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]

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# Part II: Resonant absorption of bosonic dark matter in molecules

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

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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

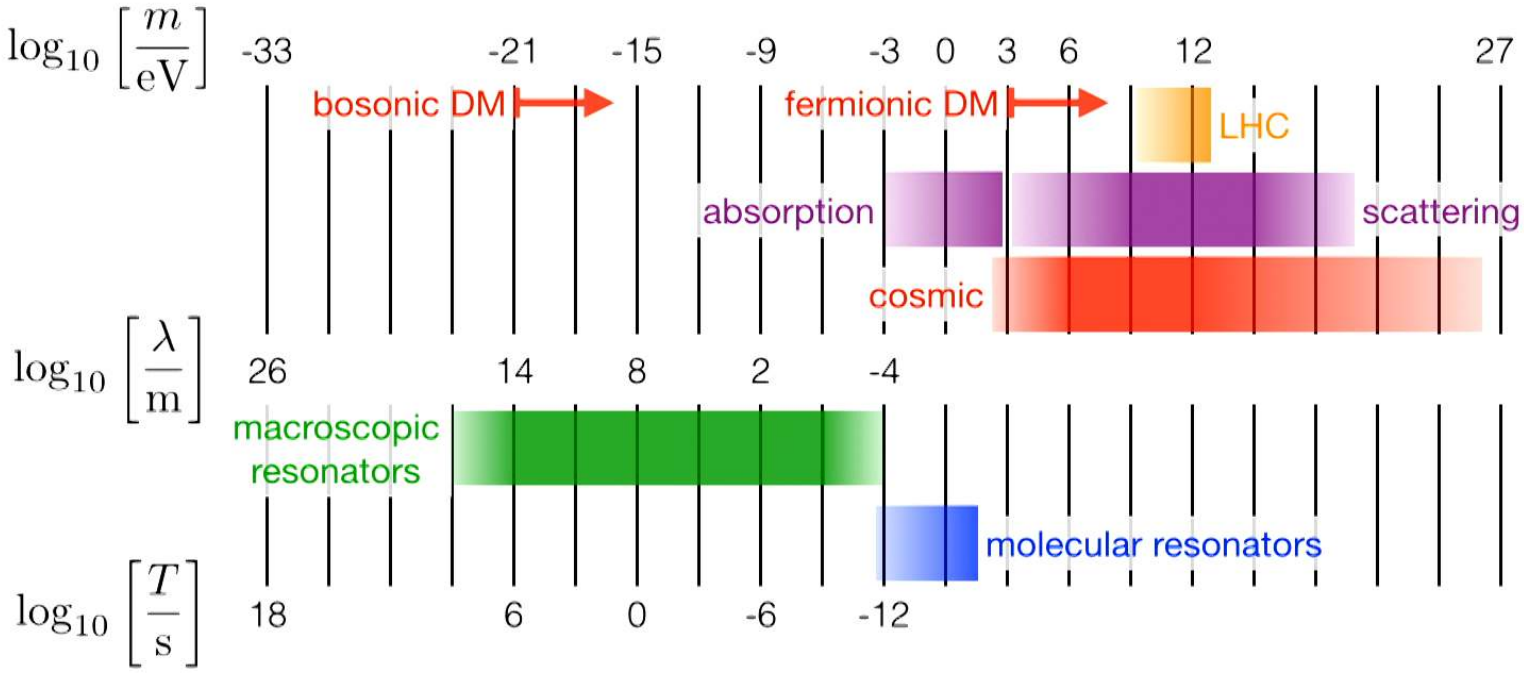
## experimental frontiers:

high-energy  cosmic  intensity  precision

## *parametrized unknowns:

dark matter | baryon asymmetry | inflation | g-2

# Scales of dark matter

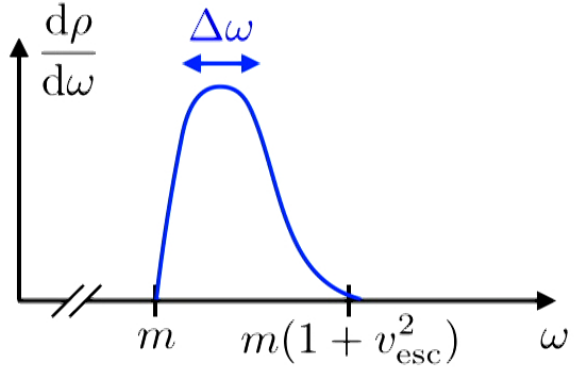



absorption ⟶ monochromatic signal: $\omega = m(1 + v^2)$

# Bosonic dark matter fields and interactions

vector $|\mathbf{A}'|$
scalar $\phi$
pseudoscalar $a$

$$\Big\} \simeq \frac{\sqrt{2\rho_{\rm DM}}}{\omega}\cos(\omega t)$$




production: { inflationary perturbations (spin-1)
misalignment mechanism (spin-0)

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

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

↓

3 kV/m

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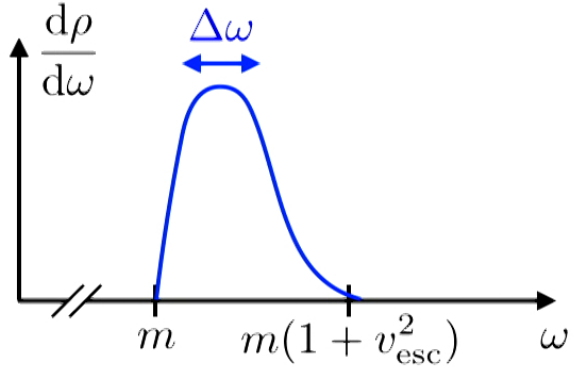


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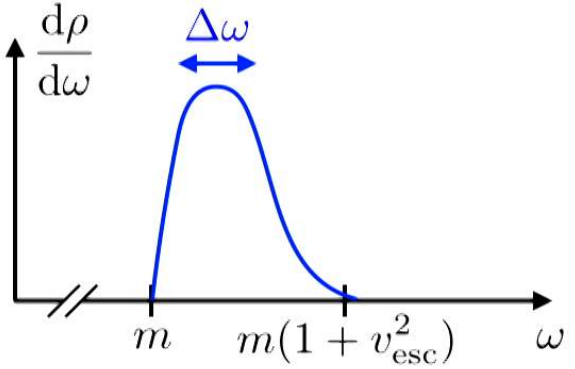


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$$\delta H = \epsilon \mathbf{E}' \cdot \boldsymbol{\mu}_e \qquad \boldsymbol{\mu}_e = e\sum_\psi q_\psi \mathbf{r}_\psi$$

