Resonant absorption of dark matter in molecules

Ken Van Tilburg (NYU & IAS)

arXiv:1709.05354

with Asimina Arvanitaki (PI), Savas Dimopoulos (SU)

work in progress with: Karl Berggren (MIT), SaeWoo Nam (NIST)
Masha Baryakhtar, Junwu Huang, Robert Lasenby (PI)

KITP, 2018/03/29

“Problems” in particle physics

Standard Model of particle physics accurately describes every known experiment and observation to the measured and calculated precision*

theoretical frontiers:

mathematical structures | numerological curiosities | computational precision

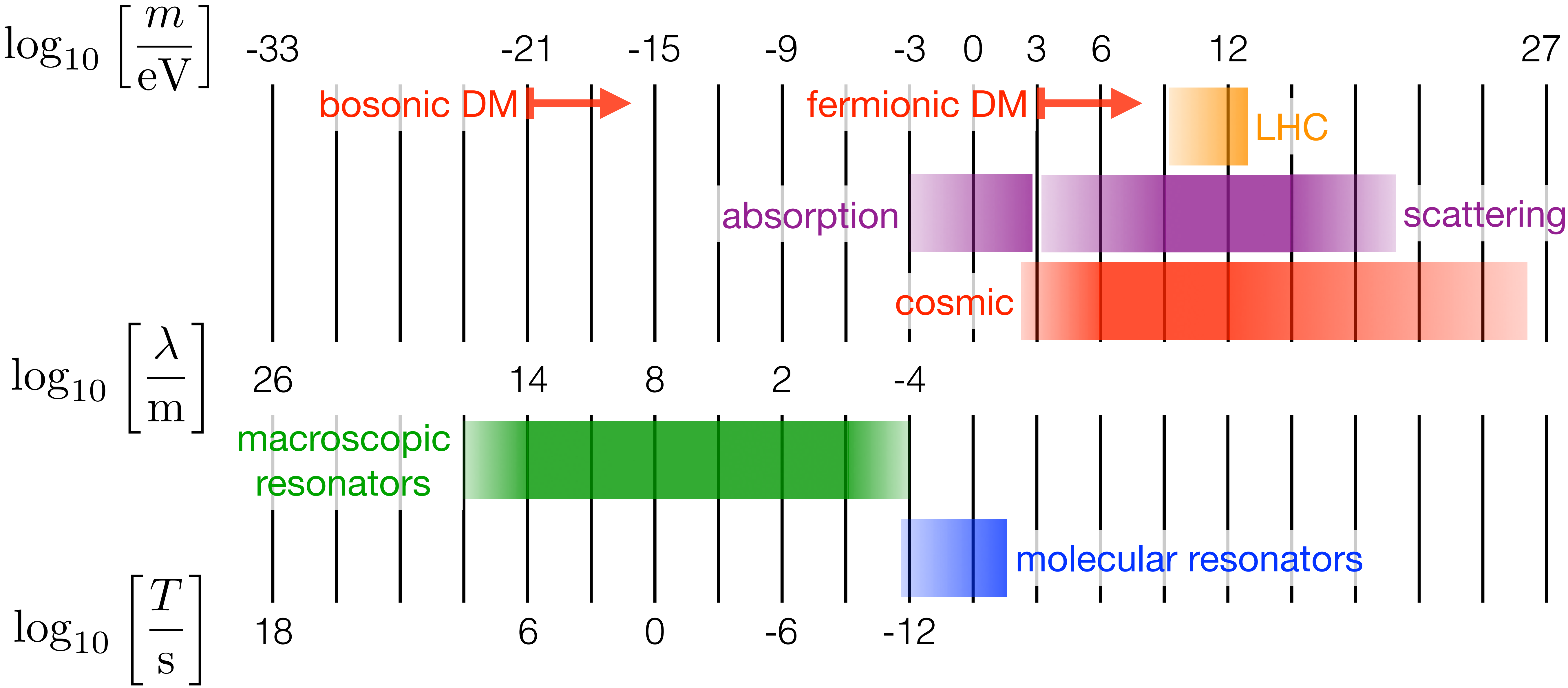
experimental frontiers:

high-energy | cosmic | intensity | precision

*parametrized unknowns:

dark matter | baryon asymmetry | inflation

Scales of dark matter



absorption ⟶ narrowband signal: $\omega = m\left(1 + \frac{v^2}{2}\right)$

Outline

(1) Dark matter fields can resonantly excite a molecular system

bosonic DM couplings | two-level system dynamics | molecular levels

(2) Experimental setup

configurations | photon detection | backgrounds | discrimination

(3) Dark matter sensitivity $0.2\ \mathrm{eV} < m < 20\ \mathrm{eV}$

hidden vectors | moduli | axions

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Why is a molecular gas a good dark matter detector?

calculable
- signal rate
- backgrounds

discrimination power
- energy resolution: $\Delta\omega/\omega \ll 10^{-6}$
- control variables: P, T, E, B
- selection rules
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Bosonic dark matter couplings

EFT of DM bosons coupled to electrons, quarks, photons, gluons

spin-1

$\epsilon A'_\mu J^\mu_{\mathrm{EM}}$	$g A'_\mu J^\mu_{B-L}$

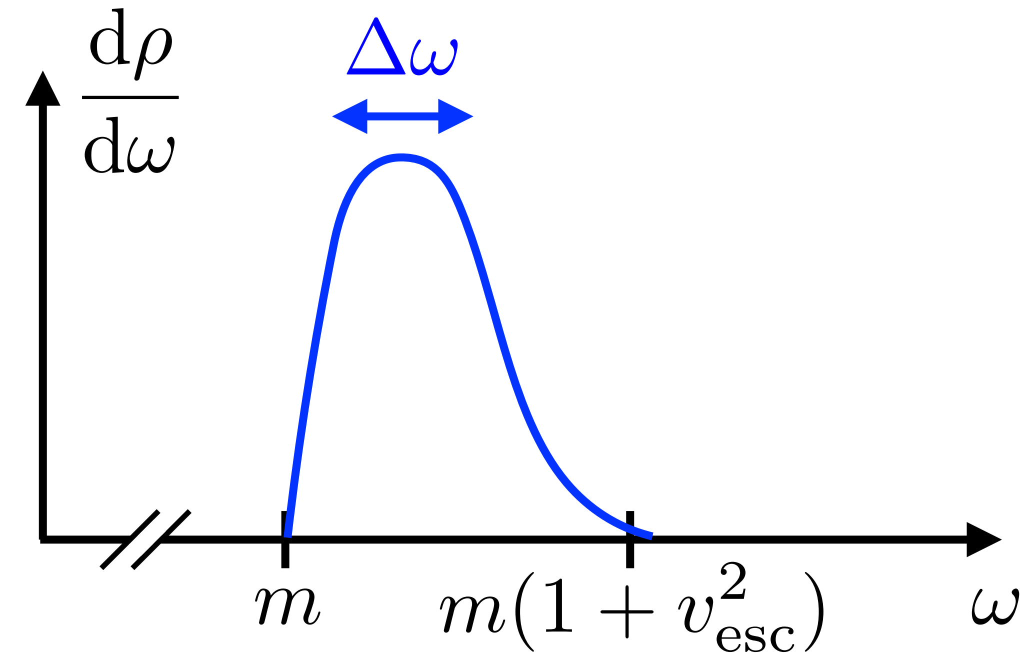
---

spin-0

parity-even	parity-odd
$\phi \bar{e} e$	$(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e$
$\phi \bar{q} q$	$(\partial_\mu a)\bar{q}\gamma^\mu\gamma_5 q$
ϕF^2	$aF\tilde{F}$
ϕG^2	$aG\tilde{G}$

Bosonic dark matter fields and interactions

$$\left.\begin{array}{rc} \text{vector} & |\mathbf{A}'| \\ \text{scalar} & \phi \\ \text{pseudoscalar} & a \end{array}\right\} \simeq \frac{\sqrt{2\rho_{\mathrm{DM}}}}{\omega}\cos(\omega t)$$



production: $\begin{cases}\text{inflationary perturbations (spin-1)} \\ \text{misalignment mechanism (spin-0)}\end{cases}$

e.g. hidden photon: $\delta\mathcal{L} = \epsilon A'_\mu J^\mu_{\mathrm{EM}}$

$$\delta H = \epsilon \underset{\downarrow \atop \text{3 kV/m}}{\mathbf{E}'} \cdot \boldsymbol{\mu}_e$$

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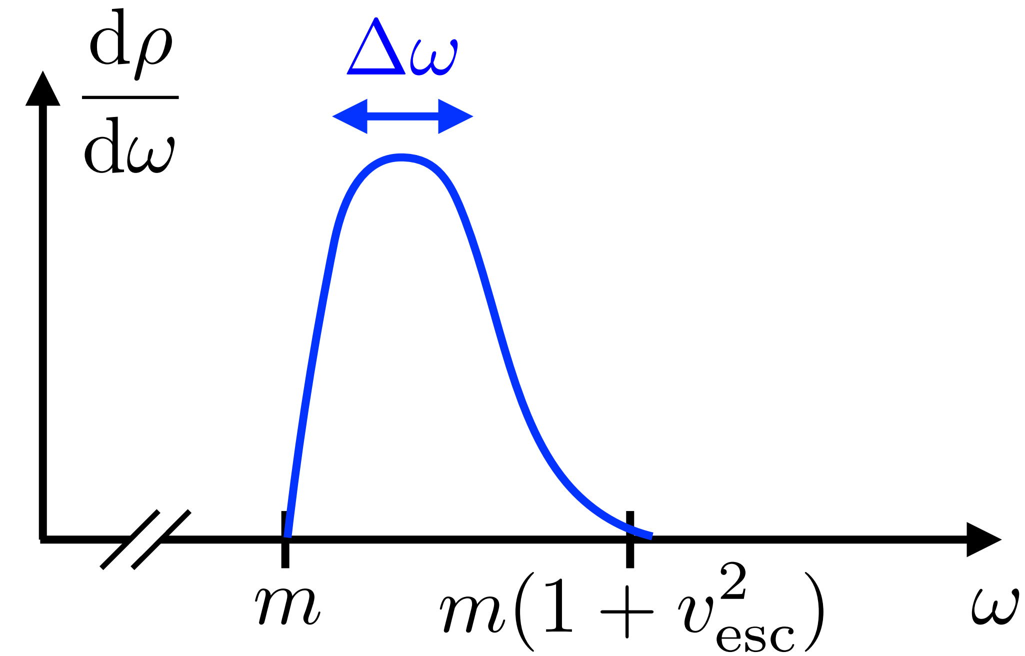

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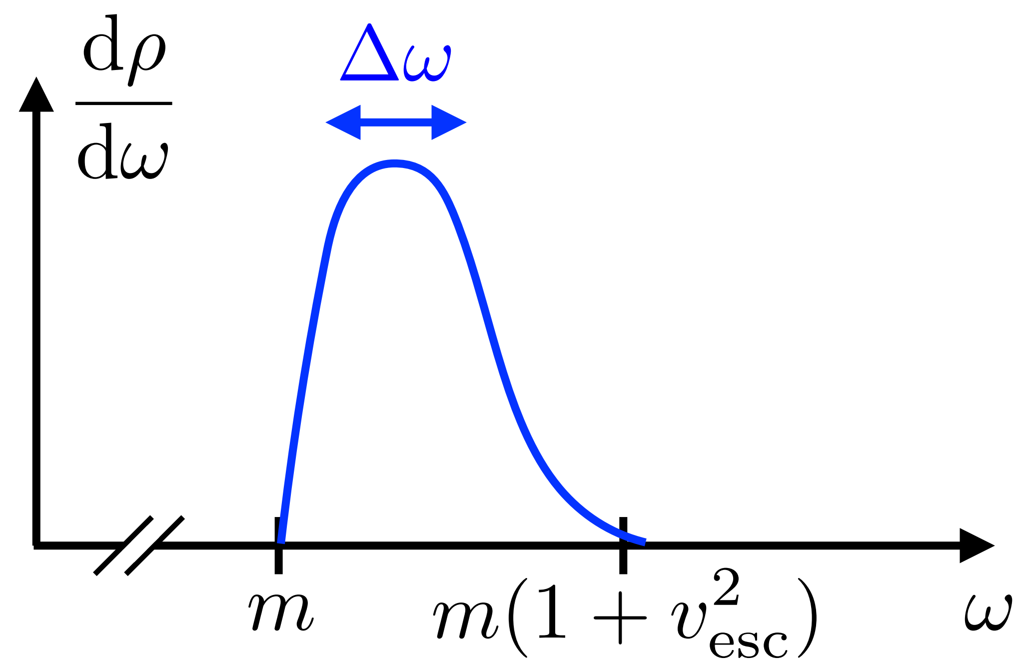

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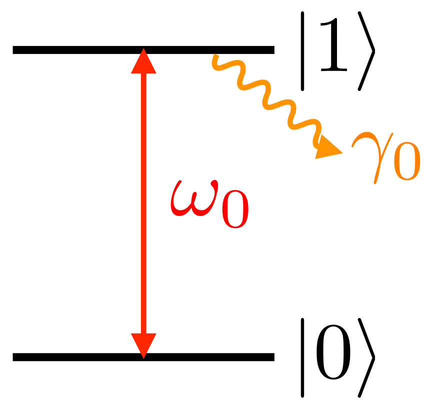
3 kV/m

equivalent to shining 20kW laser in a 1m² beam waist area

Resonant excitation of a two-level system



$$\langle 1|\delta H|0\rangle \sim \Omega\cos(\omega t)$$

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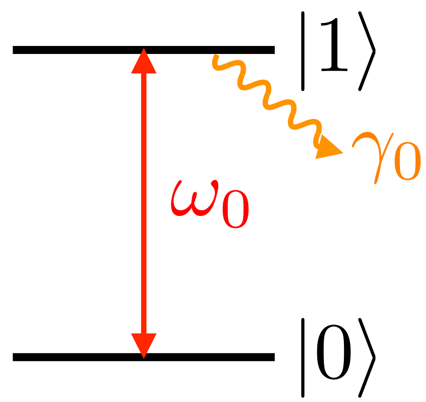

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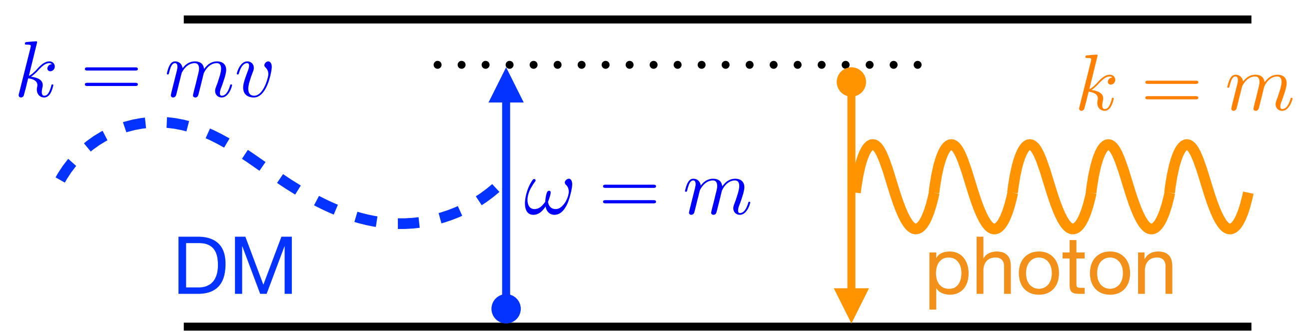

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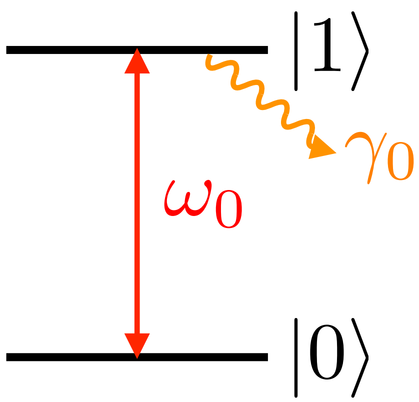
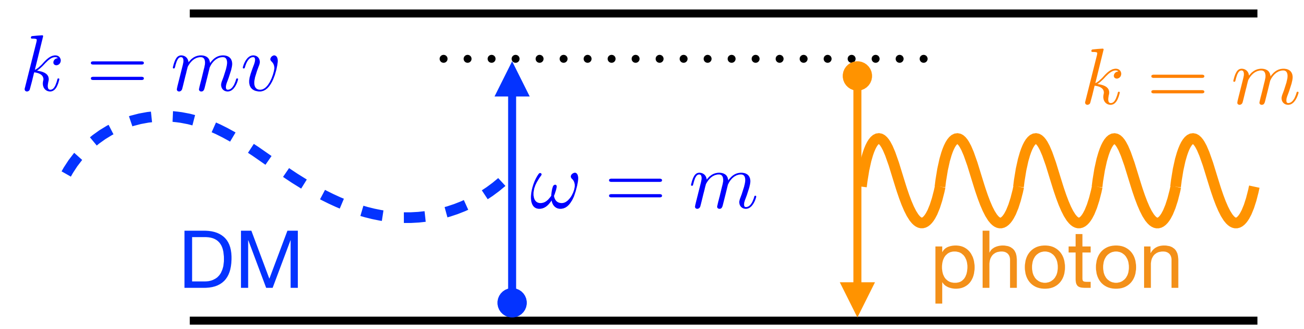




$$\langle 1|\delta H|0\rangle \sim \Omega \cos(\omega t)$$

$$\Gamma_{\rm abs} = nV \underbrace{\frac{|\Omega|^2}{\gamma}}_{\text{on-resonance absorption rate per molecule}} \frac{1}{1 + \underbrace{\frac{4(\omega_0-\omega)^2}{\gamma^2}}_{\text{lineshape}}}$$

nV: # molecules

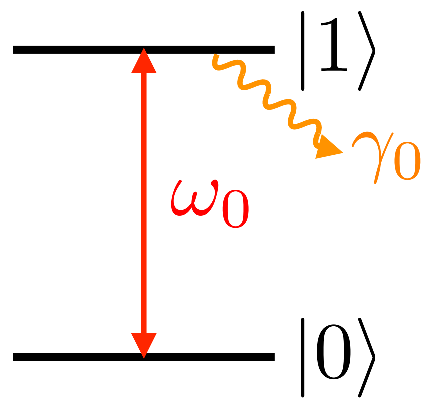
$$\gamma = \gamma_{\rm rad} + 2\gamma_{\rm col} + \frac{\Delta\omega}{\pi}$$

