Direct detection of dark matter through molecular excitations

J. Pérez-Ríos[1], H. Ramani[2], O. Slone[3], E. Figueroa[4] and R. Essig[5]

[1]School of Science and Technology, Universidad del Turabo, USA

[2]Berkeley Center for Theoretical Physics, Berkeley University, USA

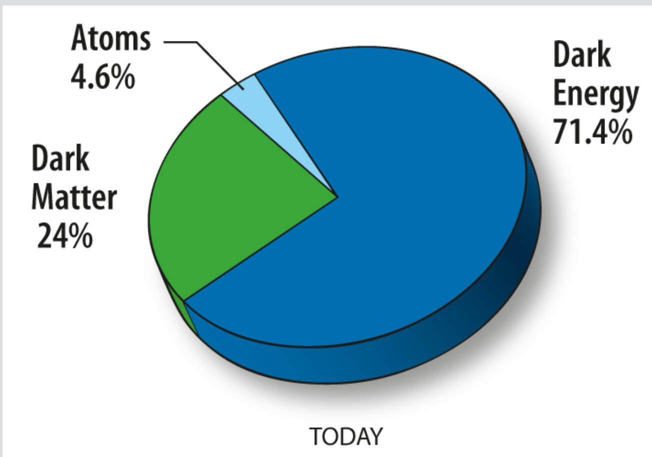
[3]Princeton Center for Theoretical Science, Princeton University, USA

[4]Department of Physics and Astronomy, Stony Brook University, USA

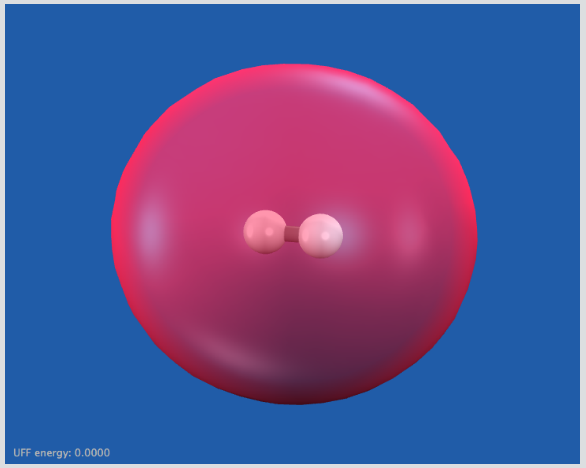
[5]C. N. Yang Institute for Theoretical Physics, Stony Brook University, USA

Outlook

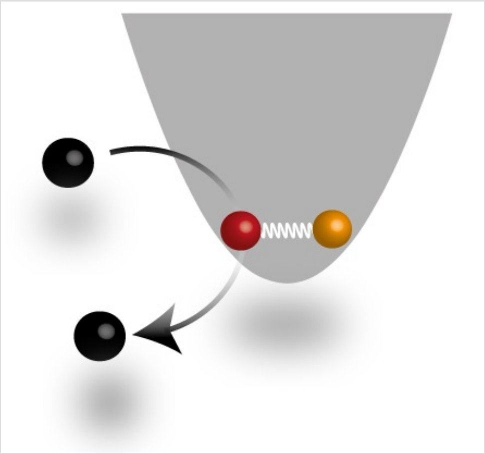
Dark Matter



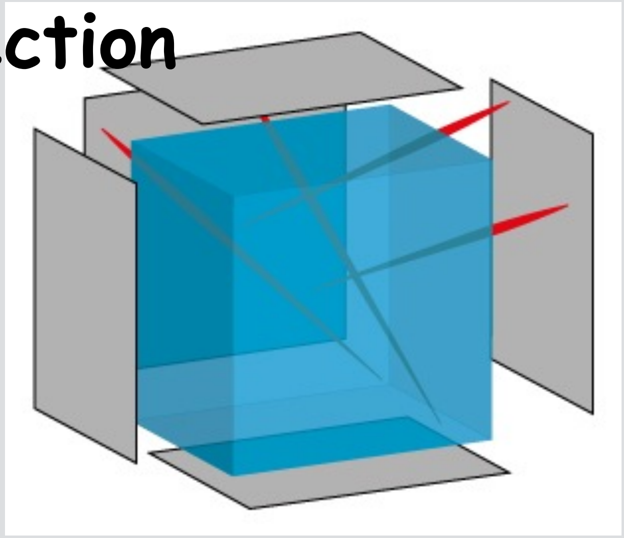
Molecules



Molecules as a probe of DM?



A novel approach for DM detection



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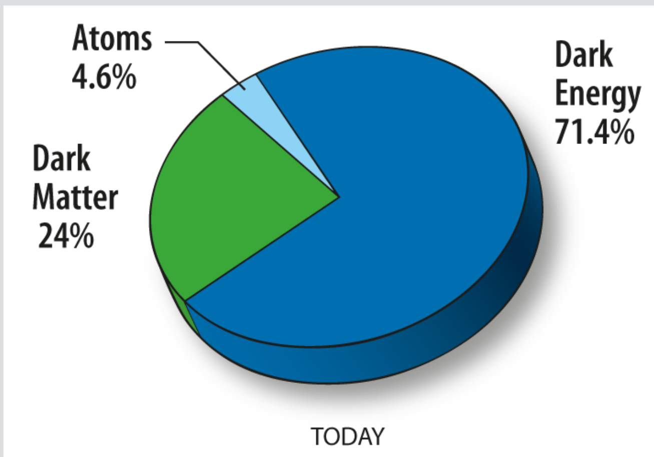

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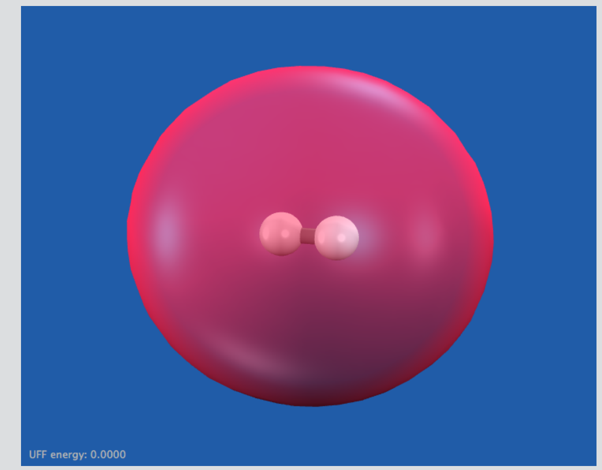

