Light Dark Photon Detection with Atomic Transitions

Ningqiang Song

Based on arXiv **1909.07387** with Joseph Bramante and Amit Bhoonah

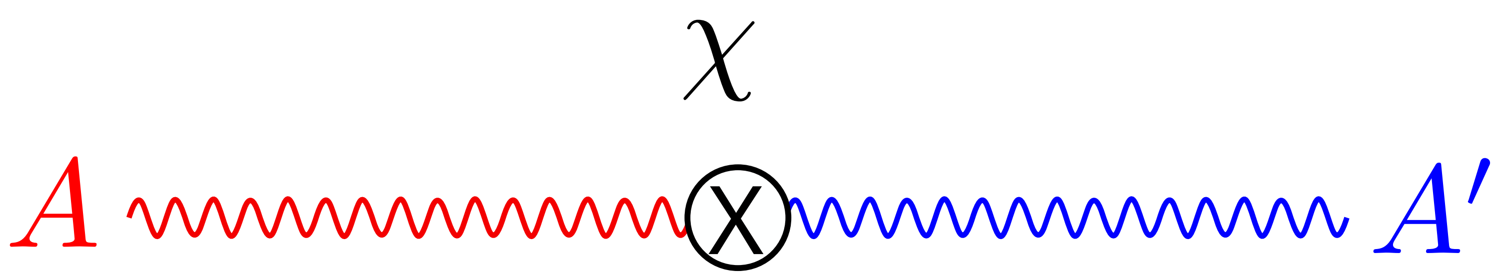
Queen's University, McDonald Institute, Perimeter Institute

Jan 9, 2021

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's UNIVERSITY

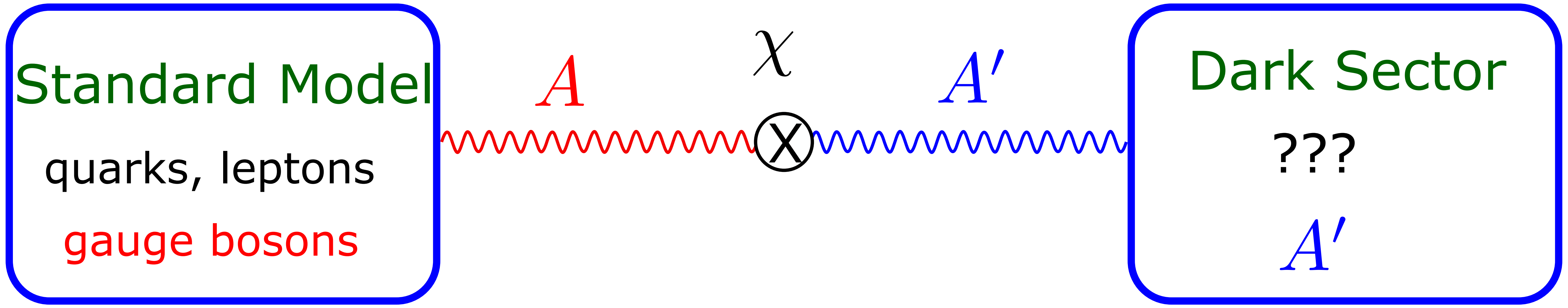
Dark Photon and Kinetic Mixing



Galison, Manohar’ 1984
Holdom’ 1986

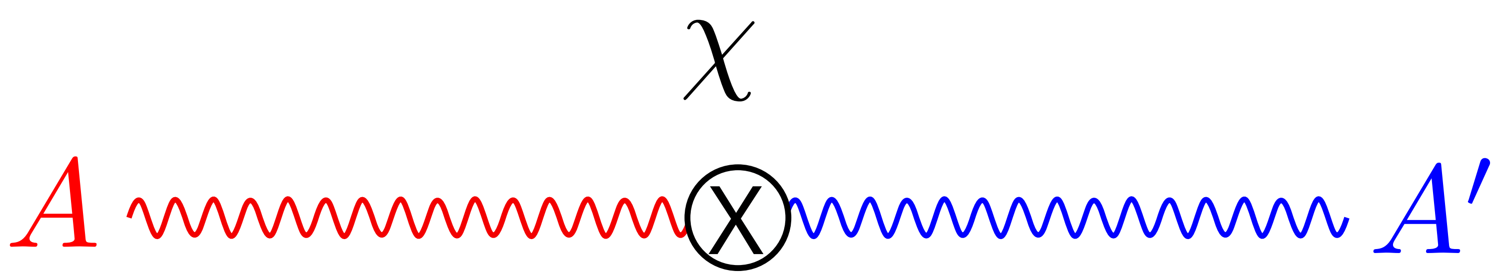
$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\chi F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - eJ^\mu_{\text{em}}A_\mu$$

Well motivated in SUSY, string theories, or as dark matter or dark sector mediator



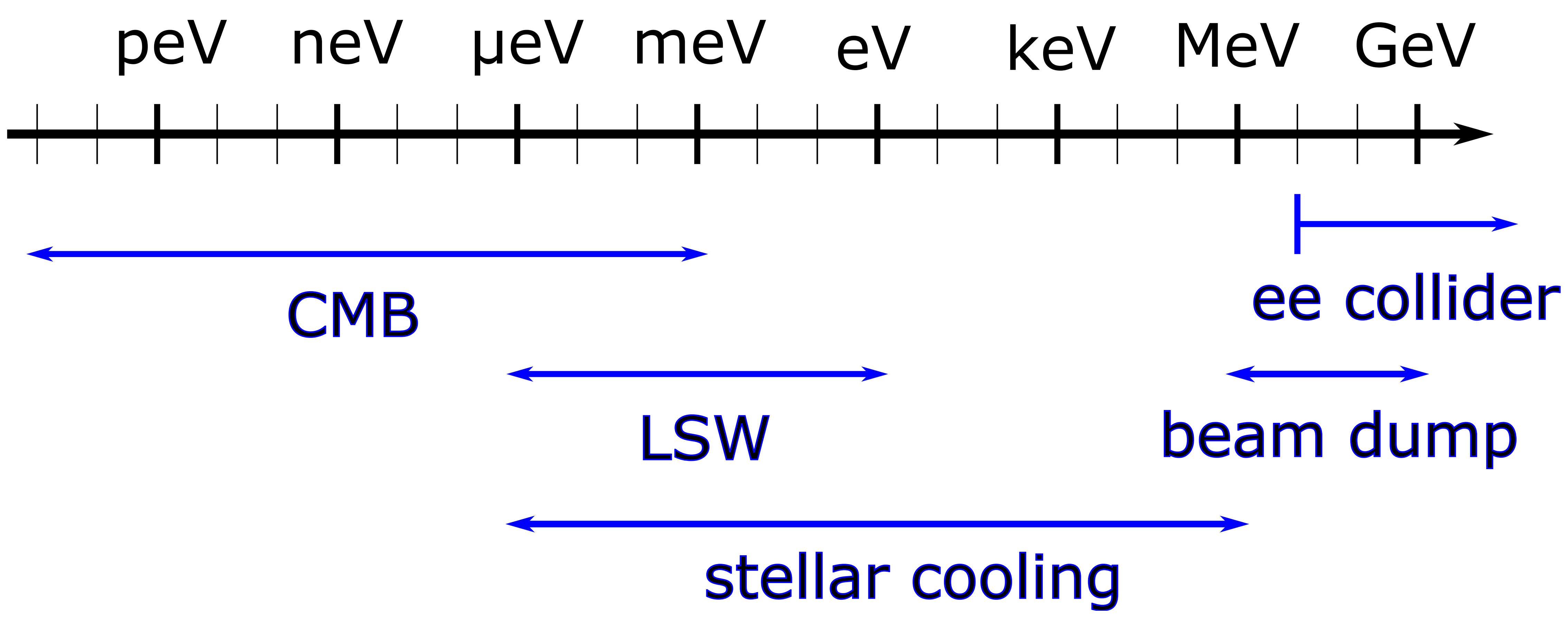
Pospelov’ 2008
Ackerman, Buckley, Carrol, Kamionkowsk’ 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner’ 2008

Dark Photon and Kinetic Mixing

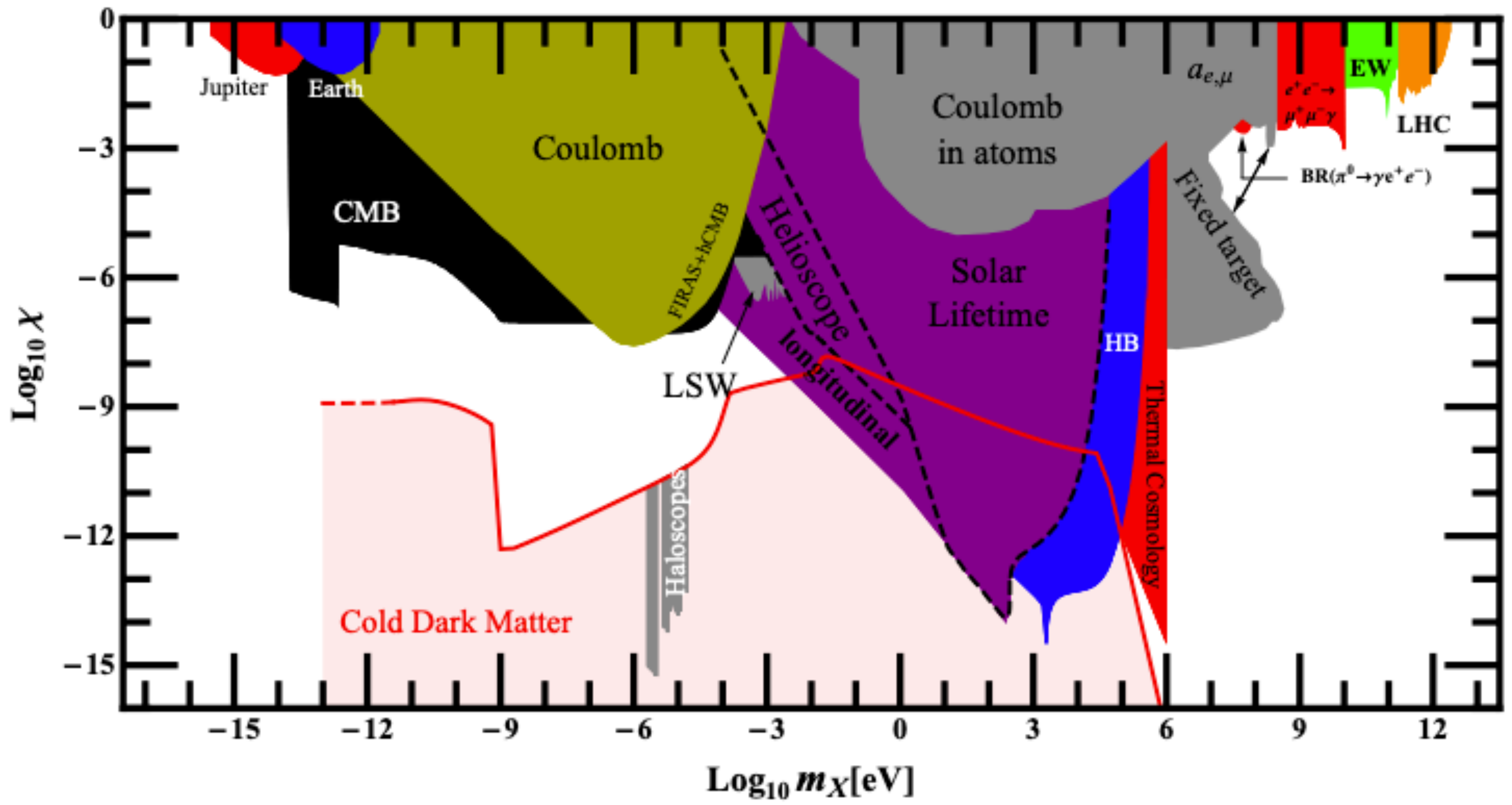


Galison, Manohar’ 1984
Holdom’ 1986

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\chi F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - eJ^\mu_{\text{em}}A_\mu$$