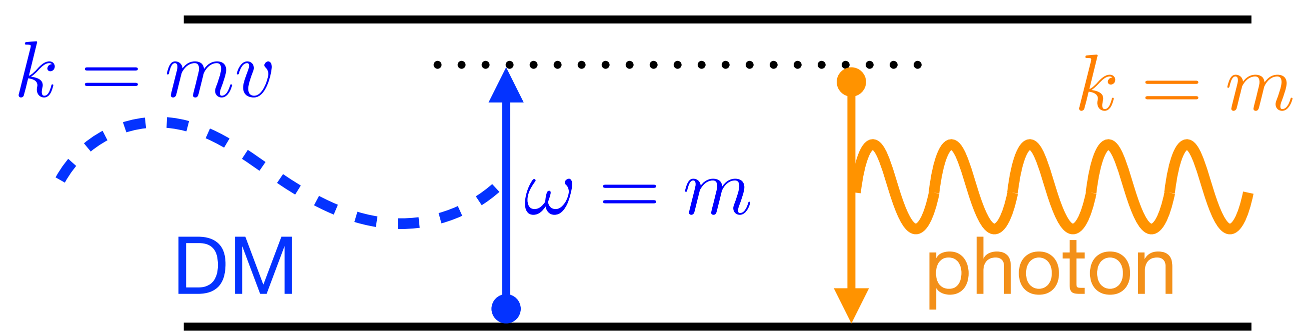
$$\gamma_{\rm rad} \simeq \bar{r}\gamma_0 + \sum_i \gamma_i$$

$$\gamma_{\rm col} = n\sigma_{\rm col} v_{\rm mol}$$

$\Delta\omega_{\rm Doppler}$ negligible

Resonant excitation of a two-level system





$$\langle 1|\delta H|0\rangle \sim \Omega\cos(\omega t)$$

$$|\Psi(t)'\rangle = e^{-i\int_0^t \delta H\, dt'}|0'\rangle \simeq |0'\rangle - \frac{i}{2}\Omega\frac{e^{i(\omega_0-\omega)t}-1}{i(\omega_0-\omega)}|1'\rangle$$

$$\Gamma_{\rm abs} = \underbrace{nV}_{\#\text{ molecules}}\underbrace{\frac{|\Omega|^2}{\gamma}}_{\substack{\text{on-resonance}\\ \text{absorption rate per molecule}}}\underbrace{\frac{1}{1+\frac{4(\omega_0-\omega)^2}{\gamma^2}}}_{\text{lineshape}}$$

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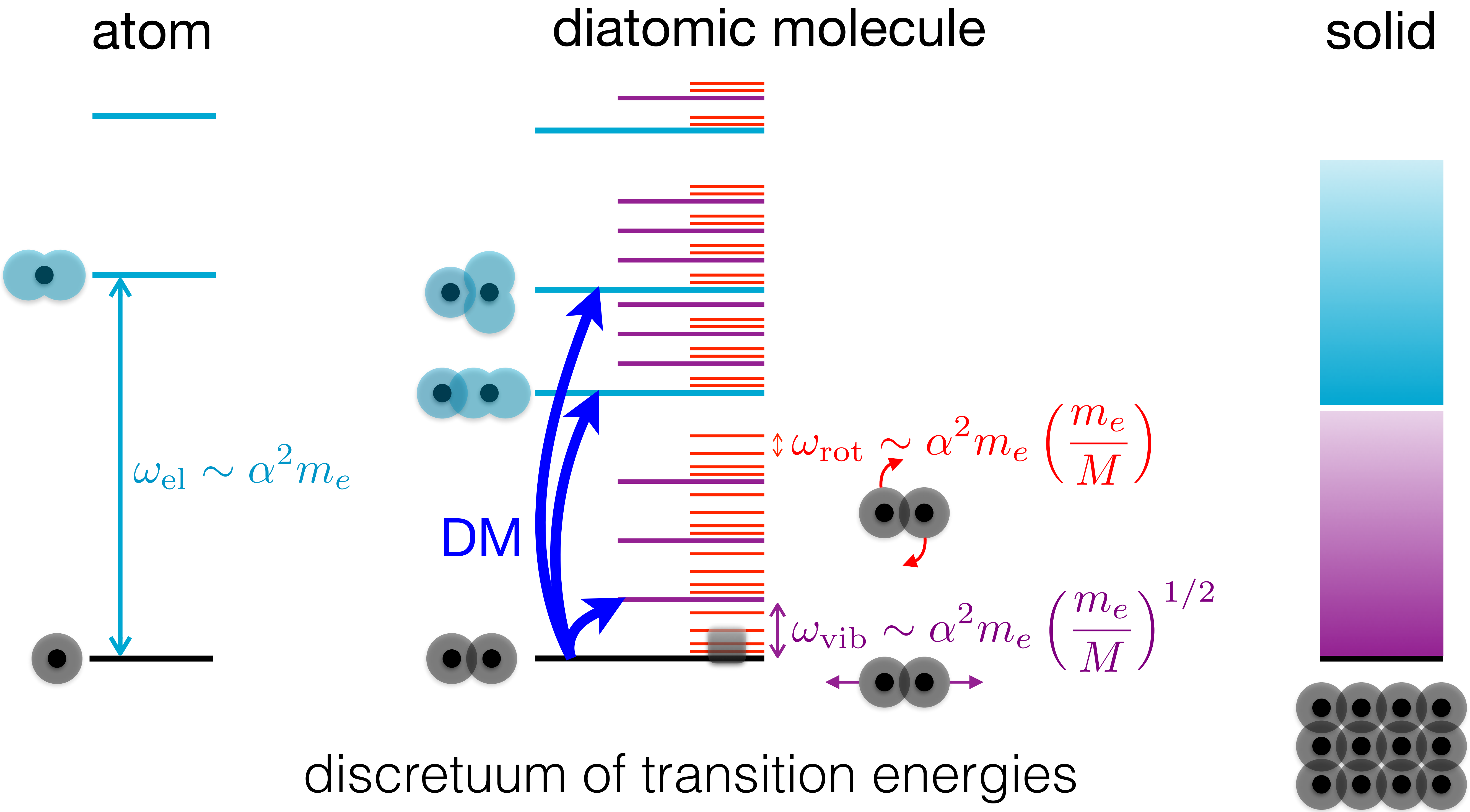
Molecular levels and transitions



discretuum of transition energies

=

multimode resonator

DM absorption rate

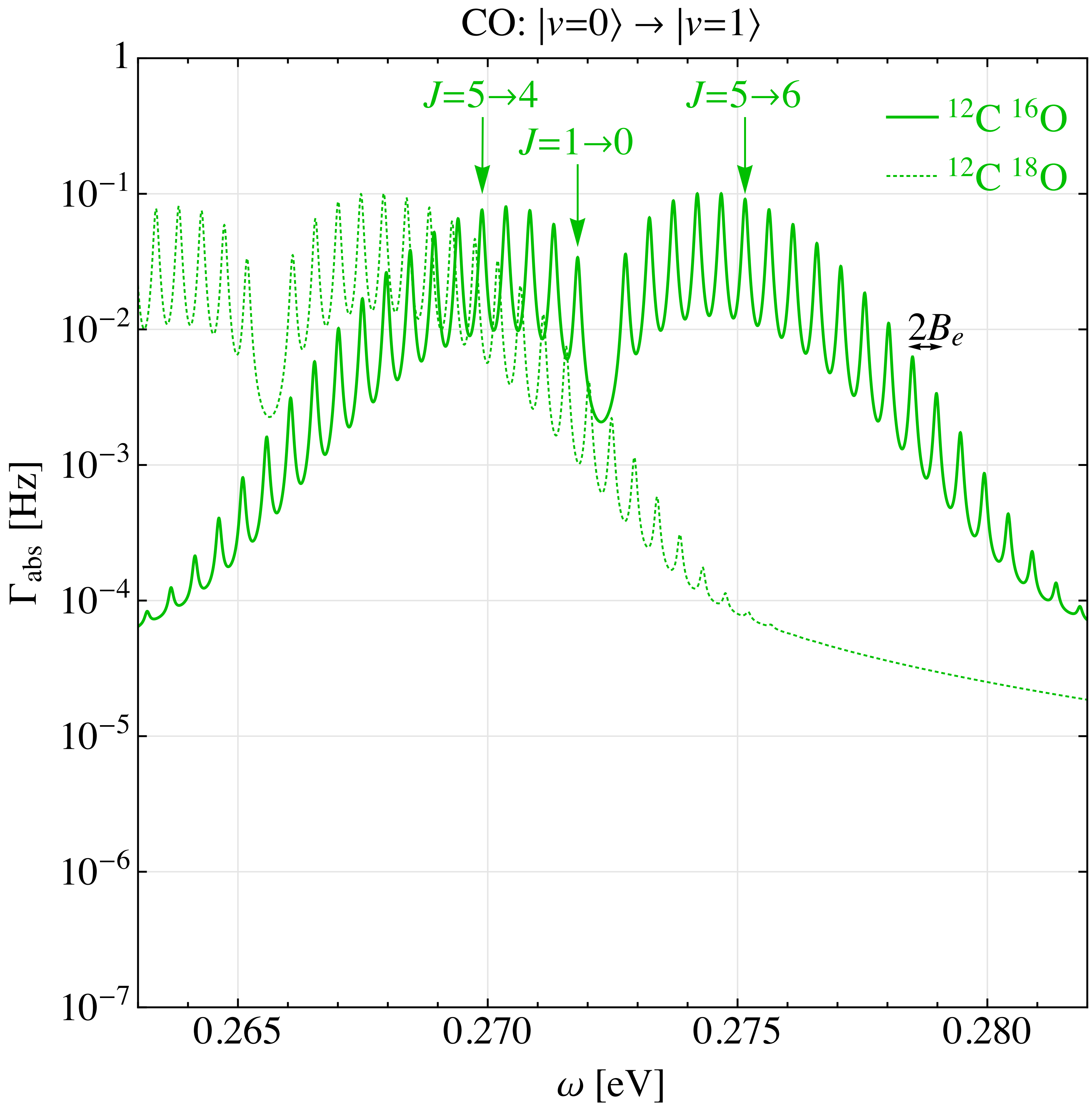
hidden photon DM

$\epsilon = 10^{-12}$

$V = 300\ \mathrm{cm}^3$

$T = 100\ \mathrm{K}$

$P = 5\ \mathrm{bar}$



DM absorption rate

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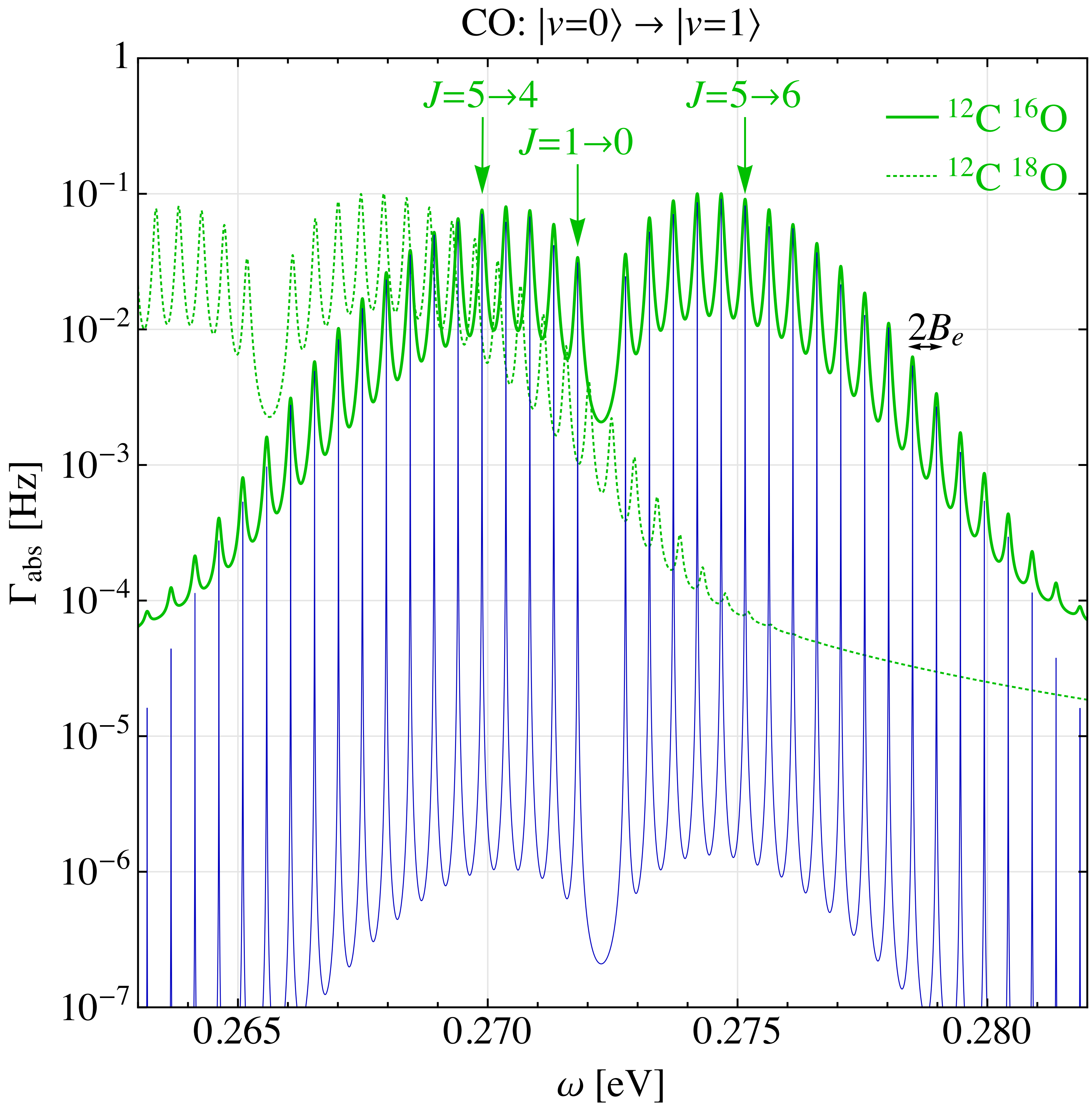
$P = 0.05\ \mathrm{bar}$



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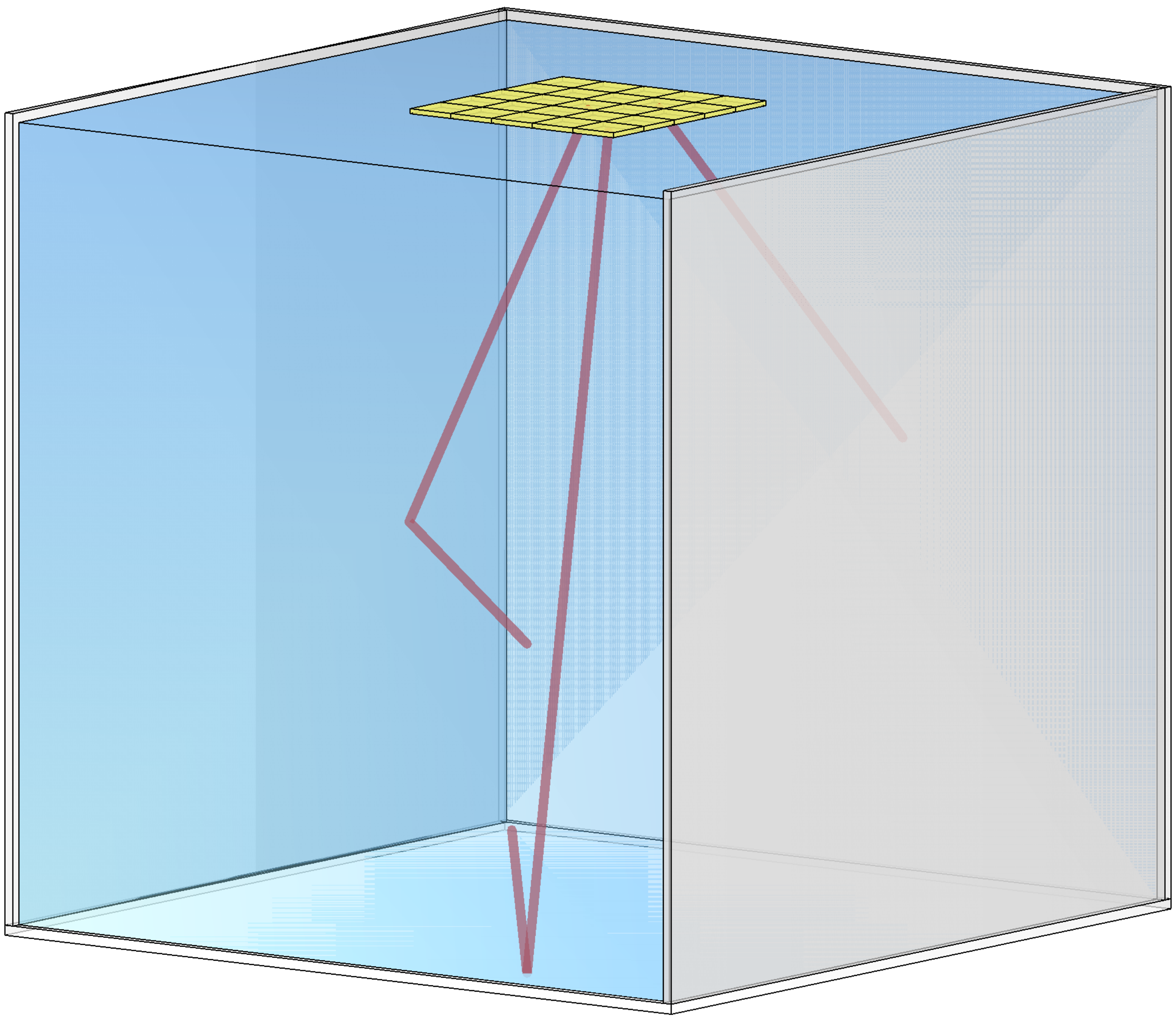
Bulk configuration