3 kV/m

equivalent to shining 20kW laser in a 1m$^2$ beam waist area

# Part I: Light scalars

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

## 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

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

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

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

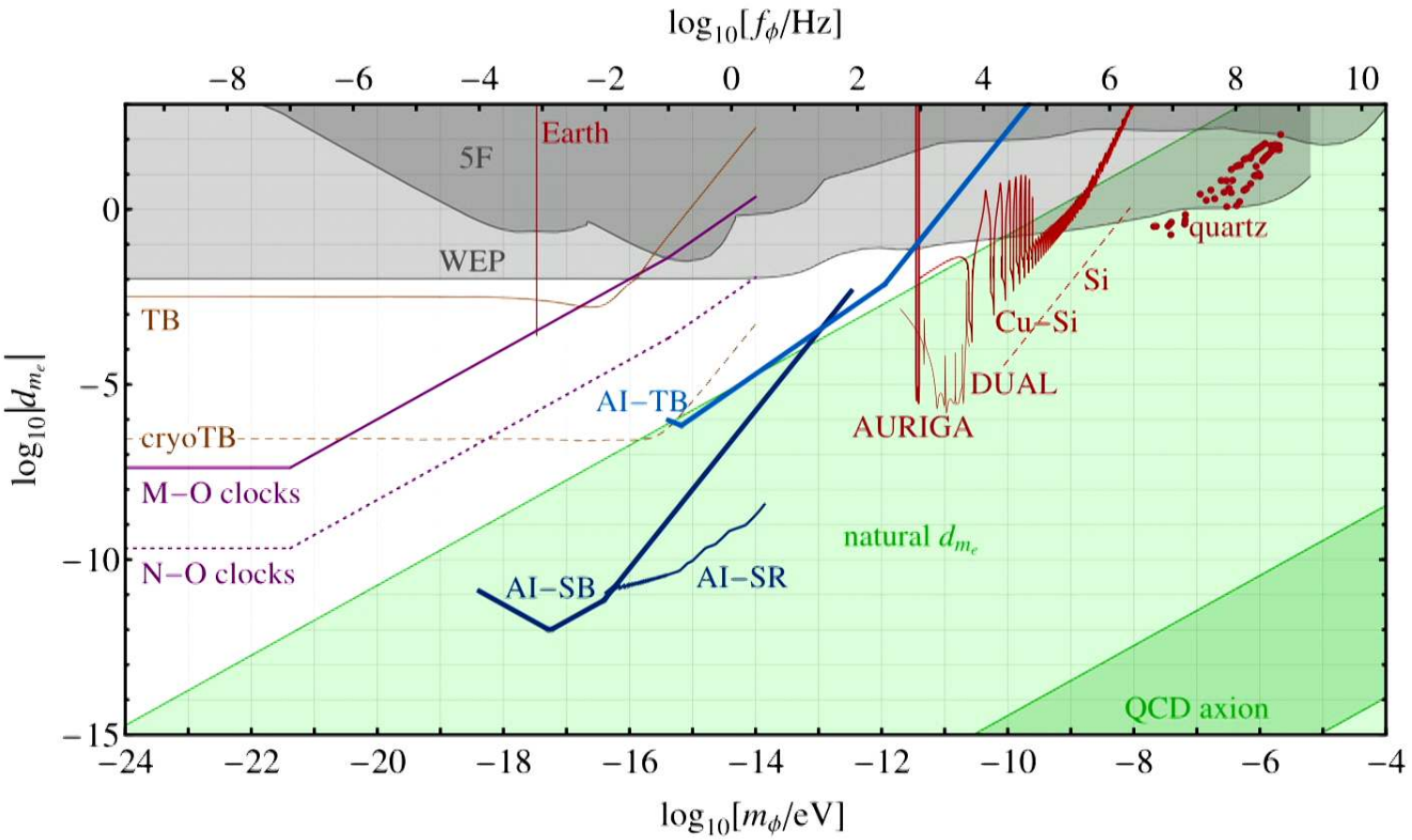
## detection

atomic clocks & interferometers

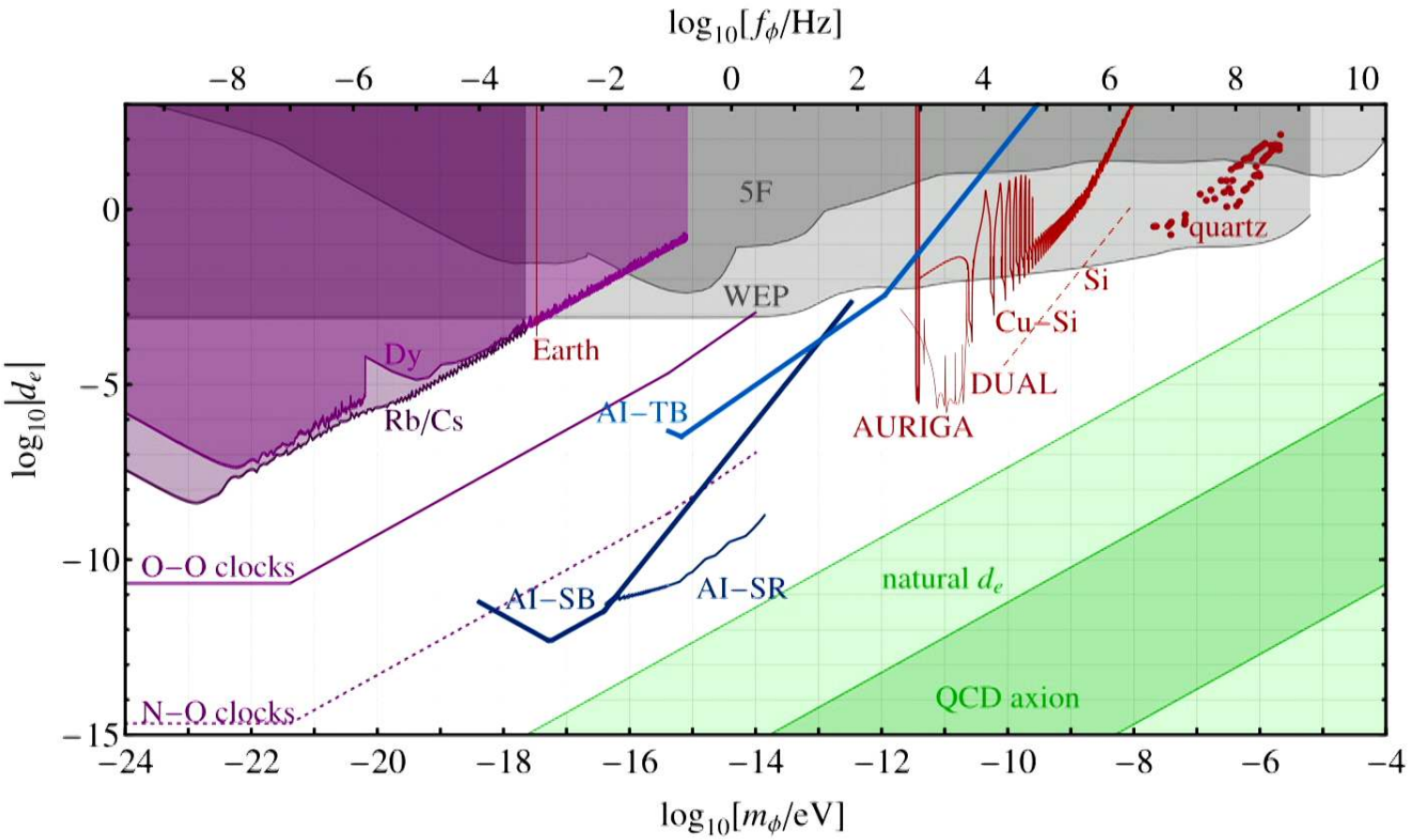
mechanical resonators

accelerometers

# Electron modulus



# Photon modulus



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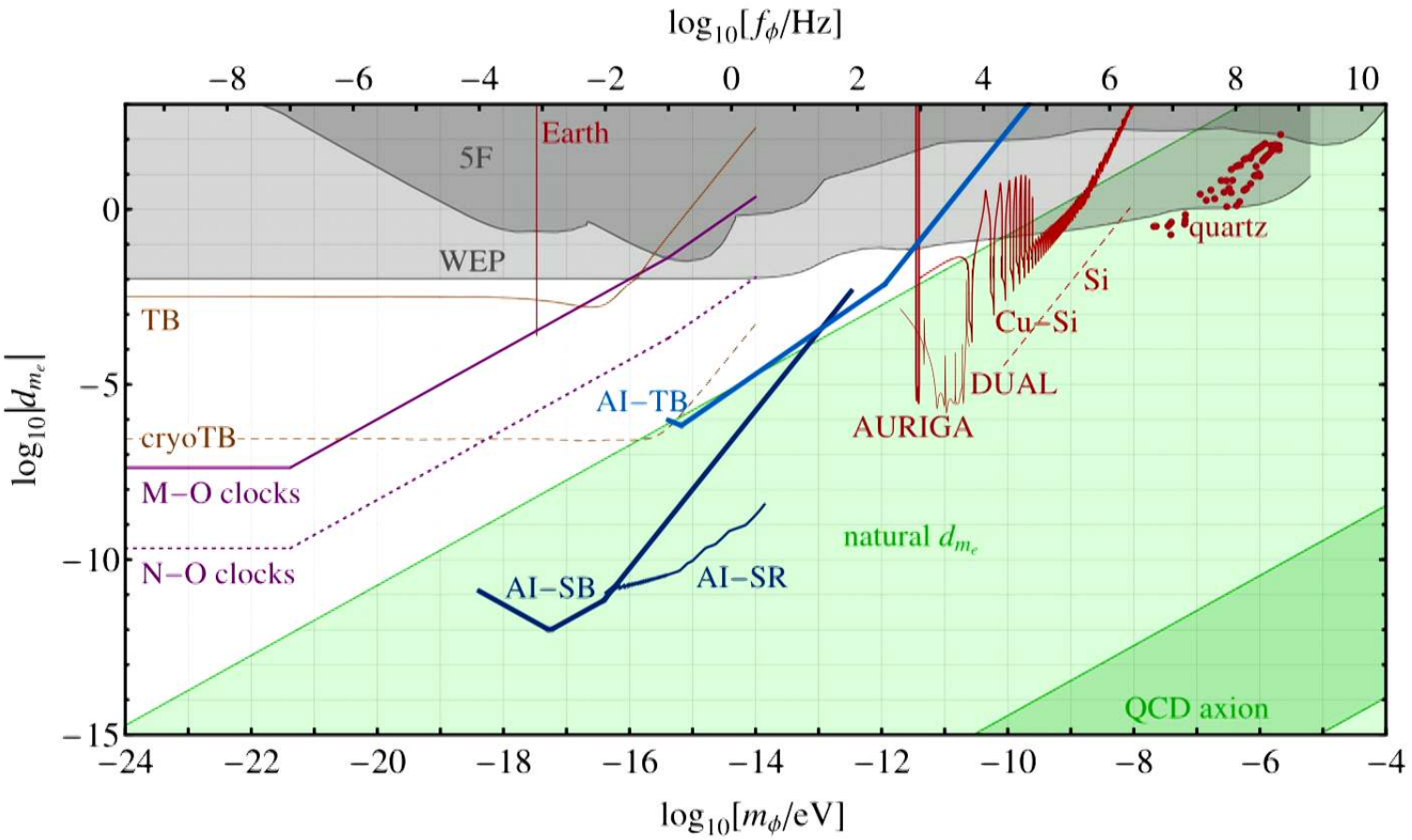

# Outline: Part II

(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 $0.2\ \mathrm{eV} < m < 20\ \mathrm{eV}$

hidden vectors | moduli | axions

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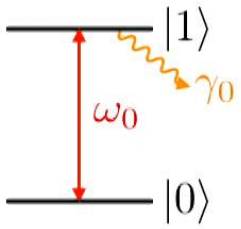