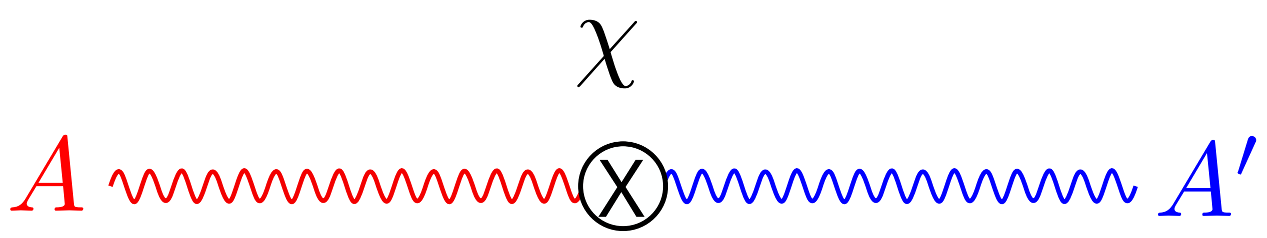


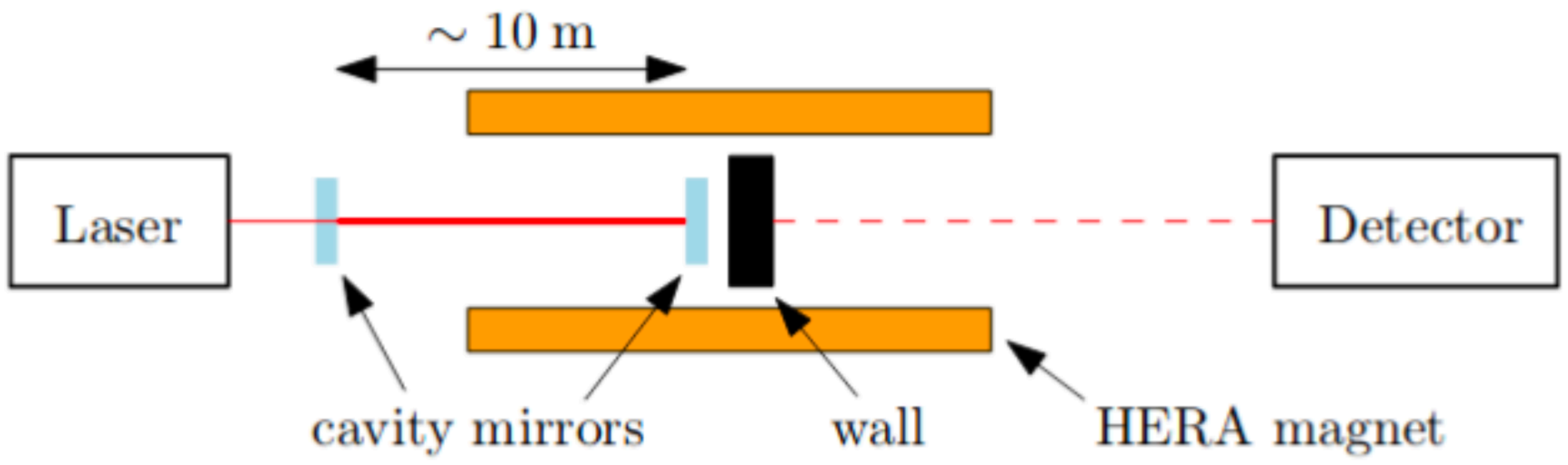
Jaeckel, 1303.1821



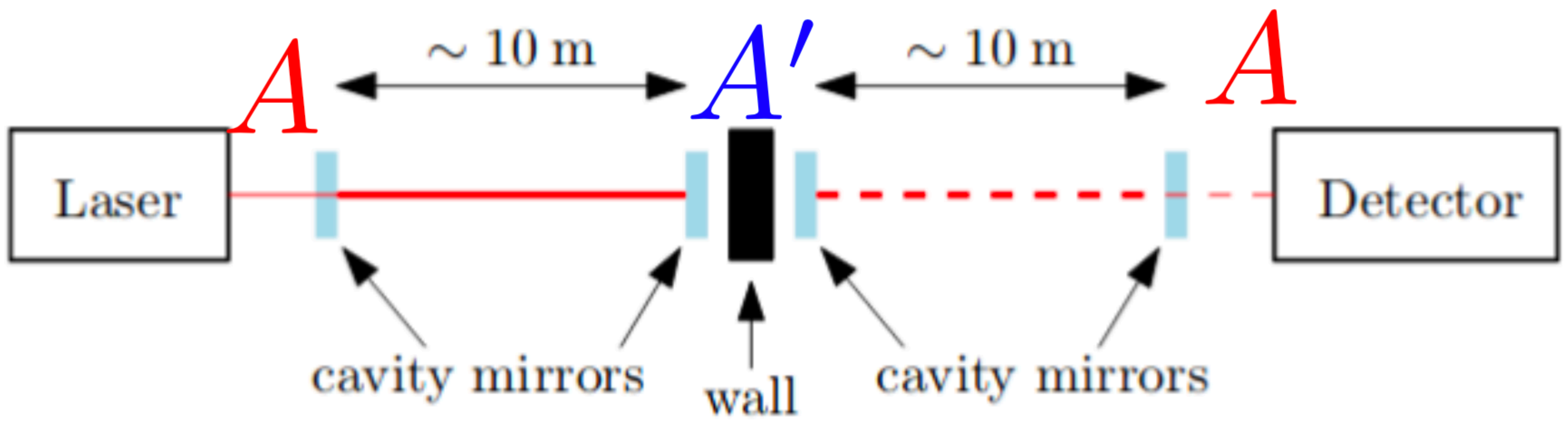
Light Shinning through the Wall

- Light Shining Though Walls (LSW): ALPS



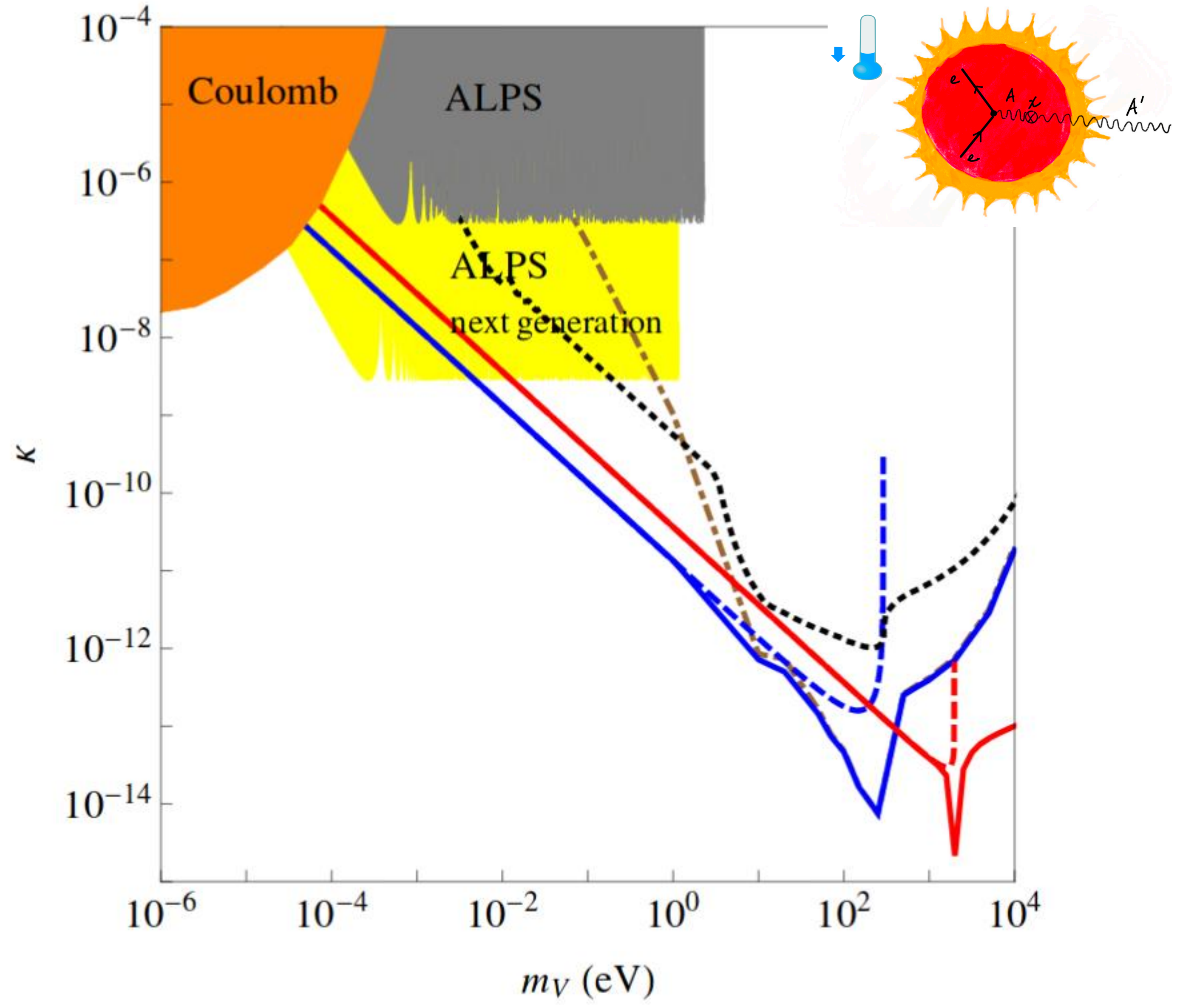


(a) ALPS-I



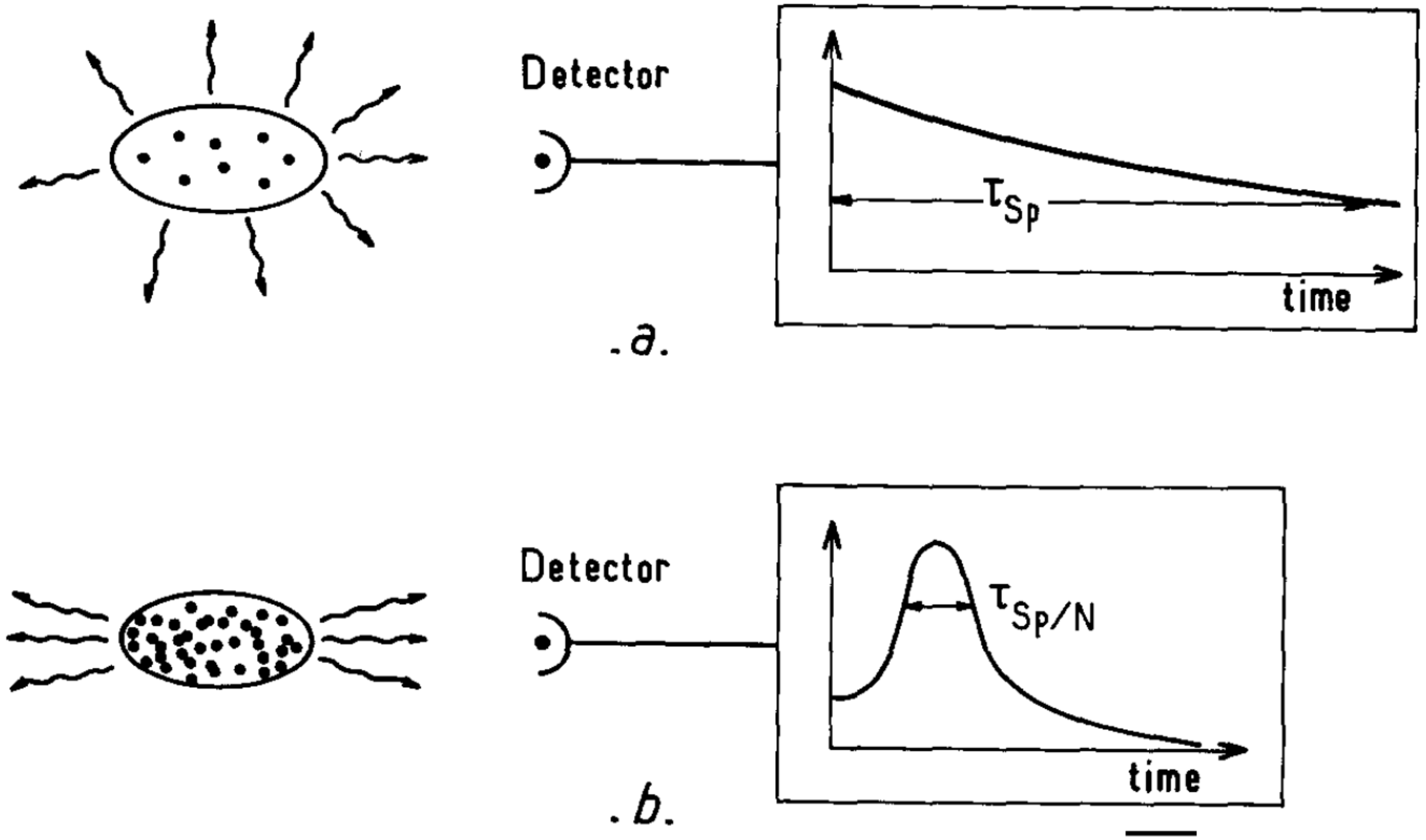
(b) ALPS-IIa

ALPS II, 1302.5647



An, Pospelov, Pradler, 2013, 2020

Improved LSW: Superradiance

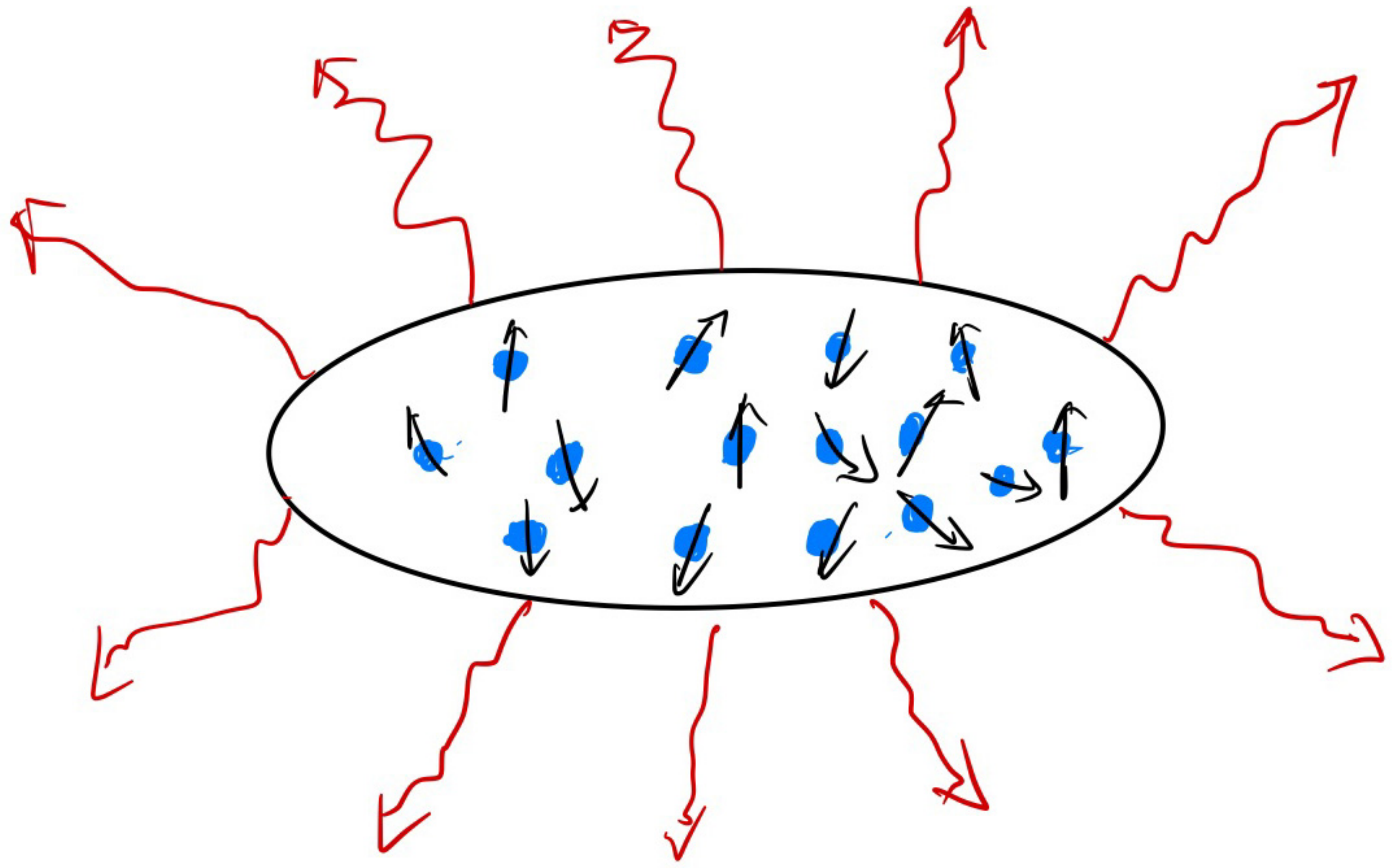


Dicke' 1954,
Gross, Haroche' 1982

- Spontaneous emission: isotropic, exponential decay
- Superradiance (SR): anisotropic, collective deexcitation of the atomic system