Phase I

$$V = (0.3\ \mathrm{m})^3$$
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$$\mathrm{DCR} = 1\ \mathrm{Hz}$$

Phase II

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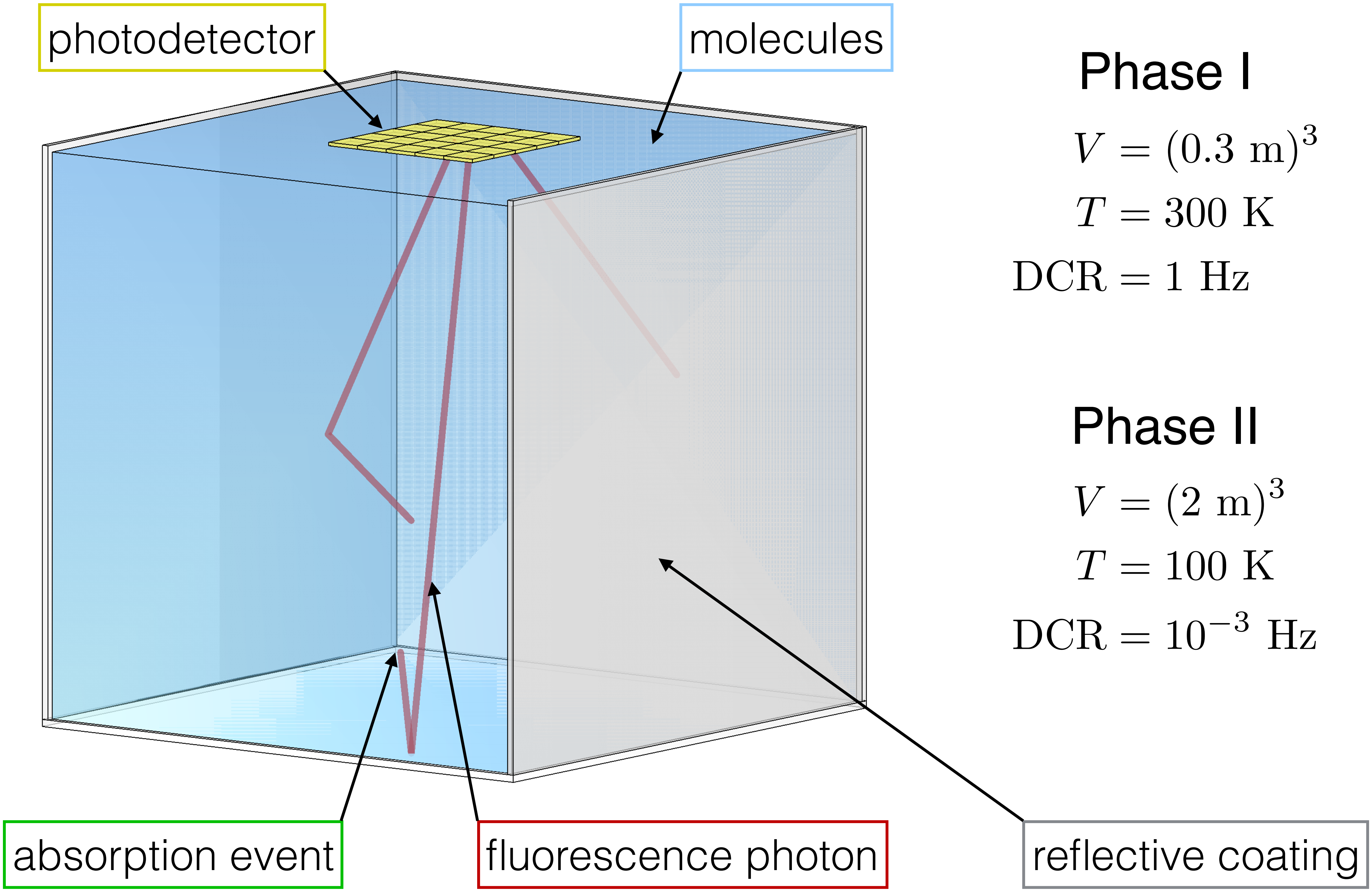

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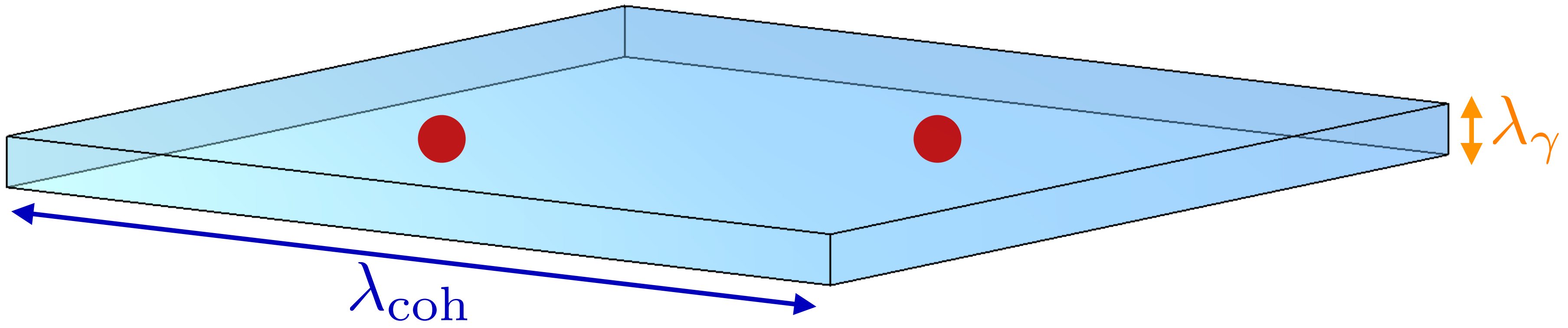
Cooperative radiation

coherence length: $\lambda_{\rm coh} = \dfrac{2}{mv_0}$

$$f(\mathbf{v}) \propto \exp\left[-\frac{(\mathbf{v}-\mathbf{v}_{\rm lab})^2}{v_0^2}\right]$$

typical deBroglie wavelength: $\lambda_{\rm dB} \sim \dfrac{2\pi}{mv_{\rm lab}}$

photon wavelength: $\lambda_\gamma = \dfrac{2\pi}{m}$



$$|0\rangle + \varepsilon e^{-i[mt+\varphi(\mathbf{x})]}|1\rangle$$

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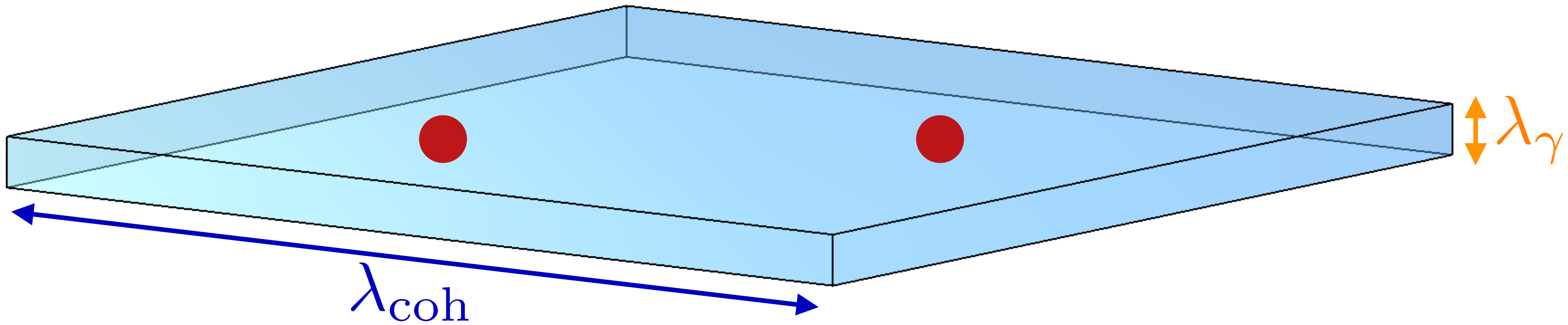

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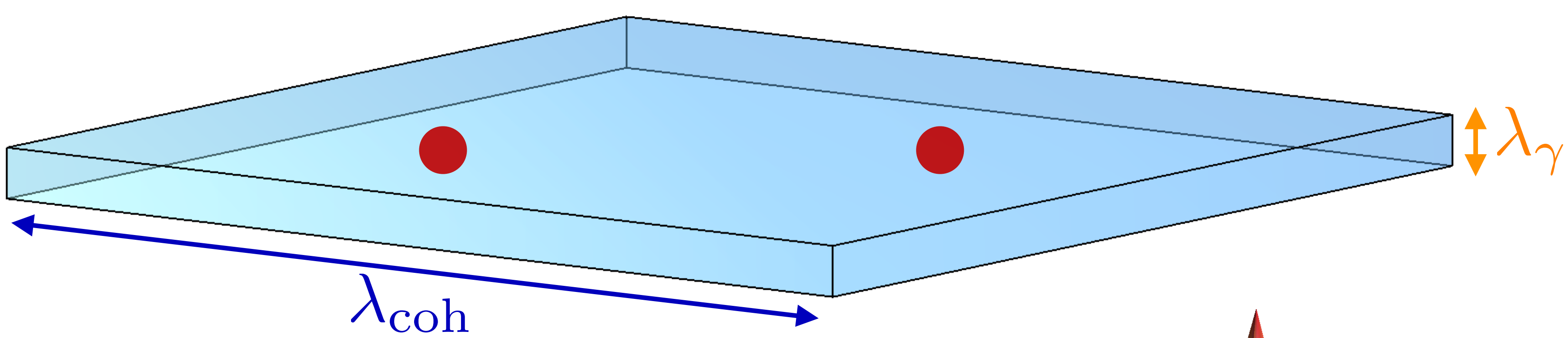

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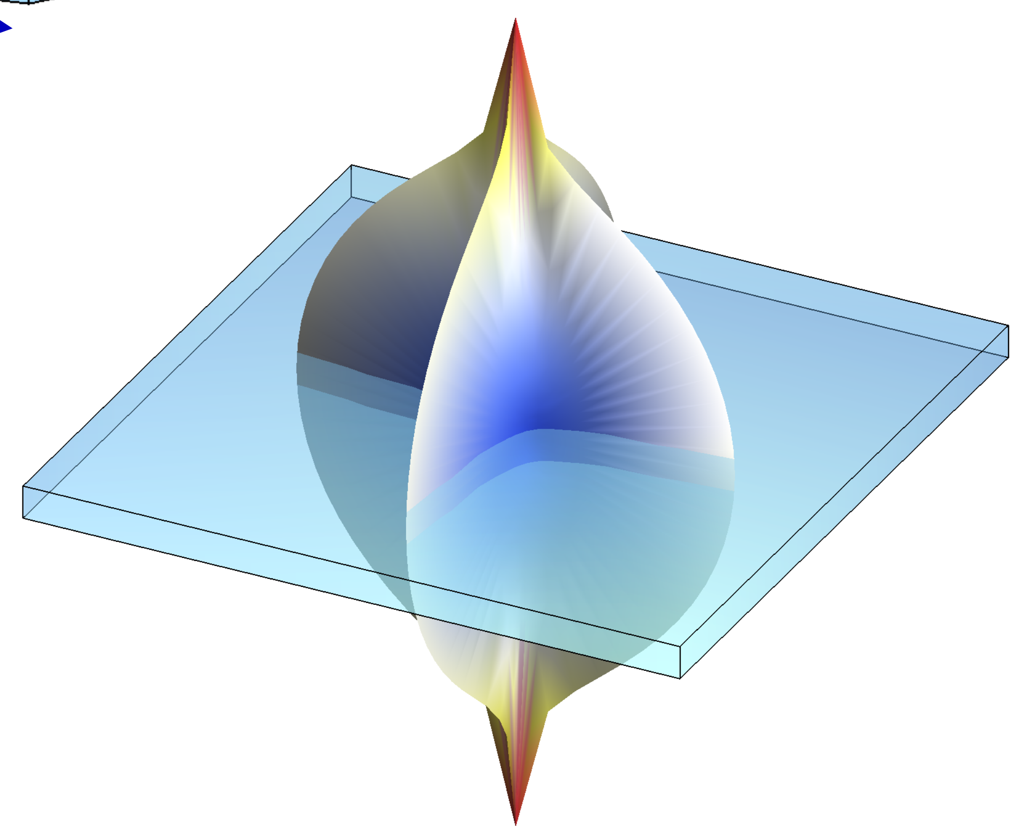

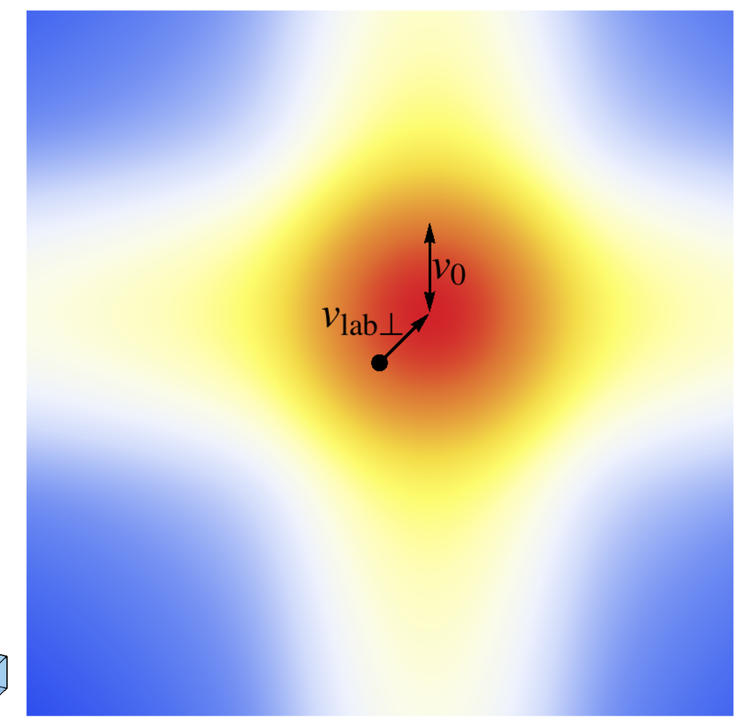

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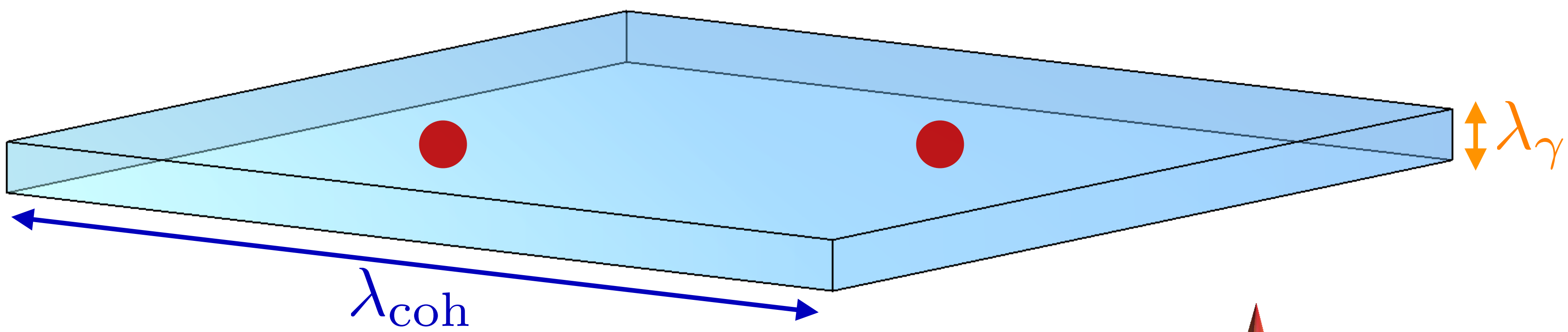