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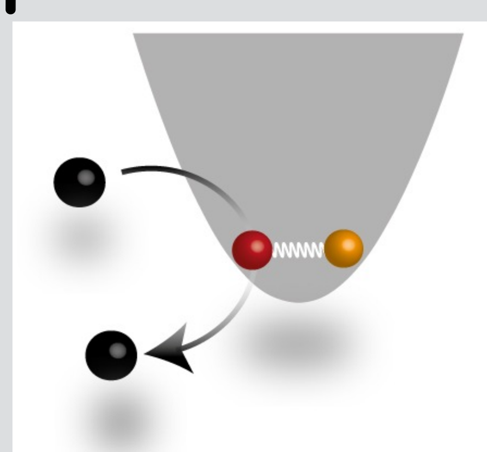

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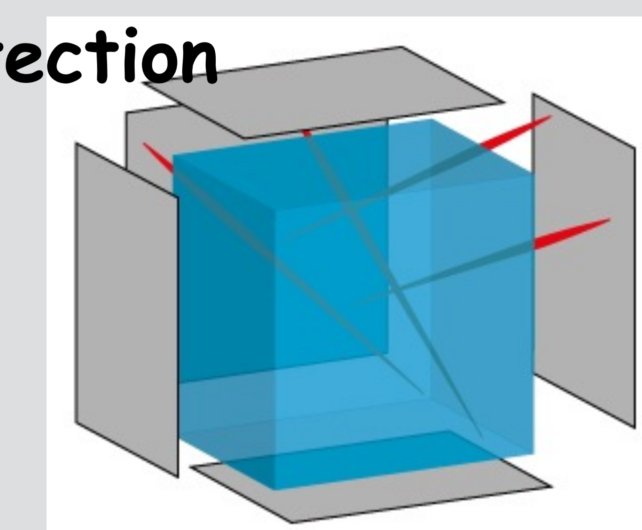

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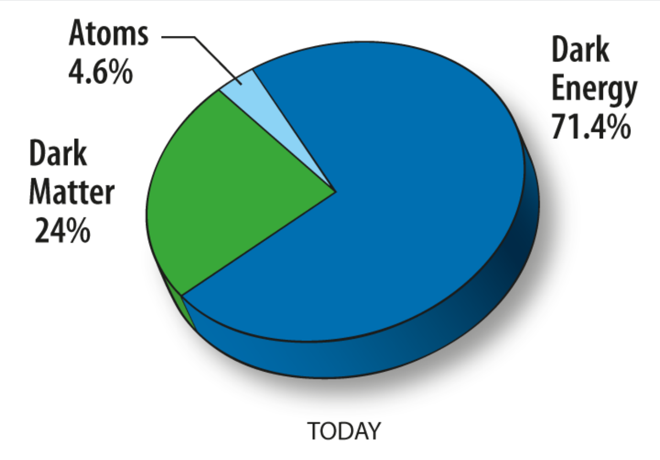

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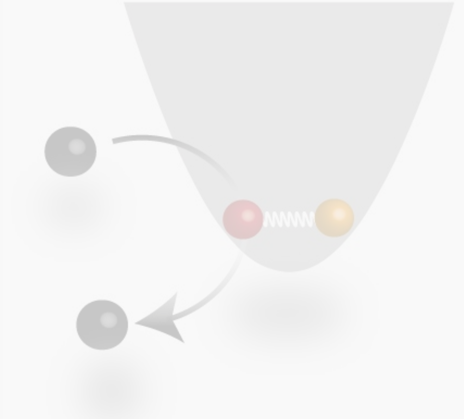

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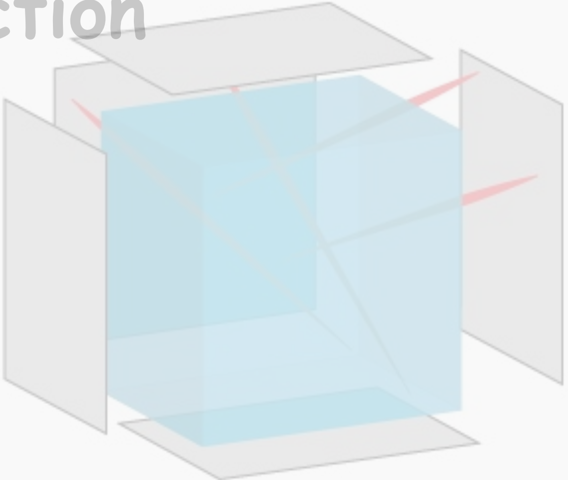