Macro Superradiance

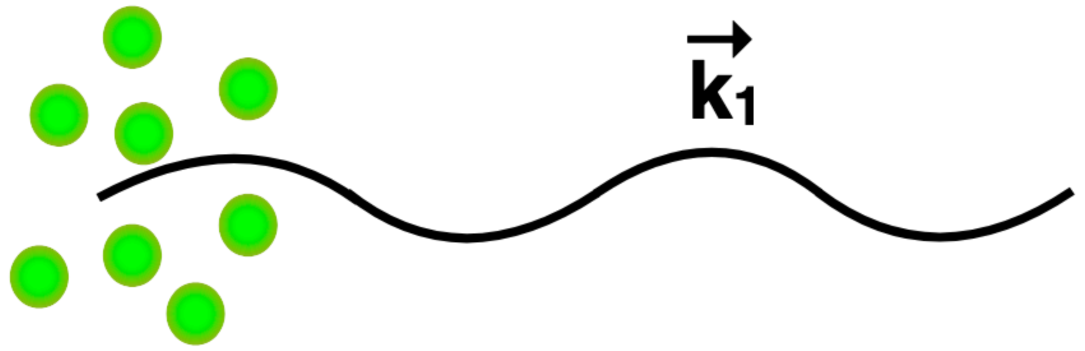
Spontaneous emission



$\Gamma \propto N\Gamma_0$

Dicke 1954, Gross, Haroche, 1982

Dicke Superradiance



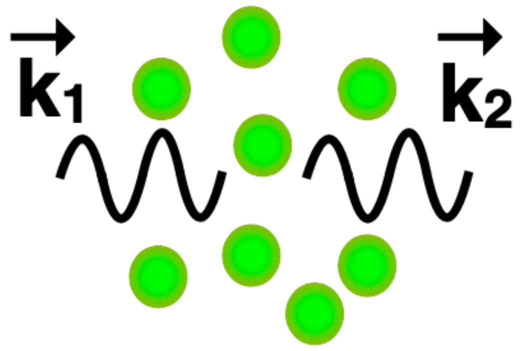
$-\Delta\vec{k} = \vec{k}_1$

$$\Gamma \propto |\sum_a e^{-ikx_a}|^2 \Gamma_0$$

$$\propto N^2\Gamma_0$$

Harris, Jain, 1997, Yoshimura, 2006

Macro Superradiance



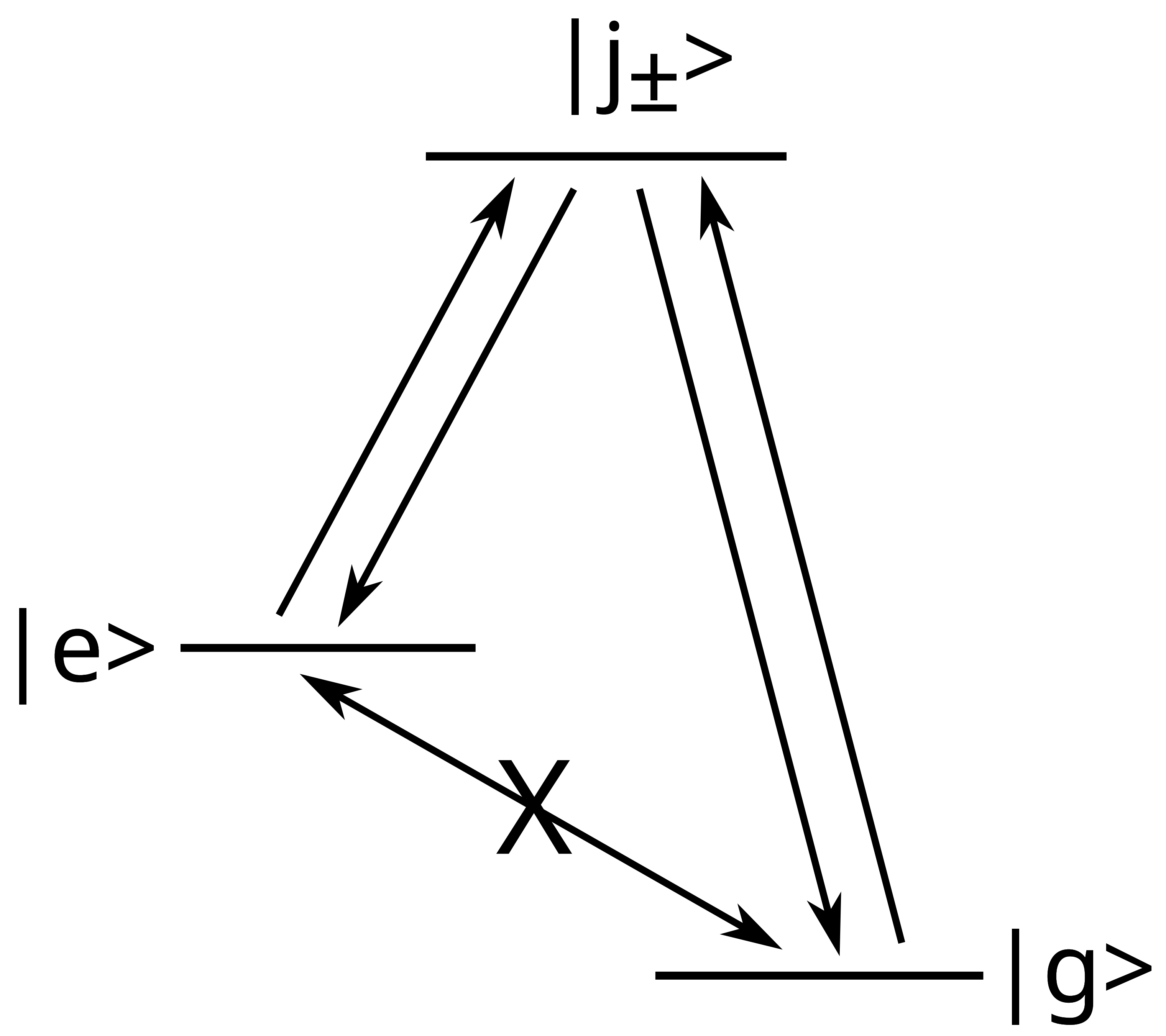
$-\Delta\vec{k} = \vec{k}_1 + \vec{k}_2 =$ 

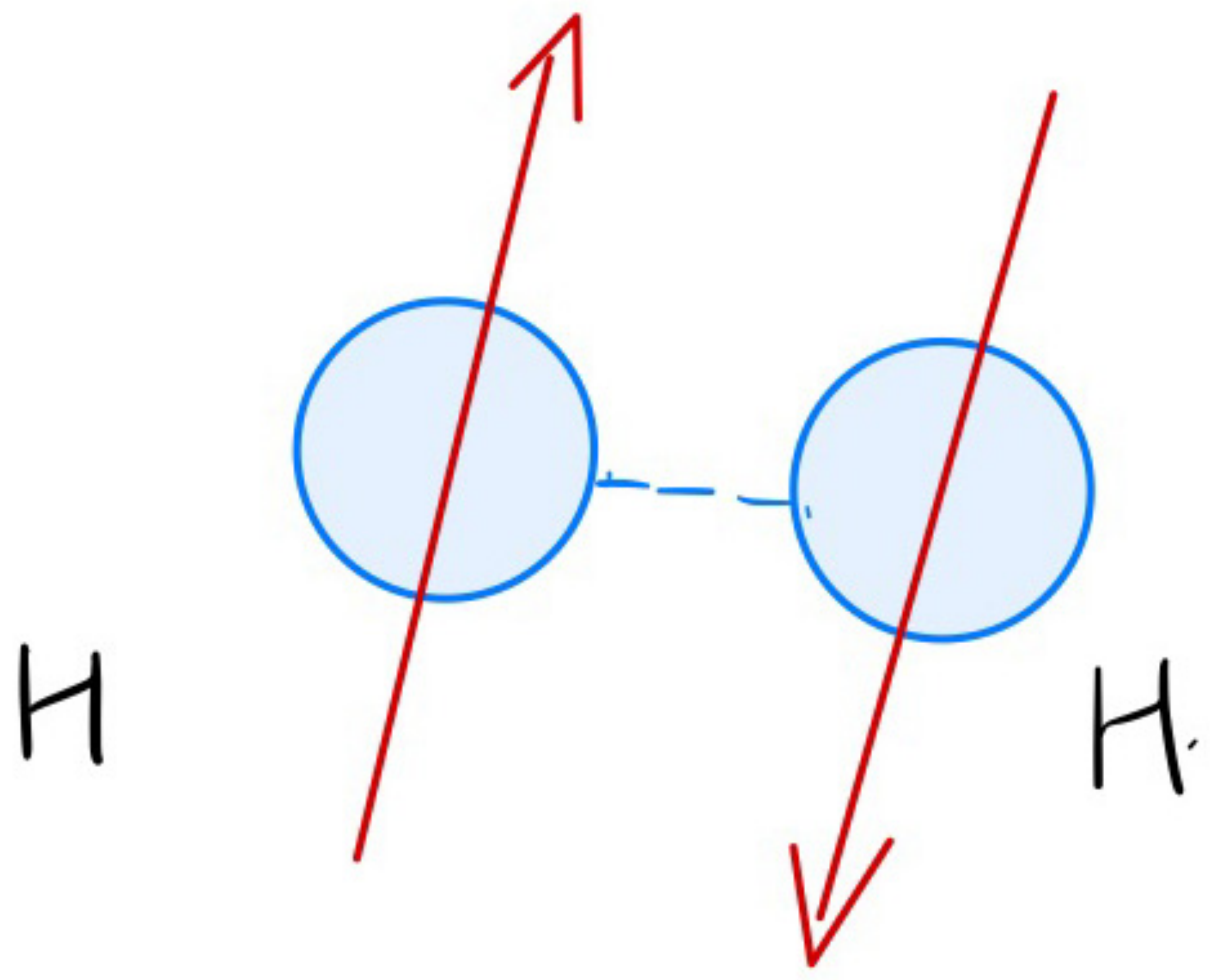
$$\Gamma \propto |\sum_a e^{-i\Delta k x_a}|^2 \Gamma_0$$

$$\propto N^2\Gamma_0$$

- Dicke SR: Condition $k \cdot L \lesssim 1 \Rightarrow$ Coherence length $L \sim 1/k \sim \lambda \sim \mu$m
- Macro SR: Condition $\Delta k \cdot L \lesssim 1 \Rightarrow$ Coherence length $L \sim 1/\Delta k \gg \lambda \sim \mu$m

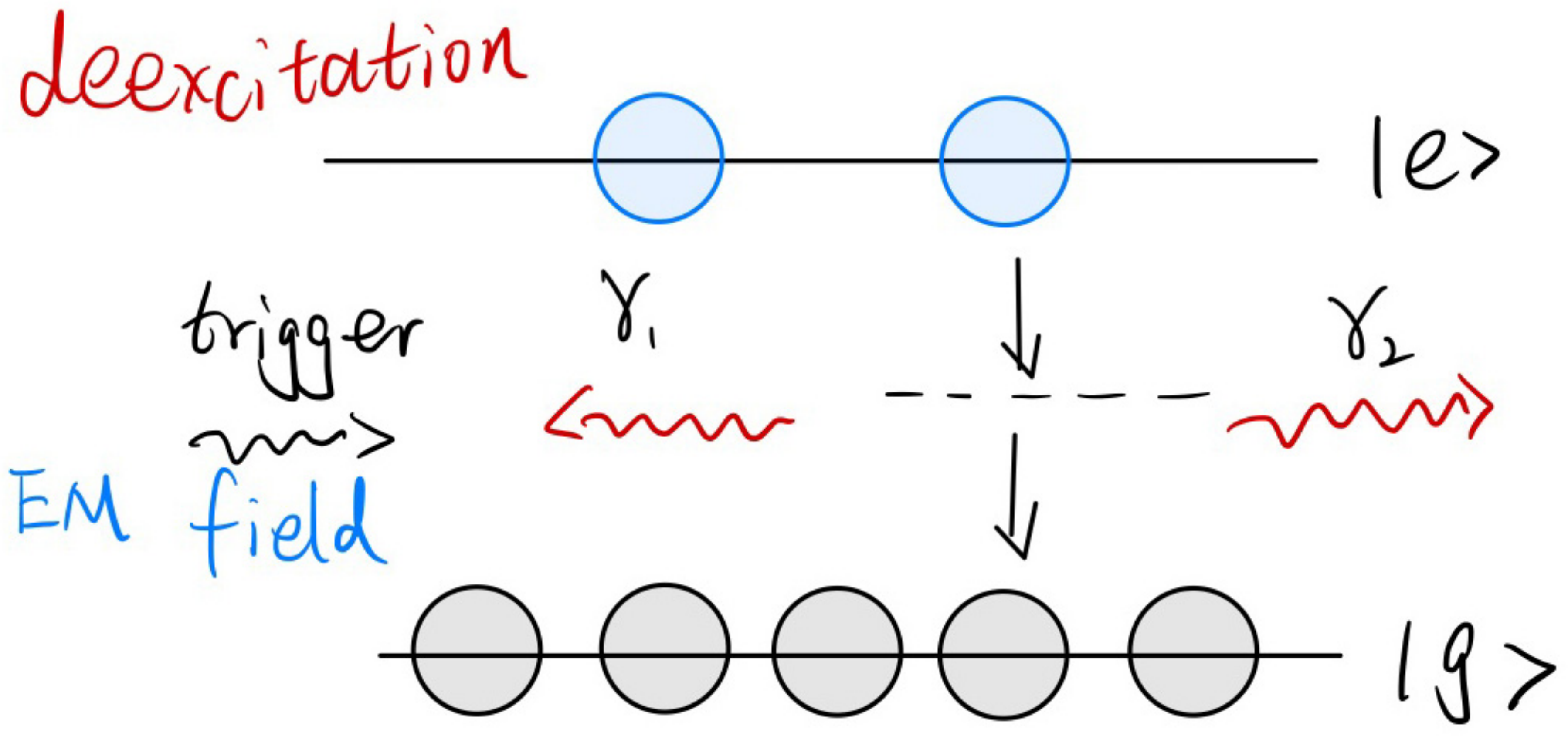
Macro Superradiance: Atomic System





- E1 dipole transitions between the ground state $|g\rangle$ and excited state $|e\rangle$ are forbidden due to selection rule
- Dipole transitions through virtual states $|j_{\pm}\rangle$ are allowed
- Choose the first vibrational states of parahydrogen molecules $\mathrm{pH_2}$

