Title: Searches for light scalar dark matter

Date: Aug 23, 2017 03:00 PM

URL: http://pirsa.org/17080031

Abstract:

Part I: Searches for light scalar dark matter

clocks — arXiv:1405.2925 [A. Arvanitaki, J. Huang, KVT]
arXiv:1503.06886 [KVT, D. Budker group]
[E. Marti]

rods — arXiv:1508.01798 [A. Arvanitaki, S. Dimopoulos, KVT]
[M. Tobar], [L. Taffarello]

interferometry — arXiv:1606.04541
[A. Arvanitaki, P. Graham, J. Hogan, S. Rajendran, KVT]
[H. Mueller], [M. Kasevich]

accelerometers — [A. Geraci], [G. Gratta], [H. Paik], [E. Adelberger]

Part II: Resonant absorption of bosonic dark matter in molecules

arXiv:1708.xxxxx [A. Arvanitaki, S. Dimopoulos, L. Hollberg, KVT]

Ken Van Tilburg (NYU & IAS)

Experimental Techniques in Table-Top Fundamental Physics
Perimeter, 2017/08/23

Current "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 tools numerological curiosities computational precision

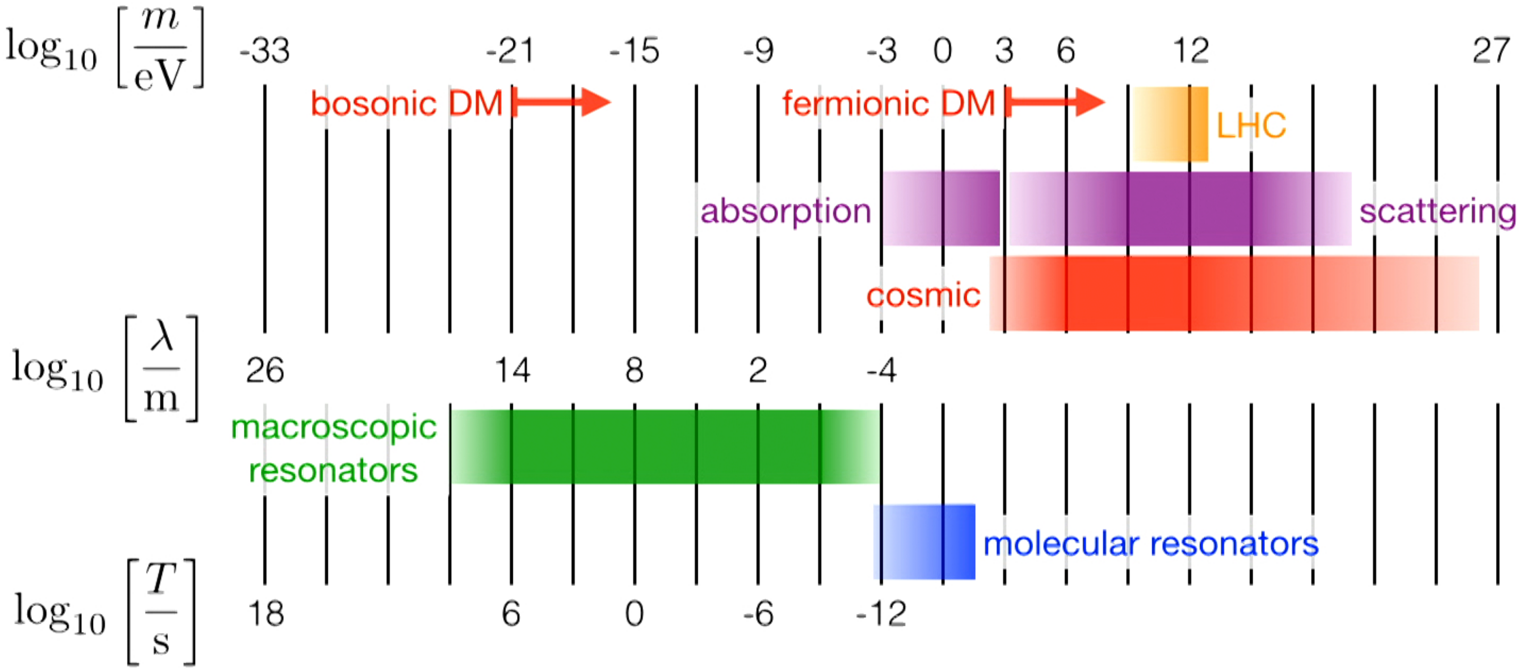
experimental frontiers:

high-energy cosmic intensity precision

***parametrized unknowns:**

dark matter | baryon asymmetry | inflation | g-2

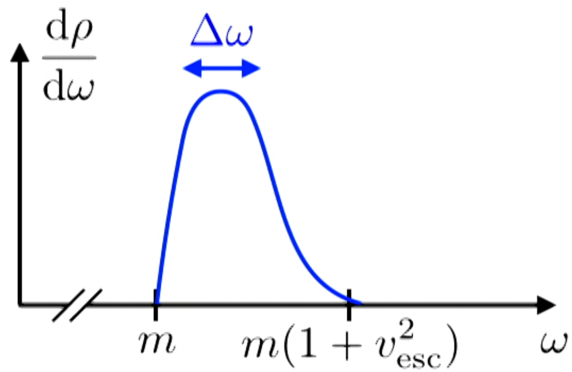
Scales of dark matter



absorption ⟶ monochromatic signal: $\omega = m(1+v^2)$

Bosonic dark matter fields and interactions

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



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

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

$$\delta H = \epsilon \mathbf{E}' \cdot \boldsymbol{\mu}_e$$

↓ 3 kV/m


e.g. hidden

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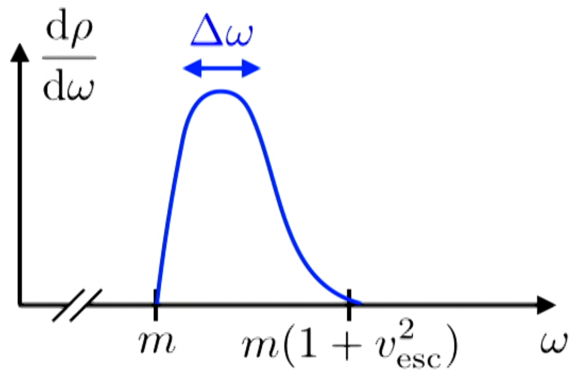

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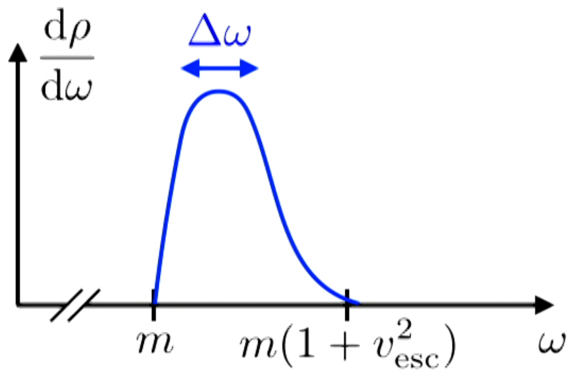

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$$\delta H = \epsilon \mathbf{E}' \cdot \boldsymbol{\mu}_e \qquad \boldsymbol{\mu}_e = e\sum_\psi q_\psi \mathbf{r}_\psi$$

