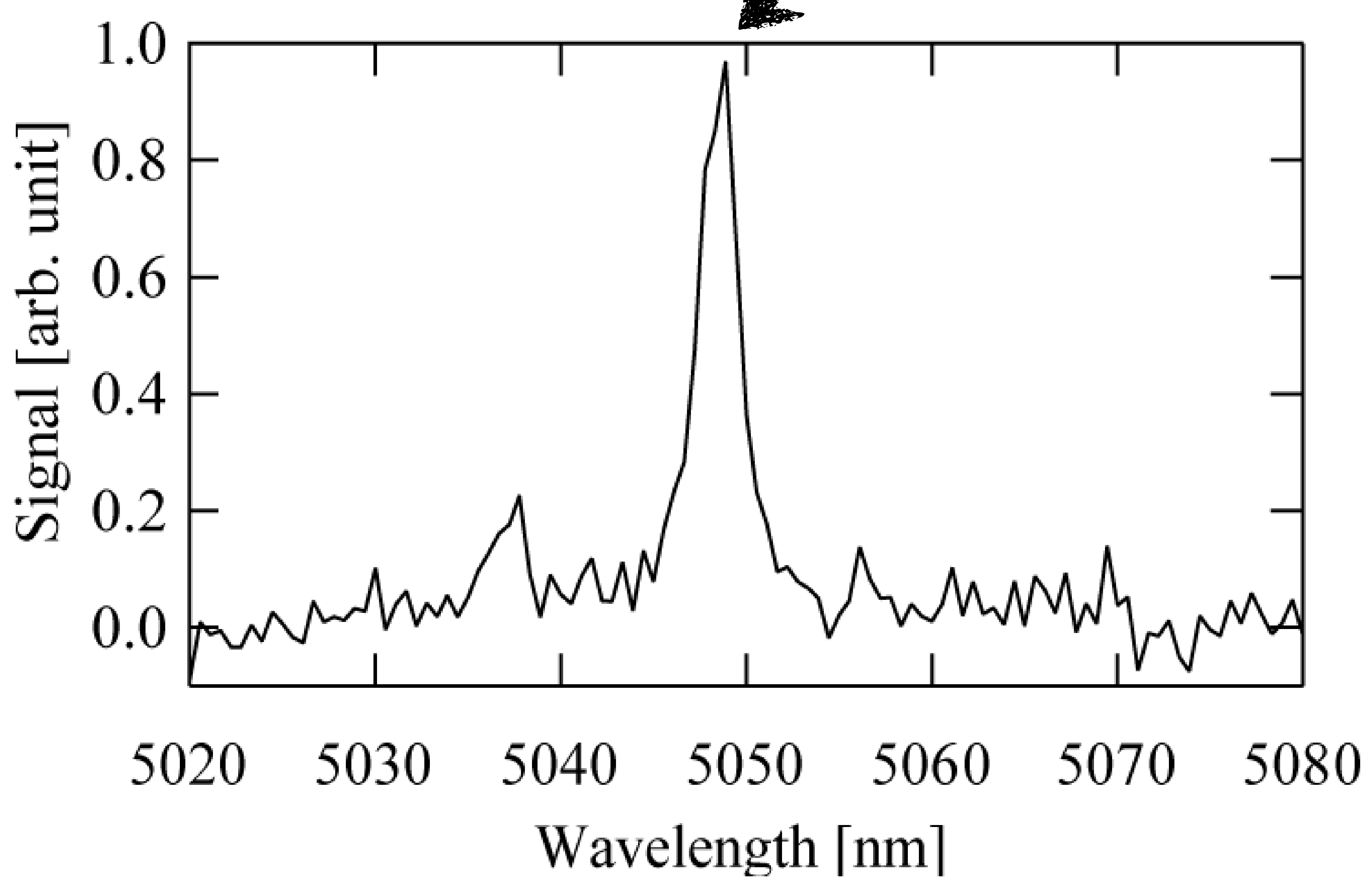
$$150\ \mu\mathrm{J},\ \ 2\ \mathrm{ns}$$