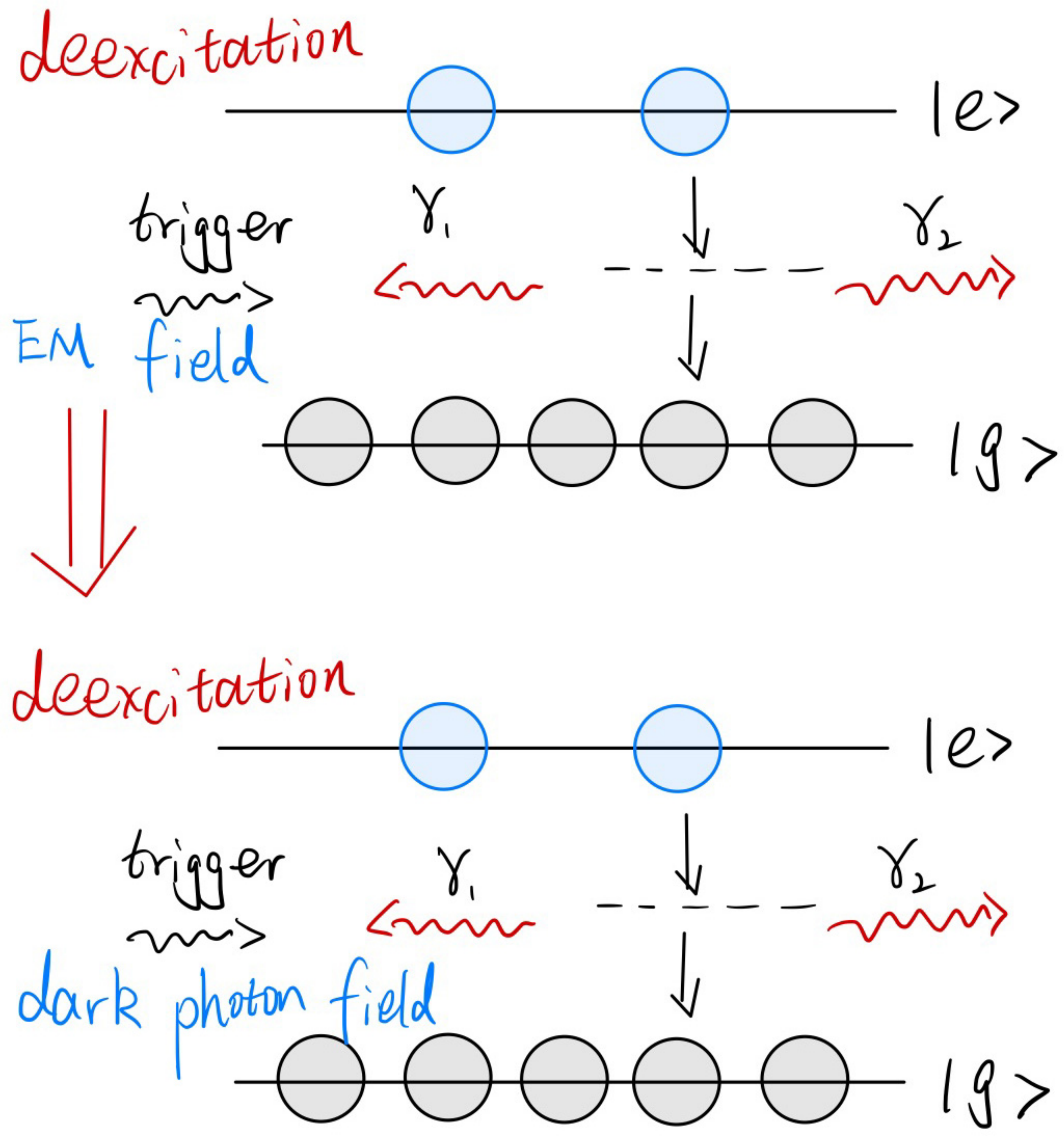
Triggered Superradiance



$$H = H_0 - \vec{d} \cdot \vec{E}$$

Electric field can tigger the collective deexcitation of $\mathrm{pH_2}$

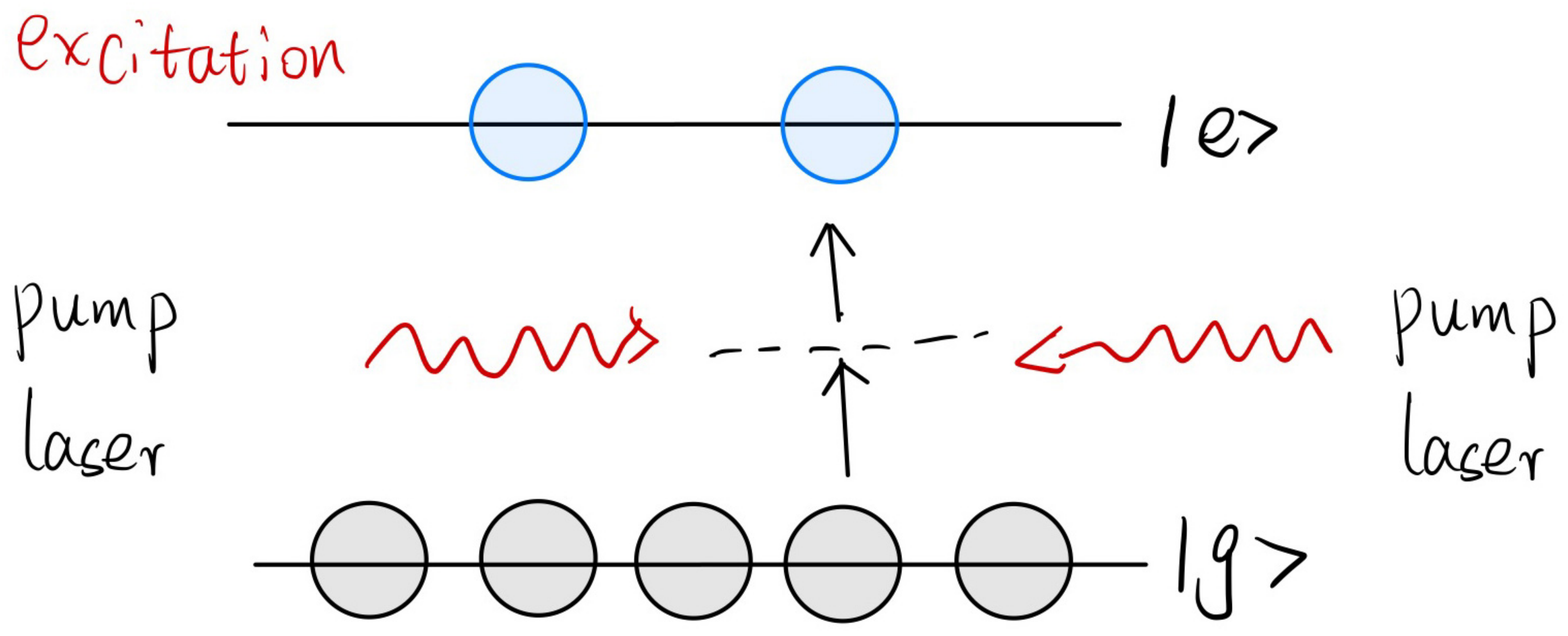
Triggered Superradiance



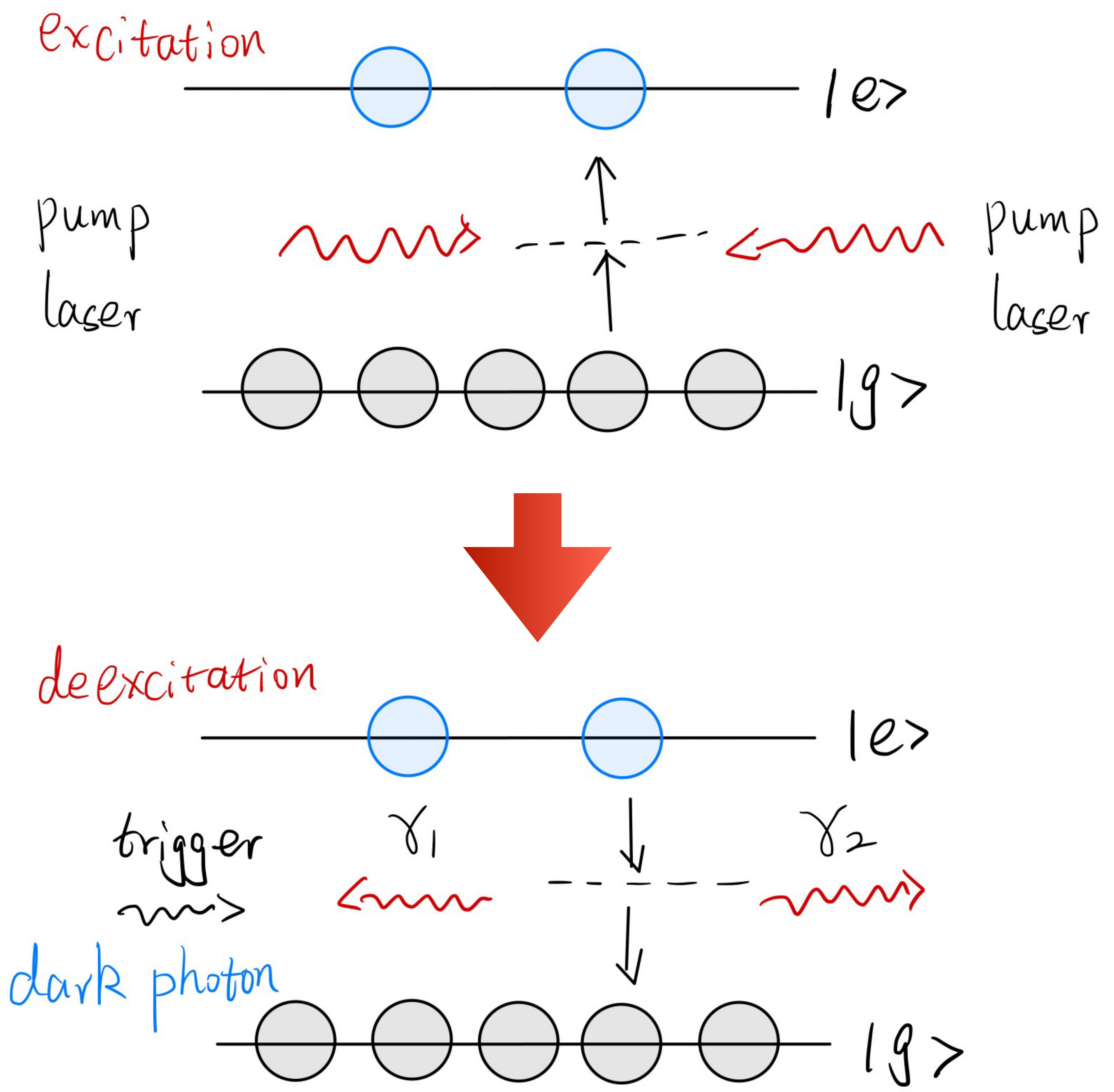
$$H = H_0 - \vec{d} \cdot (\vec{E} + \chi \vec{E}')$$

Dark photon field tiggers the collective deexcitation of $\mathrm{pH_2}$

Triggered Superradiance



Triggered Superradiance



$$H = H_0 - \vec{d} \cdot (\vec{E} + \chi \vec{E}')$$

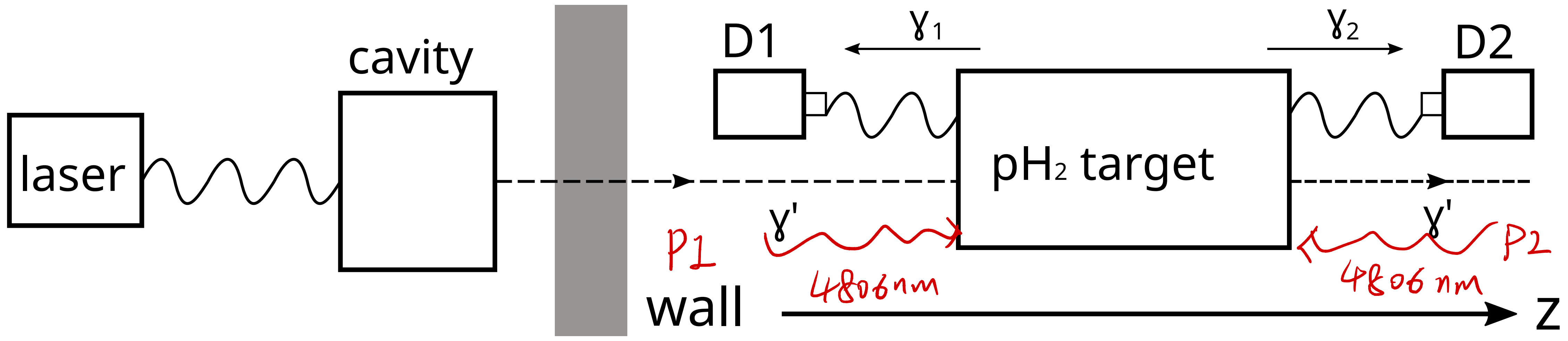
Dark photon field tiggers the collective deexcitation of $\mathrm{pH_2}$