↓ 3 kV/m

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

Part I: Light scalars

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2$$
$$+ \sqrt{4\pi G_N}\, \phi \left[\underbrace{+\frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu}}_{\alpha \text{ changes}} \underbrace{- \frac{d_g \beta_3}{2 g_3} G^A_{\mu\nu} G^{A\mu\nu}}_{\Lambda_{\rm QCD} \text{ changes}} \underbrace{- d_{m_e} m_e \bar{e} e - \sum_{q=u,d} (d_{m_q} + \gamma_{m_q} d_g) m_i \bar{\psi}_i \psi_i}_{\text{electron and quark masses change}} \right]$$

theories

Higgs portal

dilaton, radion

QCD axion

any Yukawa/gauge modulus

phenomenology

$$m_e(t, \mathbf{x}) = m_e \left[1 + d_{m_e} \sqrt{4\pi G_N}\, \phi(t, \mathbf{x}) \right]$$
$$\alpha(t, \mathbf{x}) = \alpha \left[1 + d_e \sqrt{4\pi G_N}\, \phi(t, \mathbf{x}) \right]$$

physical effects

$\omega_{\rm clock} [\alpha, m_e, m_q, \Lambda_{\rm QCD}]$

$$L_{\rm rod} = \frac{N}{\alpha m_e}$$

$$\mathbf{a} = -\frac{\nabla M}{M}$$

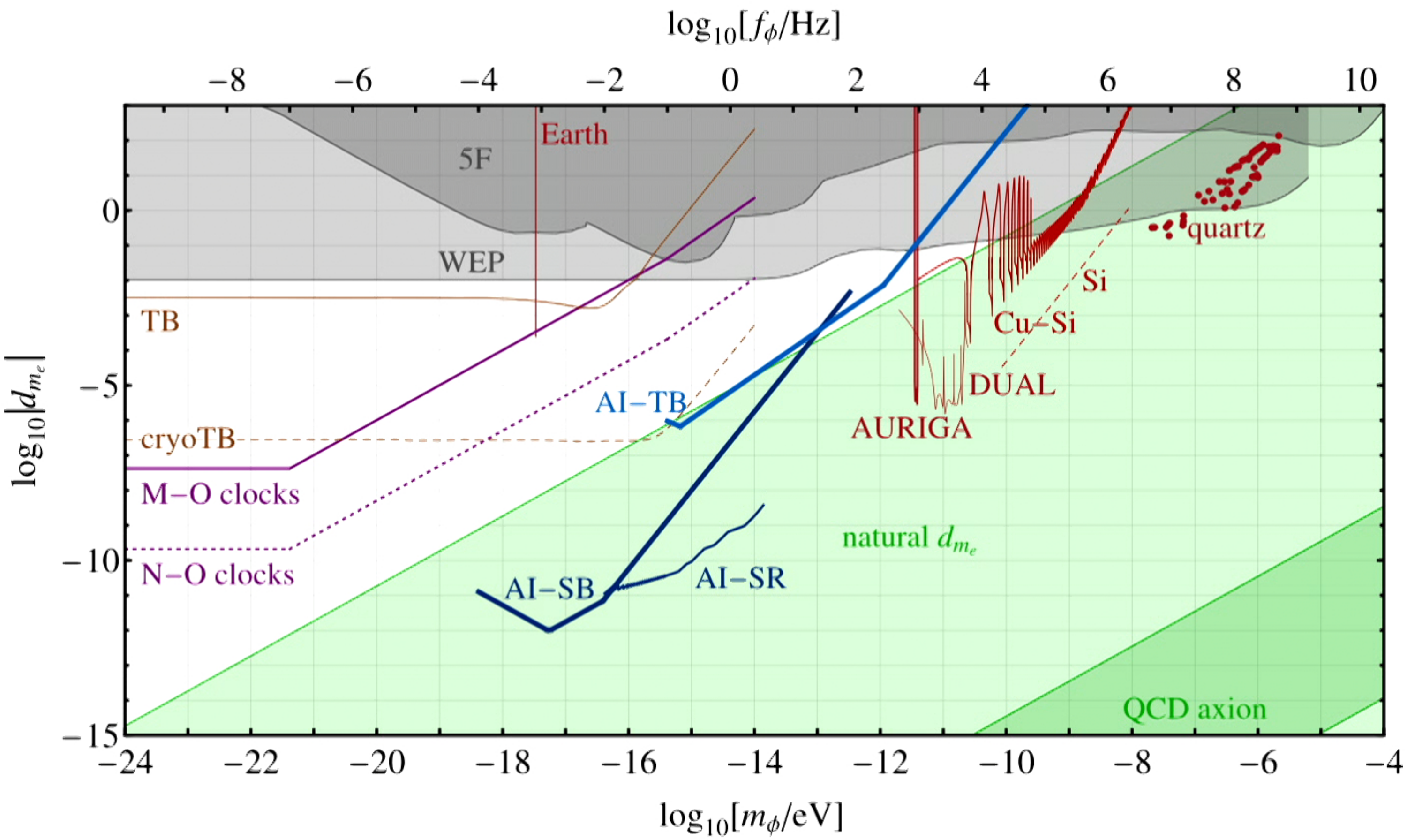
detection

atomic clocks & interferometers

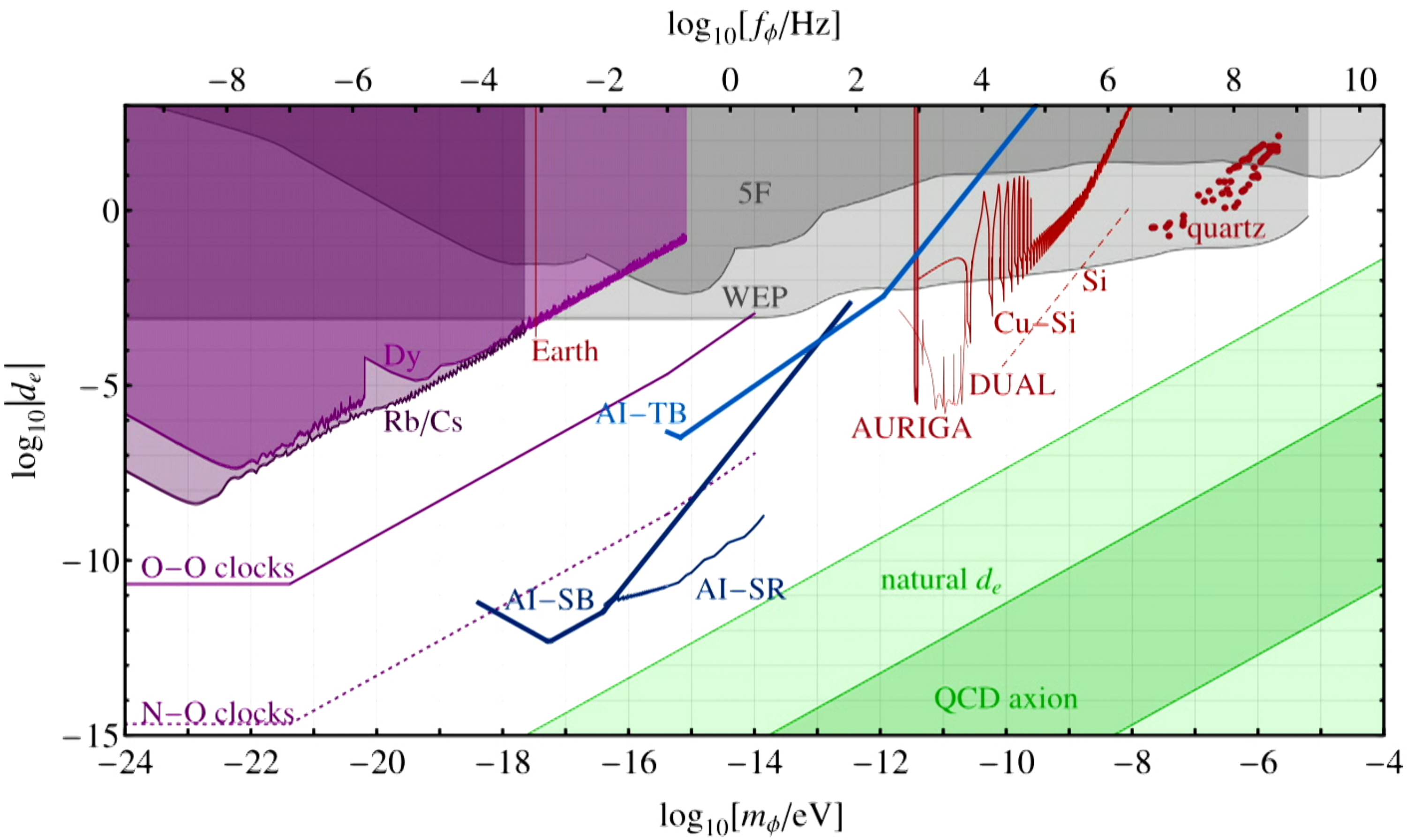
mechanical resonators

accelerometers

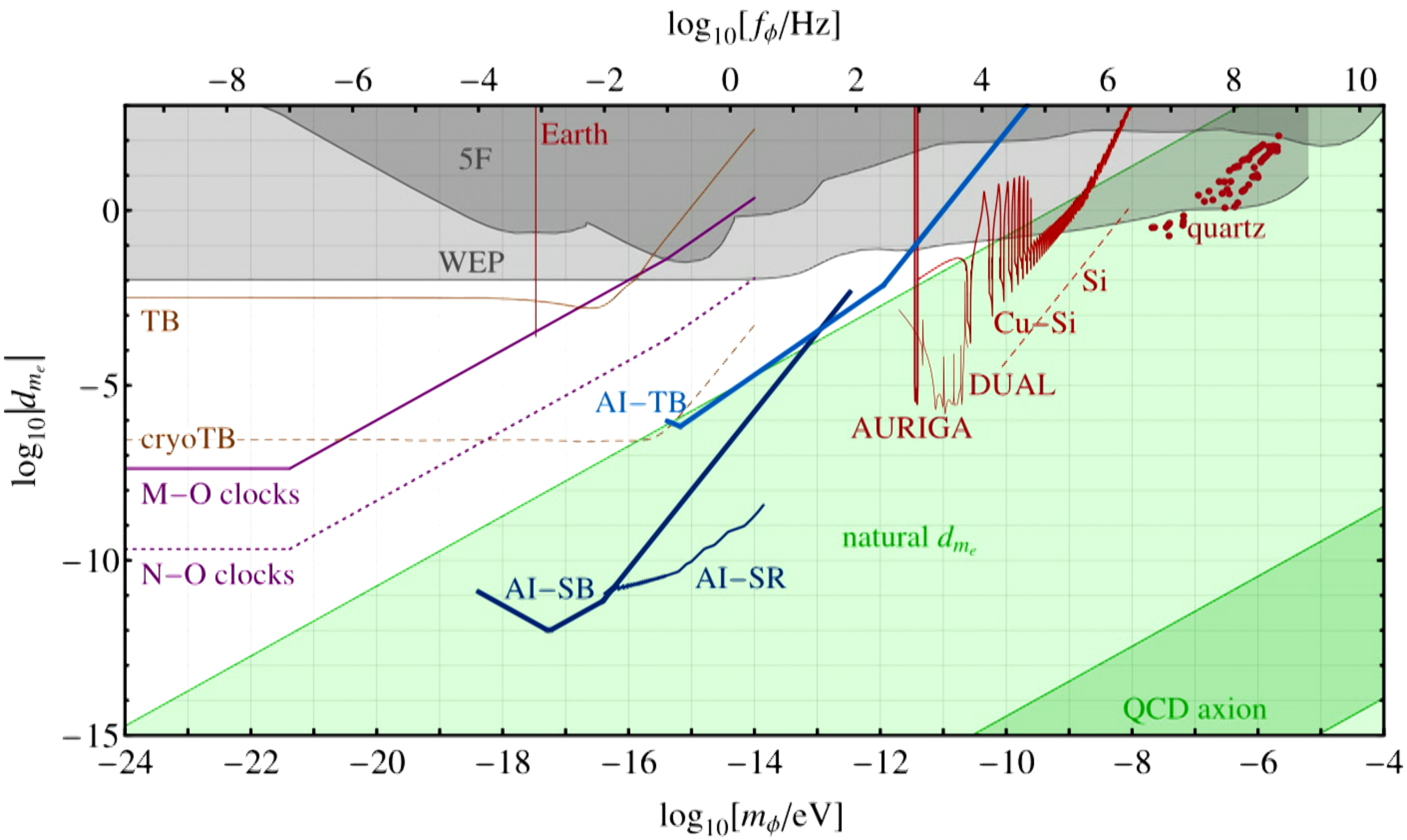
Electron modulus



Photon modulus



Electron modulus



Outline: Part II