Why is a molecular gas a good dark matter detector?

calculable { signal rate, backgrounds }

discrimination power

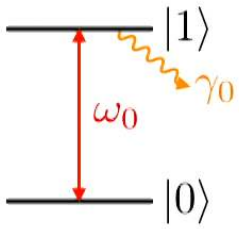
established field with rapid technology advancements

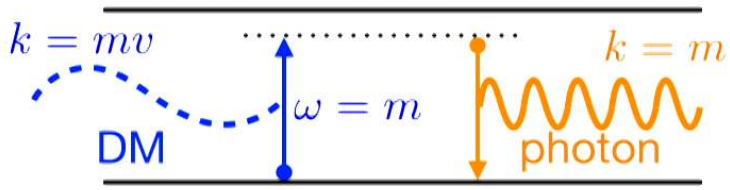
# Resonant excitation of a two-level system




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

# Resonant excitation of a two-level system




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

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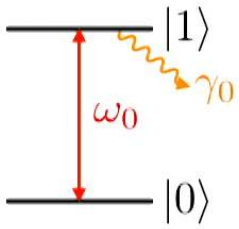


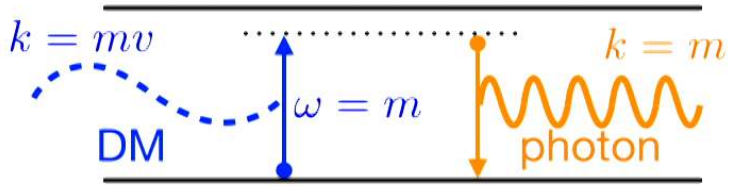


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$$\Gamma_{\rm abs} = nV\,\underbrace{\frac{|\Omega|^2}{\gamma}}_{\text{on-resonance absorption rate per molecule}}\;\underbrace{\frac{1}{1+\frac{4(\omega_0-\omega)^2}{\gamma^2}}}_{\text{lineshape}}$$

# molecules

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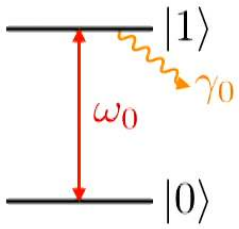