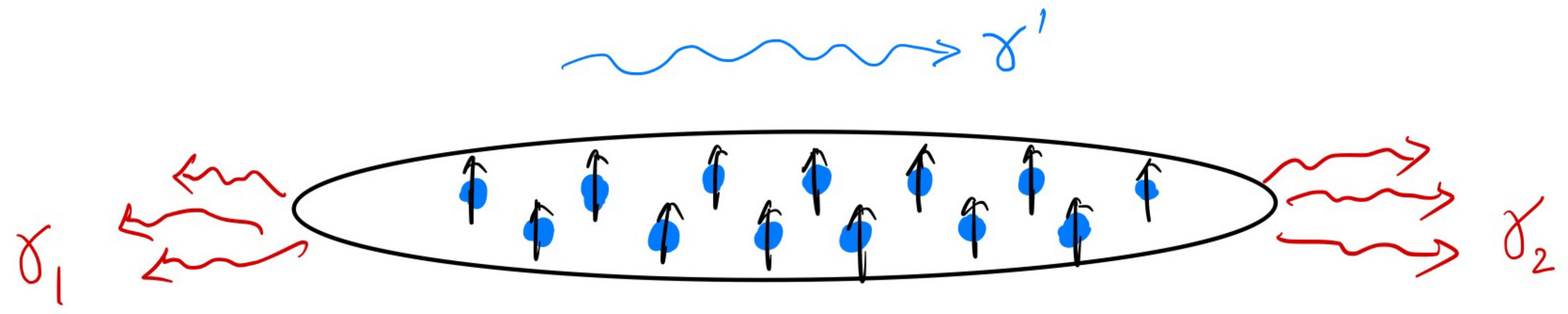
Experimental Setup

Modified light-shining-through-wall setup

- Parahydrogen (pH_2) sample prepared in coherent excited states

Bhoonah, Bramante, **NS**, PRD 2020/1909.07387





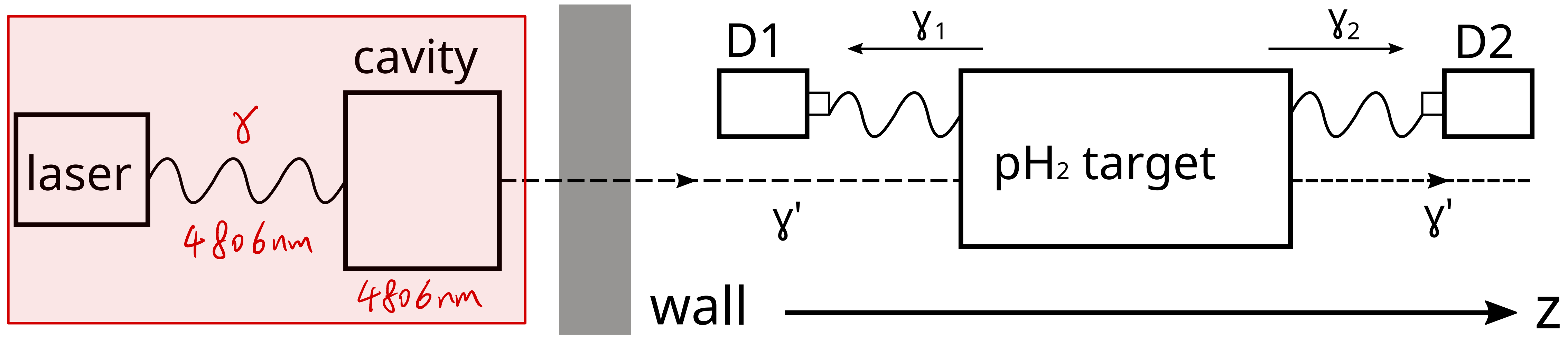
Experimental Setup

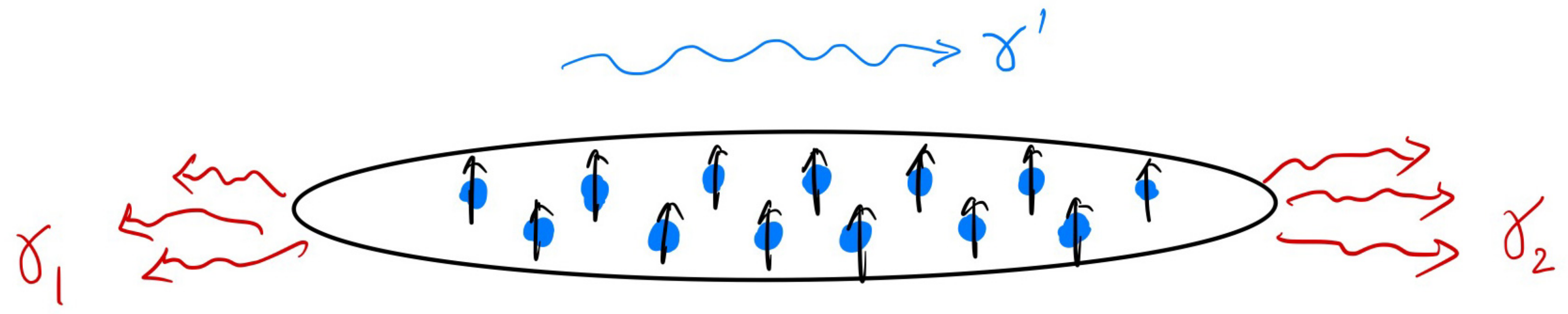
Modified light-shining-through-wall setup

- Parahydrogen (pH_2) sample prepared in coherent excited states

- Shine laser to the wall

Bhoonah, Bramante, **NS**, PRD 2020/1909.07387



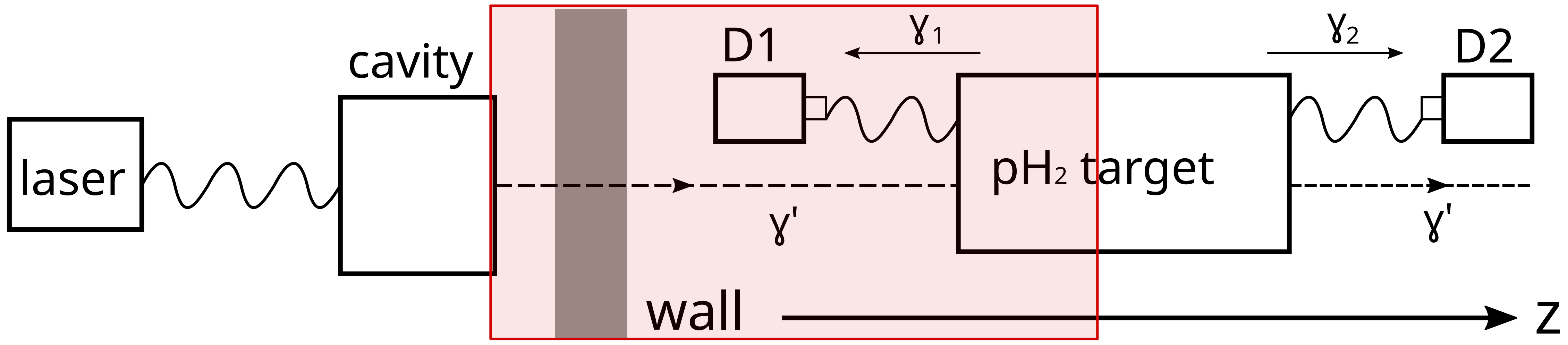


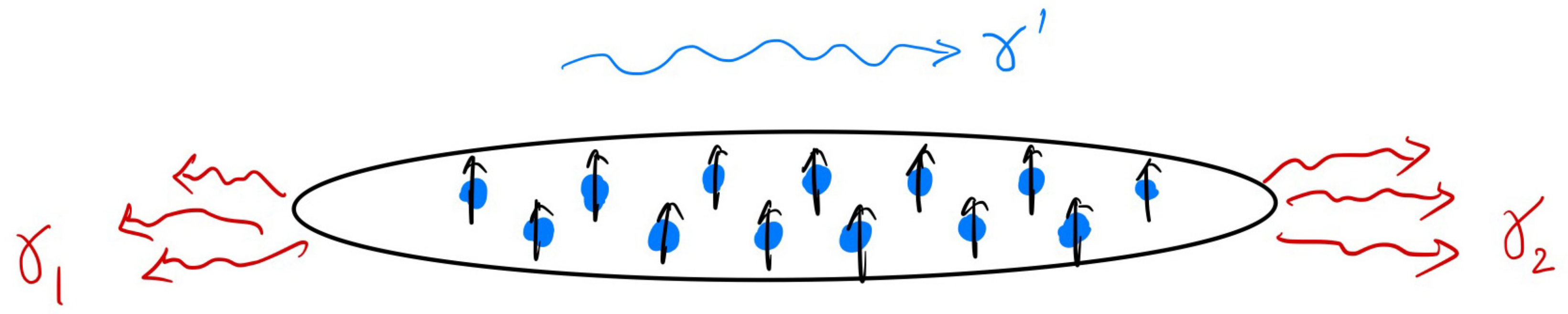
Experimental Setup

Modified light-shining-through-wall setup

- Parahydrogen (pH_2) sample prepared in coherent excited states
- Shine laser to the wall
- Dark photons penetrate the wall and deexicte pH_2

Bhoonah, Bramante, **NS**, PRD 2020/1909.07387

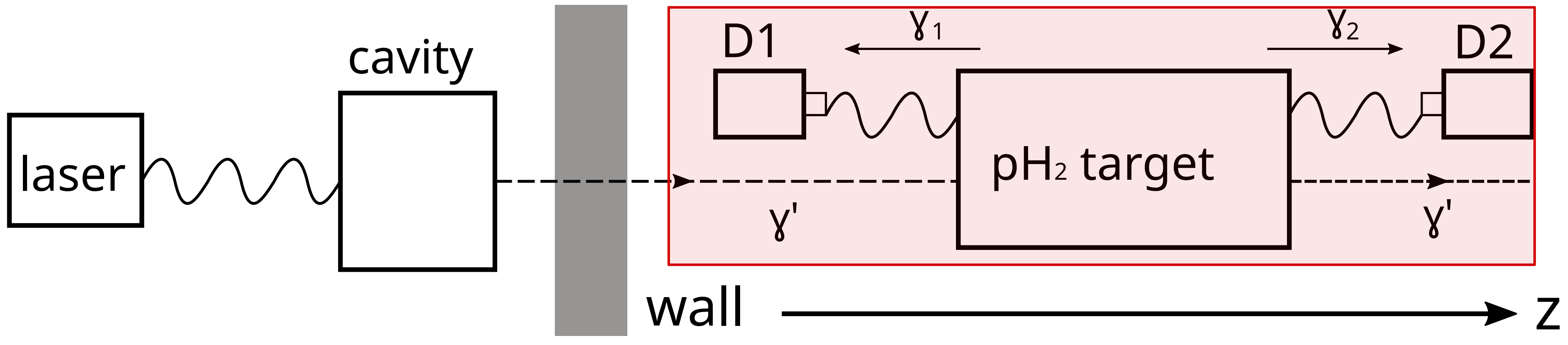


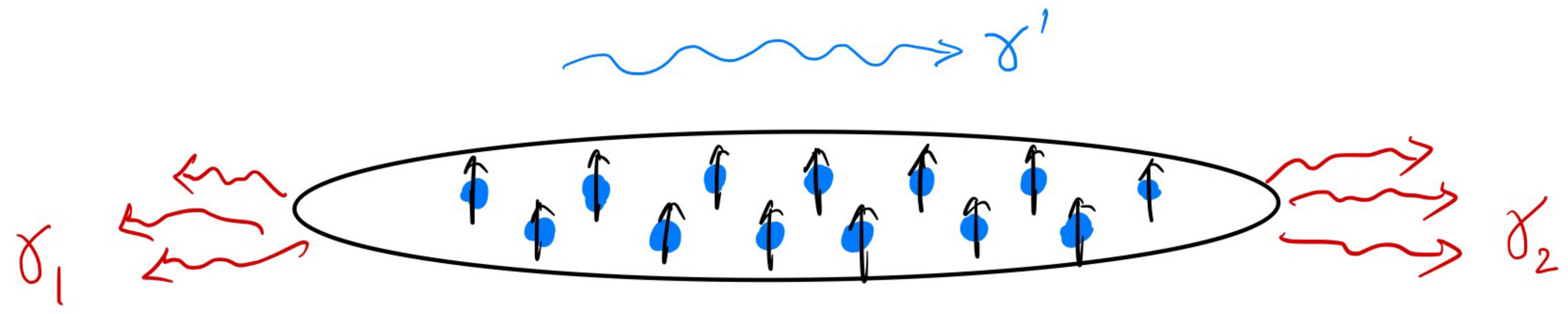


Experimental Setup

Modified light-shining-through-wall setup

Bhoonah, Bramante, **NS**, PRD 2020/1909.07387





- Parahydrogen (pH_2) sample prepared in coherent excited states
- Shine laser to the wall
- Dark photons penetrate the wall and deexicte pH_2
- Collect photons at two target ends

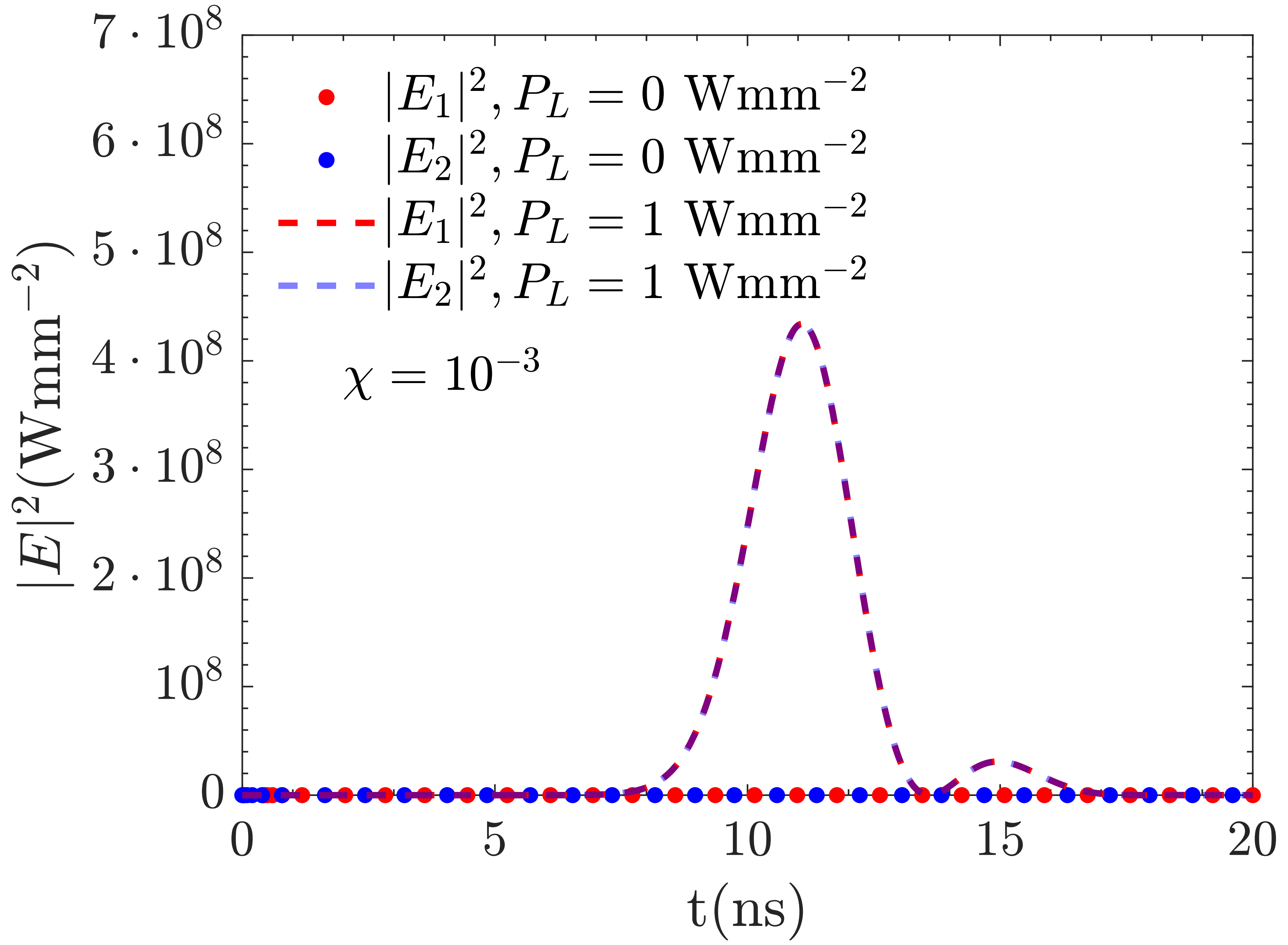
$$(\partial_t - \partial_z)E_1 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})E_1 + 2a_{eg}\rho^*_{ge}(E_2^* + \chi\eta E'^*)]\,,$$