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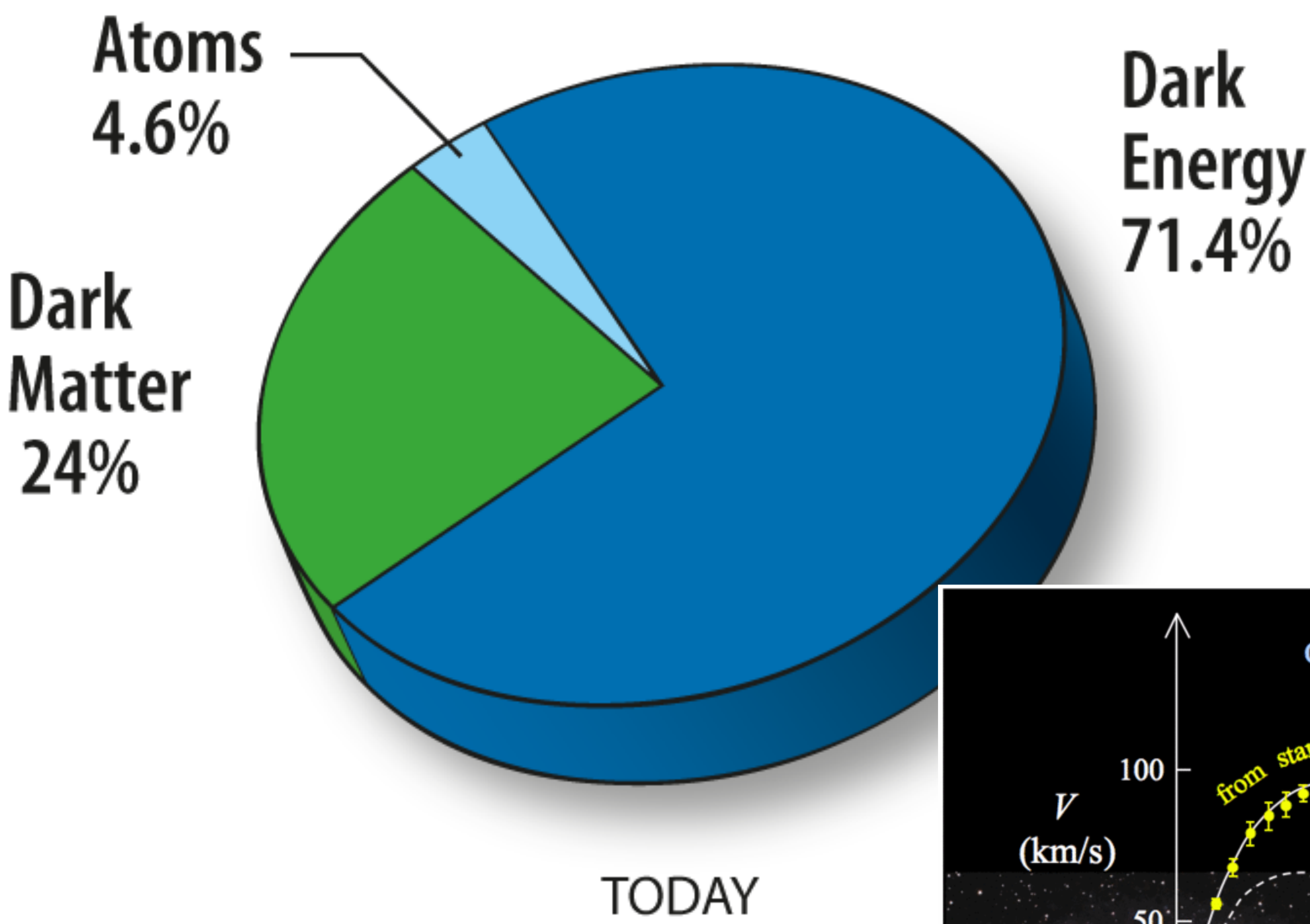
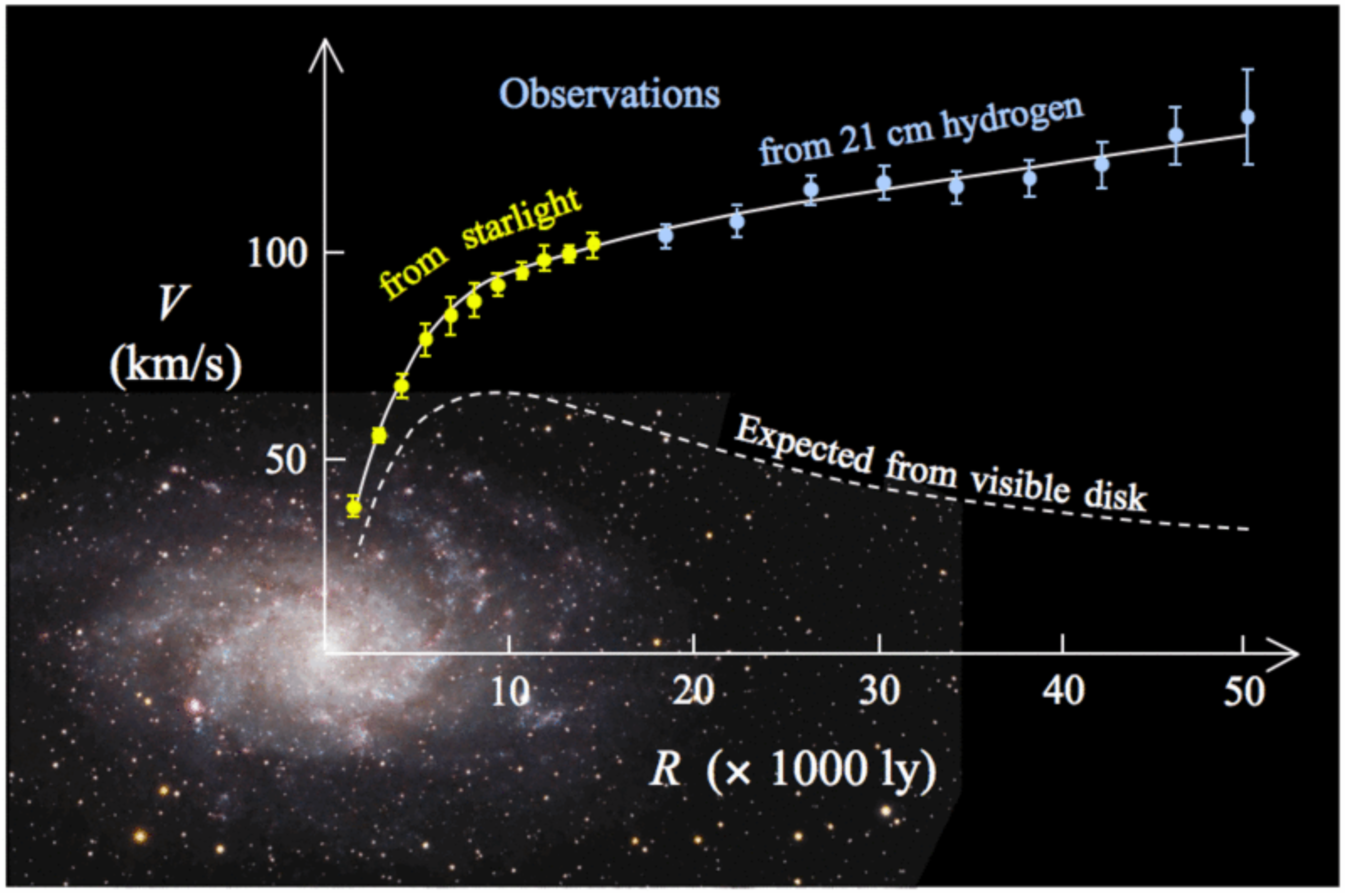


Atoms
4.6%
Dark
Energy
71.4%
Dark
Matter
24%
TODAY



Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

Dark Matter

Dark Matter Candidates from Particle Physics and Methods of Detection

Jonathan L. Feng

Department of Physics and Astronomy, University of California, Irvine, California 92697;
email: jlf[at]uci.edu

Annu. Rev. Astron. Astrophys. 2010. 48:495–545

Table 1 Summary of dark matter particle candidates, their properties, and their potential methods of detection