Results

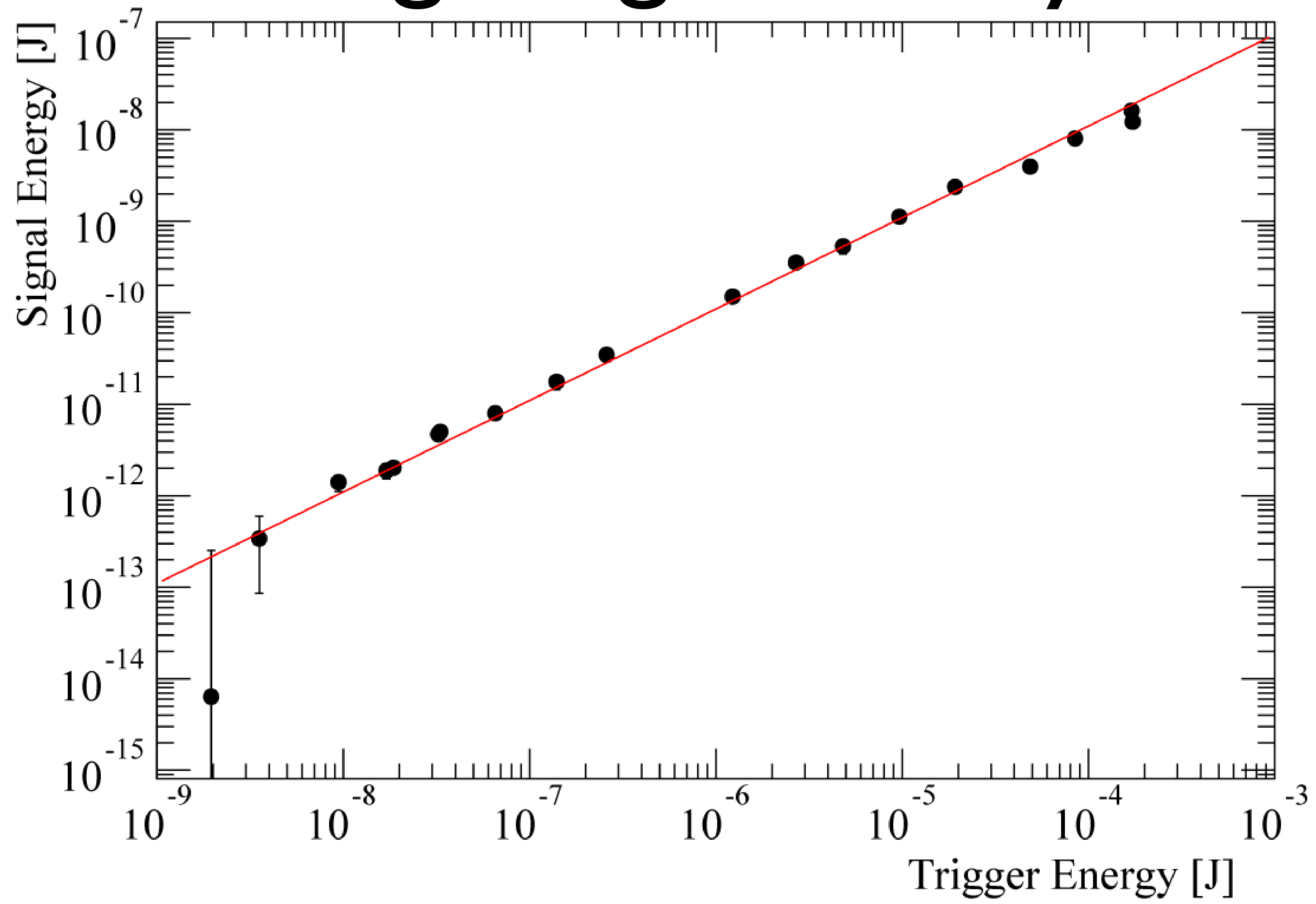
Estimated coherence (from sidebands)