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

dynamics of a driven two-level system | overview of molecular levels

(2) Experimental setup

configurations | photon detection | backgrounds | discrimination

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

hidden vectors | moduli | axions

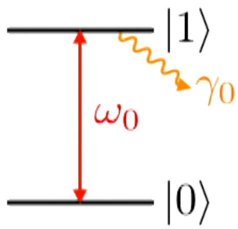
Why is a molecular gas a good dark matter detector?

calculable { signal rate, backgrounds }

discrimination power

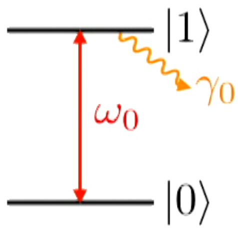
established field with rapid technology advancements

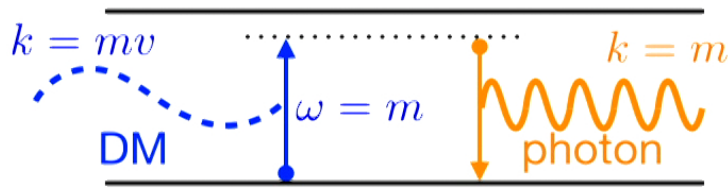
Resonant excitation of a two-level system



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

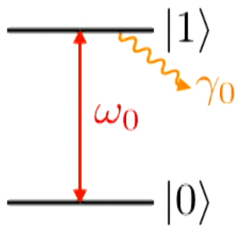
Resonant excitation of a two-level system

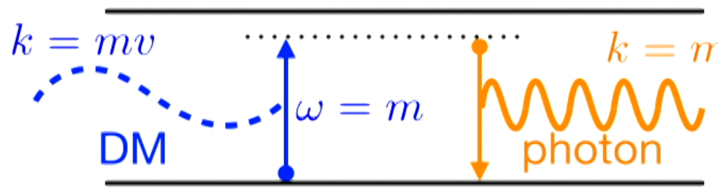




$$\langle 1|\delta H|0\rangle \sim \Omega\cos(\omega t) \qquad |\Psi(t)'\rangle = e^{-i\int_0^t \delta H dt'}|0'\rangle \simeq |0'\rangle - \frac{i}{2}\Omega\frac{e^{i(\omega_0-\omega)t}-1}{i(\omega_0-\omega)}|1'\rangle$$

Resonant excitation of a two-level system





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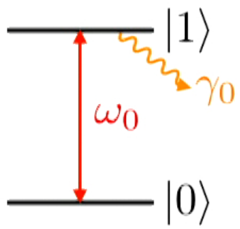
$$\Gamma_{\rm abs} = nV \frac{|\Omega|^2}{\gamma} \frac{1}{1+\frac{4(\omega_0-\omega)^2}{\gamma^2}}$$