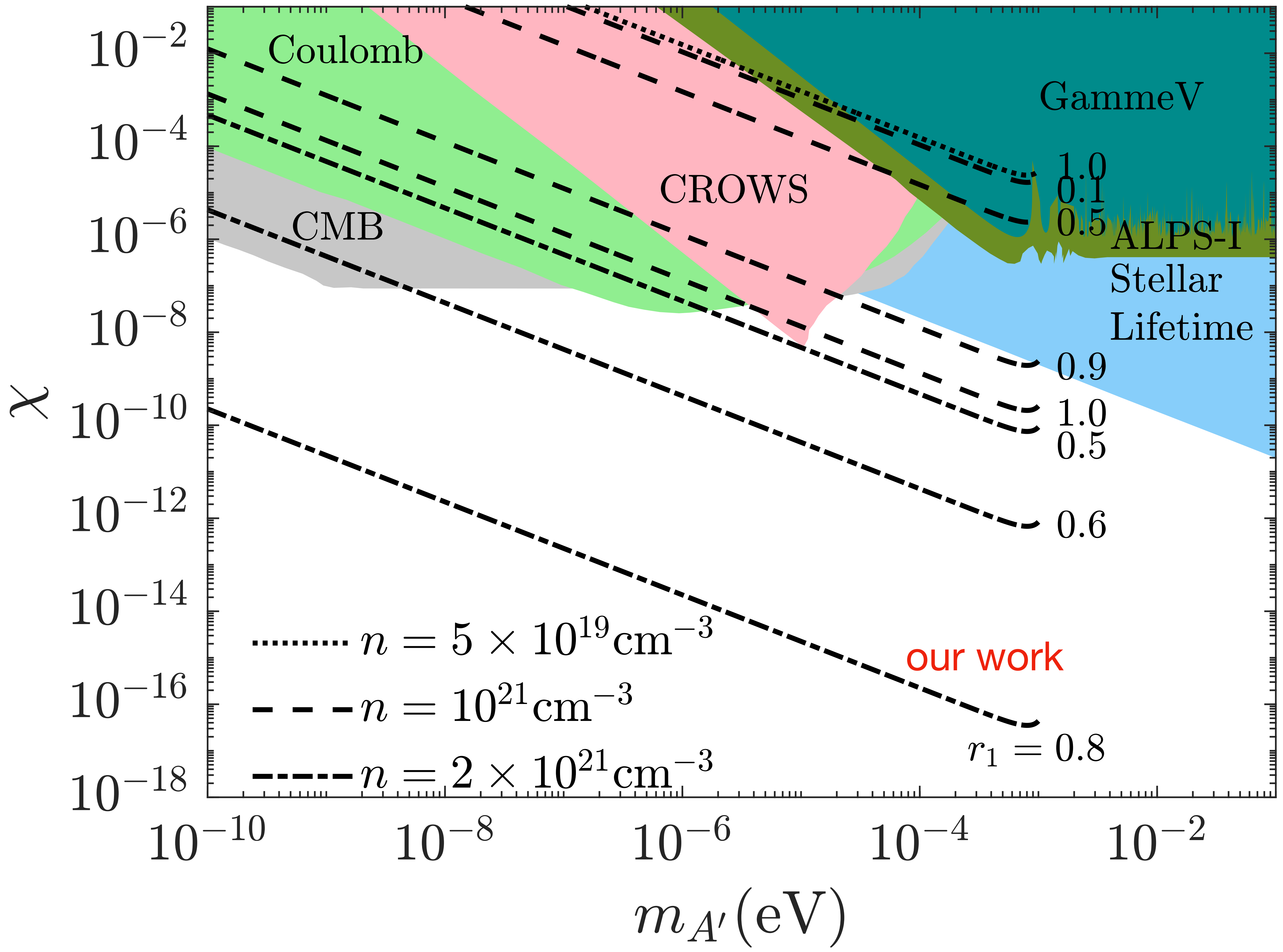
$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(E_2 + \chi\eta E') + 2a_{eg}\rho^*_{ge}E_1^*]\,,$$

$$(\partial_t + \partial_z)E' = \frac{i\omega^2 n}{\omega + k}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(2\chi^2\eta E' + \chi E_2) + 2a_{eg}\rho^*_{ge}\chi E_1^*]$$

Sensitivity

Bhoonah, Bramante, **NS**, PRD 2020/1909.07387





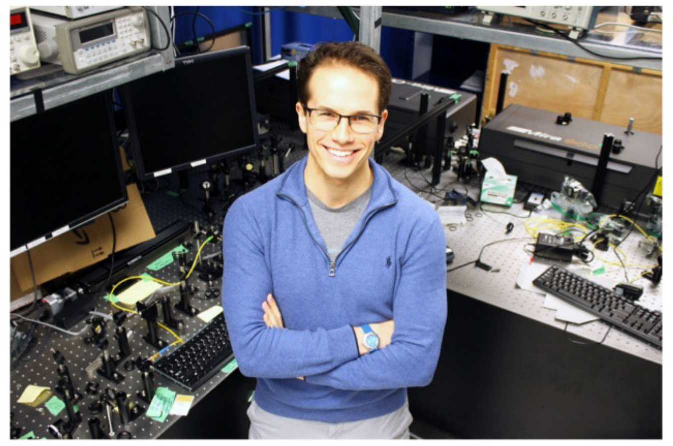
- Sub-meV dark photon sensitivity advanced by orders of magnitude

$$N_s \propto P_L N_{rep} \chi^4 (N_{pass} + 1) \sin^2\left(\frac{m_{A'}^2}{4\omega} l\right)$$

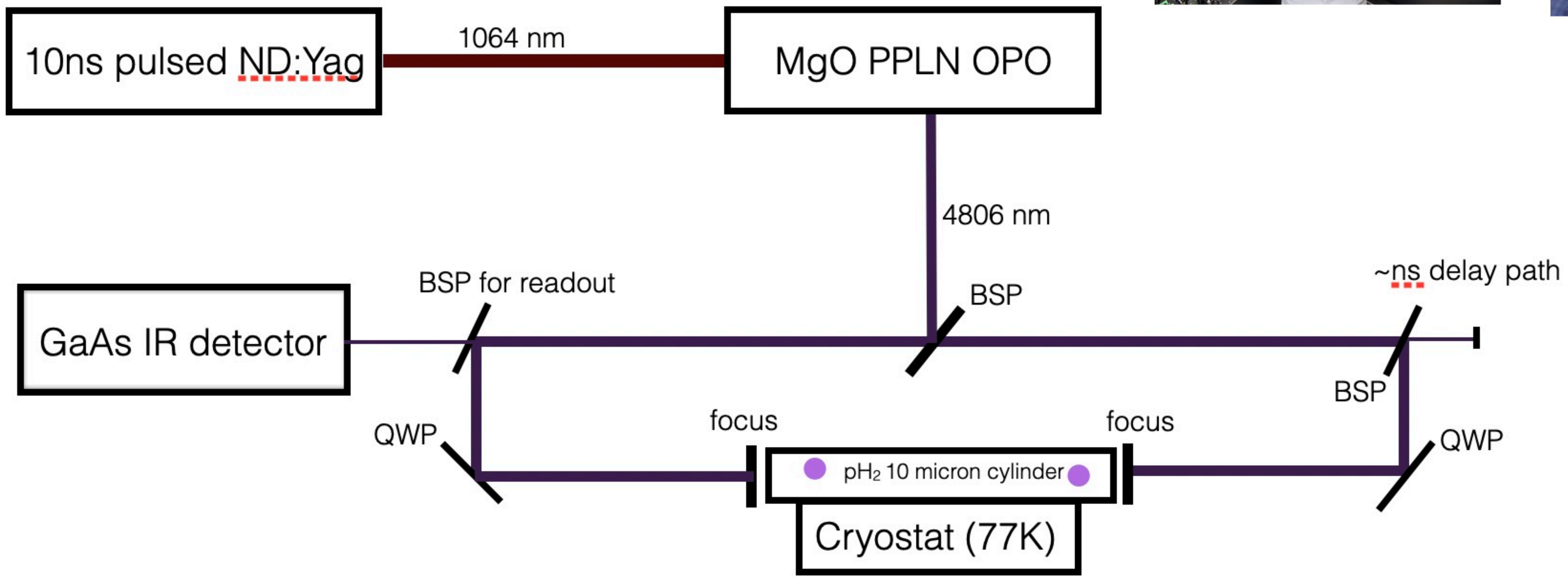
CATCHY Experiment



Coherent Atomic Transitions by Counter-pulsing HYdrogen

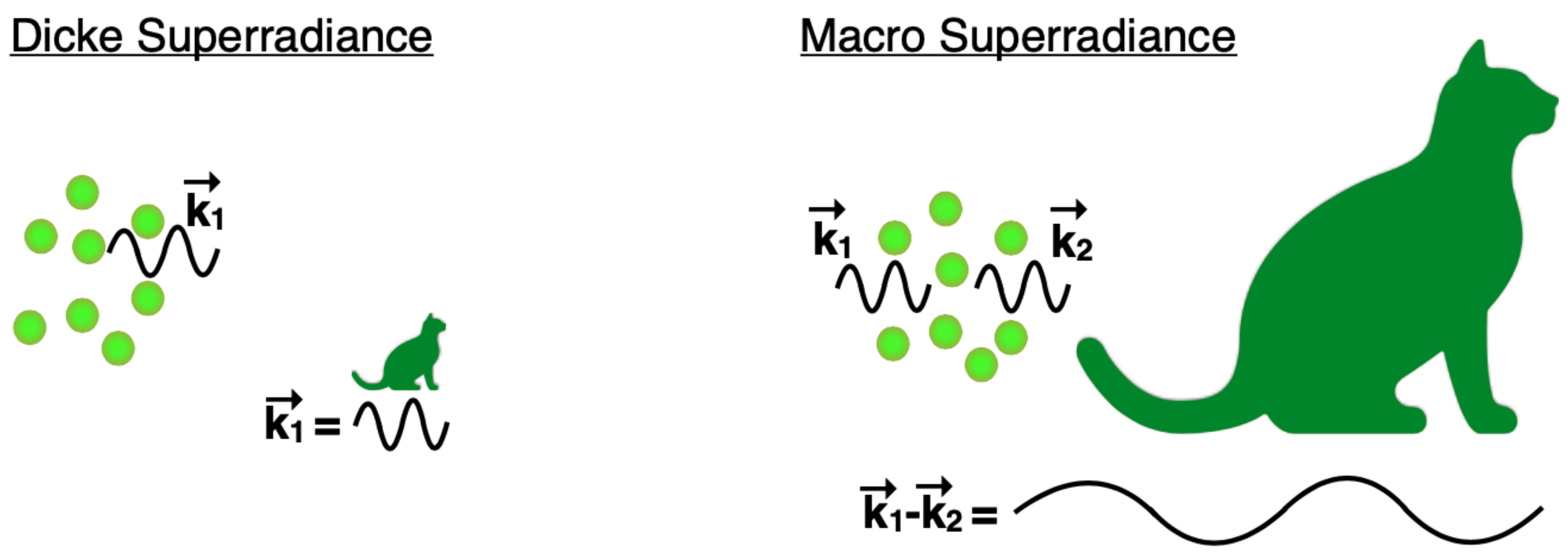


Setup A



Conclusions

- Macro superradiance achieved in a three-level atomic system at a rate $\Gamma \propto N^2$
- Dark photon field triggers collective deexcitation that leads to macro superradiance
- Sensitivity advanced by orders of magnitude with an improved LSW setup



Backup Slides

A Theoretical Overview I

Treat external fields as perturbations:

$H = H_0 + H_I = H_0 - \vec{d} \cdot (\tilde{E}_1 + \tilde{E}_2 + \chi \tilde{E}')$

Schrodinger equation: $i \frac{\partial}{\partial t} |\psi\rangle = (H_0 + H_I)|\psi\rangle$

$|\psi\rangle = c_g e^{-i\omega_g t}|g\rangle + c_e e^{-i(\omega_e + \delta)t}|e\rangle + c_{j+} e^{-i\omega_j t}|j_+\rangle + c_{j-} e^{-i\omega_j t}|j_-\rangle$

Introduce density matrix

$$\rho = \begin{pmatrix} |e\rangle\langle e| & |e\rangle\langle g| \\ |g\rangle\langle e| & |g\rangle\langle g| \end{pmatrix} = \begin{pmatrix} \rho_{ee} & \rho_{eg} \\ \rho_{ge} & \rho_{gg} \end{pmatrix}$$

Maxwell-Bloch equations

$$\partial_t \rho_{ee} = i(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}) - \frac{\rho_{ee}}{T_1}$$

$$\partial_t \rho_{ge} = i(\Omega_{gg} - \Omega_{ee} - \delta)\rho_{ge} + i\Omega_{ge}(\rho_{ee} - \rho_{gg}) - \frac{\rho_{ge}}{T_2}$$

Ω_{ij} functions of E, E',analogous to Rabi frequencies,
deexcitation time $T_1 \sim 1000$ns, decoherence time $T_2 \sim 10$ns

A Theoretical Overview II

Maxwell-Bloch equations

$$\partial_t \rho_{ee} = i(\Omega_{eg}\rho_{ge} - \Omega_{ge}\rho_{eg}) - \frac{\rho_{ee}}{T_1}$$

$$\partial_t \rho_{ge} = i(\Omega_{gg} - \Omega_{ee} - \delta)\rho_{ge} + i\Omega_{ge}(\rho_{ee} - \rho_{gg}) - \frac{\rho_{ge}}{T_2}$$

Introduce Bloch vectors

$$r_1 = \rho_{ge} + \rho_{eg}\,,\; r_2 = i(\rho_{eg} - \rho_{ge})\,,\; r_3 = \rho_{ee} - \rho_{gg}$$

$$\partial_t r_1 = \left[-\frac{a_{gg} - a_{ee}}{4}(|\bar{E}_1'|^2 + |\bar{E}_2'|^2) + \delta\right] r_2 + a_{eg}\,\mathrm{Im}(\bar{E}_1'\bar{E}_2')r_3 - \frac{r_1}{T_2}\,,$$

$$\partial_t r_2 = \left[\frac{a_{gg} - a_{ee}}{4}(|E_1'|^2 + |E_2'|^2) - \delta\right] r_1 + a_{eg}\,\mathrm{Re}(\bar{E}_1'\bar{E}_2')r_3 - \frac{r_2}{T_2}\,,$$

$$\partial_t r_3 = -a_{eg}[\mathrm{Im}(\bar{E}_1'\bar{E}_2')r_1 + \mathrm{Re}(\bar{E}_1'\bar{E}_2')r_2] - \frac{1 + r_3}{T_1}$$

where $\bar{E}_1' = \bar{E}_1 + \chi\eta\bar{E}'\,,\quad \bar{E}_2' = \bar{E}_2 + \chi\eta\bar{E}'$

A Theoretical Overview III

Field equations

$$(\partial_t^2 - \partial_z^2)\tilde{E}_i = -n\partial_t^2 \tilde{P}_i\,, \qquad (\partial_t^2 - \partial_z^2 + m_{A'}^2)\tilde{E}' = -\chi n \partial_t^2 \tilde{P}'$$