	WIMPs	SuperWIMPs	Light $\tilde{G}$	Hidden DM	Sterile ν	Axions
Motivation	GHP	GHP	GHP/NPFP	GHP/NPFP	ν Mass	Strong CP
Naturally Correct Ω	Yes	Yes	No	Possible	No	No
Production Mechanism	Freeze Out	Decay	Thermal	Various	Various	Various
Mass Range	GeV-TeV	GeV-TeV	eV-keV	GeV–TeV	keV	μeV–meV
Temperature	Cold	Cold/Warm	Cold/Warm	Cold/Warm	Warm	Cold
Collisional				√		
Early Universe		√√		√		
Direct Detection	√√			√		√√
Indirect Detection	√√	√		√	√√	
Particle Colliders	√√	√√	√√	√		

Dark Matter

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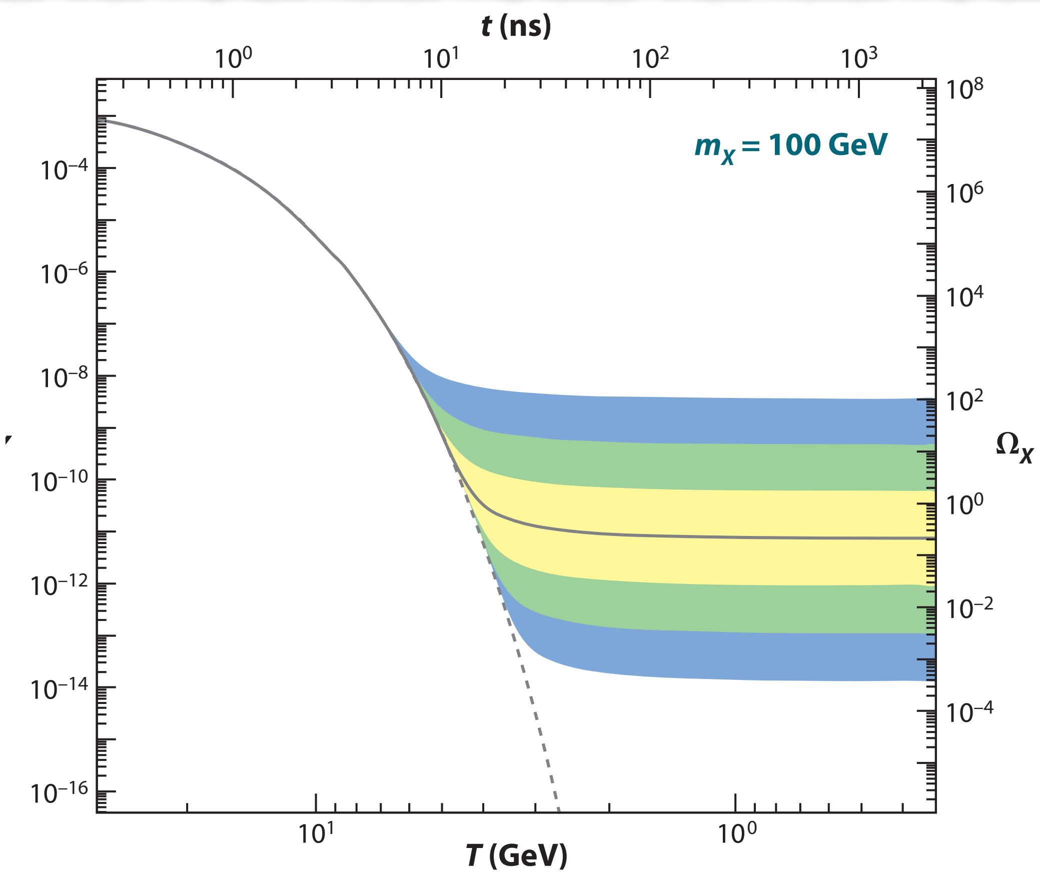

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Collisional				√		
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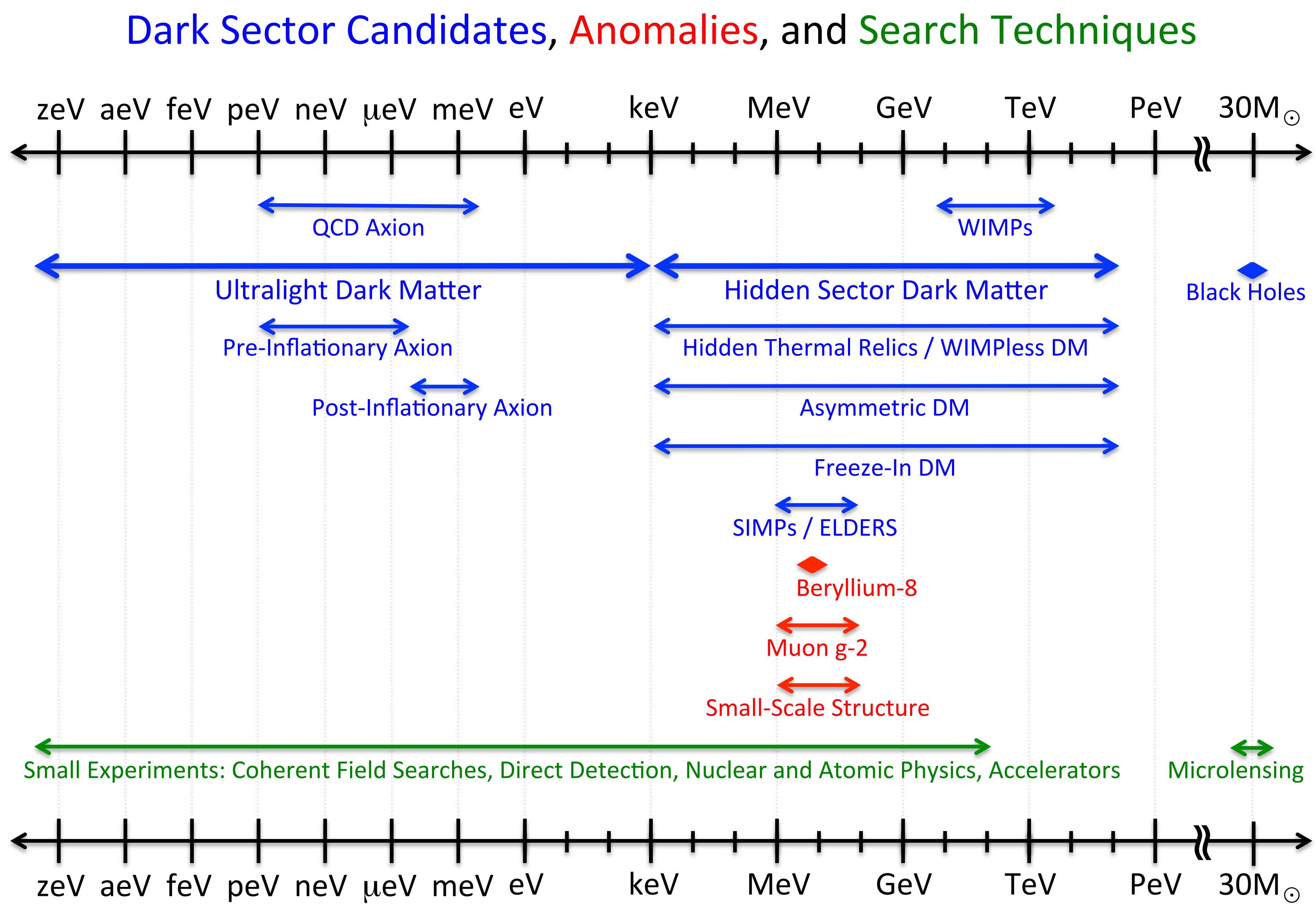
Dark Matter