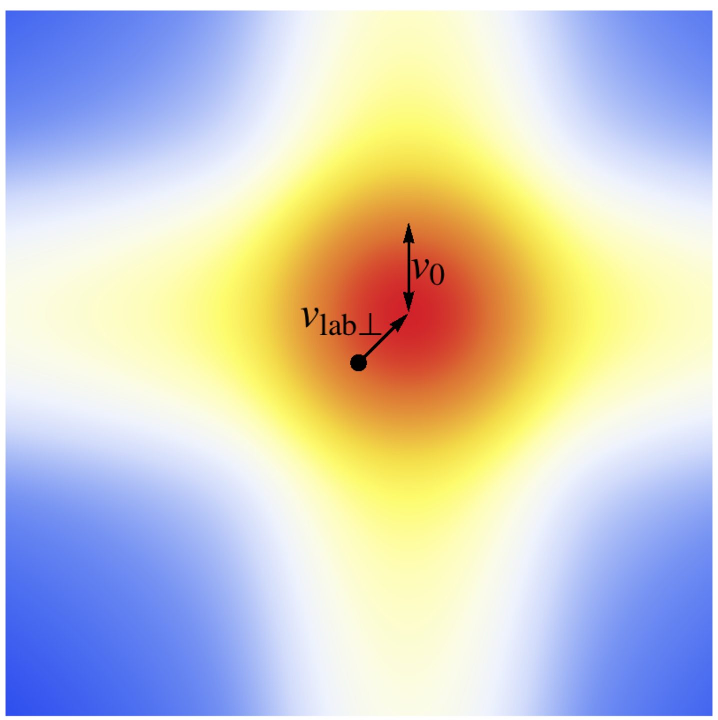

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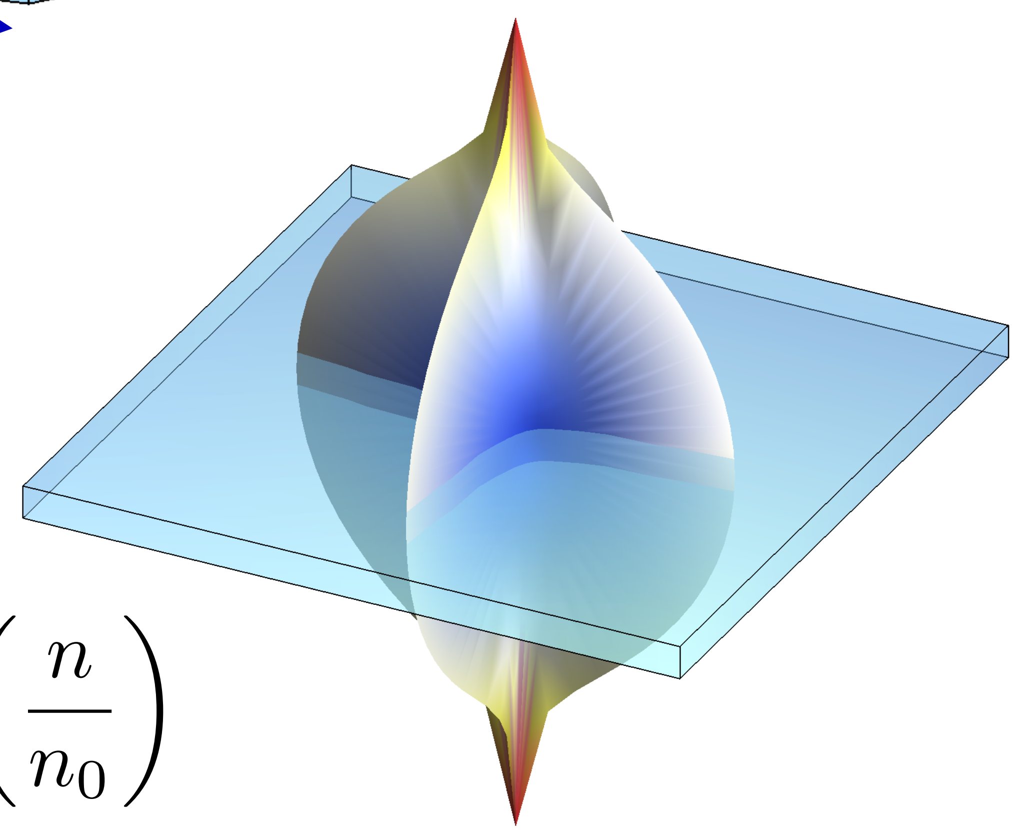
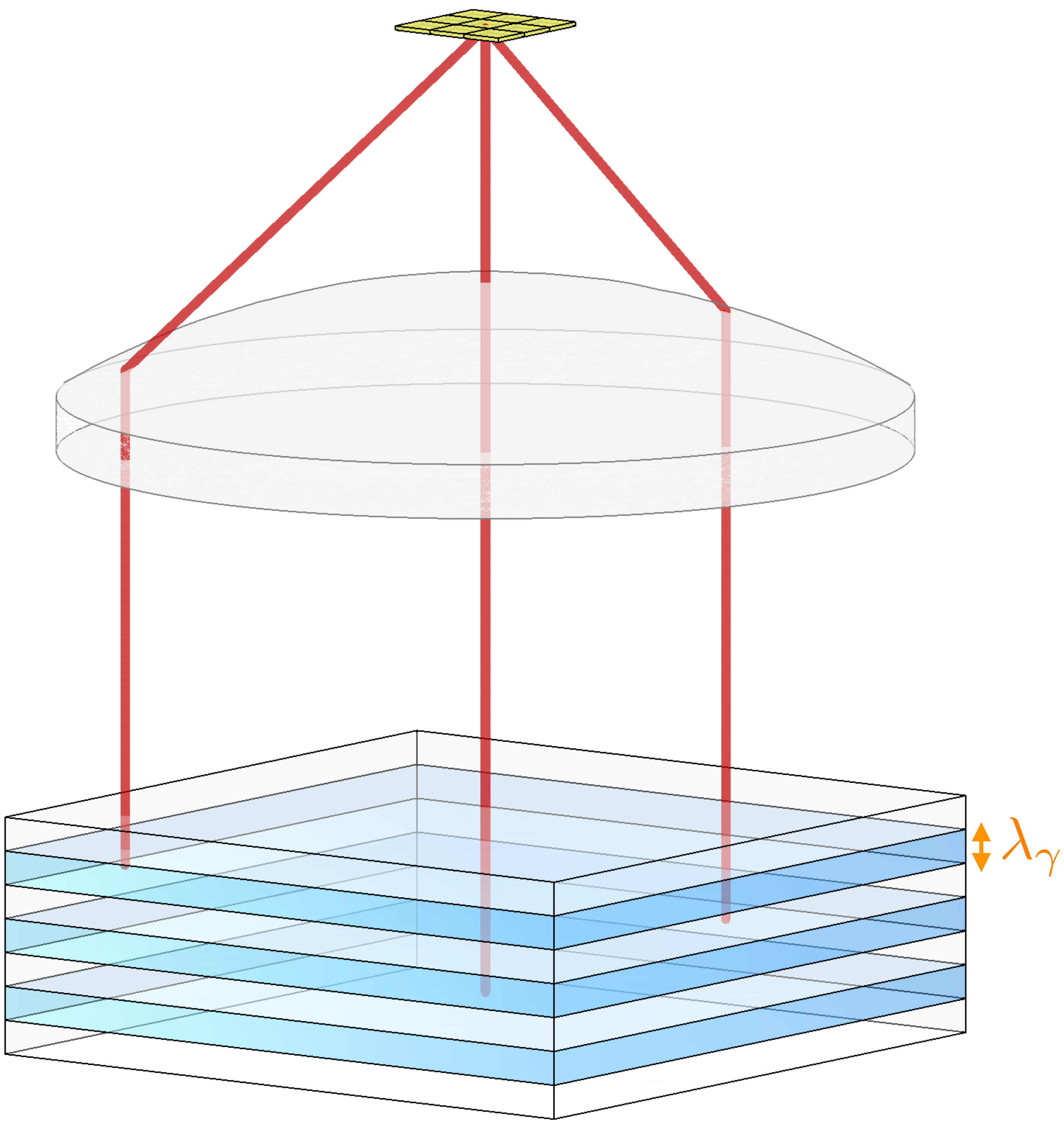
$$\bar{r} \simeq 1 + \frac{8\pi n}{m^4 R_z}$$

$$\approx 1 + \frac{5\times 10^6}{m R_z}\left(\frac{1\ \mathrm{eV}}{m}\right)^3\left(\frac{n}{n_0}\right)$$



Stack configuration



Phase I

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$$D = 1\ \mathrm{mm}$$

$$\mathrm{DCR} = 10^{-5}\ \mathrm{Hz}$$

Phase II

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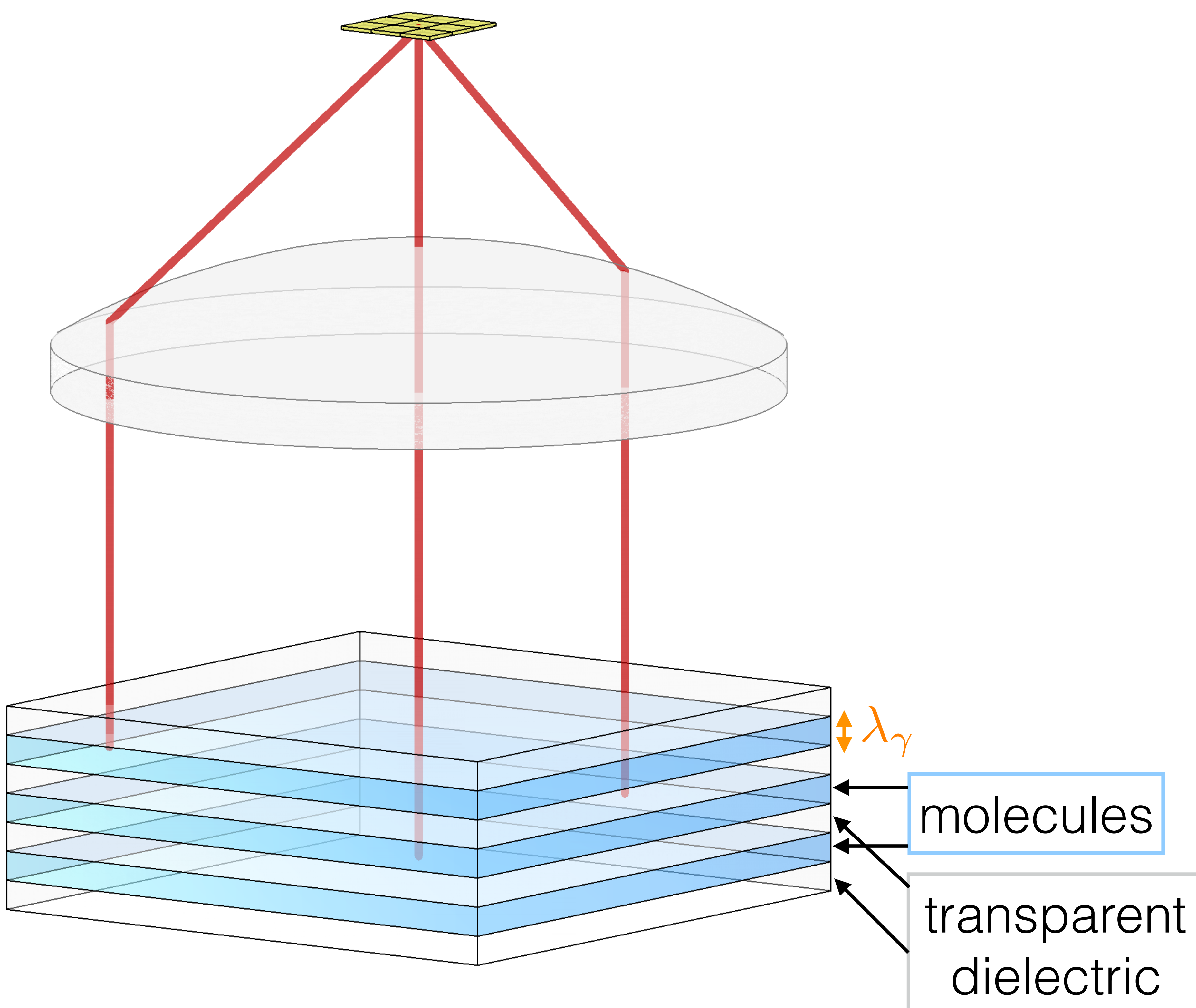

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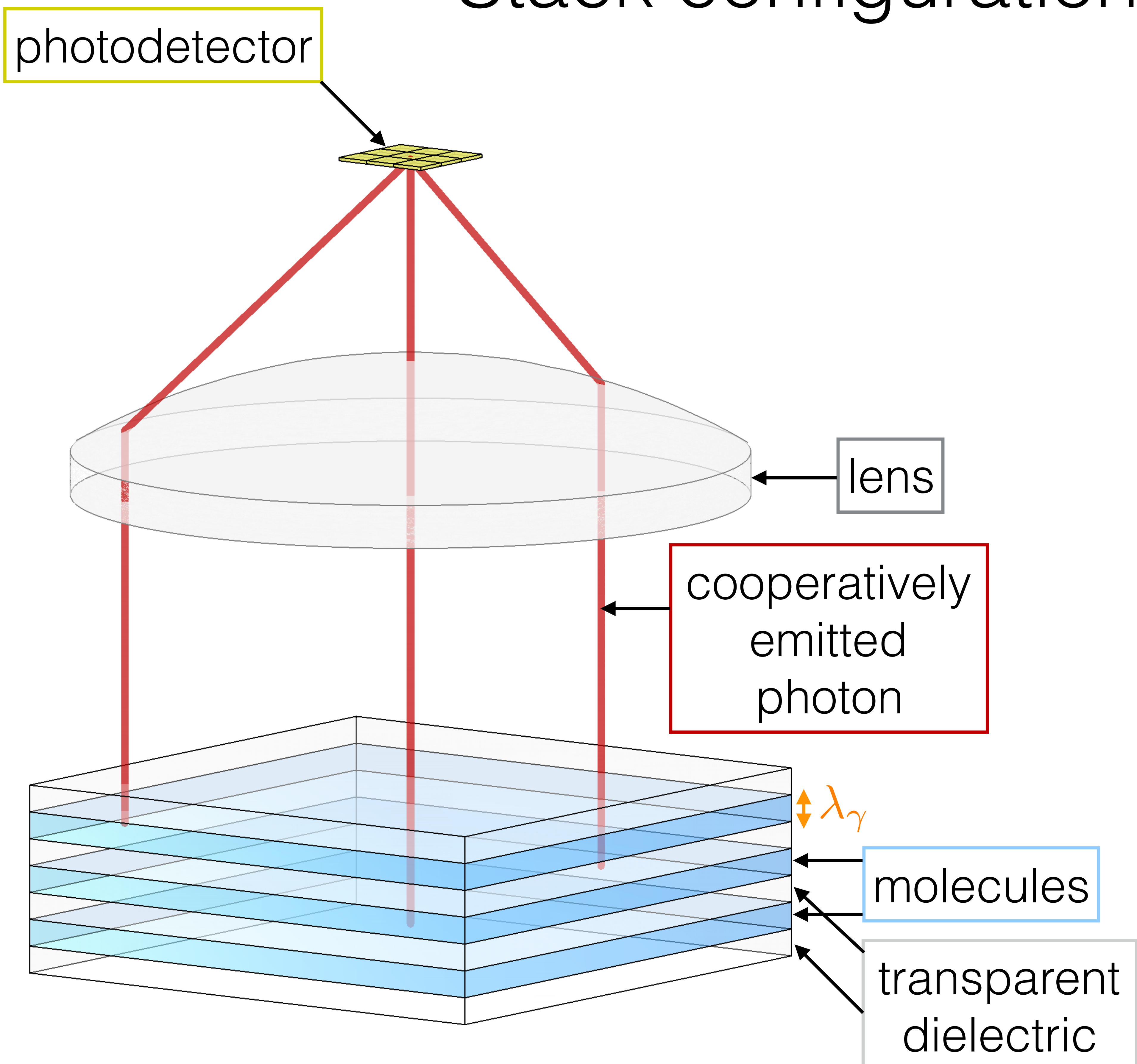