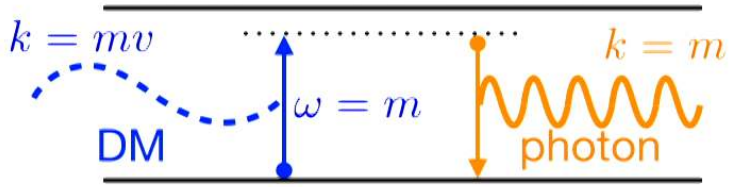


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# molecules

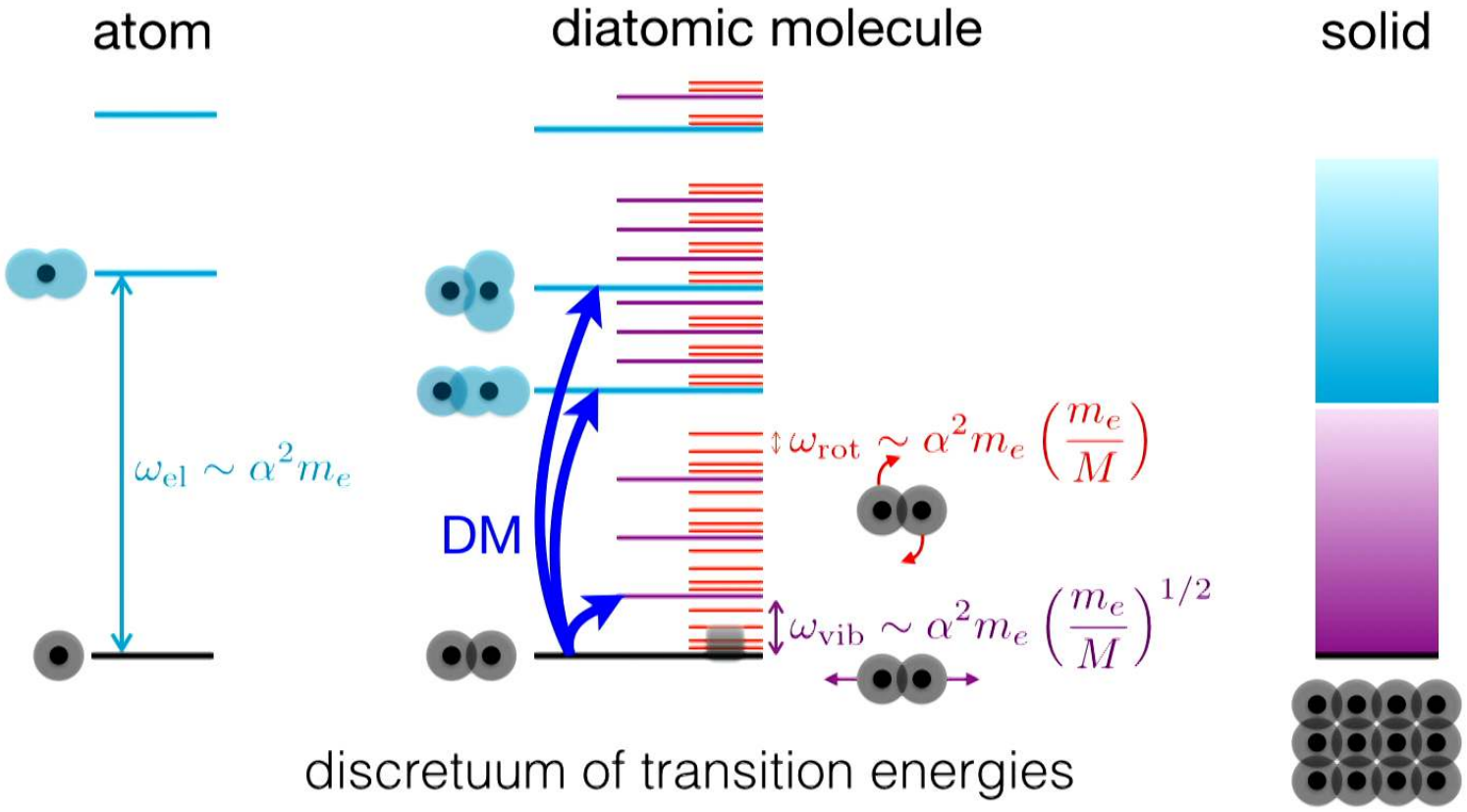
$$\gamma = \gamma_{\rm rad} + 2\gamma_{\rm col} + \frac{\Delta\omega}{\pi}$$

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

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

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

# Molecular levels and transitions




discretuum of transition energies

=

multimode resonator

# DM absorption rate

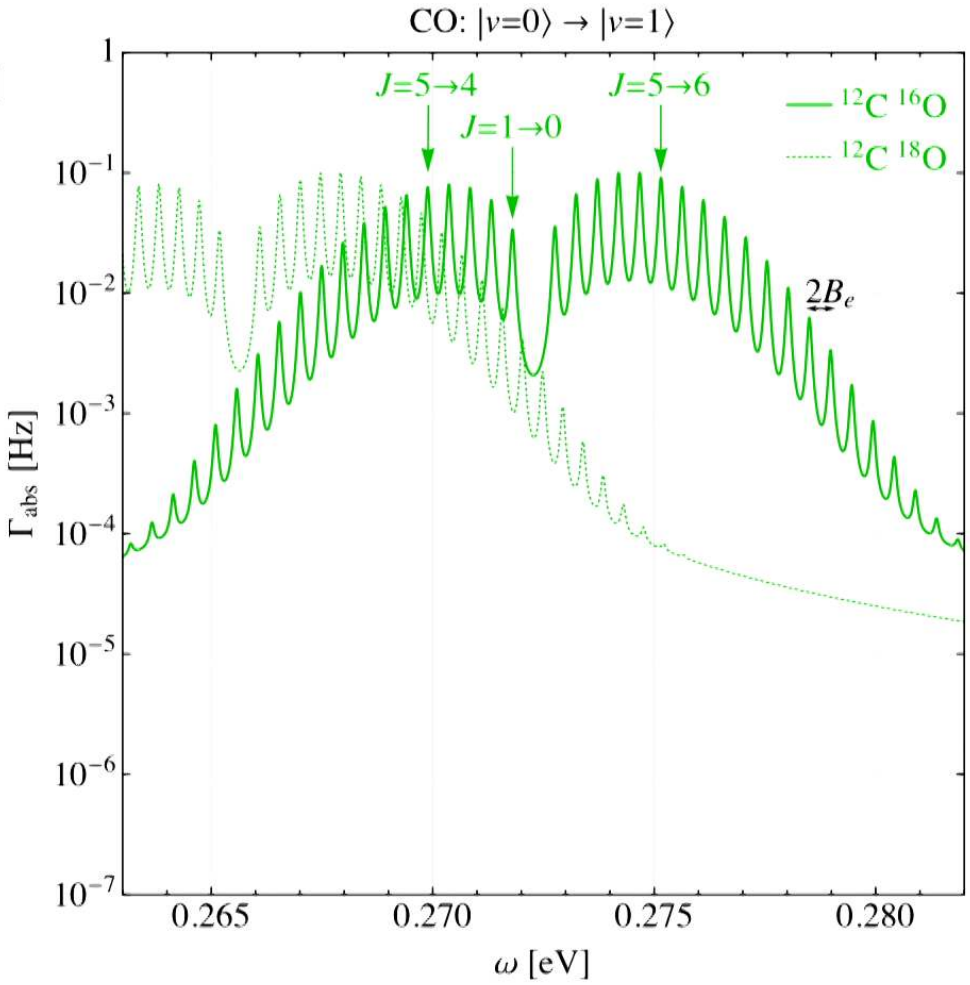
hidden photon DM

$\epsilon = 10^{-12}$

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

$T = 100\ \mathrm{K}$

$P = 5\ \mathrm{bar}$



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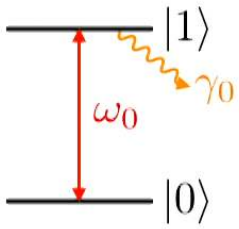