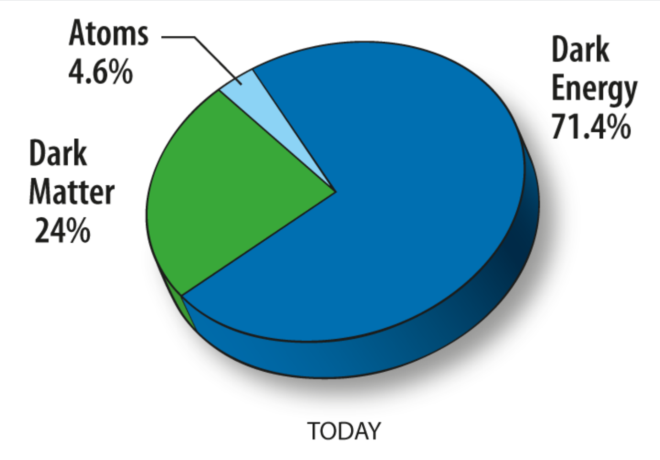
US Cosmic Visions: New Ideas in Dark Matter 2017 :
Community Report

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017



Outlook

Dark Matter



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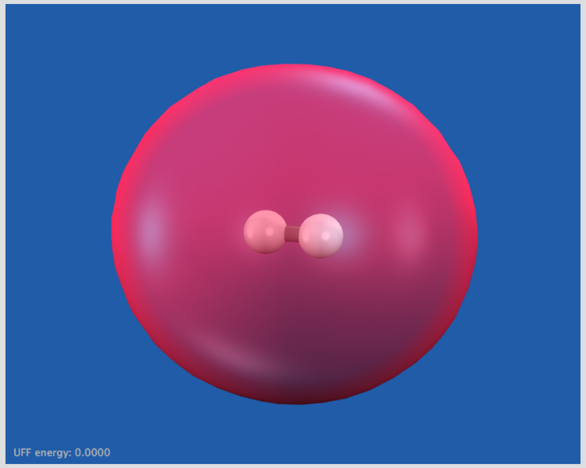

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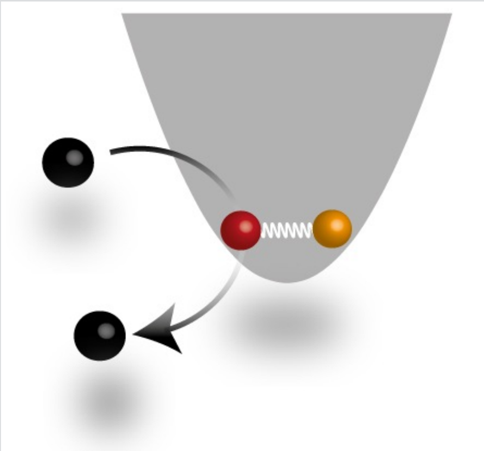

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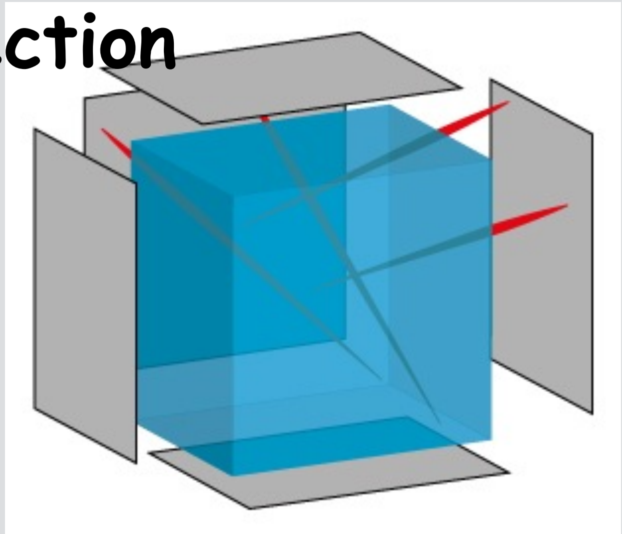

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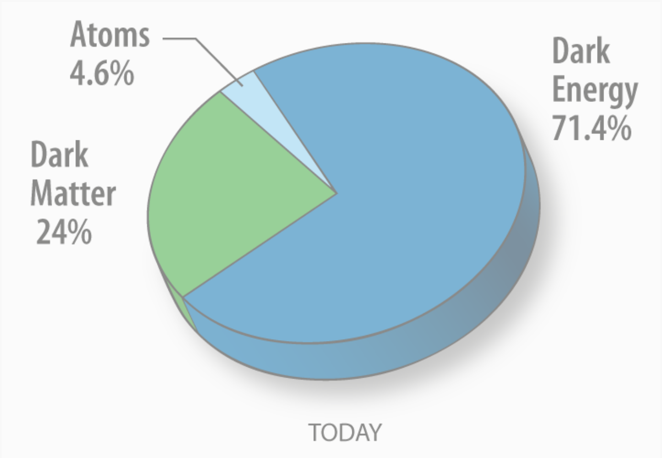
Dark Matter