$$|\rho_{eg}| \sim 0.04 \quad (\delta = -160 \text{ MHz})$$

5048 nm



sig.-trig. linearity



6×10^{11} photons/pulse

→ 10^{18} enhancement

weak field

low coherence

ハローダークフォトン/アクシオン探索計画

共同研究者

宮本祐樹，笹尾 登，Wang Jing（岡山大）

軽い暗黒物質候補

アクシオン，アクシオン様粒子

略

ダークフォトン

標準模型のゲージセクターの最小拡張　$U_X(1)$

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

kinetic mixing

２パラメーター：m_X, χ

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標準模型+ダークフォトン+インフレーション

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

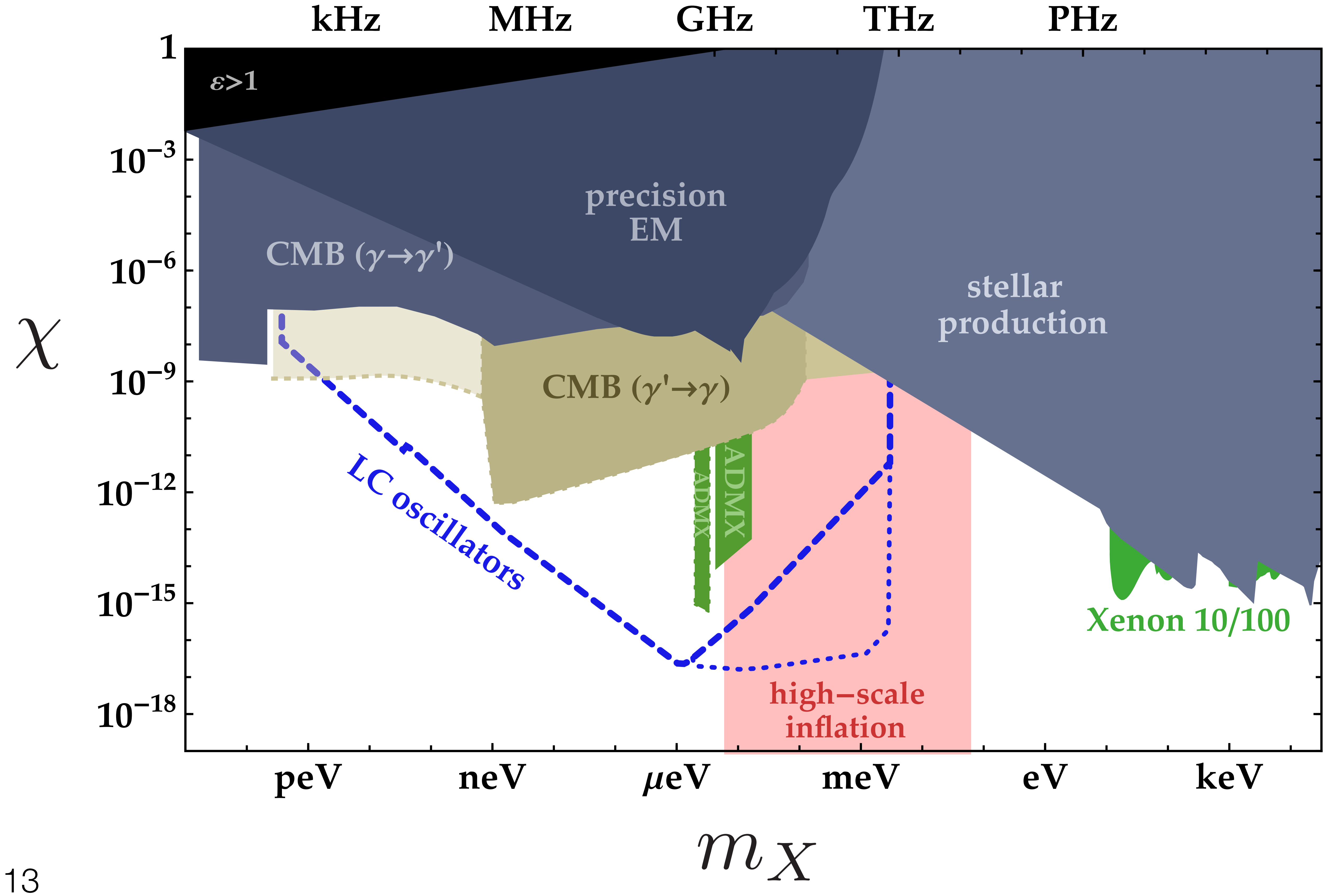
→ ダークフォトン暗黒物質

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

H_I : Hubble scale of inflation

$H_I \lesssim 10^{14}$ GeV