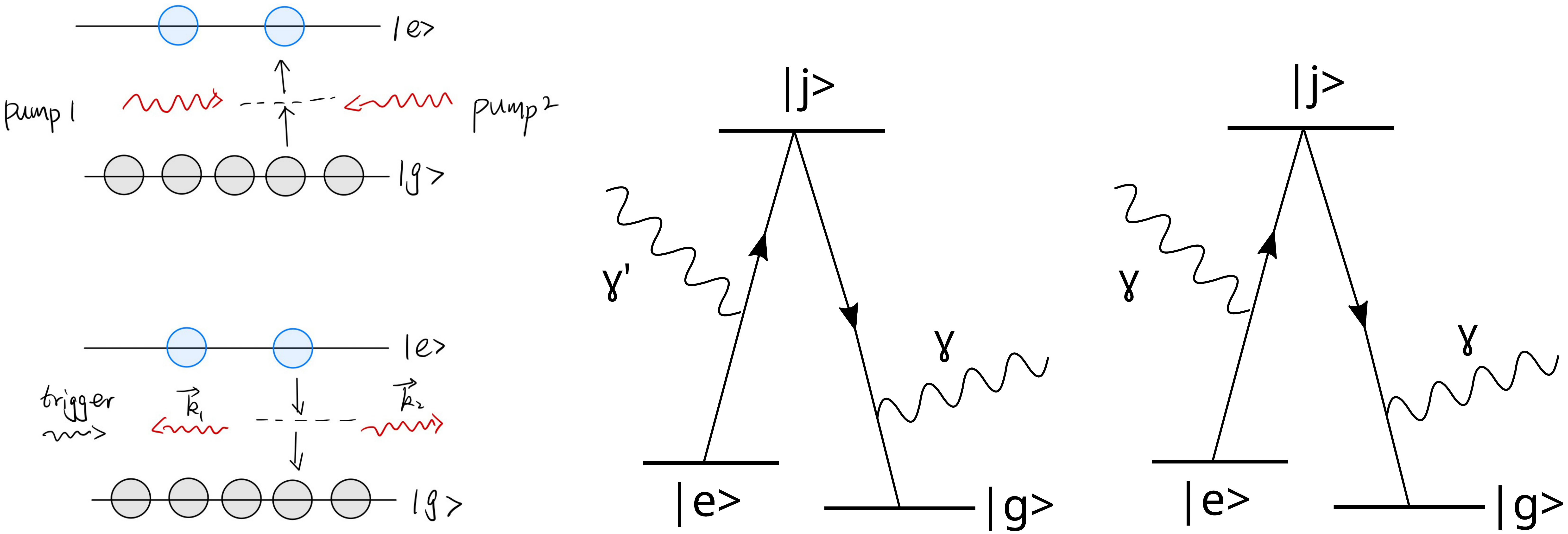
Or

$$(\partial_t - \partial_z)E_1 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})E_1 + 2a_{eg}\rho_{ge}^*(E_2^* + \chi\eta E'^*)]\,,$$

$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(E_2 + \chi\eta E') + 2a_{eg}\rho_{ge}^* E_1^*]\,,$$

$$(\partial_t + \partial_z)E' = \frac{i\omega^2 n}{\omega + k}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(2\chi^2\eta E' + \chi E_2) + 2a_{eg}\rho_{ge}^*\chi E_1^*]$$

Field Evolution



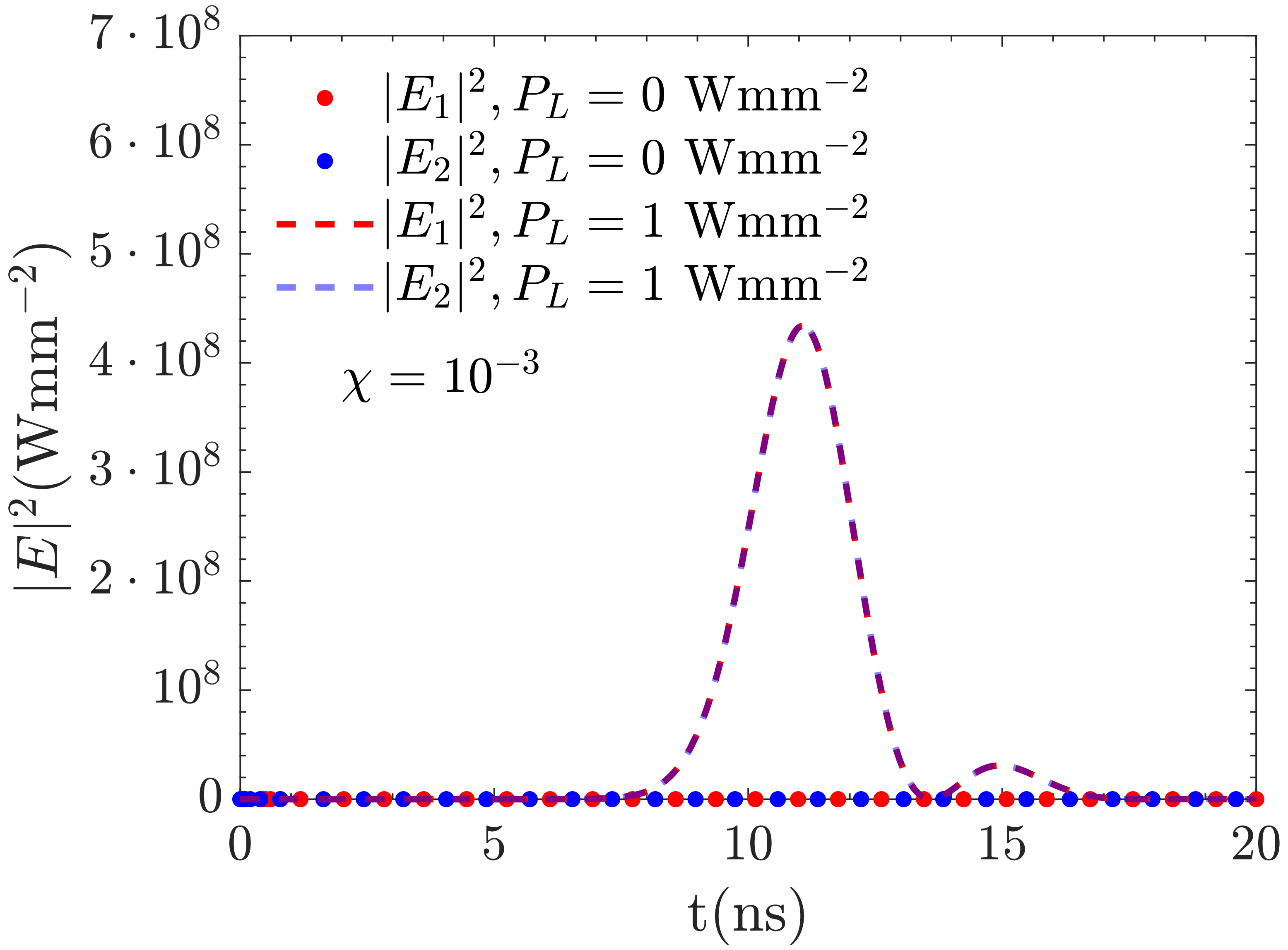
$$(\partial_t - \partial_z)E_1 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})E_1 + 2a_{eg}\rho_{ge}^*(E_2^* + \chi\eta E'^*)]\,,$$

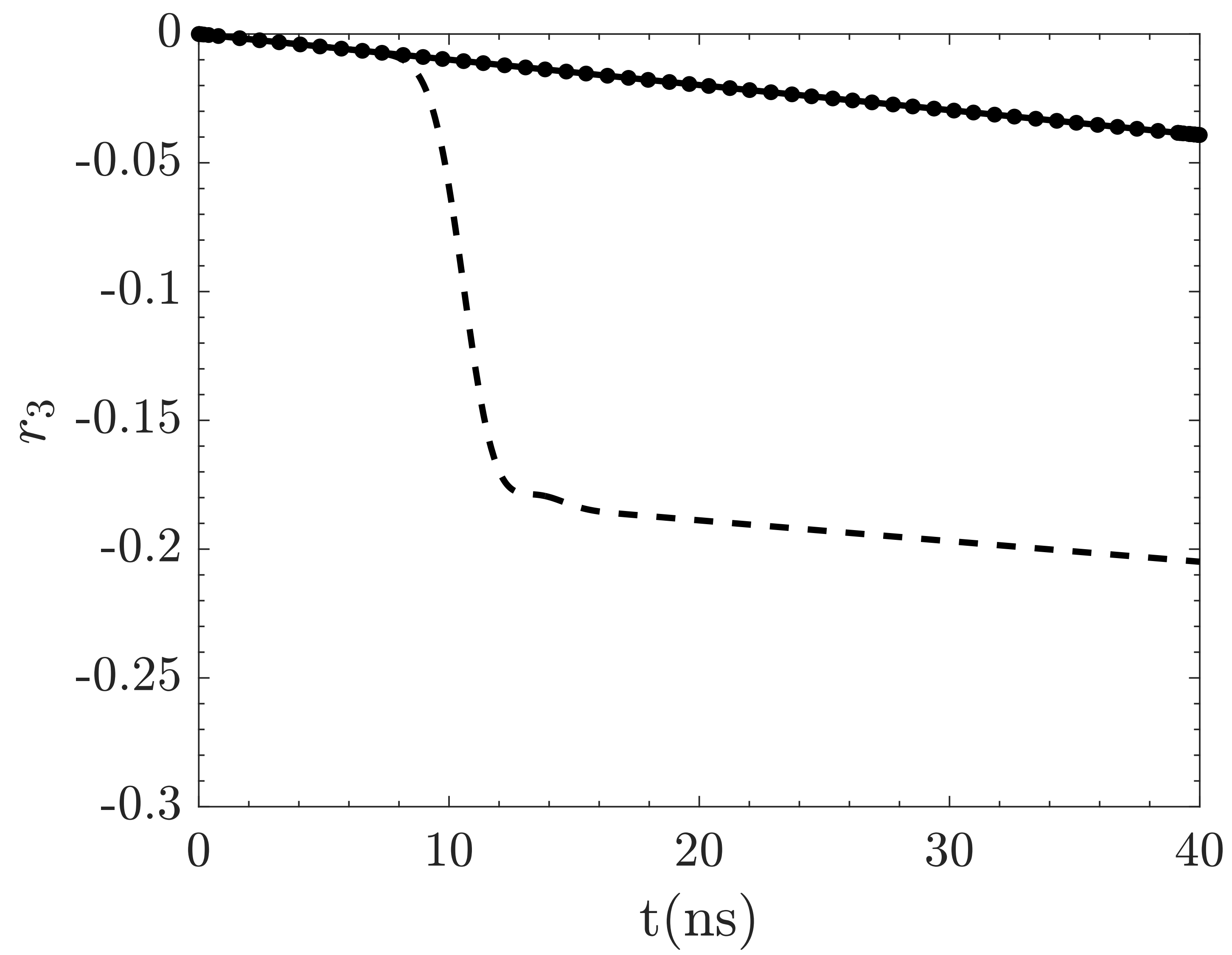
$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(E_2 + \chi\eta E') + 2a_{eg}\rho_{ge}^* E_1^*]\,,$$

$$(\partial_t + \partial_z)E' = \frac{i\omega^2 n}{\omega + k}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(2\chi^2\eta E' + \chi E_2) + 2a_{eg}\rho_{ge}^*\chi E_1^*]$$

- Dark photon triggers the emission of E_1
- E_1 triggers the emission of E_2 and E'

Field Evolution



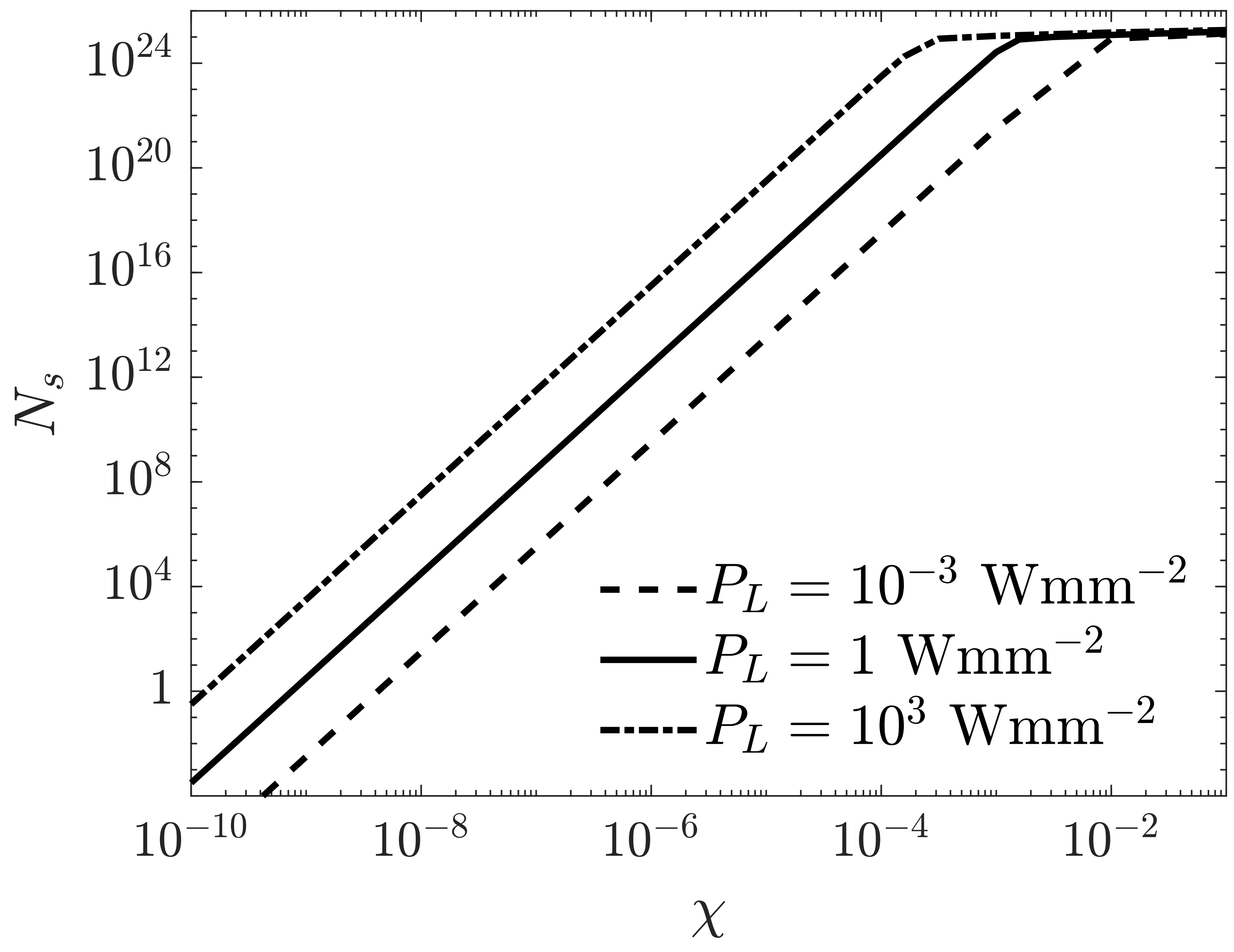


- Dark photon triggers the emission of E_1
- E_1 triggers the emission of E_2 and E'
- Symmetric emission E_1 and E_2