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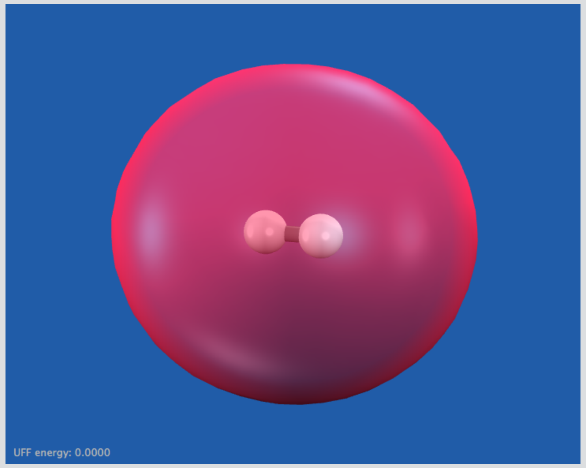

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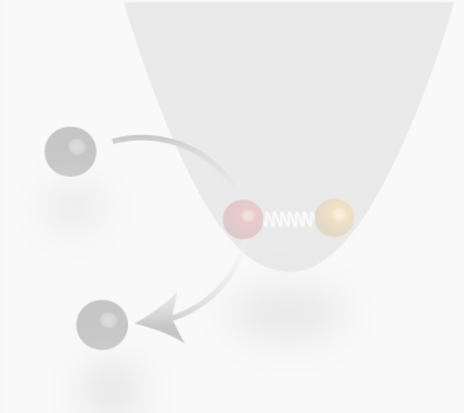

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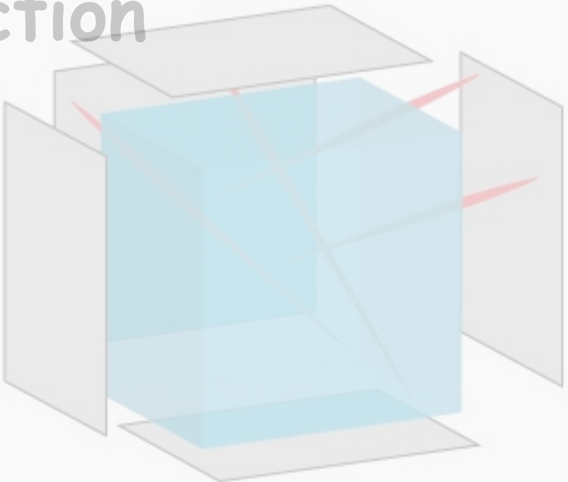

Molecules

Molecules are fun!!!!

$$H = H_{\text{el}} + T_N$$

$$H_{\text{el}} = T_e + V_{ee} + V_{NN} + V_{Ne}$$

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$$\Psi(\vec{r}, \vec{R}) = \phi_{el}(\vec{r}; \vec{R})\phi_N(\vec{R})$$

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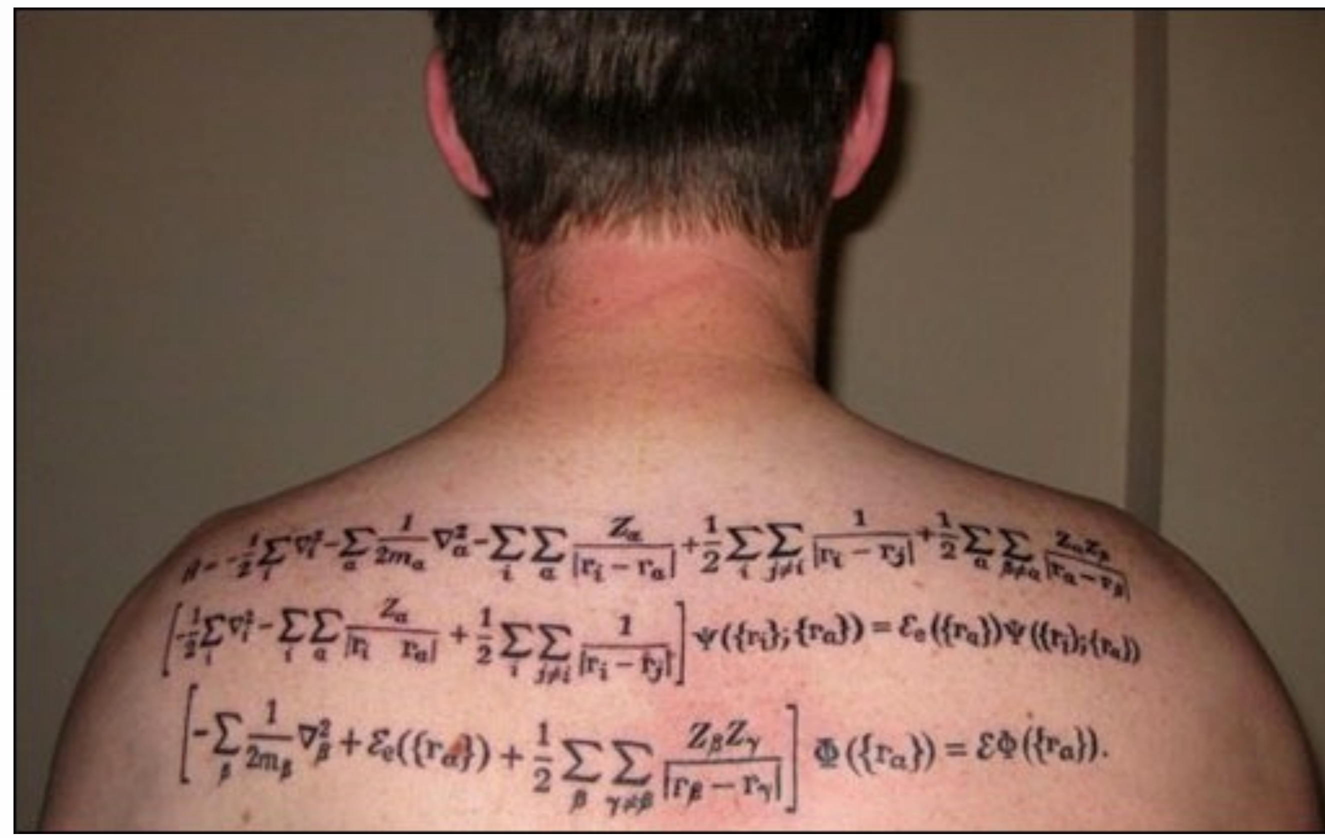