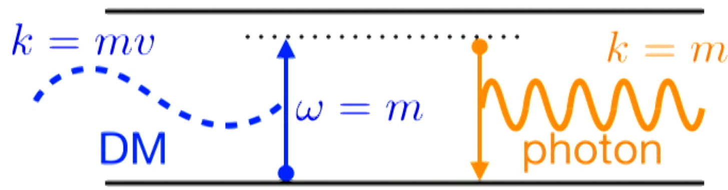
nV: # molecules

$\frac{|\Omega|^2}{\gamma}$: on-resonance absorption rate per molecule

$\frac{4(\omega_0-\omega)^2}{\gamma^2}$: lineshape

Resonant excitation of a two-level system





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\# molecules

on-resonance
absorption rate per molecule

lineshape

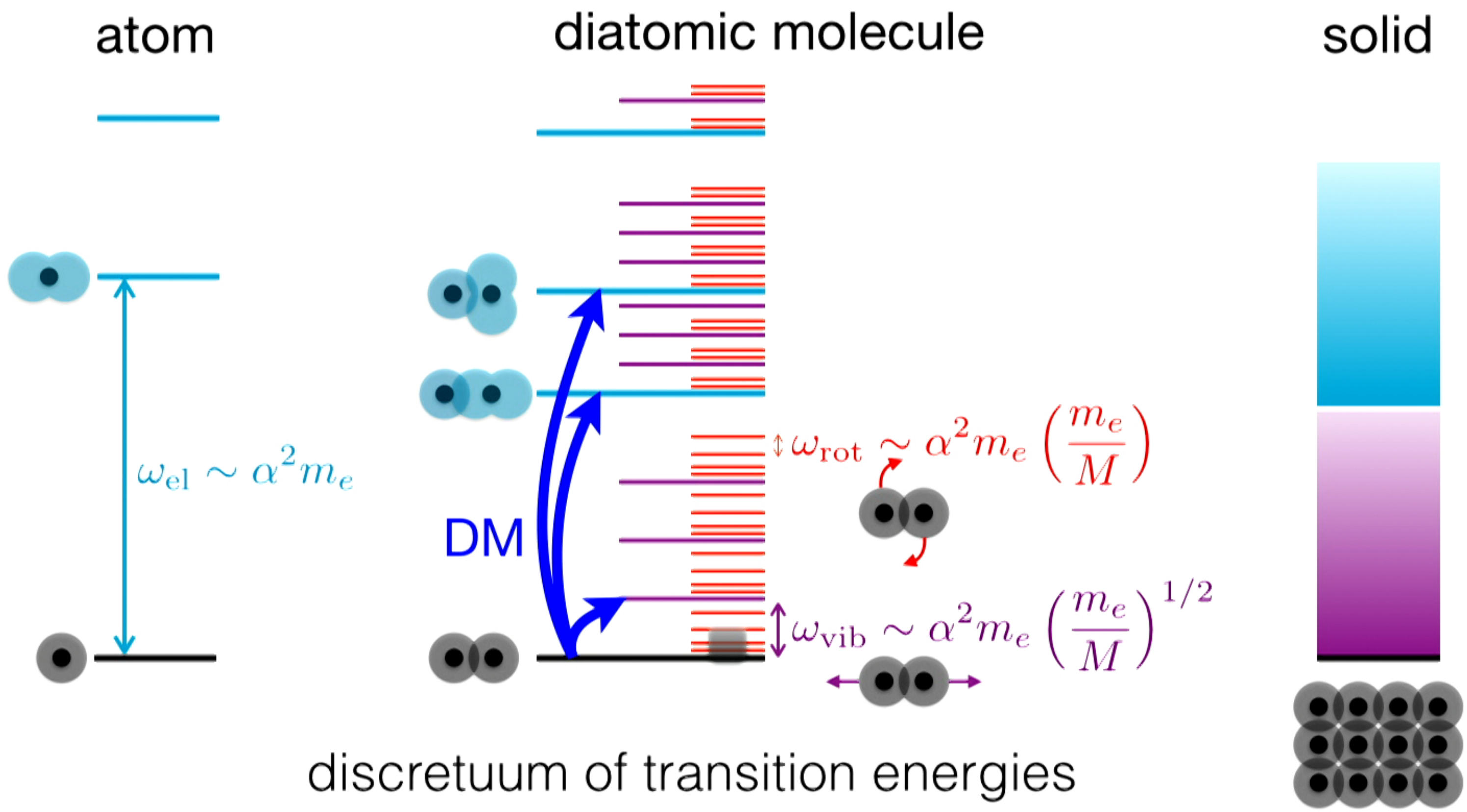
$$\gamma = \gamma_{\rm rad} + 2\gamma_{\rm col} + \frac{\Delta\omega}{\pi}$$