Signal vs Background

Signal: integrate the output electric field within $\sim$20 ns

$$N_s^1 = \frac{A}{\omega}\int_0^t |E_1(t')|^2 dt' = \frac{A}{\omega}\int_0^t |E_2(t')|^2 dt'$$



$E' \propto \chi\sqrt{P_L}\sin(\frac{m_{A'}^2}{4\omega}l)$, $E_1 \propto \chi E'$

# of signal photon $N_s \propto P_L N_{\rm rep}\chi^4(N_{\rm pass}+1)\sin^2\left(\frac{m_{A'}^2}{4\omega}l\right)$

Signal vs Background

Signal: integrate the output electric field within ∼20 ns

$$N_s^1 = \frac{A}{\omega} \int_0^t |E_1(t')|^2 dt' = \frac{A}{\omega} \int_0^t |E_2(t')|^2 dt'$$

$$N_s \propto P_L N_{\rm rep} \chi^4 (N_{\rm pass} + 1) \sin^2 \left(\frac{m_{A'}^2}{4\omega} l \right)$$

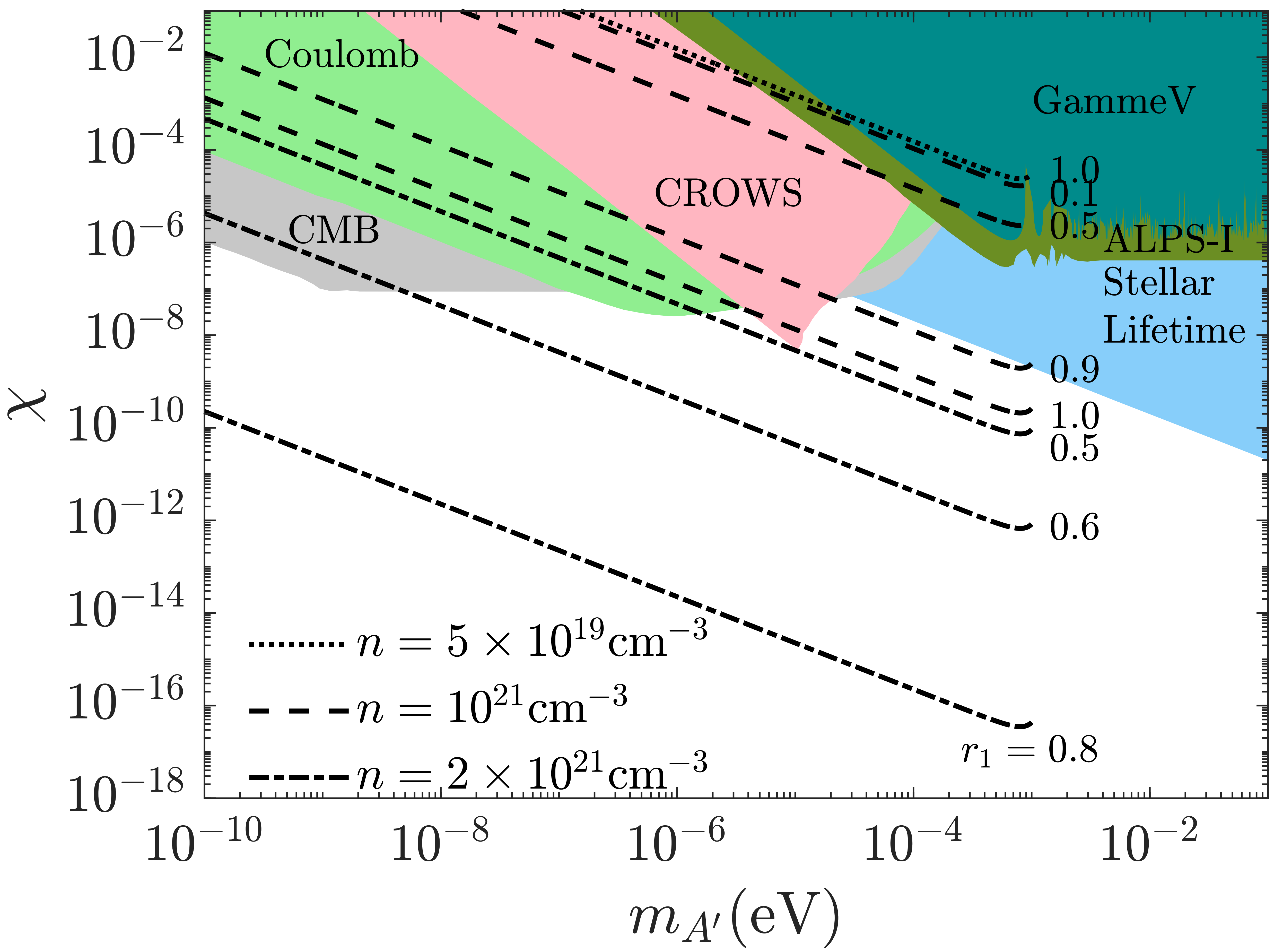
Background: Spontaneous two-photon emission with frequency $\omega_1 + \omega_2 = \omega_{eg}$ into random solid angle

Rate $\frac{d\Gamma_{\rm sp}}{dz} = \frac{\omega_{eg}^7}{(2\pi)^3} N |a_{eg}|^2 z^3 (1 - z)^3$, $z = \omega_1/\omega_{eg}$

For $N \sim 10^{22}$, $N_{background} = 2N \frac{d\Gamma_{\rm sp}}{dz} \Delta z \Delta t \frac{\Delta\Omega}{4\pi} = 4.3 \times 10^{-9}$

Two-photon background can be neglected!

Dark Photon Sensitivity



Bhoonah, Bramante, **Song**' 2019

Superradiance condition

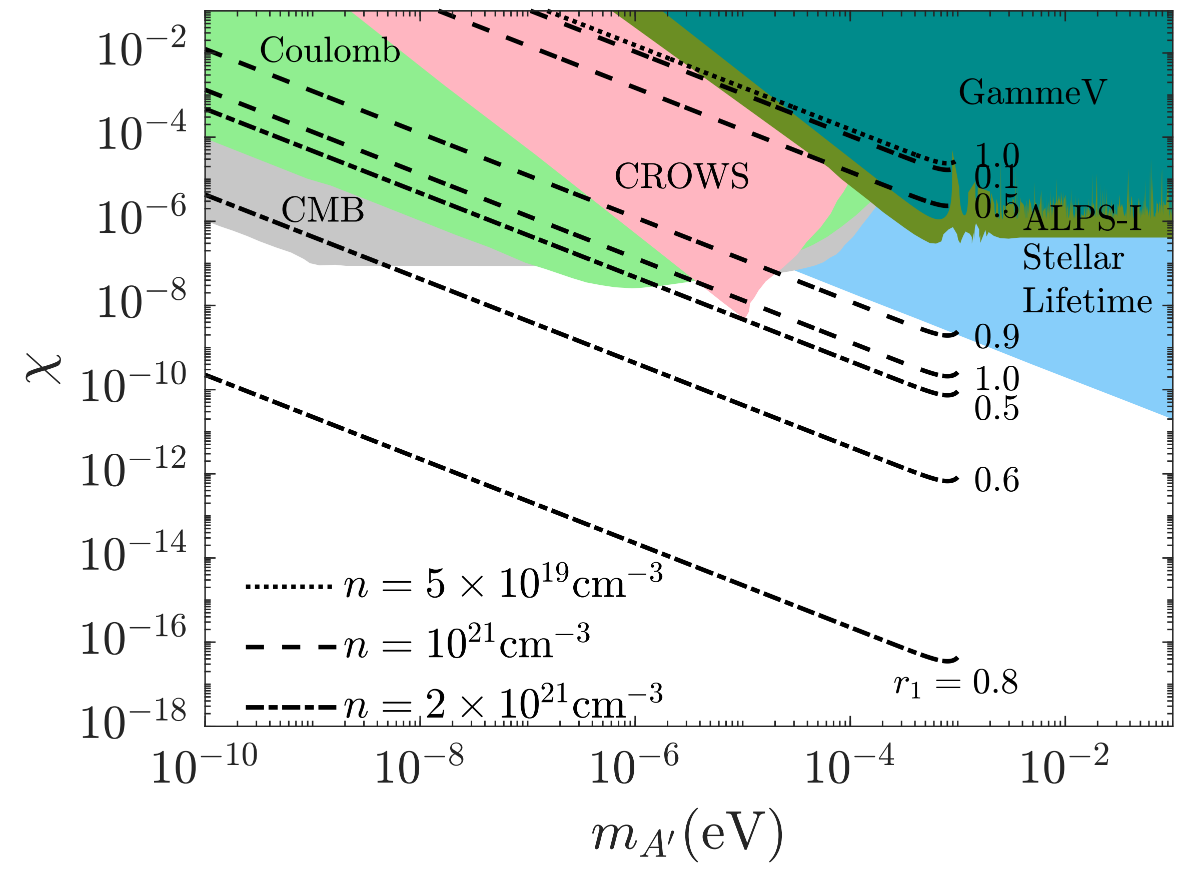
$$\Delta k \cdot L = (k_1 - k')L = (\omega - \sqrt{\omega^2 - m_{A'}^2})L \lesssim 1 \Rightarrow m_{A'} \lesssim \text{meV}$$

Dark Photon Sensitivity

$$(\partial_t - \partial_z)E_1 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})E_1 + 2a_{eg}\rho^*_{ge}(E_2^* + \chi\eta E'^*)]\,,$$

$$(\partial_t + \partial_z)E_2 = \frac{i\omega n}{2}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(E_2 + \chi\eta E') + 2a_{eg}\rho^*_{ge}E_1^*]\,,$$

$$(\partial_t + \partial_z)E' = \frac{i\omega^2 n}{\omega + k}[(a_{ee}\rho_{ee} + a_{gg}\rho_{gg})(2\chi^2\eta E' + \chi E_2) + 2a_{eg}\rho^*_{ge}\chi E_1^*]$$

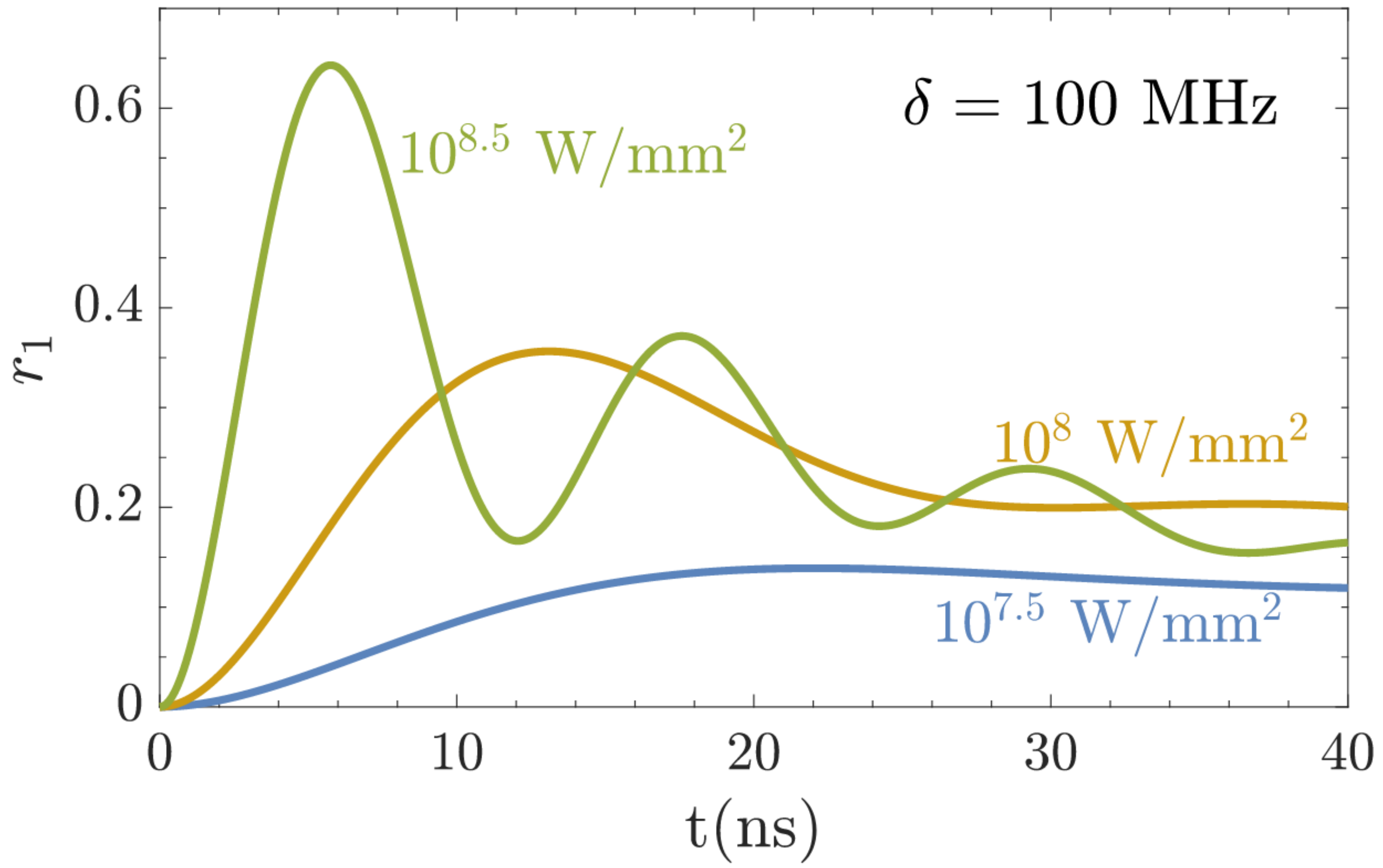


- Neglect propagation term, drop r_2 and spatial dependence
- $\partial_t^2 E_1 - n^2\Omega_r^2 E_1 = 0\,,\ \Omega_r^2 \propto \omega^2|a_{eg}r_1|^2$
- $N_s \propto \int |E_1|^2 dt \sim \frac{1}{n\Omega} e^{2n\Omega_r\Delta t}$

The sensitivity scales exponentially with number density n and coherence r

Technical Challenge

Large coherence⇒ powerful laser



Large number density and long decoherence time⇒ low T

pH_2 Reference	Density (cm^{-3})	Temperature (K)	Decoherence Time (ns)
[60]	$10^{19} - 10^{20}$	80-500	~ 10
[42]	5.6×10^{19}	78	~ 8 (est)
[37]	$10^{19} - 5 \times 10^{20}$	78	~ 10 (est)
[61]	2.6×10^{22}	4.2	$\gtrsim 140$