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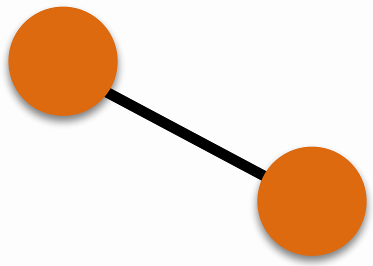

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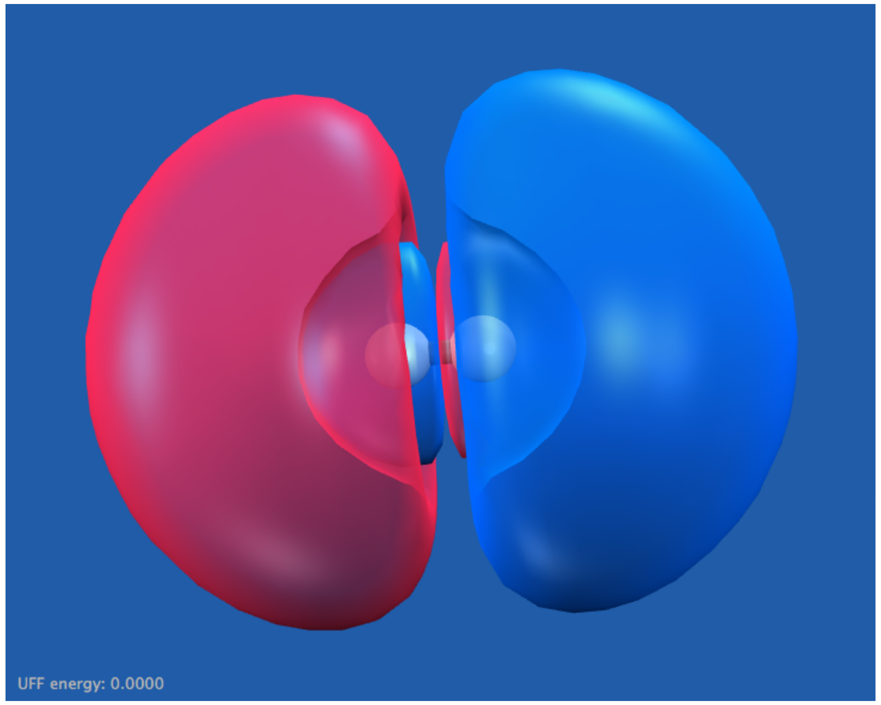

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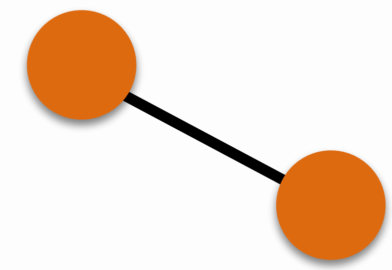

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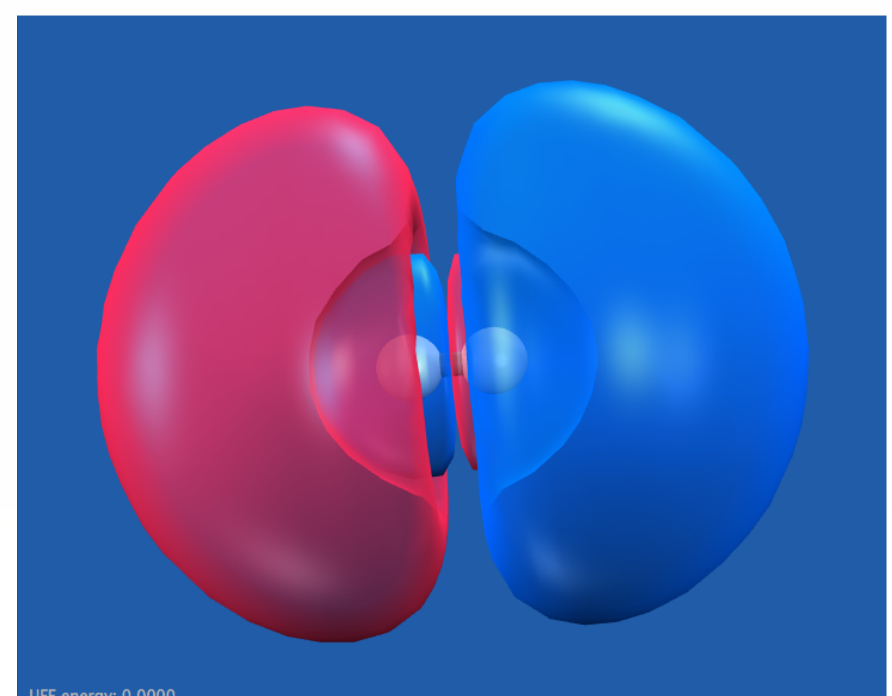