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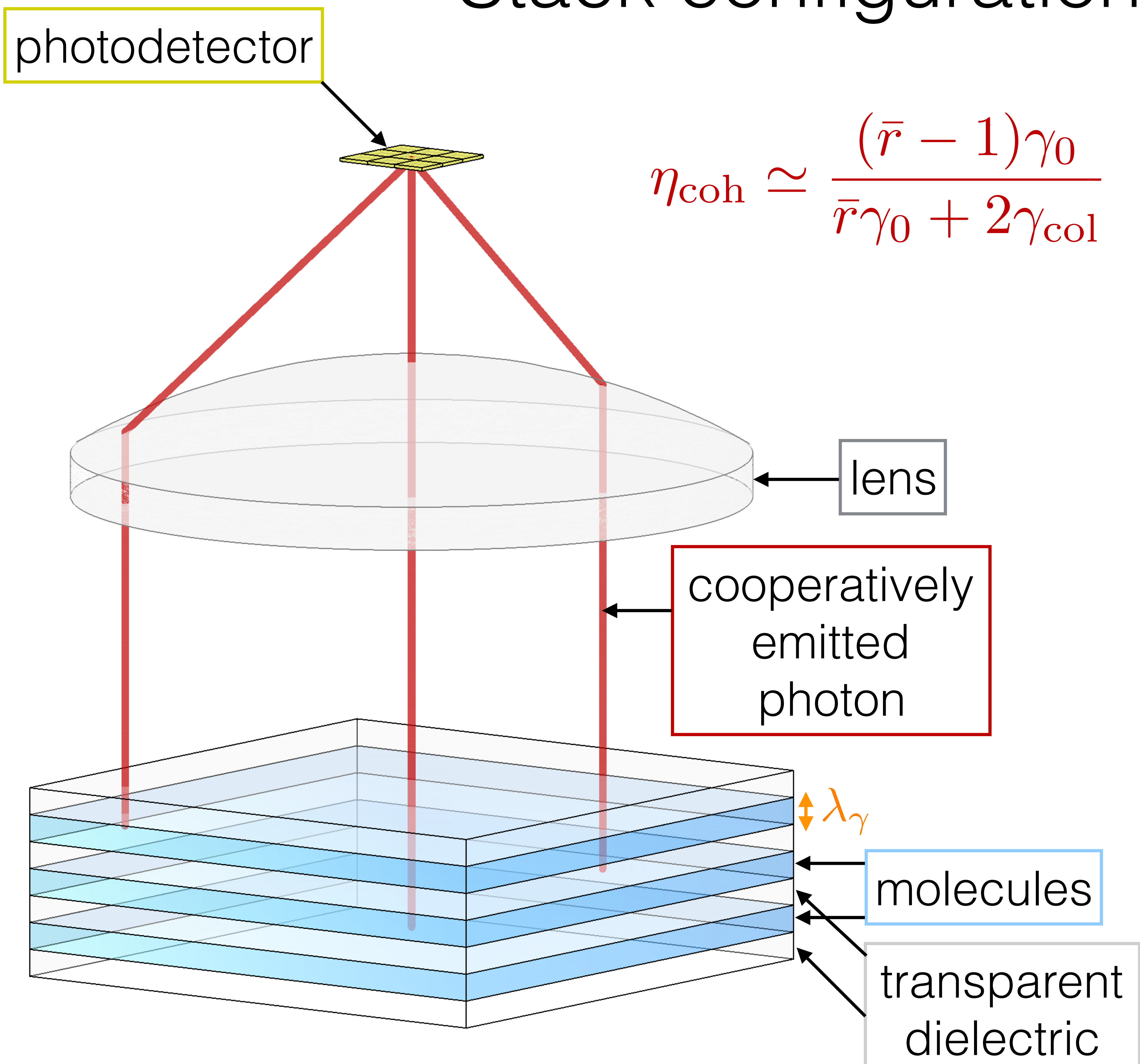

$$\eta_{\rm coh} \simeq \frac{(\bar{r}-1)\gamma_0}{\bar{r}\gamma_0 + 2\gamma_{\rm col}}$$

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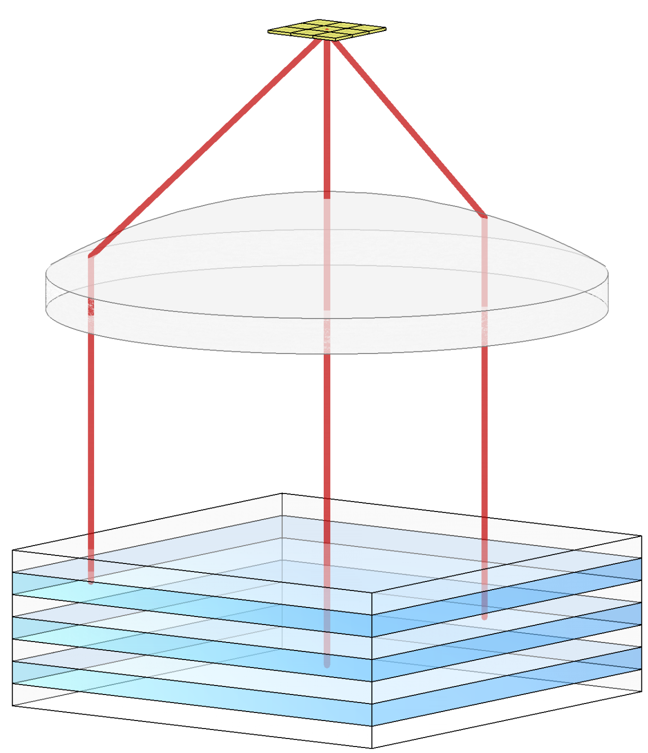
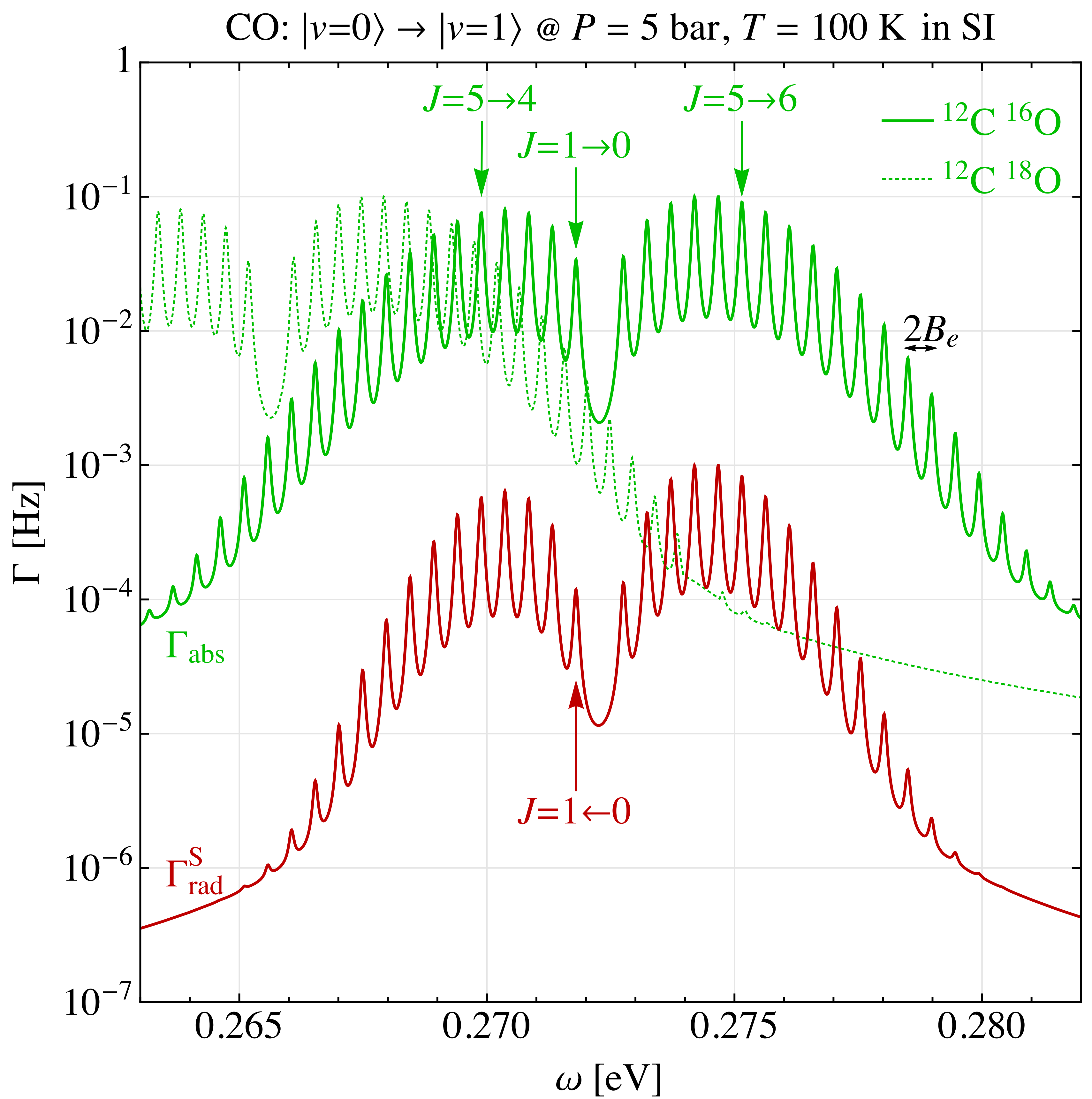
Absorption + Cooperative emission

hidden photon DM

$\epsilon = 10^{-12}$



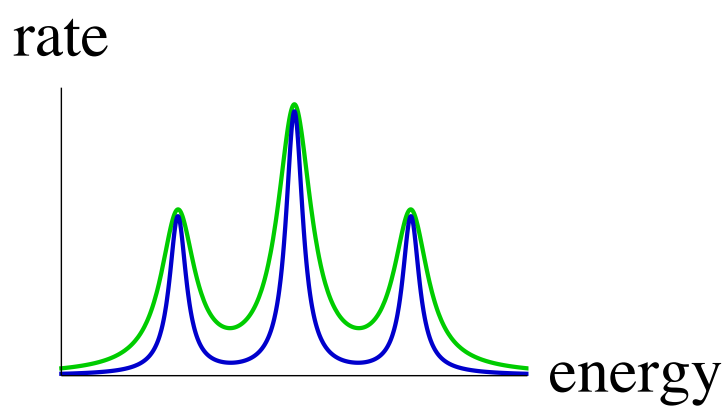
$V = \pi(30\ \mathrm{cm})^2(1\ \mathrm{mm})$



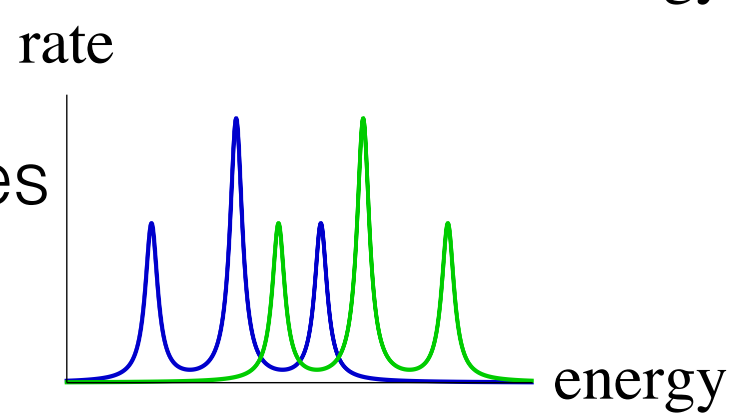
Key considerations

frequency coverage

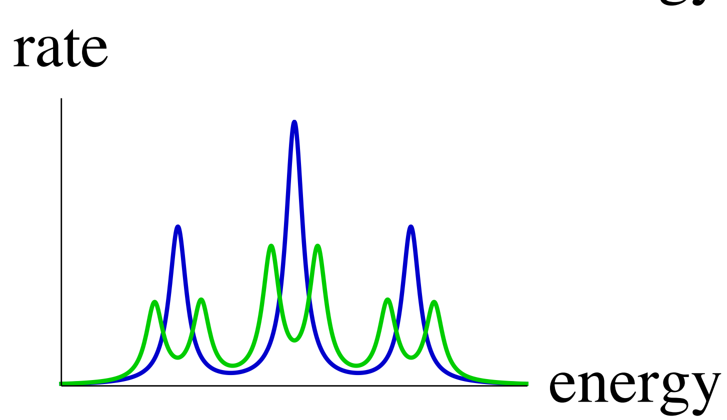
collisional broadening



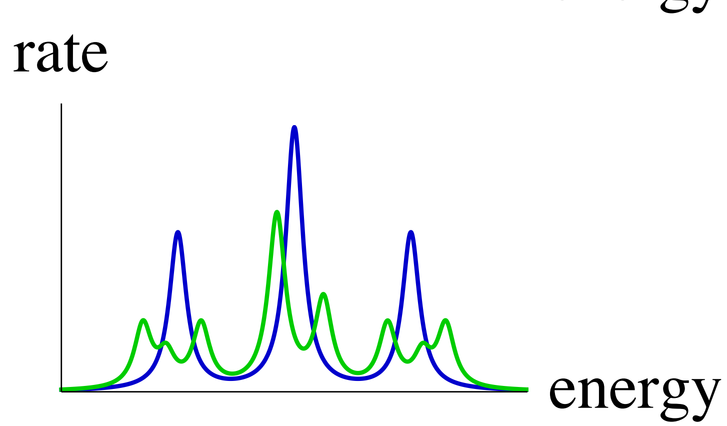
molecular species or isotope shift



Zeeman tuning (magnetic field)

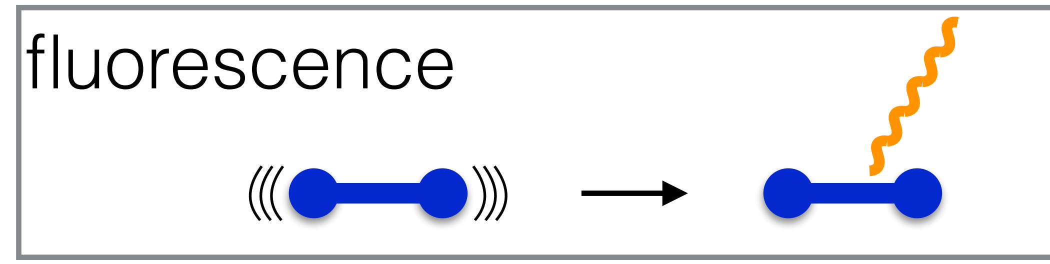


Stark tuning (electric field)

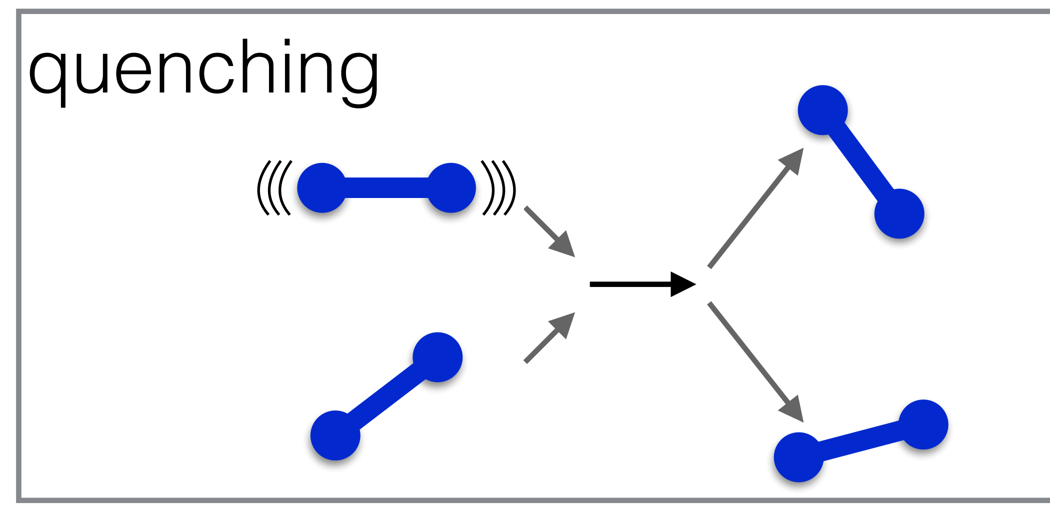


radiative efficiency

Bulk:



before



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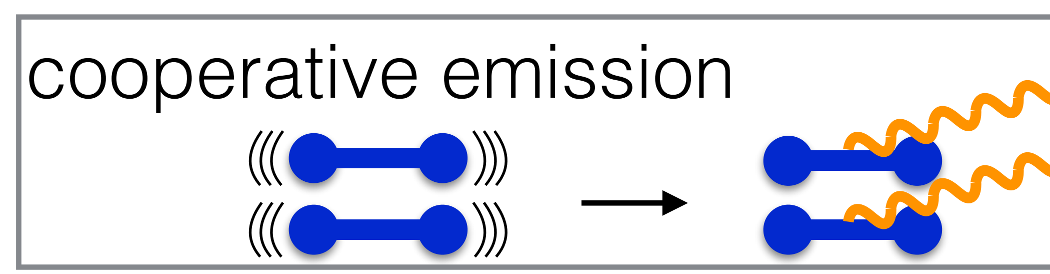

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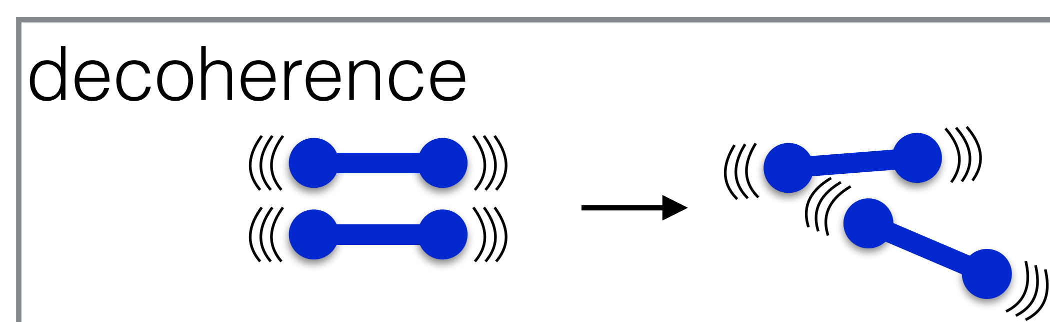


Photon detection

$$\Gamma_{\text{det}} = \eta_{\text{det}} \Gamma_{\text{rad}} = \eta_{\text{det}} \eta_{\text{rad}} \Gamma_{\text{abs}} \qquad \eta_{\text{det}} \sim \eta_{\text{opt-thin}} \eta_{\text{refl}} \eta_{\text{transm}} \eta_{\text{PD}}$$