→ $m \gtrsim 10^{-5}$ eV

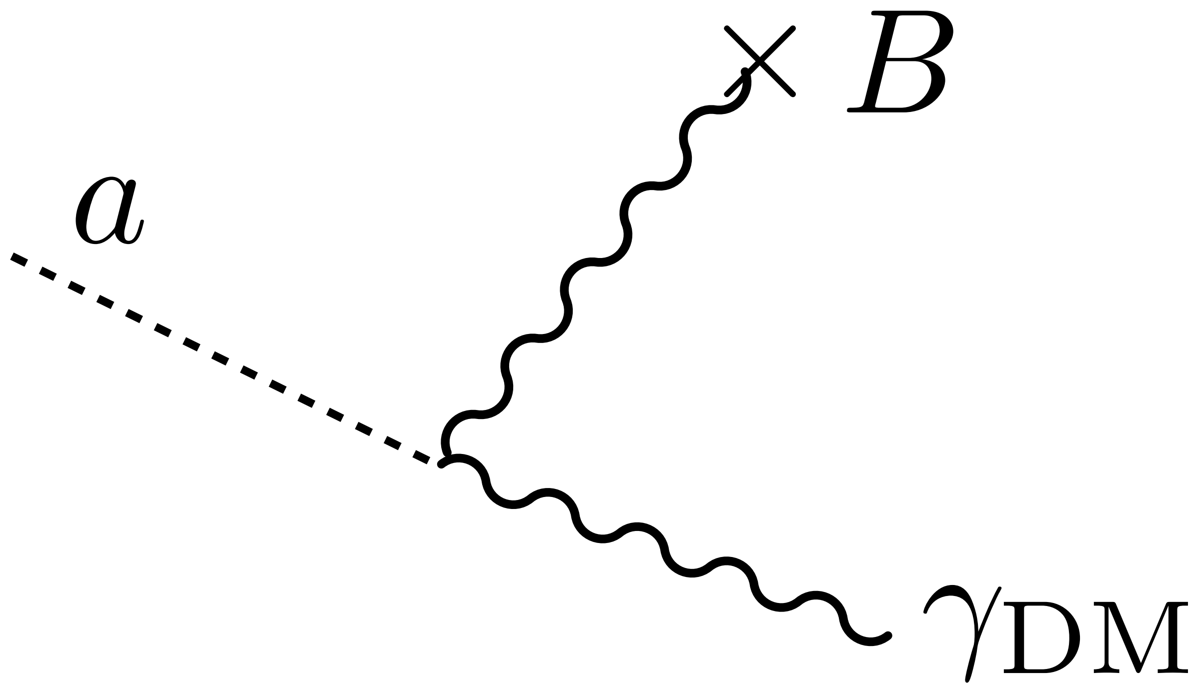


coherently oscillating

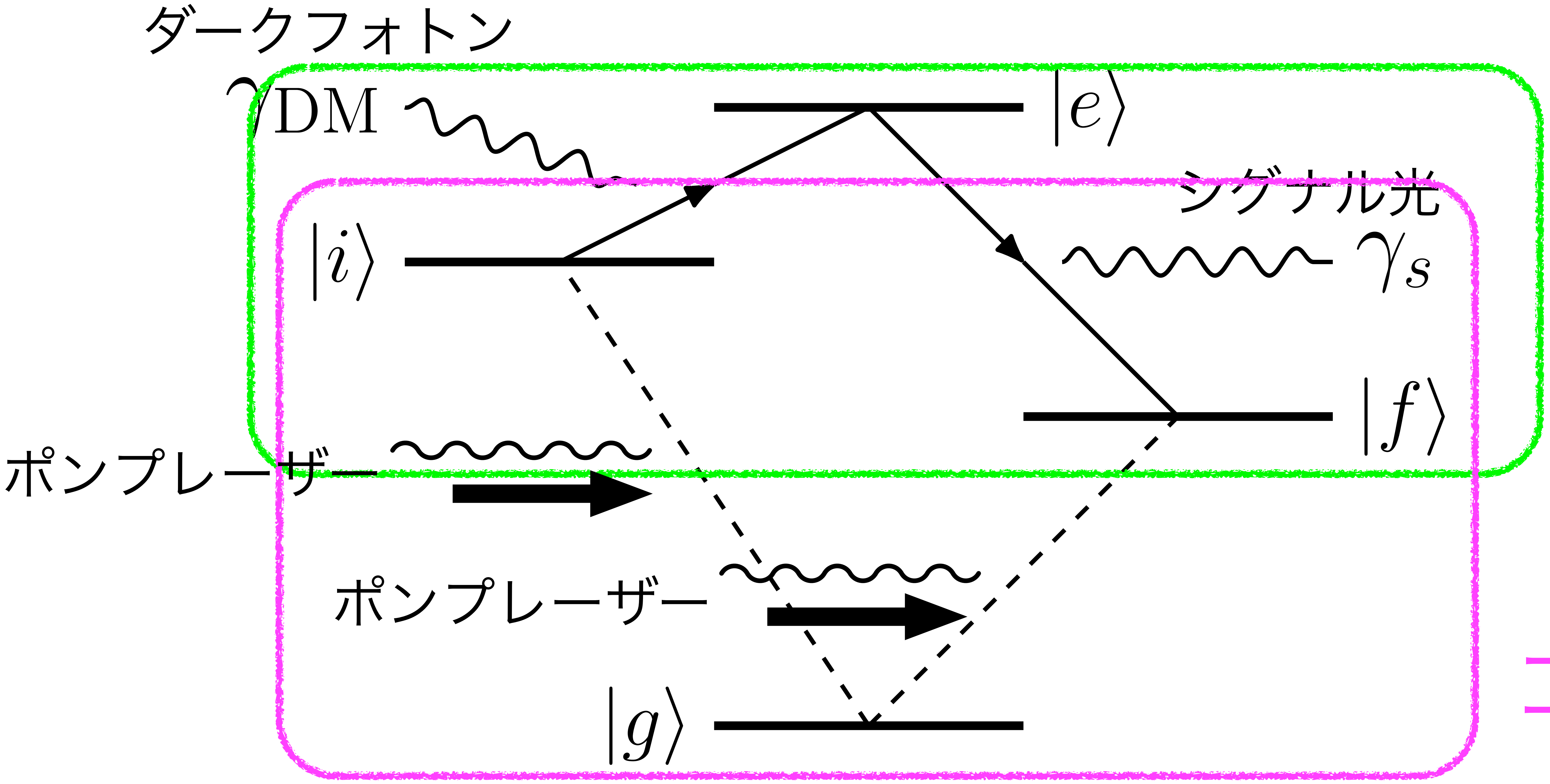
$X^\mu \propto e^{im_X t}$

探索原理

アクシオンの場合



ダークフォトン吸収励起



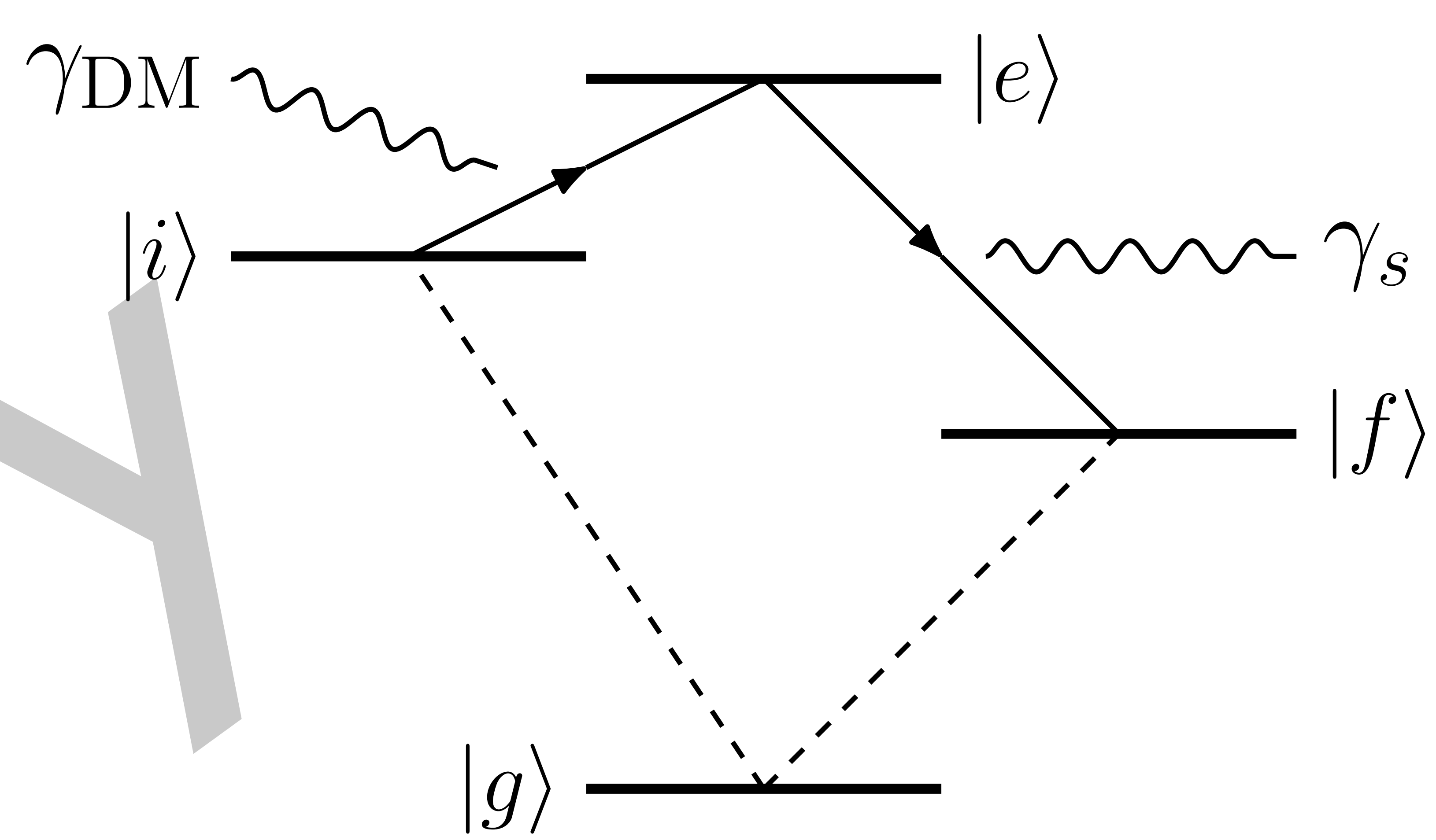
$\gamma_{\rm DM} + |i\rangle \to |e\rangle \to |f\rangle + \gamma_s$

コヒーレンス生成

マクロコヒーレンス

ダークフォトン，シグナル光，ポンプレーザーで運動量保存.