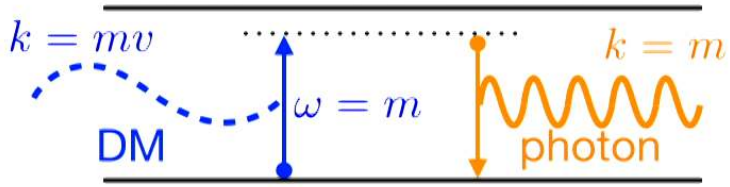


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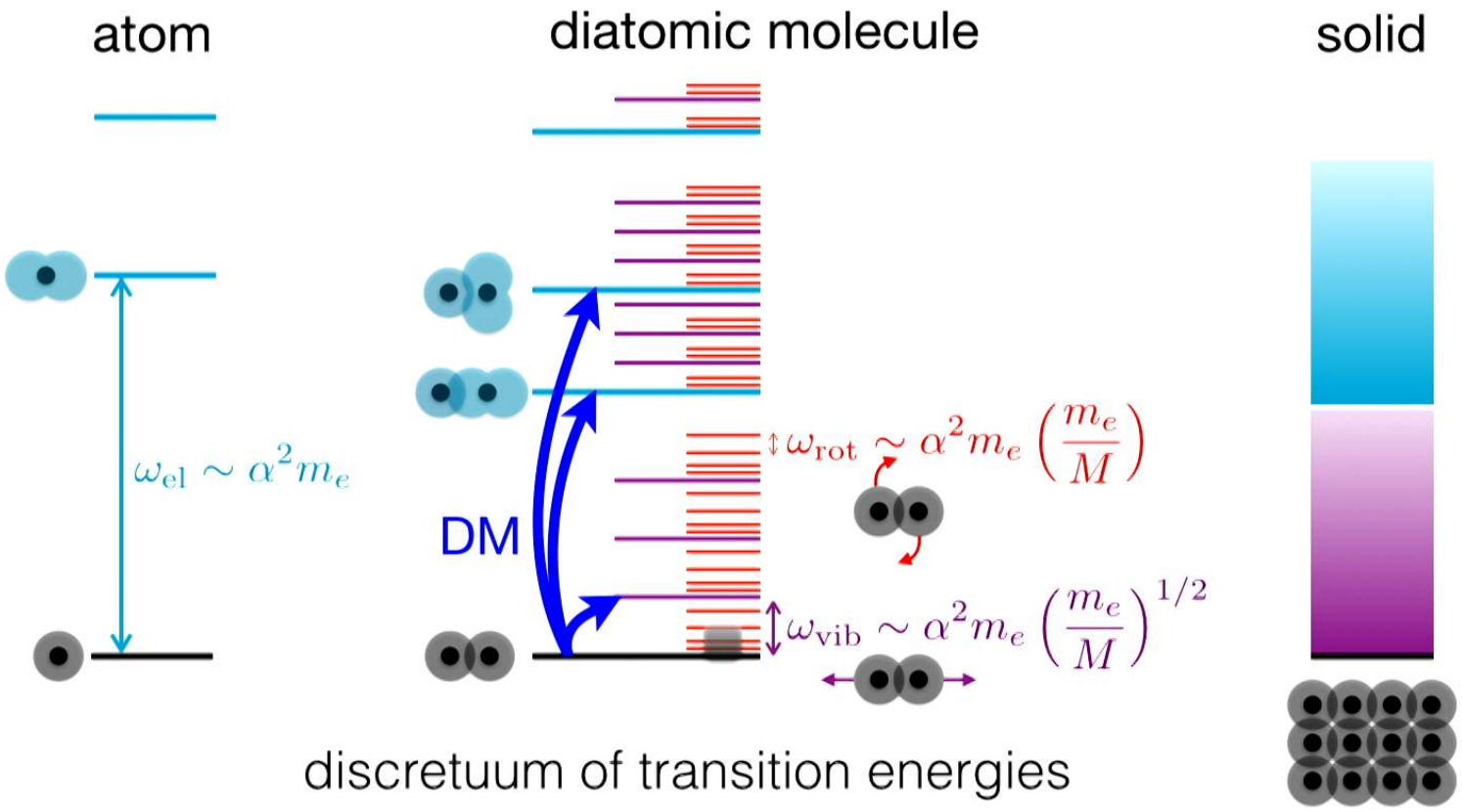


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dynamics of a driven two-level system | overview of molecular levels

(2) Experimental setup

configurations | photon detection | backgrounds | discrimination

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

hidden vectors | moduli | axions

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Why is a molecular gas a good dark matter detector?

calculable { signal rate, backgrounds

discrimination power

established field with rapid technology advancements

# Key considerations

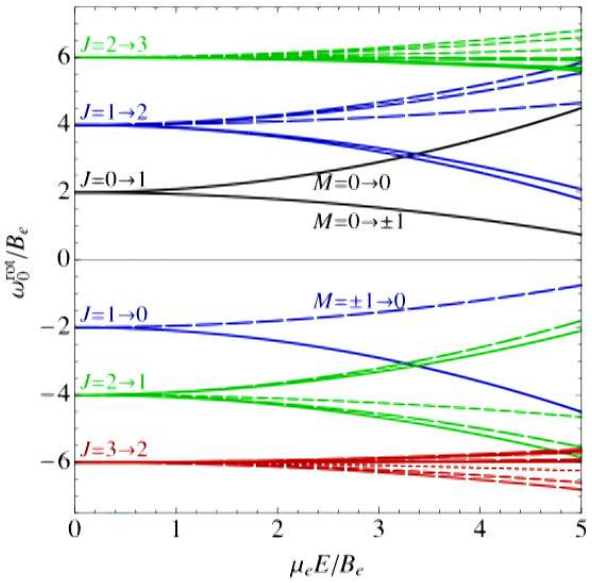
## frequency coverage

— collisional broadening

— molecular species/isotope

— Zeeman tuning

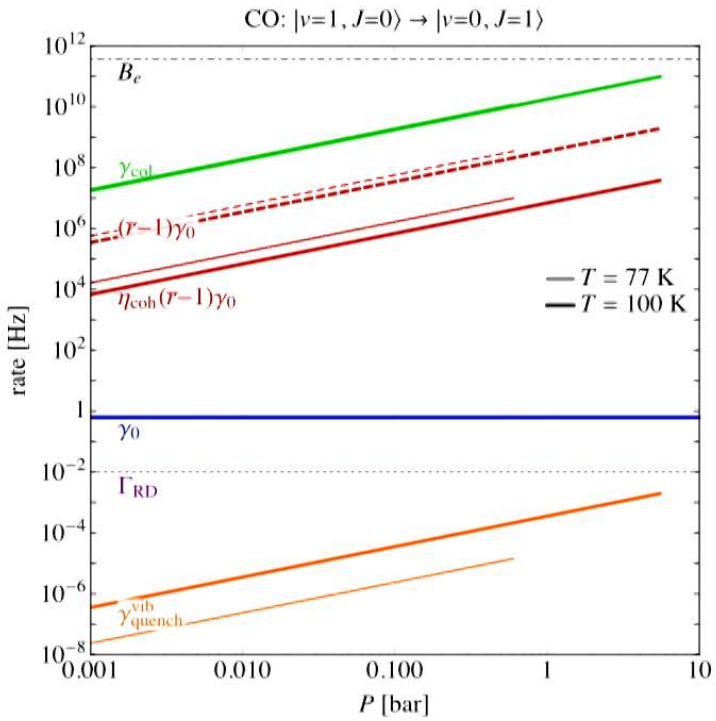
— Stark tuning:



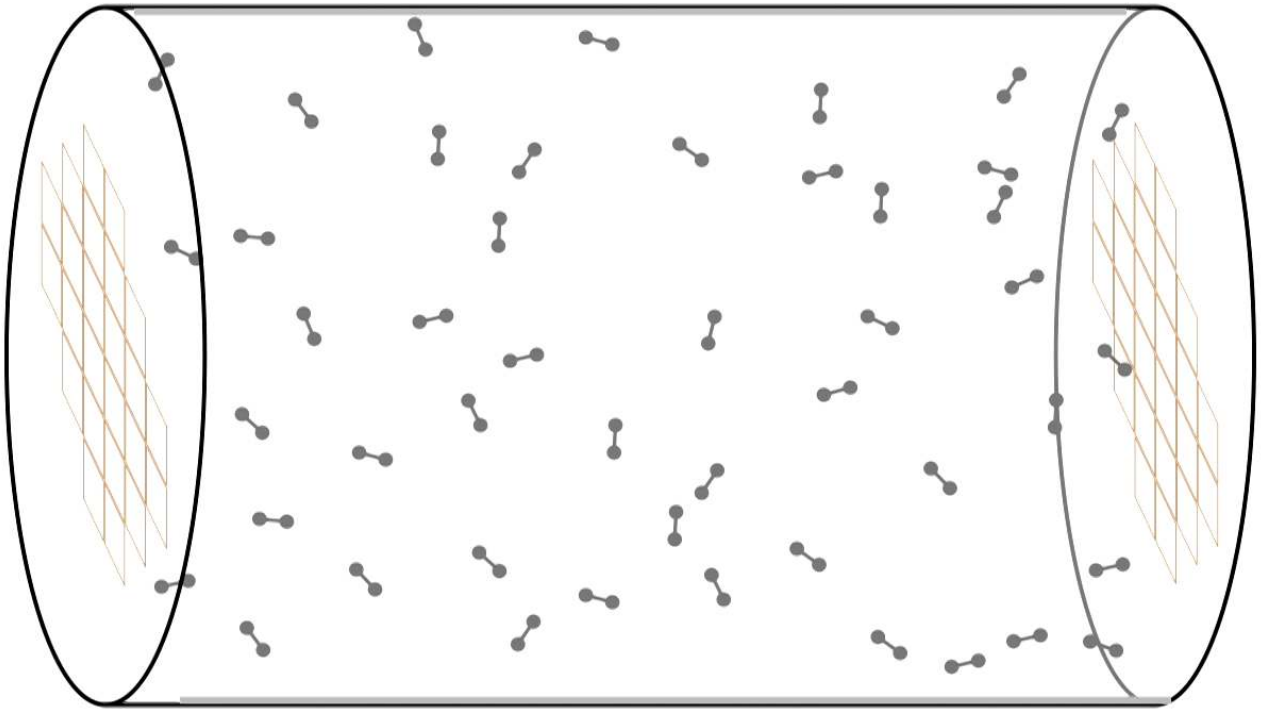

## radiative efficiency

— 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:
$V = (0.3\ \text{m})^3$
$T = 300$ K
PMT

Phase II:
$V = (2\ \text{m})^3$
$T = 100$ 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

$\mathrm{DCR} = 1$ Hz

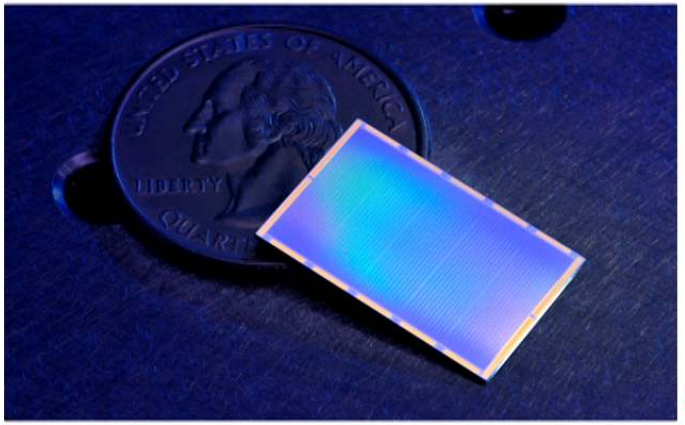
$\eta_{\rm det} \sim 0.3$

Phase II: MKID

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

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

$\Delta E \sim 0.1$ eV



# Cooperative radiation

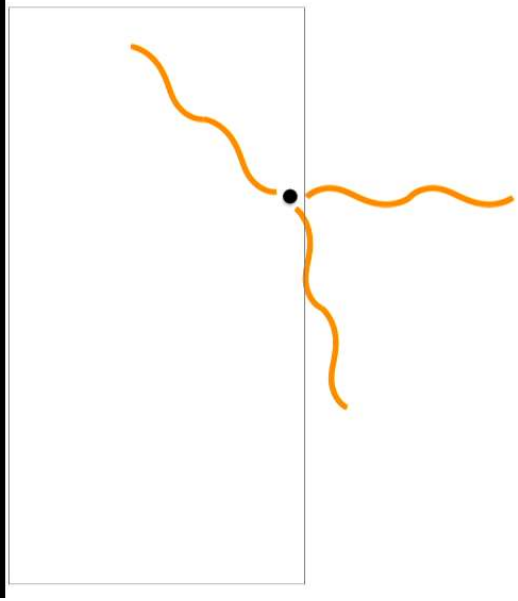
"Add before you square" – M. Kasevich (2017)

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

coherence length: $\lambda_{\rm coh} = \dfrac{2}{m v_0}$

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

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




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

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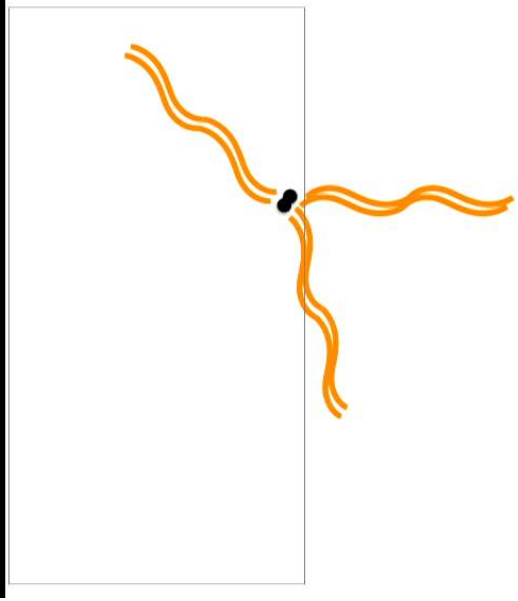


$$\gamma_{\rm rad} = 2\gamma_0$$

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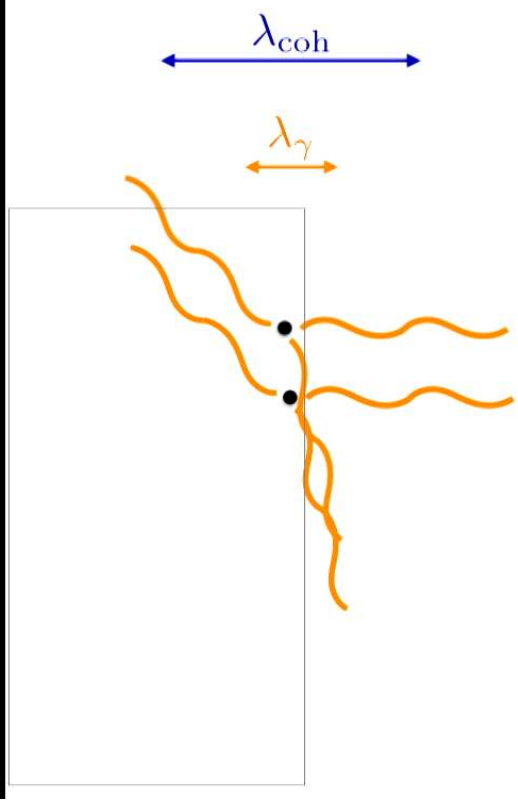