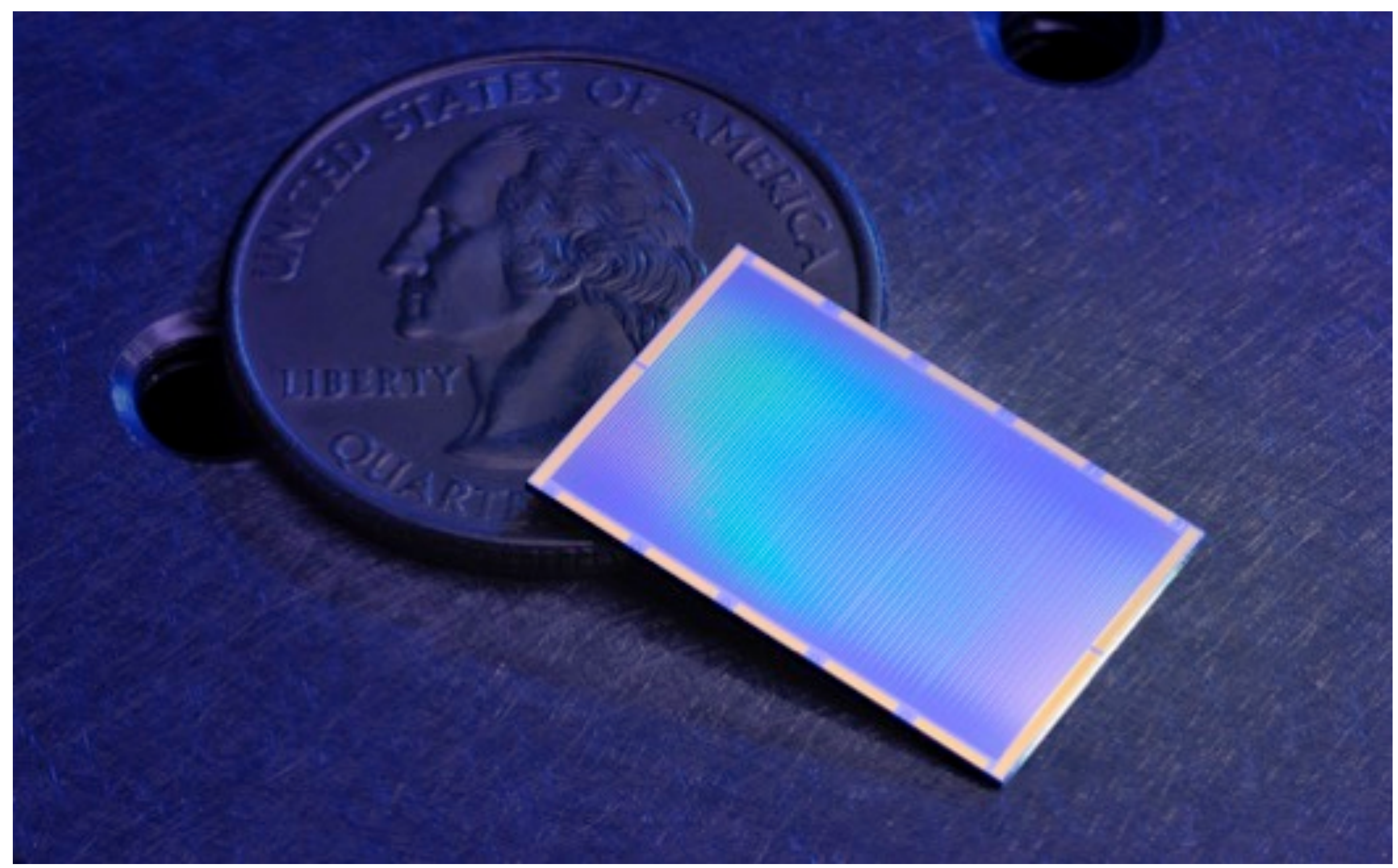
Bulk Phase I: PMT

$$\eta_{\text{det}} \sim 0.3$$

Hamamatsu

Bulk Phase II:
Stack Phase I + II: MKID

$$\eta_{\text{det}} \sim 0.5 \qquad \Delta E \sim 0.1 \text{ eV}$$



B. Mazin

Backgrounds

dark count rate (DCR): high-reflectivity coatings
cryogenic photodetectors: SNSPD, MKID, TES

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thermal occupation / BBR: $nVe^{-\frac{\omega_0}{T}} \ll 1$

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natural/cosmogenic radioactivity: high-purity shield + components

10^{-12} mass fraction ^{238}U $\longrightarrow$ $\Gamma_{\rm RD} \sim 10^{-2}\ {\rm Hz}$ for meter-scale volume

veto trigger: $\left\{ \begin{array}{l} \text{many, high-}E\text{ particles} \\ \text{ionized electrons} \\ \text{timing + fast relaxation} \end{array} \right.$

Stack configuration: 84% of signal in 10^{-7} solid angle

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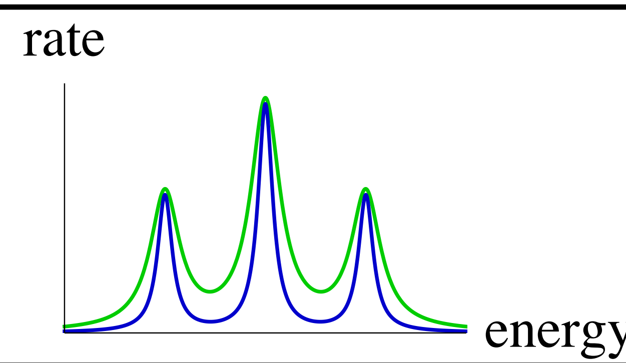
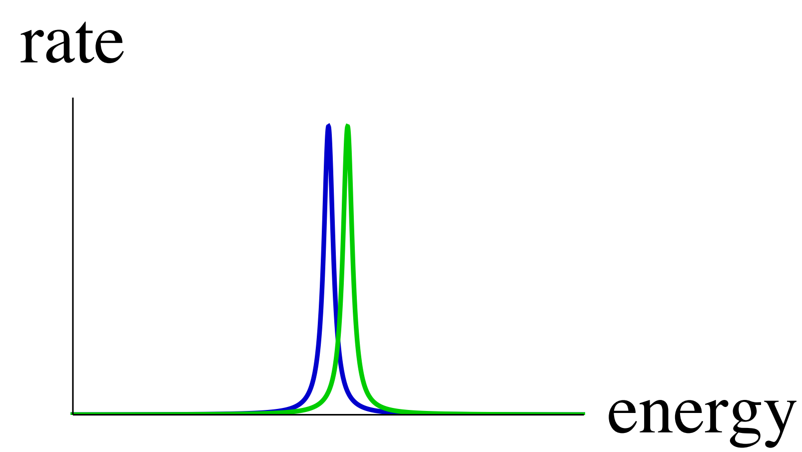
cosmic rays: underground and/or muon scintillator (99.9%)

Signal discrimination

	DM	radioactivity cosmic rays
collisional broadening:		$\propto n^1$ or $\propto n^0$
frequency shifts: species isotope Stark Zeeman		broadband
selection rules:	allowed + forbidden	allowed
directional emission:	solid angle $\sim 10^{-6}$	solid angle $\sim 4\pi$

(1) Dark matter fields can resonantly excite a molecular system

bosonic DM couplings | two-level system dynamics | molecular levels

(2) Experimental setup

configurations | photon detection | backgrounds | discrimination

(3) Dark matter sensitivity $0.2\ \mathrm{eV} < m < 20\ \mathrm{eV}$

hidden vectors | moduli | axions

Why is a molecular gas a good dark matter detector?

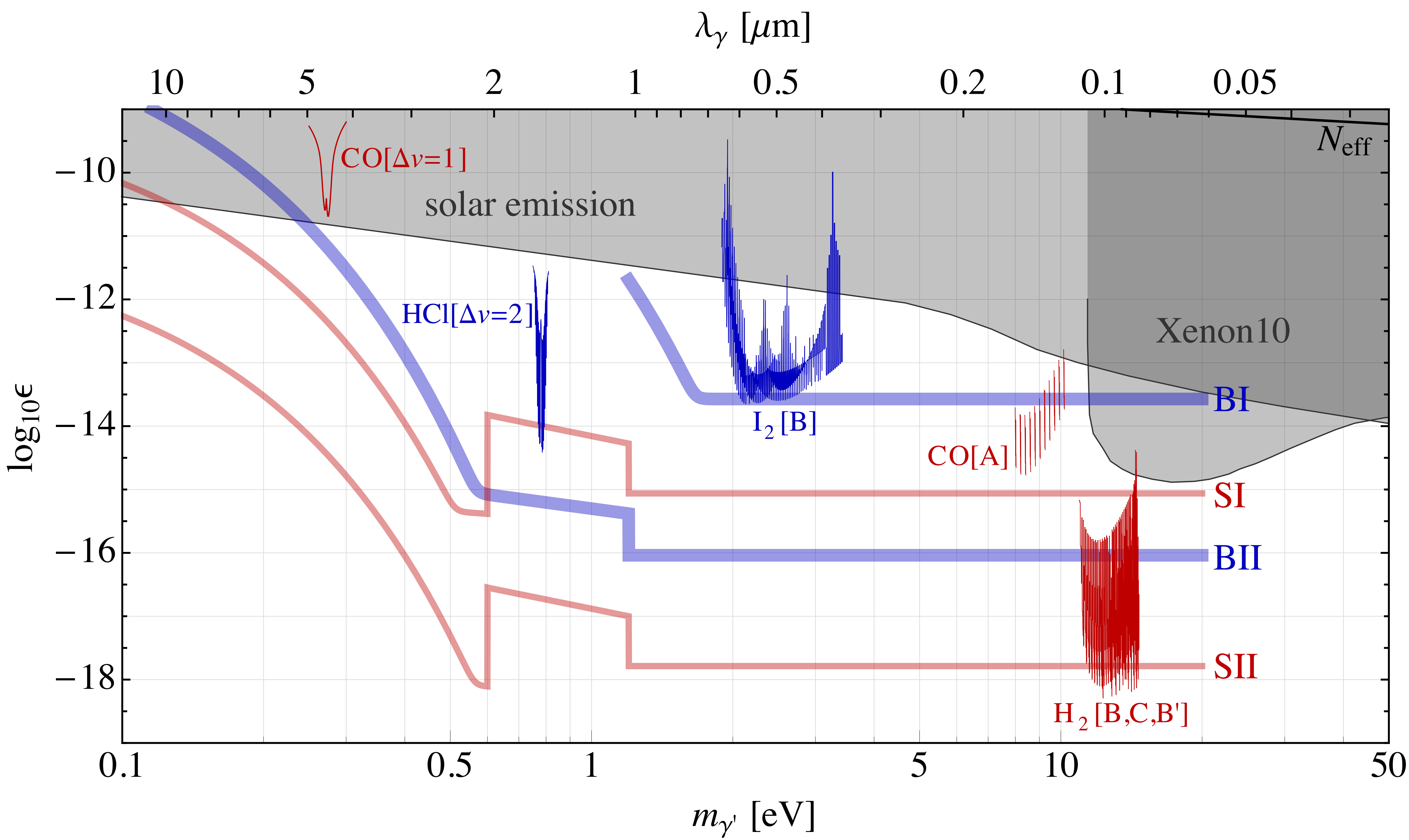
calculable
- signal rate
- backgrounds

discrimination power
- energy resolution: $\Delta\omega/\omega \ll 10^{-6}$
- control variables: P, T, E, B
- selection rules
- directional focusing: $\Delta\theta/\theta \lesssim 10^{-6}$

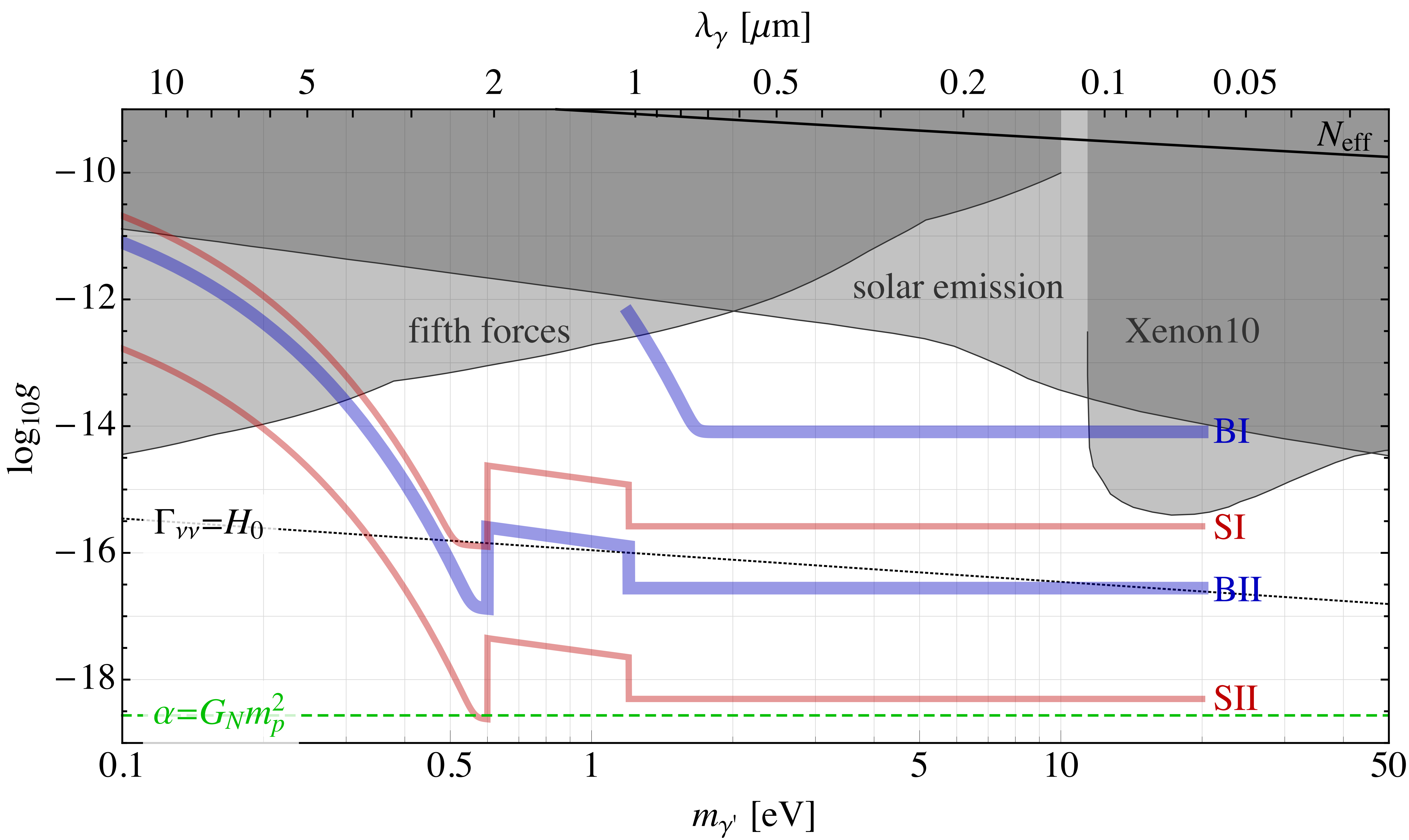
DM-induced transitions

DM type		Interaction Hamiltonian δH	Transition type and selection rules		Ω [rad s^{-1}]
spin-0	parity-even	$(d_{m_e}+d_e)\tilde{\phi}k_e R_e R$	vib	$\Delta v = 1, \Delta J = 0$	$5.5\times10^{-9}\frac{d_{m_e}}{10^6}$
		$(3d_{m_e}+4d_e)\tilde{\phi}\frac{k_e}{2}(R-R_e)^2$	vib	$\Delta v = 2, \Delta J = 0$	$7.1\times10^{-10}\frac{d_{m_e}}{10^6}$
		$(d_g+Q_{\hat{m}_q}d_{\hat{m}_q})\tilde{\phi}\frac{\nabla_N^2}{2M}$	vib	$\Delta v = 2, \Delta J = 0$	$2.4\times10^{-11}\frac{d_{\hat{m}_q}}{10^6}\frac{Q_{\hat{m}_q}}{0.1}$
		$(\Delta Q_i d_i)M(\boldsymbol{\nabla}\tilde{\phi}\cdot\mathbf{R})$	**vib**	$\Delta v = 1, \Delta J = \pm1$	$3.0\times10^{-10}\frac{d_i}{10^6}\frac{\Delta Q_i}{10^{-2}}$
			rot	$\Delta J = 1$	$4.1\times10^{-13}\frac{d_i}{10^2}\frac{\Delta Q_i}{10^{-2}}$
		$(d_{m_e}+d_e)\tilde{\phi}\frac{\nabla_e^2}{2m_e}$	el	$\Delta\Lambda = 0, \Delta i = 0$	$9.5\times10^{-10}\frac{d_{m_e}}{10^6}$
		$d_{m_e}m_e\boldsymbol{\nabla}\tilde{\phi}\cdot\mathbf{r}_e$	**el**	$\lvert\Delta\Lambda\rvert\le1, \Delta i = 1$	$7.5\times10^{-11}\frac{d_{m_e}}{10^6}$
	parity-odd	$G_{aNN}\,\partial_t a\,\boldsymbol{\sigma}_N\cdot\frac{-i\boldsymbol{\nabla}_N}{M}$	**vib**	$\Delta v = 1, \Delta J = \pm1, \lvert\Delta S_N\rvert\le1$	$1.7\times10^{-10}\frac{G_{aNN}}{10^{-8}/\text{GeV}}$
			rot	$\Delta J = 1, \lvert\Delta S_N\rvert = 1$	$2.5\times10^{-11}\frac{G_{aNN}}{10^{-8}/\text{GeV}}$
		$\frac{d_\theta}{f_a}a\,\boldsymbol{\sigma}_N\cdot\mathbf{E}$	**vib**	$\Delta v = 1, \Delta J = \pm1, \lvert\Delta S_N\rvert\le1$	$4.0\times10^{-12}\frac{10^8\ \text{GeV}}{f_a}$
			rot	$\Delta J = 1, \lvert\Delta S_N\rvert\le1$	$5.8\times10^{-13}\frac{10^8\ \text{GeV}}{f_a}$
		$G_{aee}\,\partial_t a\,\boldsymbol{\sigma}_e\cdot\frac{-i\boldsymbol{\nabla}_e}{m_e}$	**el**	$\lvert\Delta\Lambda\rvert\le1, \Delta i = 1, \lvert\Delta S_e\rvert\le1$	$4.0\times10^{-10}\frac{G_{aee}}{10^{-10}/\text{GeV}}$
		$G_{a\gamma\gamma}\int \mathrm{d}^3\mathbf{x}\,a\mathbf{E}\cdot\mathbf{B}$	?	?	?
spin-1	kinetic mixing	$\epsilon\boldsymbol{\mu}_e\cdot\mathbf{E}'$	**el**	$\lvert\Delta\Lambda\rvert\le1, \Delta i = 1$	$1.5\times10^{-6}\frac{\epsilon}{10^{-14}}$
			vib	$\Delta v = 1, \Delta J = \pm1$	$1.3\times10^{-5}\frac{\epsilon}{10^{-12}}$
			rot	$\Delta J = 1$	$1.5\times10^{-2}\frac{\epsilon}{10^{-10}}$
	$B-L$ charge	$\boldsymbol{\mu}_{B-L}\cdot\mathbf{E}_{B-L}$	**el**	$\lvert\Delta\Lambda\rvert\le1, \Delta i = 1$	$5.0\times10^{-6}\frac{g}{10^{-14}}$
			vib	$\Delta v = 1, \Delta J = \pm1$	$4.3\times10^{-7}\frac{g}{10^{-14}}$
			rot	$\Delta J = 1$	$5.0\times10^{-10}\frac{g}{10^{-18}}$