Csパイロット実験計画



$$|i\rangle = 5\mathrm{p}^6 8\mathrm{p}(J=3/2)\,,\;\; E_i = 3.198\ \mathrm{eV}\,,$$

$$|e\rangle = 5\mathrm{p}^6 7\mathrm{d}(J=3/2)\,,\;\; E_e = 3.230\ \mathrm{eV}\,,$$

$$|f\rangle = 5\mathrm{p}^6 6\mathrm{p}(J=1/2)\,,\;\; E_f = 1.386\ \mathrm{eV}\,,$$

$$E_{ei} = 0.032\ \mathrm{eV} \simeq m_{\rm DM}\,,\;\; E_{ef} = 1.844\ \mathrm{eV} \simeq E_s\,,$$

$$\tau_i = 274\ \mathrm{ns}\,,\;\; \tau_e = 89\ \mathrm{ns}\,,\;\; \tau_f = 34.9\ \mathrm{ns}\,,$$

$$d_{ei} = 7.175 e a_B\,,\;\; r_{fe} = 1.03 a_B\,,$$

target spec. $n = 1\times 10^{12}\ \mathrm{cm}^{-3}\,,\;\; V = 0.1\times 0.1\times 1\ \mathrm{cm}^3$

$$\Gamma = 7.9\times 10^3 \left(\frac{\chi}{10^{-9}}\right)^2 \left(\frac{n}{10^{12}\ \mathrm{cm}^3}\right)^2 \left(\frac{\rho_{fi}}{0.25}\right)^2\ \mathrm{Hz}$$

cf. single atom rate: $\Gamma_0 = 1.8\times 10^{-8}\left(\frac{\chi}{10^{-9}}\right)^2\ \mathrm{Hz}$

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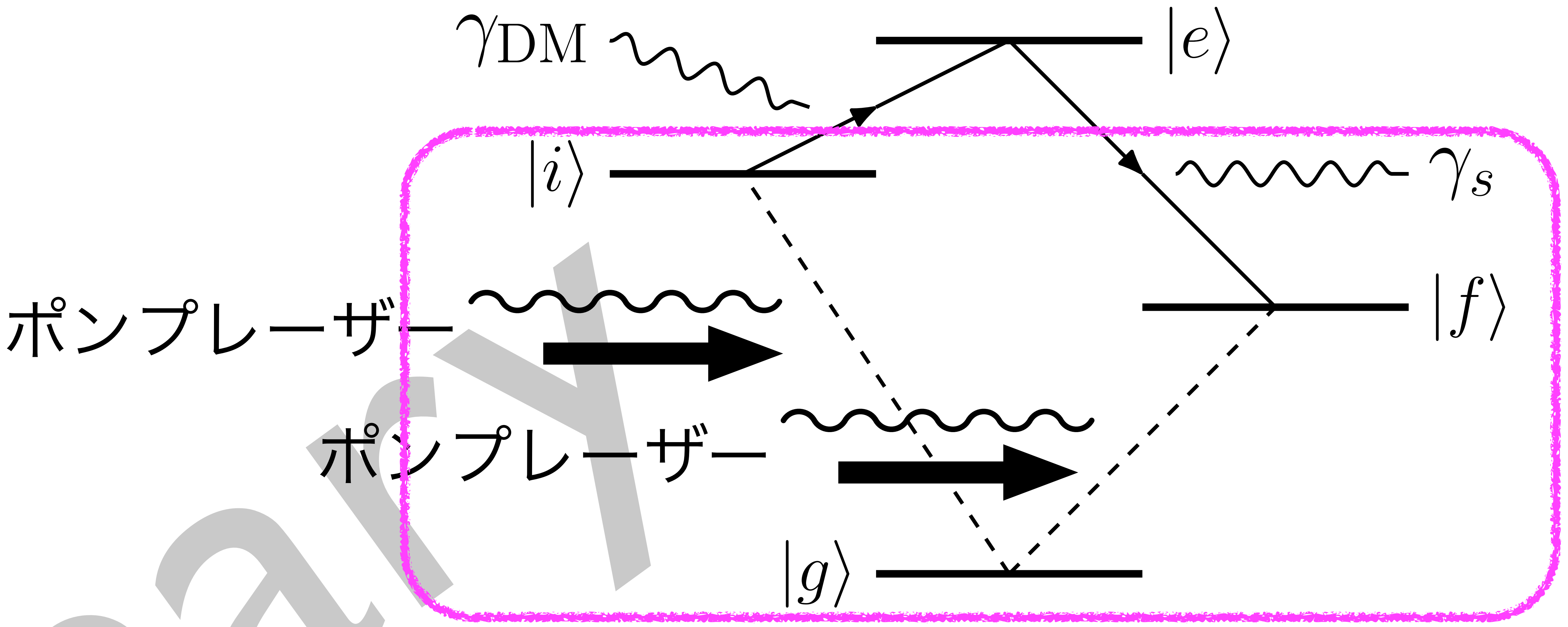
コヒーレンス生成