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

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

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

Molecular levels and transitions



discretuum of transition energies

=

multimode resonator

DM absorption rate

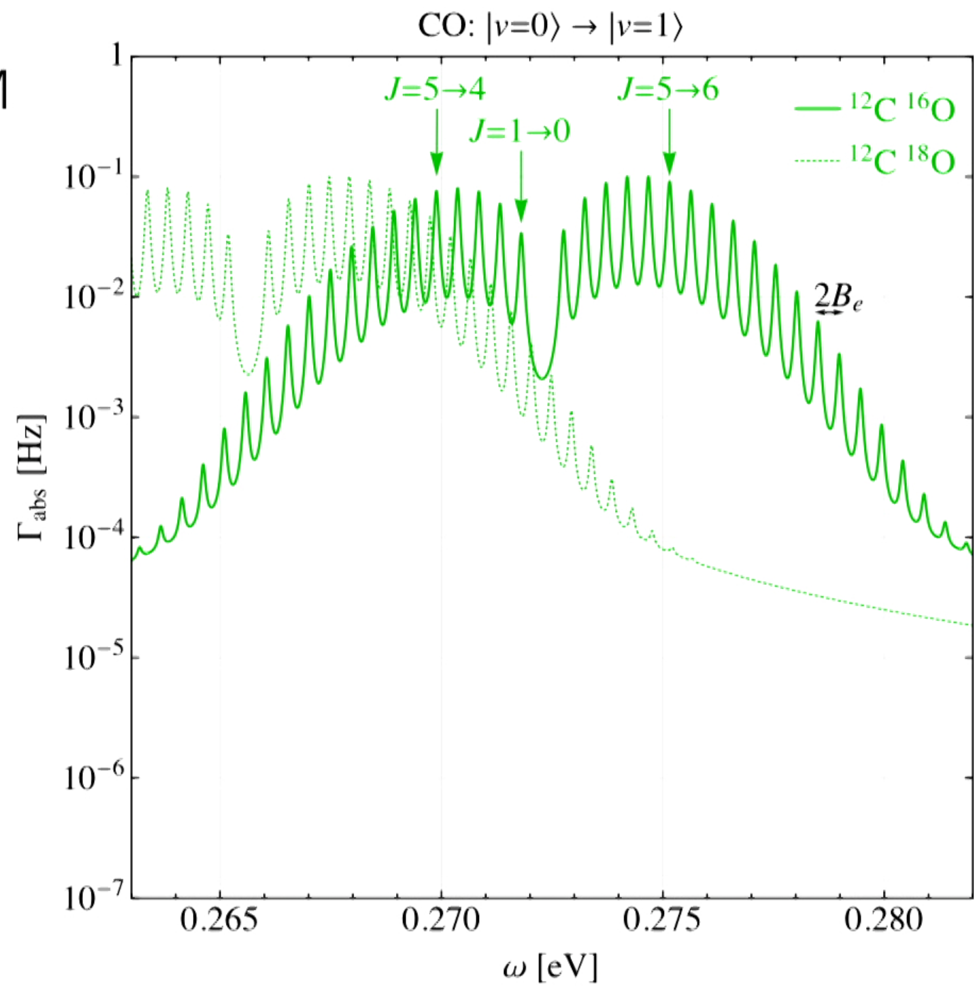
hidden photon DM

$\epsilon = 10^{-12}$

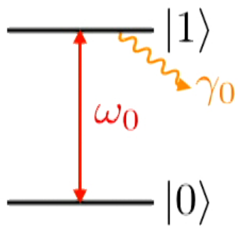
$V = 300 \text{ cm}^3$

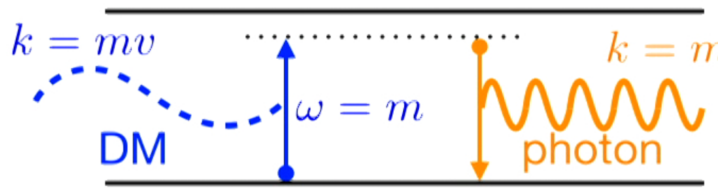
$T = 100 \text{ K}$

$P = 5 \text{ bar}$



Resonant excitation of a two-level system





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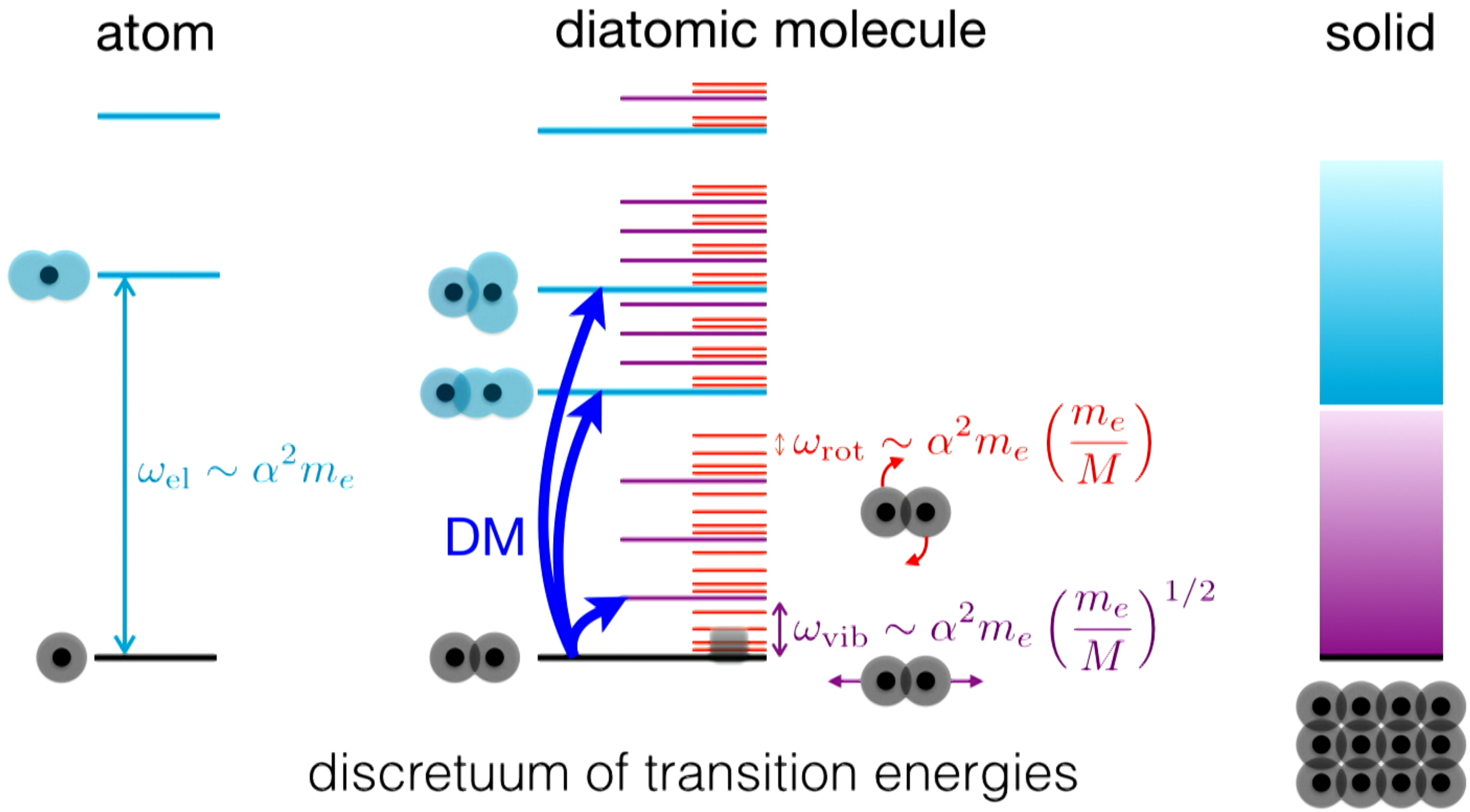
Molecular levels and transitions



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hidden vectors | moduli | axions

Why is a molecular gas a good dark matter detector?

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discrimination power

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Key considerations

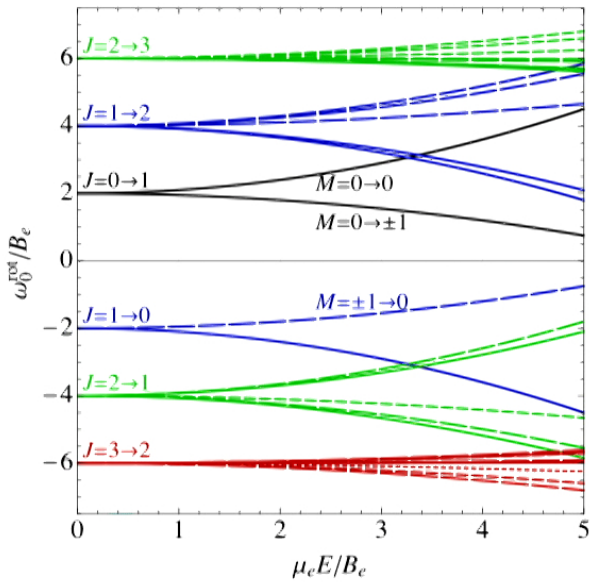
frequency coverage

— collisional broadening

— molecular species/isotope

— Zeeman tuning

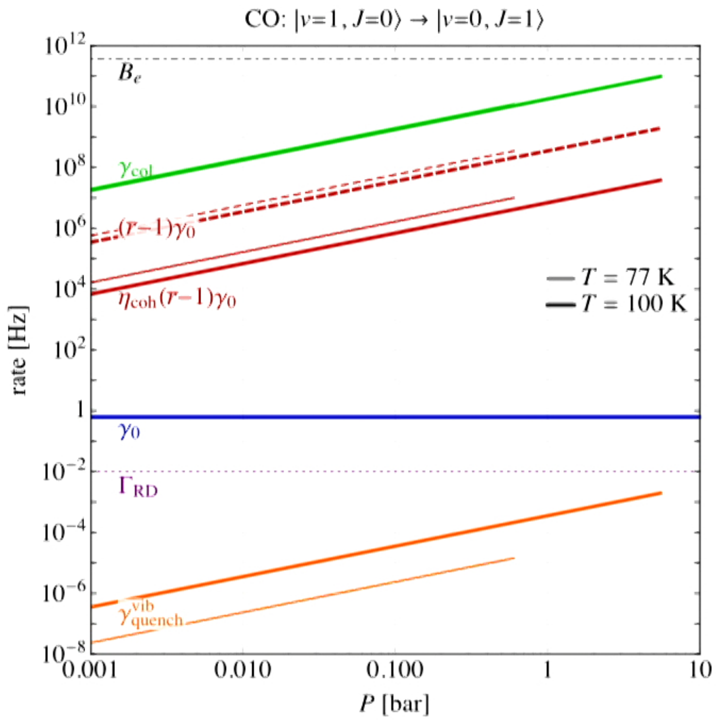
— Stark tuning:



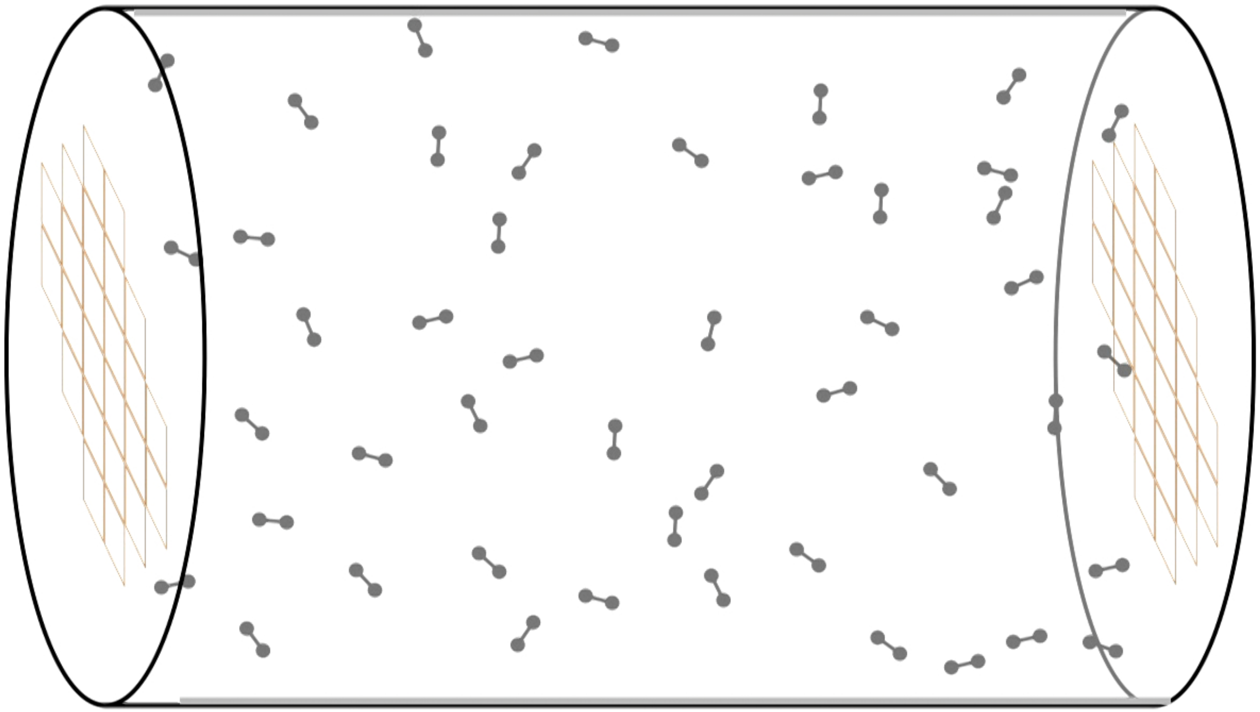
radiative efficiency

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

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



Bulk configuration



Phase I:
$V = (0.3\ m)^3$
$T = 300$ K
PMT

Phase II:
$V = (2\ m)^3$
$T = 100$ K
MKID

Photon detection

$$\Gamma_{\rm sig} = \eta \Gamma_{\rm abs} \qquad \eta = \eta_{\rm rad}\eta_{\rm refl}\eta_{\rm thick}\eta_{\rm det} \sim 1$$

Phase I: PMT

$\mathrm{DCR} = 1\ \mathrm{Hz}$

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

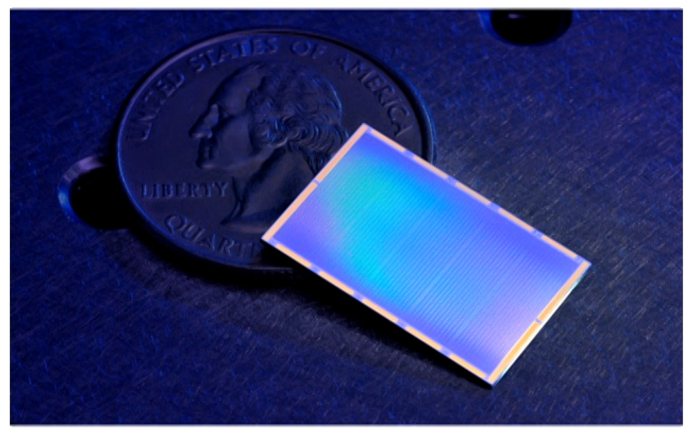
Phase II: MKID

$\mathrm{DCR} \lesssim 10^{-3}\ \mathrm{Hz}$

$\eta_{\rm det} \sim 0.5$

$\Delta E \sim 0.1\ \mathrm{eV}$


Hamamatsu


B. Mazin

Cooperative radiation

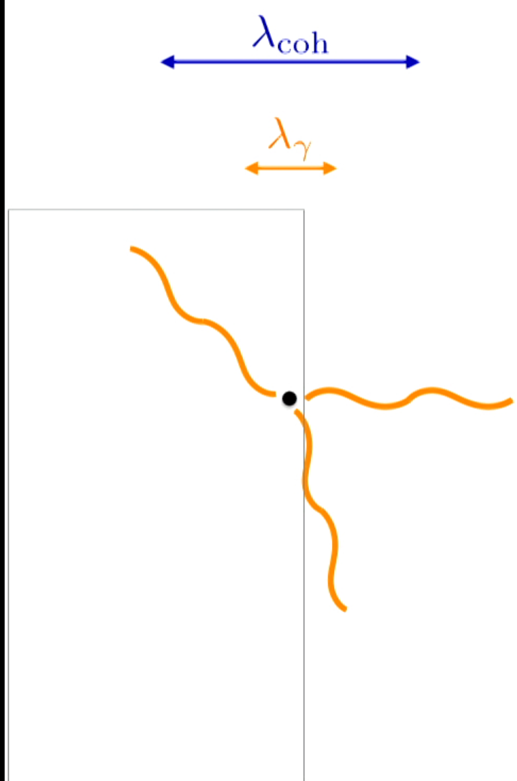
"Add before you square" – M. Kasevich (2017)

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

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

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

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



$$\gamma_{\rm rad} = \gamma_0$$

Cooperative radiation

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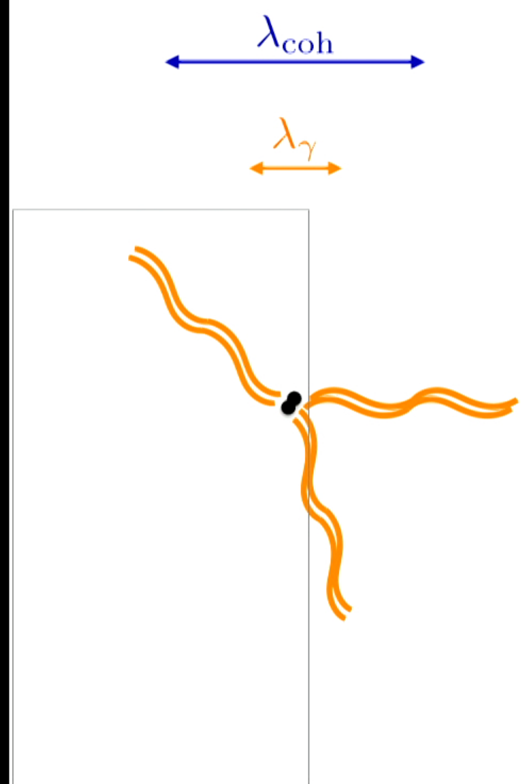