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$$\gamma_{\rm rad} = r(\theta,\varphi)\gamma_0$$

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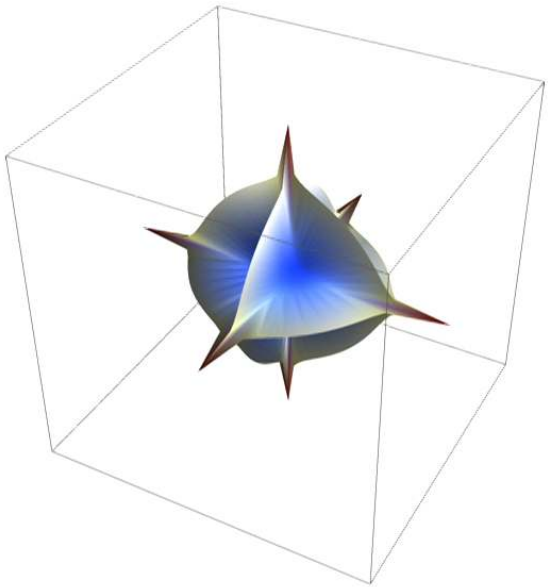

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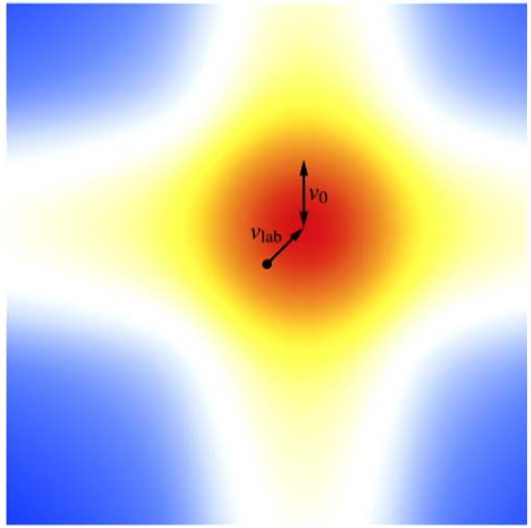
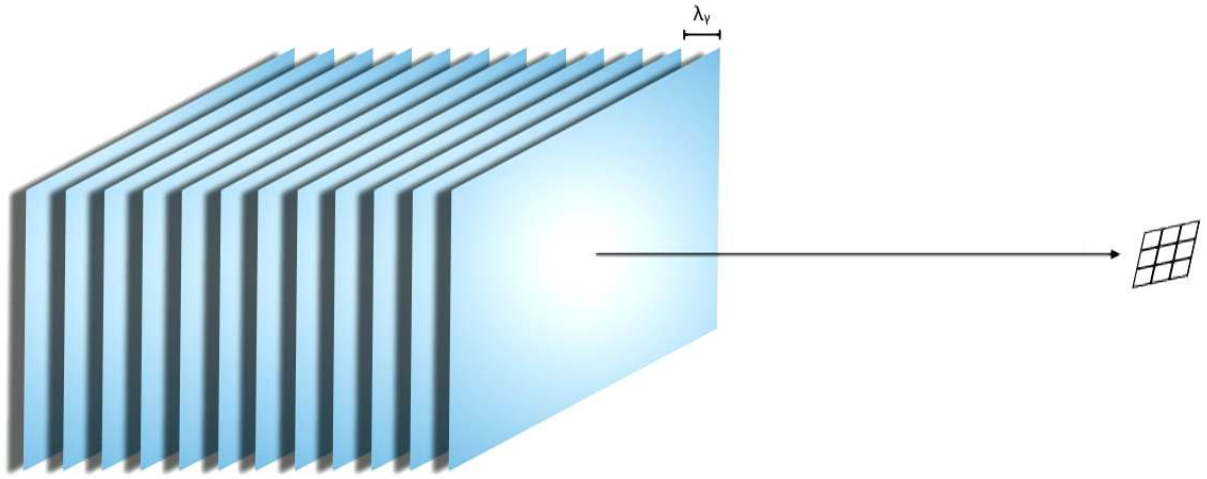


# Stack configuration

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

— enhance radiative width:

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

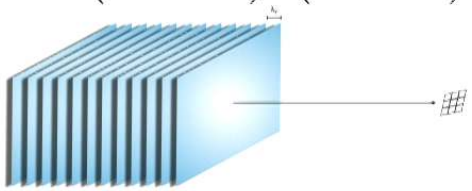


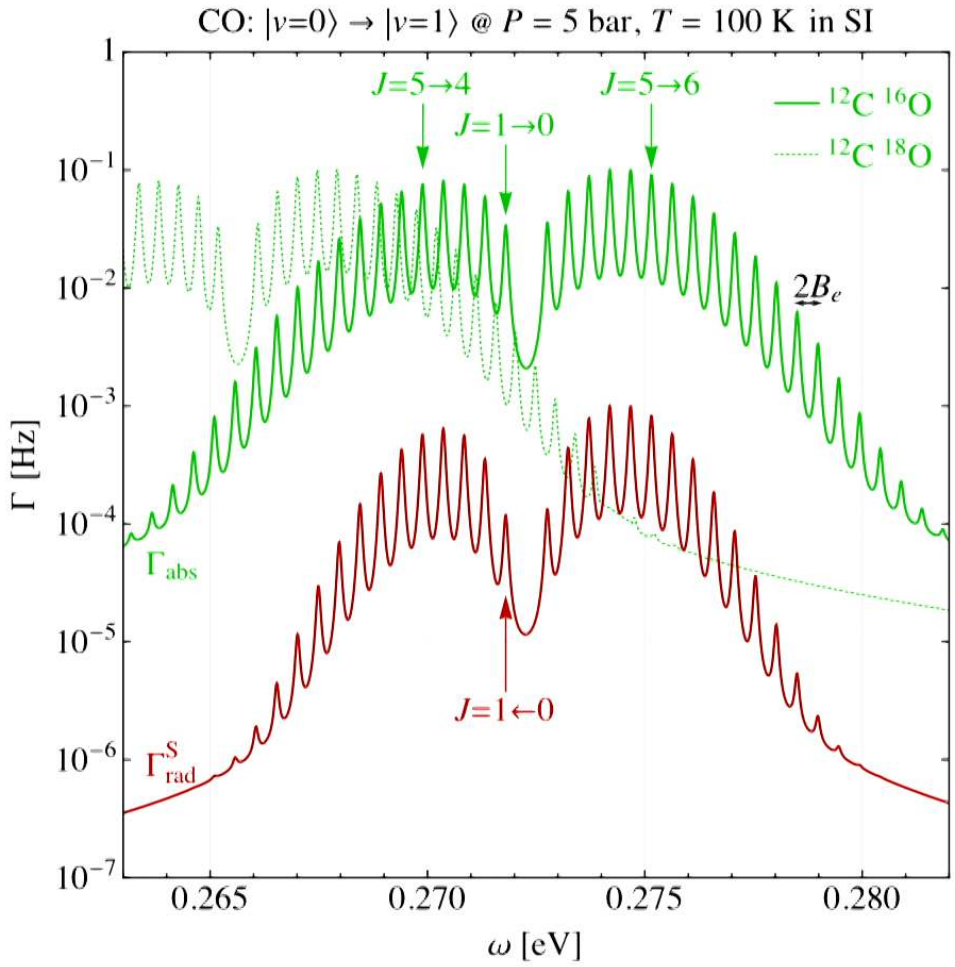
# Absorption + Cooperative fluorescence

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 → $\Gamma_{\rm RD} \sim 10^{-2}$ Hz for meter-scale volume

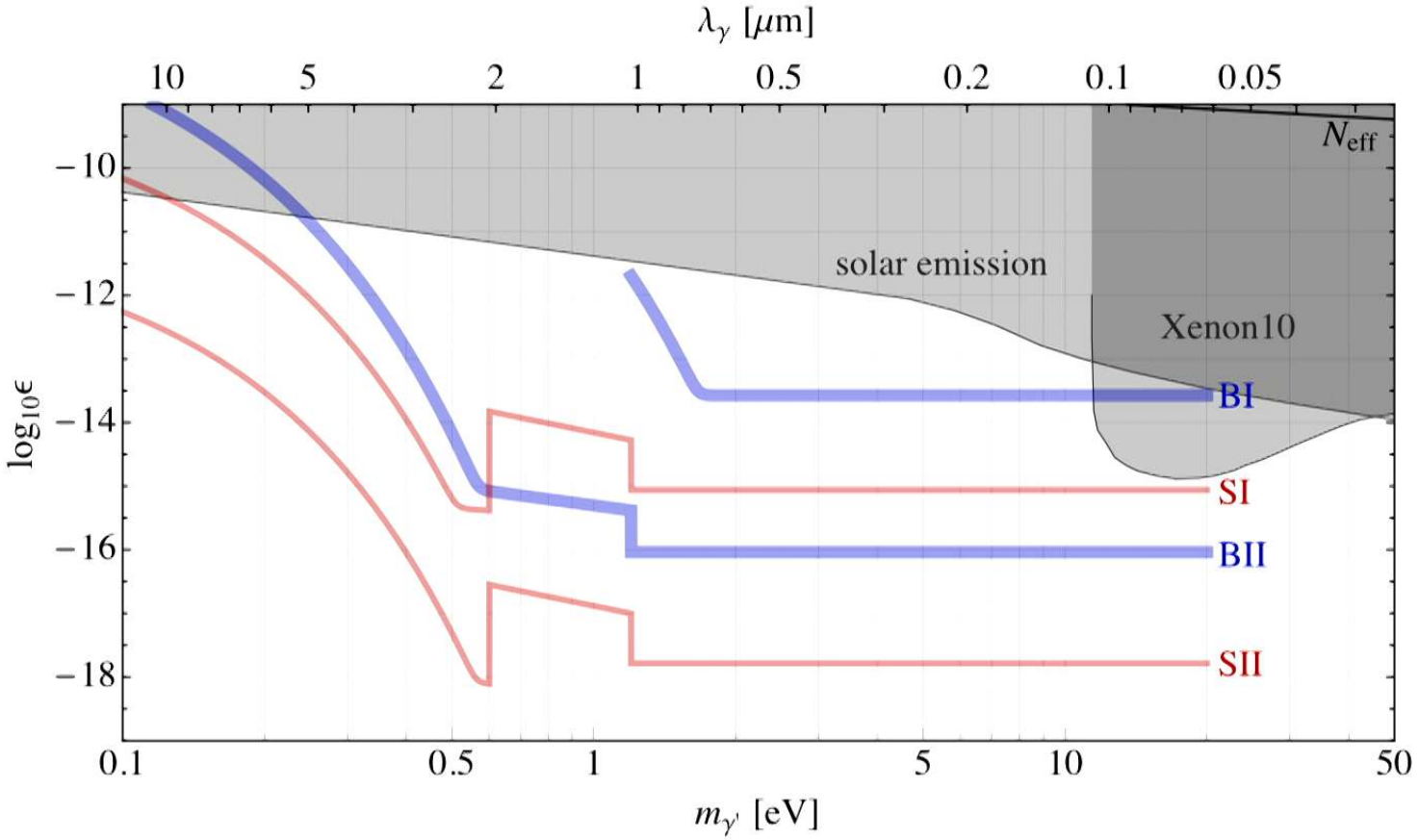
Bulk Phase I: subdominant to DCR

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: $m < 0.2$ 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 $\delta H$ | Transition type and selection rules | | $\Omega\,[\mathrm{rad\ s^{-1}}]$ |
|---|---|---|---|---|---|
| spin-0 | parity-even | $(d_{m_e}+d_e)\tilde{\phi}k_eR_eR$ | 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** | $\Delta v=1,\Delta J=\pm1,\lvert\Delta S_N\rvert\le1$ | $1.7\times10^{-10}\,\frac{G_{aNN}}{10^{-8}/\mathrm{GeV}}$ |
| | | | **rot** | $\Delta J=1,\lvert\Delta S_N\rvert=1$ | $2.5\times10^{-11}\,\frac{G_{aNN}}{10^{-8}/\mathrm{GeV}}$ |
| | | $\frac{d_g}{f_a}a\,\boldsymbol{\sigma}_N\cdot\mathbf{E}$ | **vib** | $\Delta v=1,\Delta J=\pm1,\lvert\Delta S_N\rvert\le1$ | $4.0\times10^{-12}\,\frac{10^8\ \mathrm{GeV}}{f_a}$ |
| | | | **rot** | $\Delta J=1,\lvert\Delta S_N\rvert\le1$ | $5.8\times10^{-13}\,\frac{10^8\ \mathrm{GeV}}{f_a}$ |
| | | $G_{aee}\,\partial_t a\,\boldsymbol{\sigma}_e\cdot\frac{-\mathrm{i}\boldsymbol{\nabla}_e}{m_e}$ | **el** | $\lvert\Delta\Lambda\rvert\le1,\Delta i=1,\lvert\Delta S_e\rvert\le1$ | $4.0\times10^{-10}\,\frac{G_{aee}}{10^{-10}/\mathrm{GeV}}$ |
| | | $G_{a\gamma\gamma}\,a\,\mathbf{E}\cdot\mathbf{B}$ | 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** | $\Delta J=1$ | $5.0\times10^{-10}\,\frac{g}{10^{-18}}$ |