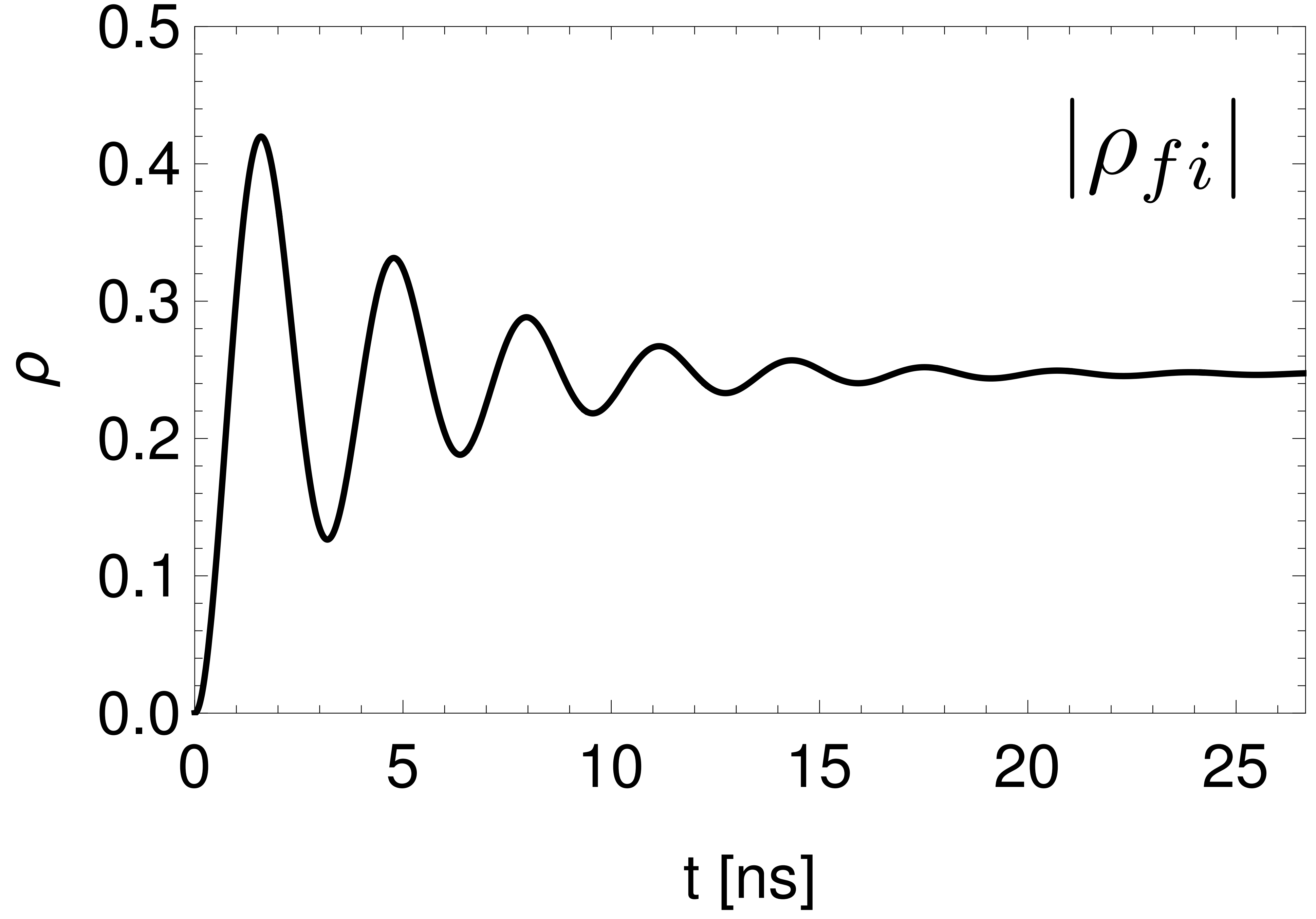
Liouville - von Neumann equation with relaxation