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typical deBroglie wavelength: $\lambda_{\text{dB}} \sim \dfrac{2\pi}{mv_{\text{lab}}}$

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

$$\gamma_{\text{rad}} = 2\gamma_0$$

Cooperative radiation

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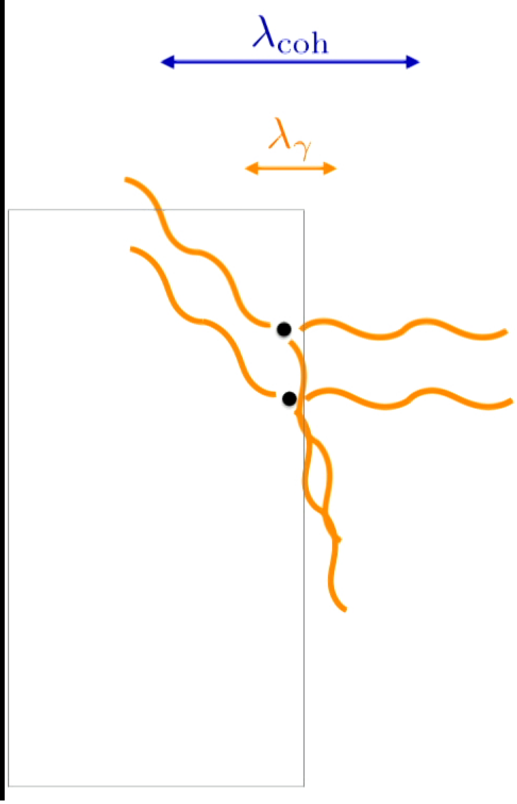

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fluorescence wavelength: $\lambda_\gamma = \dfrac{2\pi}{m}$

$$\gamma_{\rm rad} = r(\theta, \varphi)\gamma_0$$

Cooperative radiation

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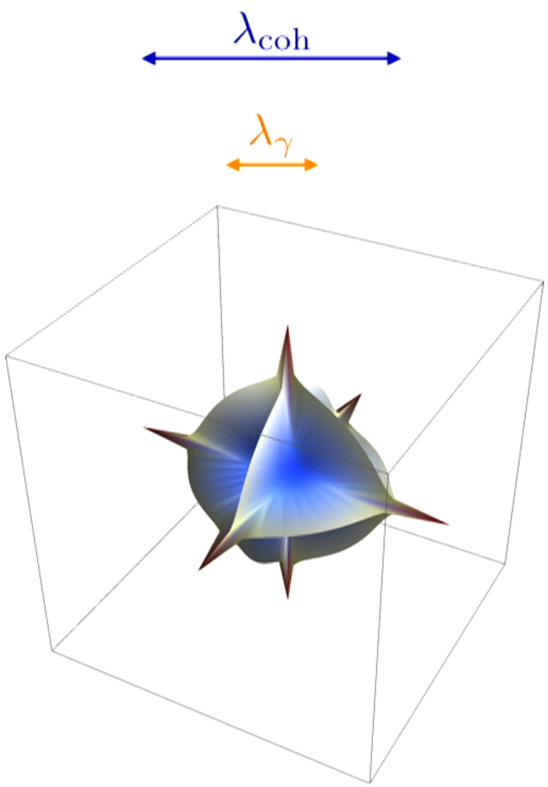

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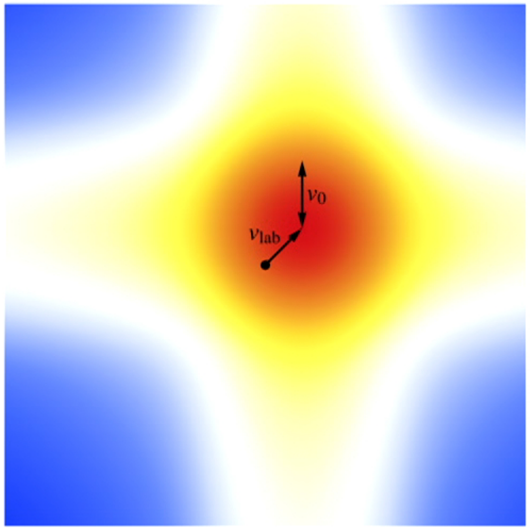
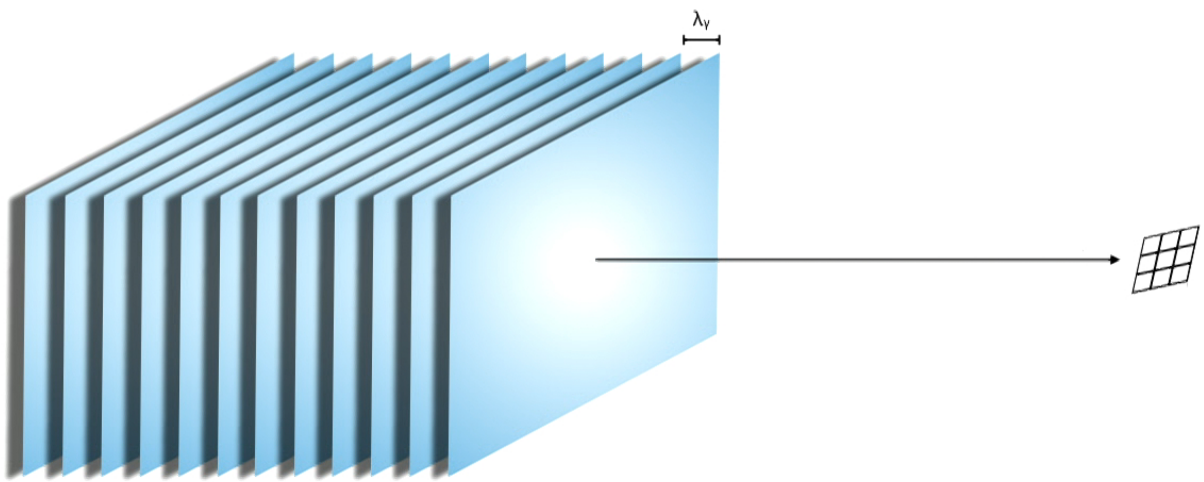


Stack configuration

— focusing: $r(\theta, \phi)$ exponentially peaked in normal direction

— enhance radiative width:

$$\bar{r} - 1 \simeq \frac{8\pi n}{m^4 R_z} \approx 1 + \frac{5.1 \times 10^6}{m R_z} \left(\frac{1\ \mathrm{eV}}{m}\right)^3 \left(\frac{n}{n_{\mathrm{st}}}\right)$$