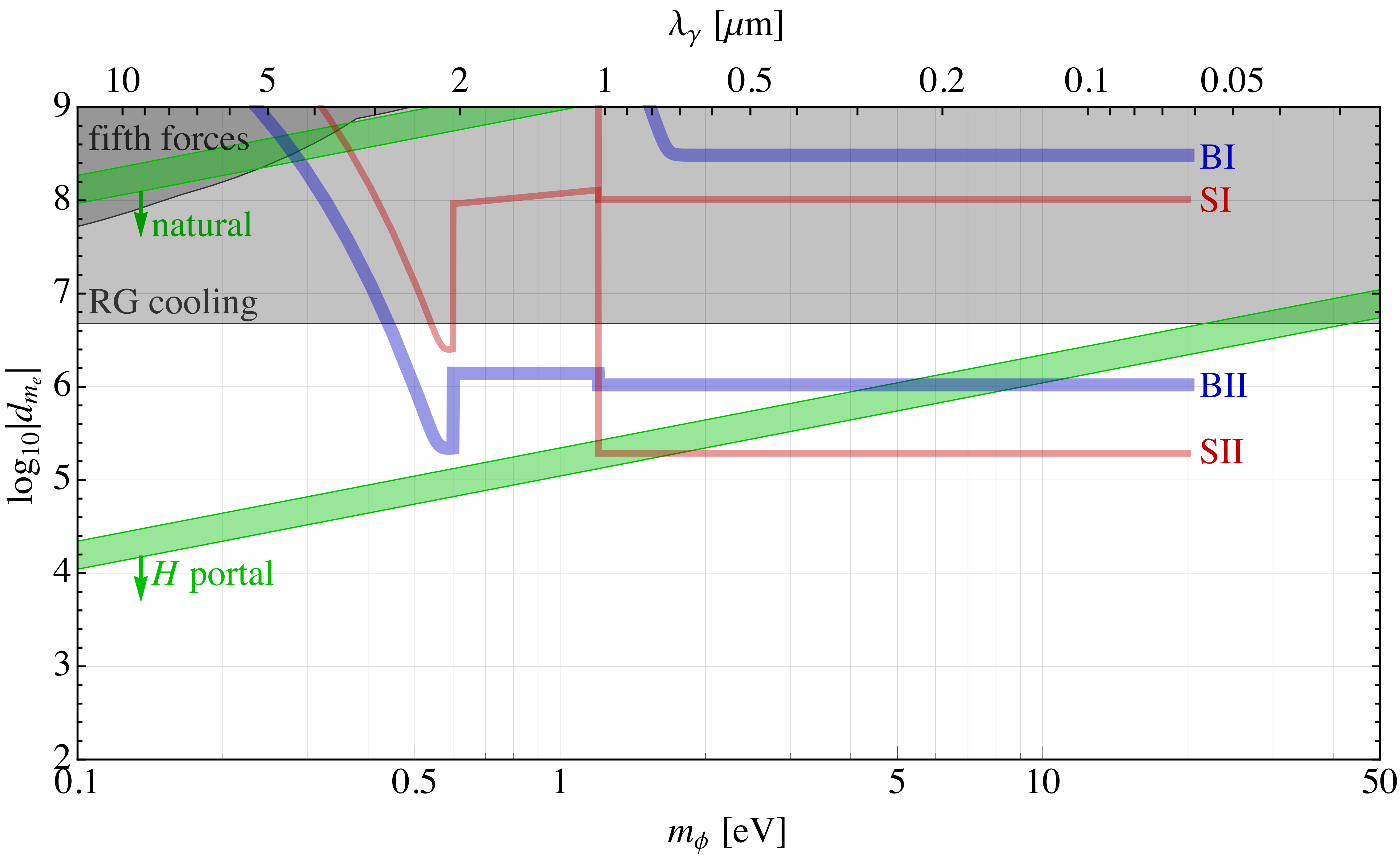
Kinematically mixed photon



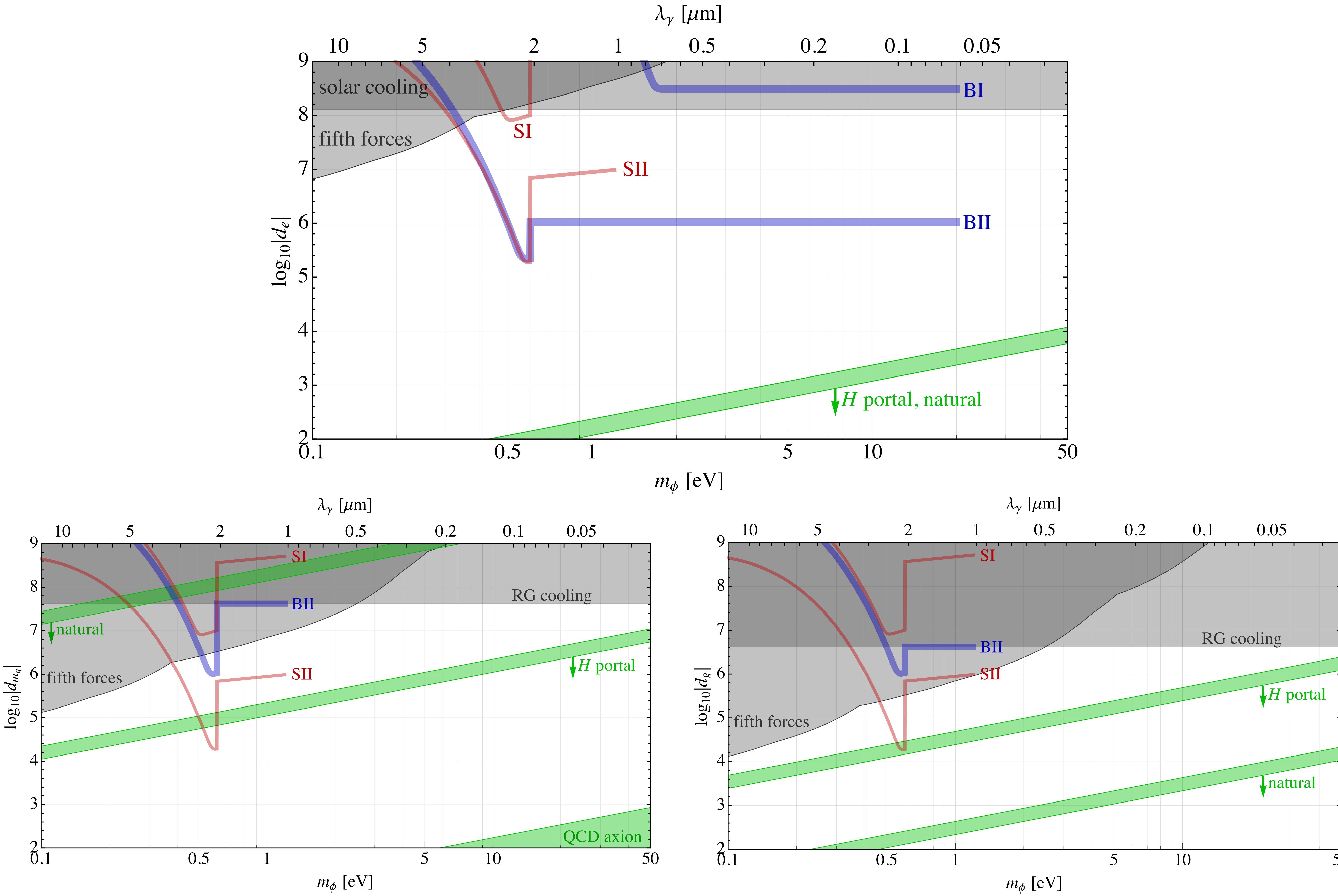
B-L gauge boson



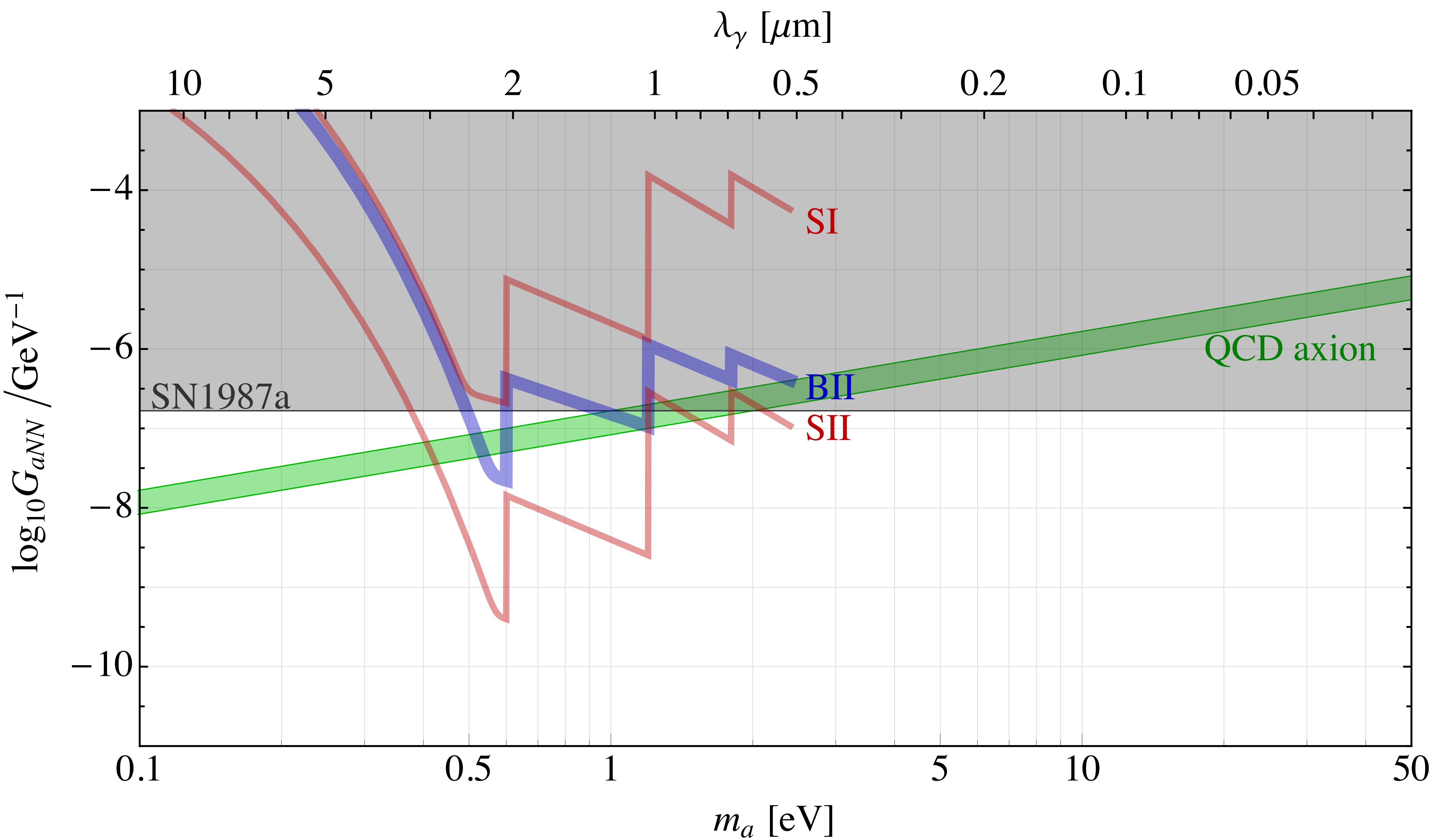
Modulus: electron coupling



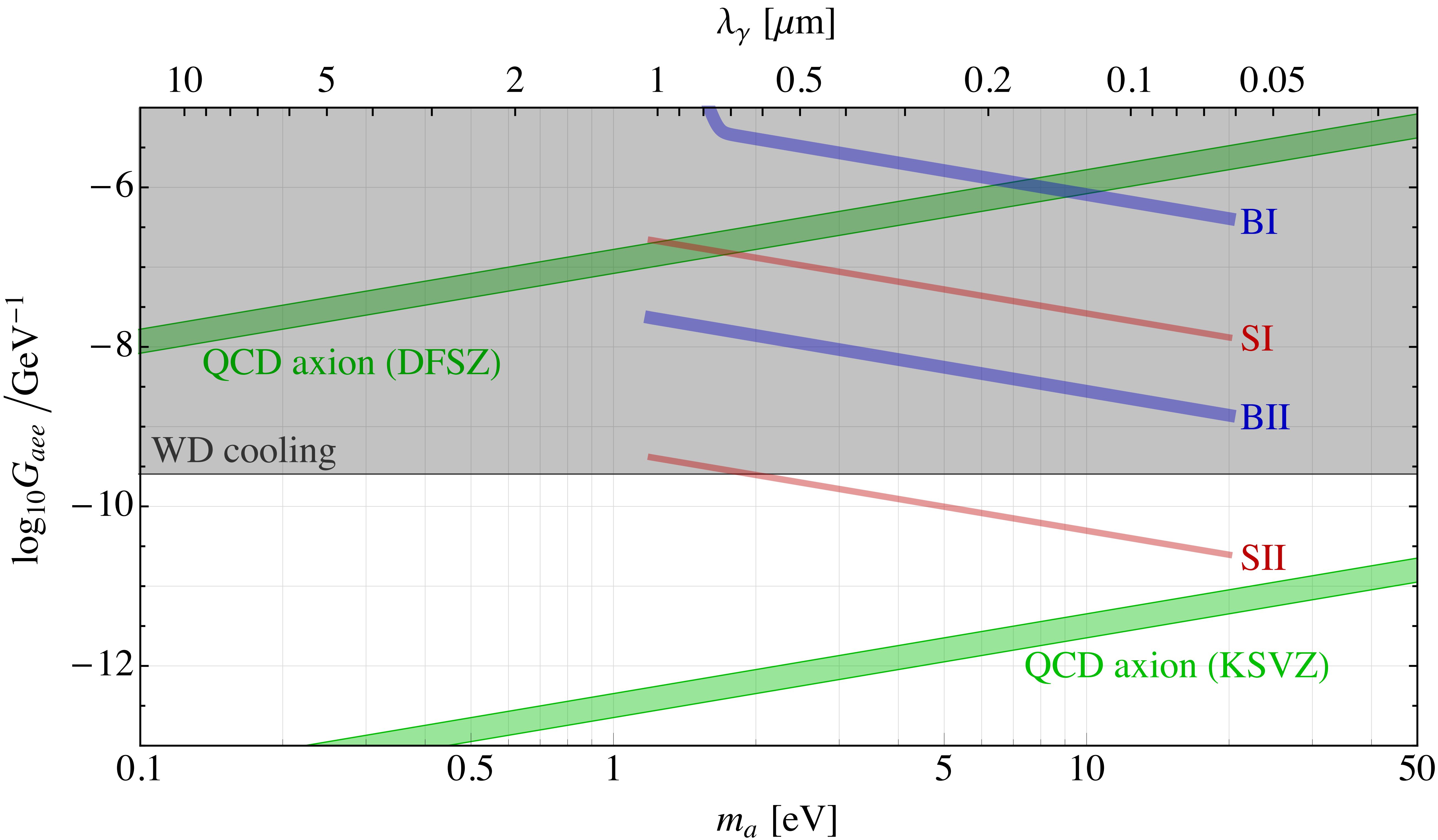
Modulus: photon, quark, gluon



Axion: nuclear coupling



Axion: electron coupling



Conclusions

(1) Dark matter fields can resonantly excite a molecular system

dark matter absorption = weak, monochromatic signal
gas of small molecules = multimode resonator with large signal rate