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

Toy parameters with radiation damping only

CW laser power: 100 mW

Laser cross section: 1mm²



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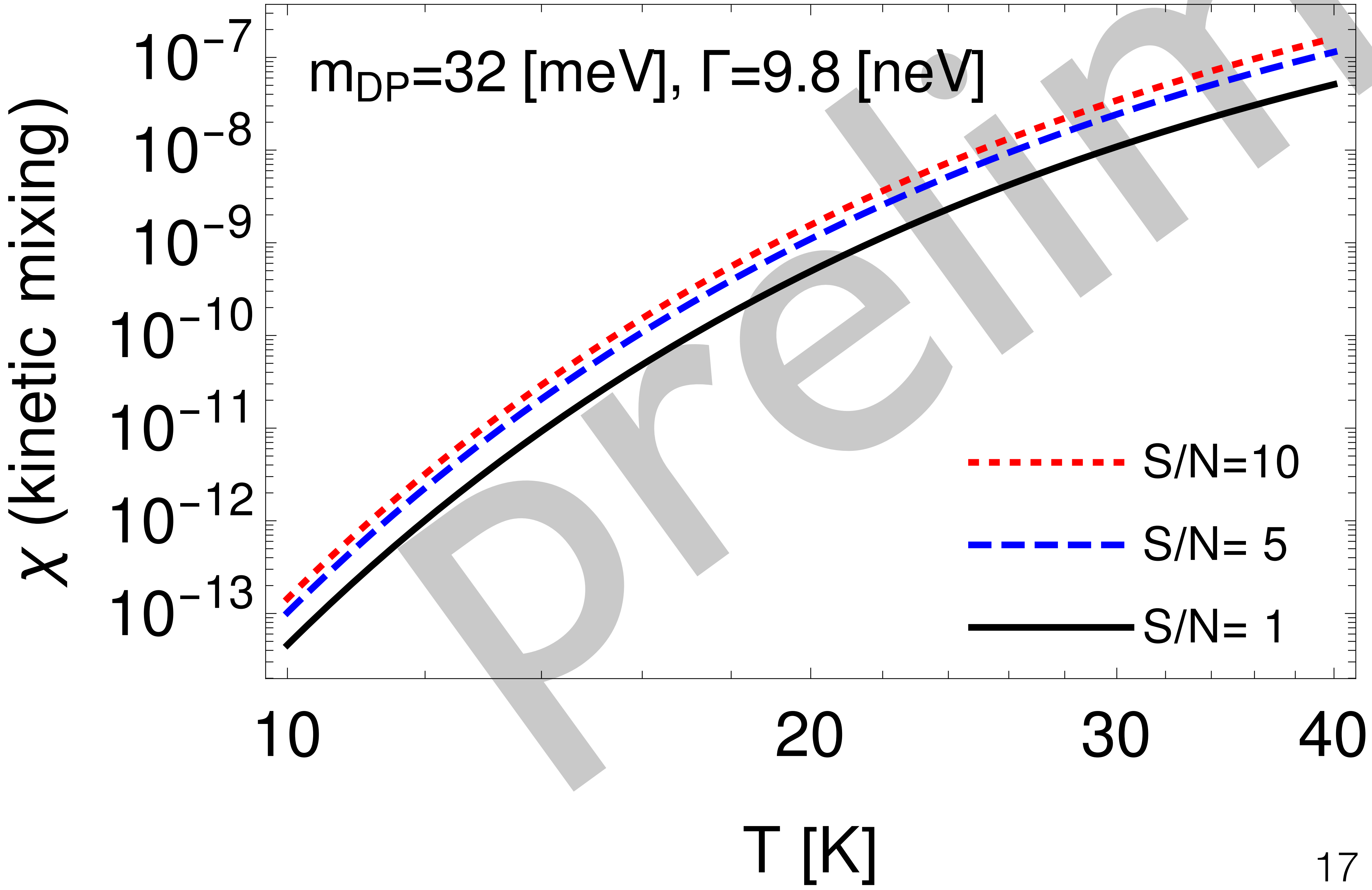
バックグラウンド例

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



まとめ

■ 原子集団のコヒーレンスを用いたレート増幅

ρ_{fi} が重要．マクロコヒーレンスと運動量保存.

■ ハローダークフォトン／アクシオン探索計画

Csパイロット実験を計画中（岡山大）

準位選定，緩和過程，バックグラウンド等，要検討

■ 理論的課題

ダークフォトン偏極の検出方法

高密度(固体)標的