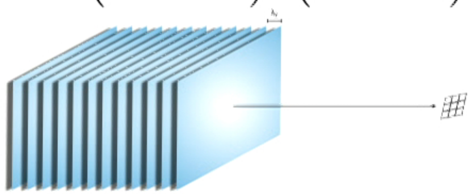


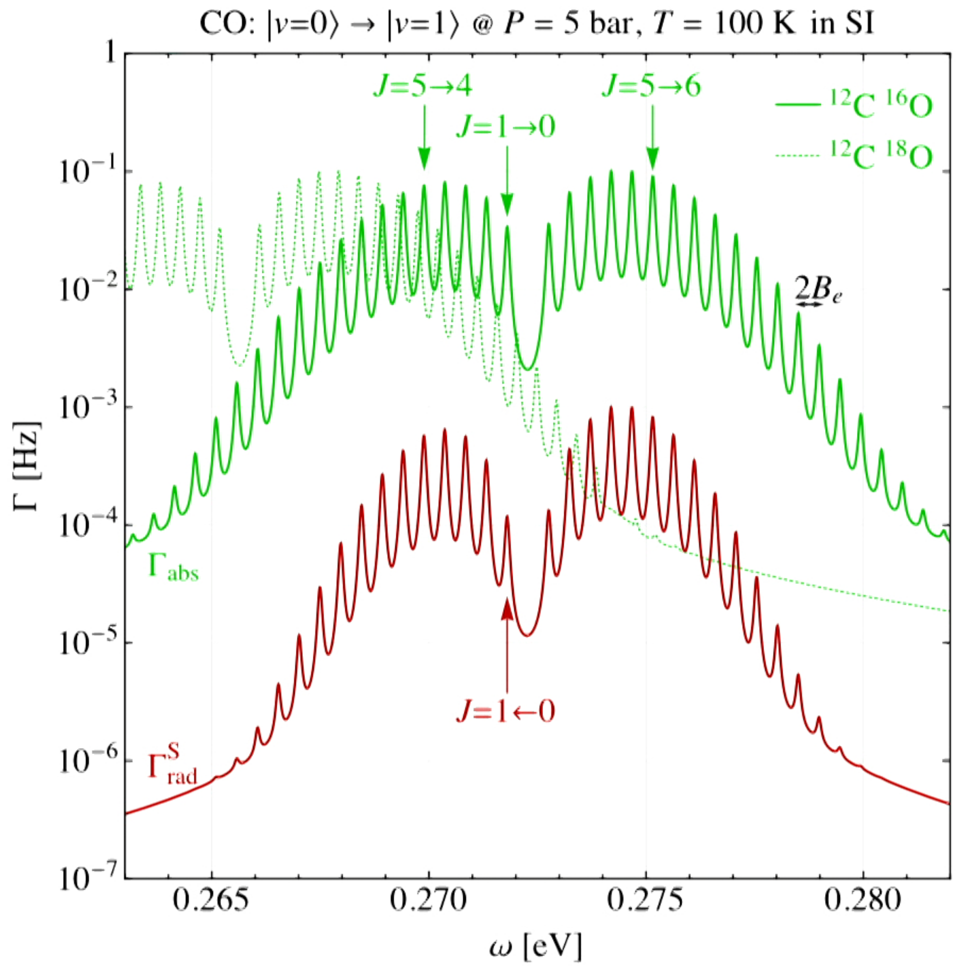
Absorption + Cooperative fluorescence

hidden photon DM

$$\epsilon = 10^{-12}$$

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





Backgrounds

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

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

natural/cosmogenic radioactivity: high-purity shield + components

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

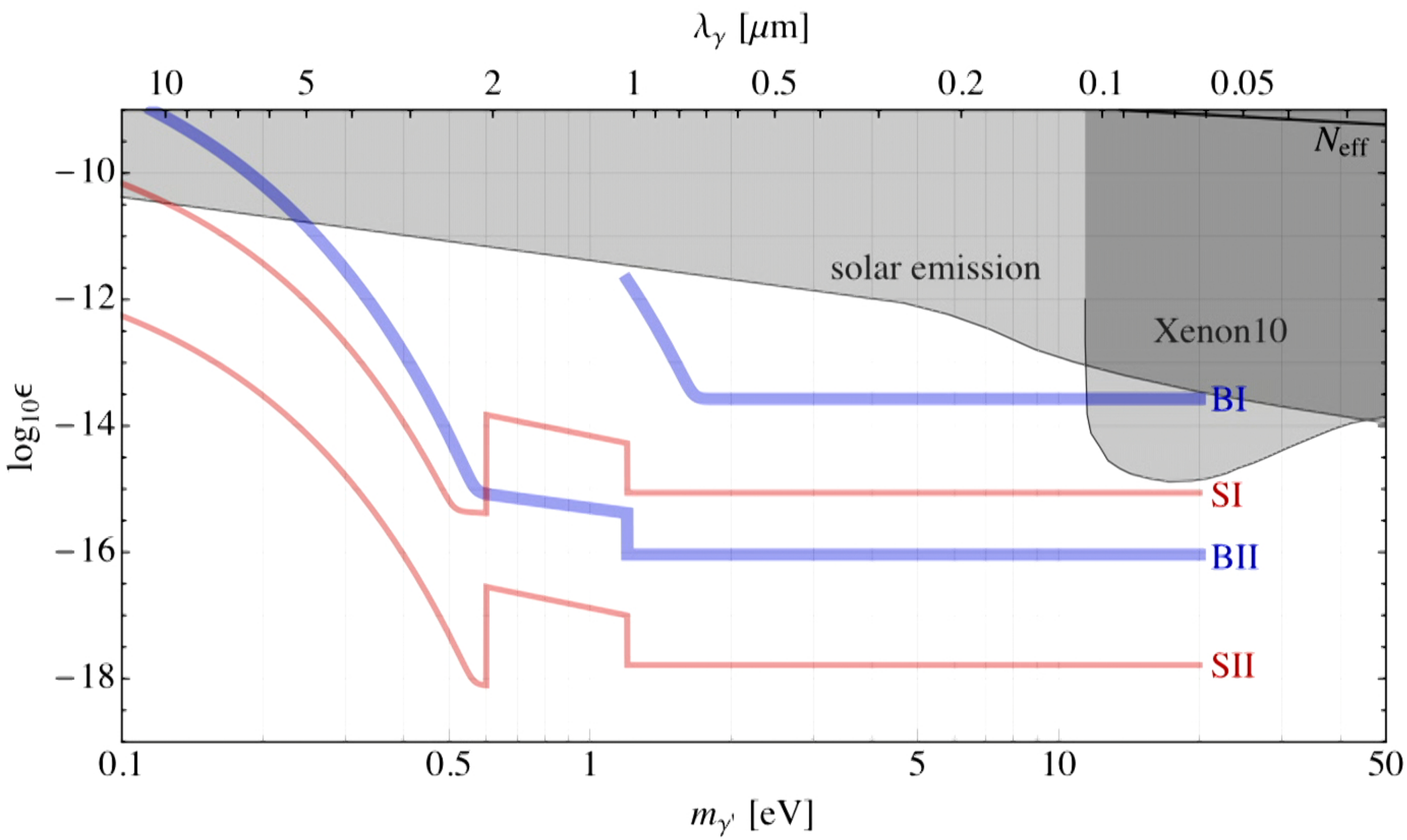
Bulk Phase I: subdominant to DCR

Bulk Phase II: veto trigger: { many, high-*E* particles
ionized electrons
timing + fast relaxation

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

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

Hidden photon



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 information

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

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

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

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

Future: $\underline{m < 0.2\ \mathrm{eV}}$ | $m > 20$ eV | other use? | map out molecular forest

Phase I prototypes

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

DM type		Interaction Hamiltonian δH	Transition type and selection rules		$\Omega\,[\text{rad s}^{-1}]$
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	$\Delta J=1$	$4.1\times10^{-13}\frac{d_i}{10^2}\frac{\Delta Q_i}{10^{-2}}$
		$(d_{m_e}+d_e)\tilde{\phi}V_e(r_e)$	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**	$\lvert\Delta\Lambda\rvert\le1, \Delta i=1, \lvert\Delta S_e\rvert\le1$	$4.0\times10^{-10}\frac{G_{aee}}{10^{-10}/\text{GeV}}$
		$G_{a\gamma\gamma}\,a\,\mathbf{E}\cdot\mathbf{B}$	el	$\Delta\Lambda=0, \Delta i=1$	
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	$\Delta J=1$	$5.0\times10^{-10}\frac{g}{10^{-18}}$