(2) Experimental setup

low background rates

tunable frequency response: superb discrimination power

established field with photodetector technology advancements

cooperative focusing effects: directional isolation and information

(3) Dark matter sensitivity $0.2 \text{ eV} < m < 20 \text{ eV}$

spin-1: mixed photon, *B-L* gauge boson, …

spin-0, parity-even: moduli fields for electron, quark, photon, gluon, …

spin-0, parity-odd: axion coupling to electrons, nucleons, photons, …

Future: <u>m < 0.2 eV</u> | m > 20 eV | other use? | map out molecular forest

Phase I prototypes

Phase II R&D: slab/stack manufacturing | optimize photodetectors

Bosonic dark matter couplings

EFT of DM bosons coupled to electrons, quarks, photons, gluons

spin-1

$$\epsilon A'_\mu J^\mu_{\rm EM} \qquad\qquad g A'_\mu J^\mu_{B-L}$$

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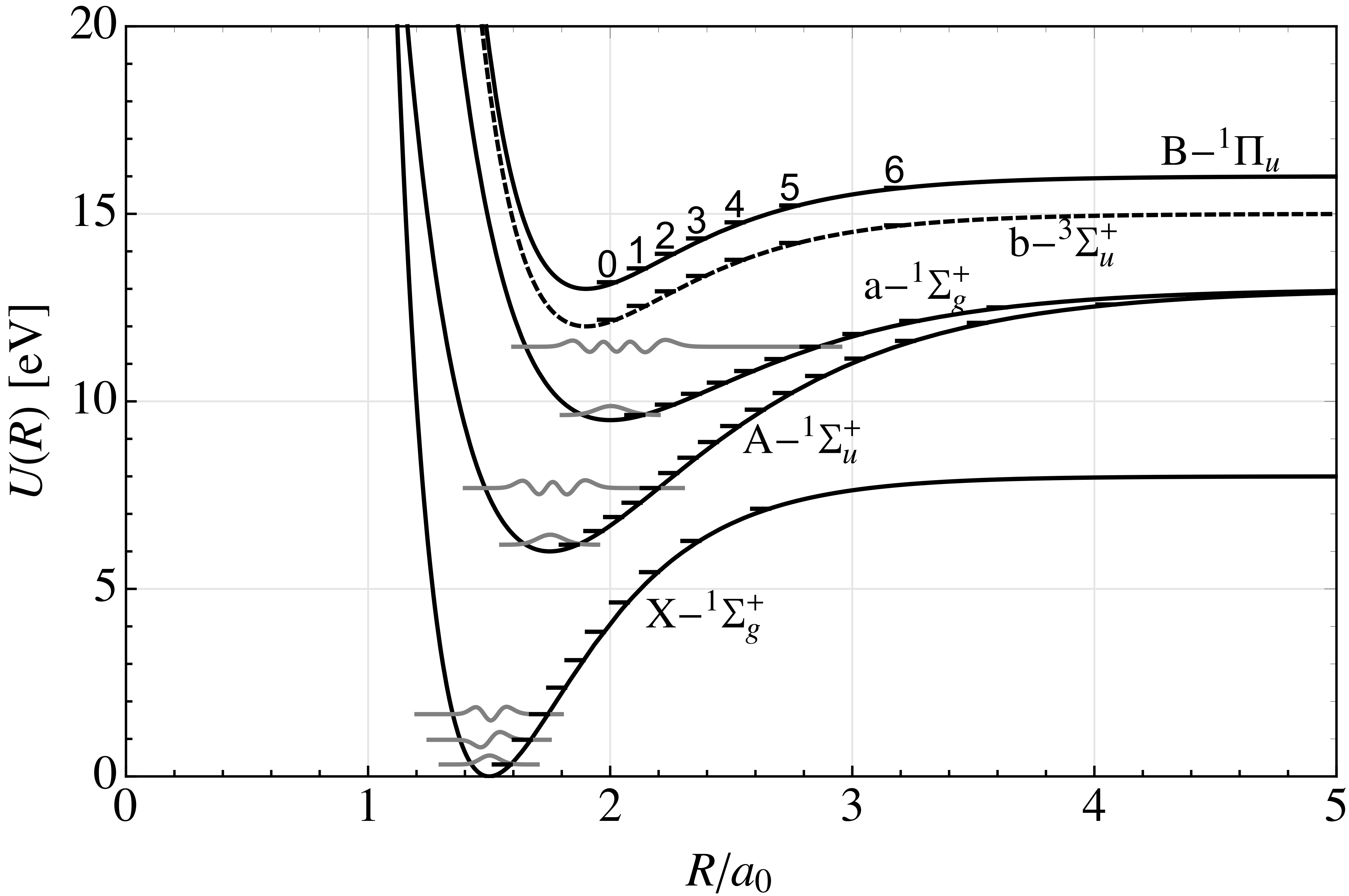
spin-0

parity-even	parity-odd
$\phi\, d_{m_e} \sqrt{4\pi G_N} m_e \bar\psi_e \psi_e$	$G_{aee} (\partial_\mu a) \bar\psi_e \gamma^\mu \gamma_5 \psi_e$
$\phi\, d_{m_q} \sqrt{4\pi G_N} m_q \bar\psi_q \psi_q$	$G_{aqq} (\partial_\mu a) \bar\psi_q \gamma^\mu \gamma_5 \psi_q$
$\phi\, d_e \sqrt{4\pi G_N} \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$	$G_{a\gamma\gamma} a \frac{1}{4} F_{\mu\nu} \tilde F^{\mu\nu}$
$\phi\, d_g \sqrt{4\pi G_N} \frac{\beta_3}{2g_3} G_{\mu\nu} G^{\mu\nu}$	$\frac{\alpha_3}{8\pi} \frac{a}{f_a} G_{\mu\nu} \tilde G^{\mu\nu}$

Electronic states of a diatomic molecule



Molecular info

molecule	χ^{el}	T_e [cm^{-1}]	ω_e [cm^{-1}]	$\omega_e x_e$ [cm^{-1}]	B_e [cm^{-1}]	α_e [cm^{-1}]	R_e [Å]	T_b [K]
$^1H^1H$	c-$^3\Pi_u$	95938	2466.8	63.51	31.07	1.42	1.037	
	EF-$^1\Sigma_g^+$	100082.3	2588.9	130.5	32.68	1.818	1.011	
	C-$^1\Pi$	100089.8	2443.77	69.524	31.362	1.664	1.0327	
	B-$^1\Sigma_u^+$	91700	1358.09	20.888	20.015	1.184	1.2928	
	X-$^1\Sigma_g^+$	0	4401.21	121.33	60.853	3.062	0.74144	20.28
$^1H^2H$	C-$^1\Pi$	100092.9	2119.6	53.31	23.522	1.096	1.0329	
	B-$^1\Sigma_u^+$	91698.3	1177.16	15.59	15.071	0.820	1.2904	
	X-$^1\Sigma_g^+$	0	3813.1	91.65	45.655	1.986	0.74142	
$^2H^2H$	X-$^1\Sigma_g^+$	0	3115.50	61.82	30.443	1.0786	0.74152	
$^{16}O^{16}O$	X-$^3\Sigma_g^-$	0	1580.19	11.98	1.44563	0.0159	1.20752	90.19
$^{12}C^{16}O$	A-$^1\Pi$	65075.7	1518.2	19.40	1.6115	0.0232	1.2353	
	a'-$^3\Sigma^+$	55825.4	1228.60	10.468	1.3446	0.0189	1.3523	
	a-$^3\Pi$	48686.70	1743.4	14.3	1.69124	0.01904	1.20574	
	X-$^1\Sigma^+$	0	2169.81358	13.28831	1.93128	0.0175	1.12832	81.65
$^{12}C^{18}O$	X-$^1\Sigma^+$	0	2117.5	12.66	1.839	0.0163	1.128	
$^{14}N^{14}N$	A-$^3\Sigma_u^+$	50203.6	1460.64	13.87	1.4546	0.0180	1.2866	
	X-$^1\Sigma_g^+$	0	2358.57	14.324	1.99824	0.017318	1.09768	77.355
$^1H^{35}Cl$	X-$^1\Sigma^+$	0	2990.946	51.8	10.59341	0.30718	1.27455	188.10
$^{127}I^{127}I$	B-$^3\Pi_{0+u}$	15769.01	125.69	0.764	0.02903	0.000158	3.024	
	X-$^1\Sigma_g^+$	0	214.50	0.614	0.03737	0.000113	2.666	457.4

Configuration summary

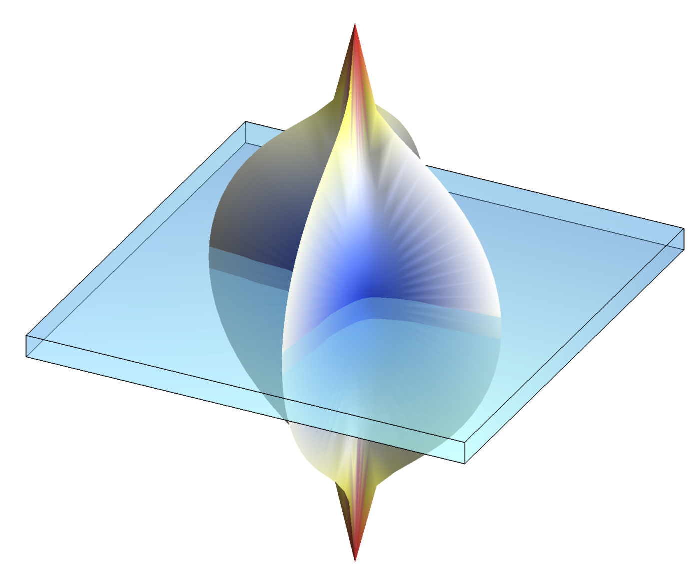
	Bulk	Stack
Phase I	$V = (0.3\text{ m})^3$, $P \sim 0.1$ bar, $T = 300$ K	$A = \pi(0.3\text{ m})^2$, $D = 1$ mm, $P \sim 10$ bar, $T \sim 100$ K
	PMT, DCR $= 1$ Hz, $A_{\text{det}} = (0.3\text{ m})^2$, $\eta_\gamma = 0.3$	MKID/TES, DCR $\lesssim 10^{-5}$ Hz, $A_{\text{det}} = (0.3\text{ mm})^2$, $\eta_\gamma = 0.5$
	any electronic $\rightarrow$ intermediate	E1-allowed electronic
	-	E1-allowed vibrational
	Stark/Zeeman tuning, $t_{\text{shot}} = 10^2$ s	collisional broadening, $t_{\text{shot}} = 10^6$ s
	$\delta\Omega \approx 2.9 \times 10^{-7}$ rad s^{-1}	$\delta\Omega \approx 9.4 \times 10^{-9}$ rad s^{-1}
Phase II	$V = (2\text{ m})^3$, $P \sim 0.1$ bar, $T \sim 100$ K	$A = \pi(2\text{ m})^2$, $D = 100$ mm, $P \sim 10$ bar, $T \sim 100$ K
	MKID array, DCR $\lesssim 10^{-3}$ Hz, $A_{\text{det}} = (0.1\text{ m})^2$, $\eta_\gamma = 0.5$	MKID/TES, DCR $\lesssim 10^{-7}$ Hz, $A_{\text{det}} = (2\text{ mm})^2$, $\eta_\gamma = 1$
	any electronic $\rightarrow$ intermediate	E1-allowed electronic
	any vibrational with optically thin fluorescence	E1-allowed vibrational
	Stark/Zeeman tuning, $t_{\text{shot}} = 10^3$ s	collisional broadening, $t_{\text{shot}} = 10^7$ s
	$\delta\Omega \approx 9.9 \times 10^{-10}$ rad s^{-1}	$\delta\Omega \approx 1.8 \times 10^{-11}$ rad s^{-1}

Cooperation number

$$A(t,\mathbf{x},\mathbf{x}') = \frac{q}{4\pi|\mathbf{x}-\mathbf{x}'|}\cos\left[\omega\left(t-|\mathbf{x}-\mathbf{x}'|\right)+\alpha_{\mathbf{v}}-m\mathbf{v}\cdot\mathbf{x}'\right]$$

$$\begin{aligned}
\langle A_{\rm tot}(t,\mathbf{x})^2\rangle_{\mathbf{v},\alpha} &= \left\langle\Big(\sum_{\mathbf{x}'}A(t,\mathbf{x},\mathbf{x}')\Big)\Big(\sum_{\mathbf{y}'}A(t,\mathbf{x},\mathbf{y}')\Big)\right\rangle_{\mathbf{v},\alpha}\\
&= \sum_{\mathbf{x}'}\left\langle A(t,\mathbf{x},\mathbf{x}')^2\right\rangle_{\mathbf{v},\alpha} + \sum_{\mathbf{x}'}\sum_{\mathbf{y}'\neq\mathbf{x}'}\left\langle A(t,\mathbf{x},\mathbf{x}')A(t,\mathbf{x},\mathbf{y}')\right\rangle_{\mathbf{v},\alpha}\\
&\simeq \int_V \mathrm{d}^3\mathbf{x}'n(\mathbf{x}')\frac{q^2}{2(4\pi)^2L^2}\\
&\quad+\iint_V \mathrm{d}^3\mathbf{x}'\mathrm{d}^3\mathbf{y}'n(\mathbf{x}')n(\mathbf{y}')\frac{q^2}{2(4\pi)^2L^2}\int \mathrm{d}^3\mathbf{v}f(\mathbf{v})\cos\left[m(\hat{\mathbf{x}}-\mathbf{v})\cdot(\mathbf{x}'-\mathbf{y}')\right]\\
&\equiv \frac{q^2}{2(4\pi)^2L^2}nVr(\hat{\mathbf{x}})
\end{aligned}$$

$$\bar{r}\simeq 1+\frac{8\pi n}{m^4R_z}\approx 1+\frac{5\times10^6}{mR_z}\left(\frac{1\ \mathrm{eV}}{m}\right)^3\left(\frac{n}{n_0}\right)$$



Key considerations

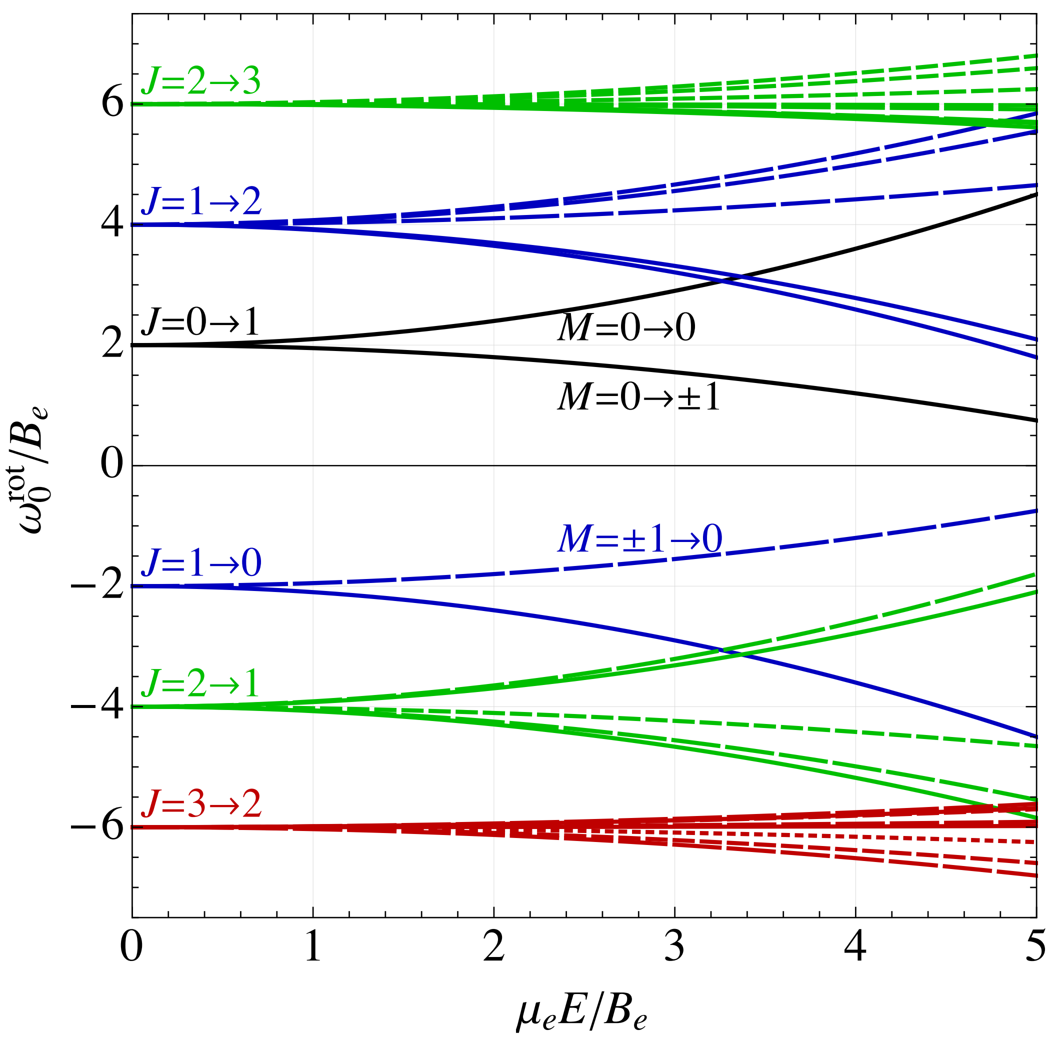
frequency coverage

— collisional broadening

— molecular species/isotope

— Zeeman tuning

— Stark tuning:



radiative efficiency

— Bulk: $\gamma_0 + \sum_i \gamma_i \gtrsim \gamma_{\mathrm{quench}}$

— Stack: $(\bar{r}-1)\gamma_0 \sim \gamma_{\mathrm{col}}$