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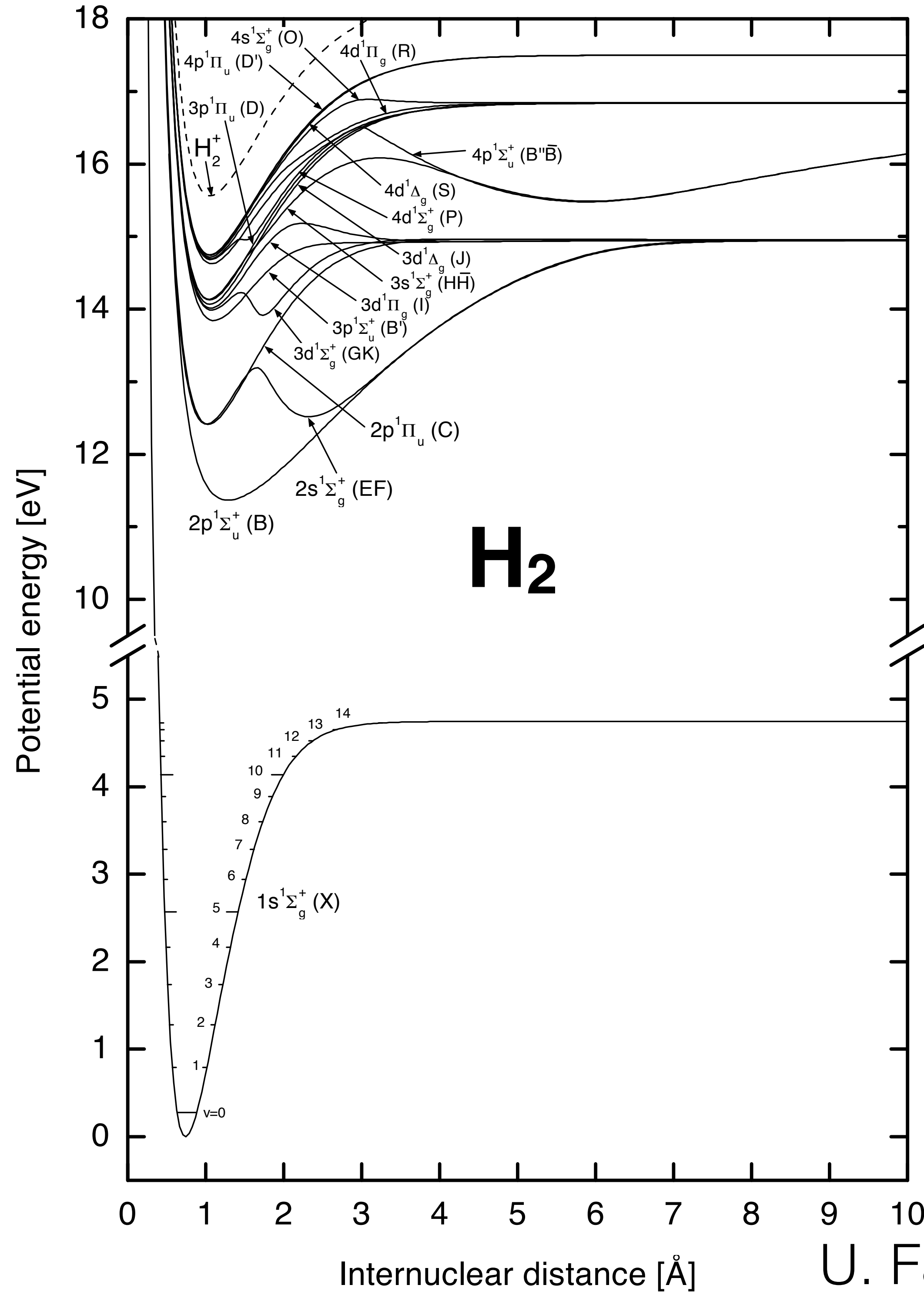

U. Fantz and D. Wünderlich

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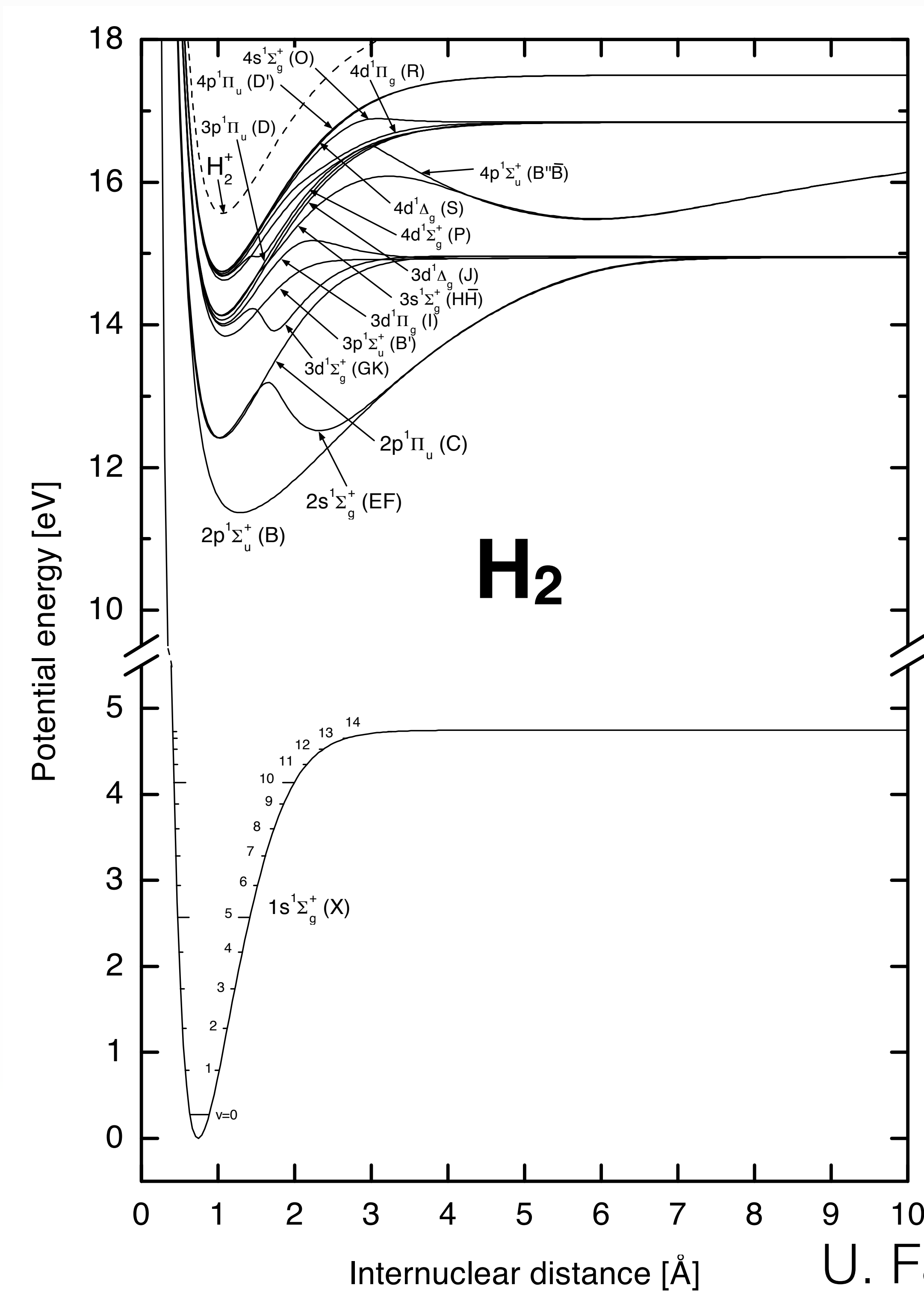

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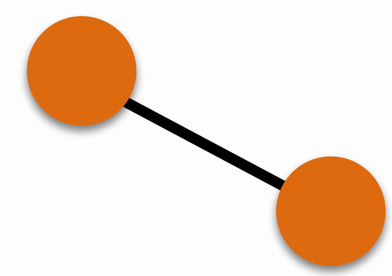

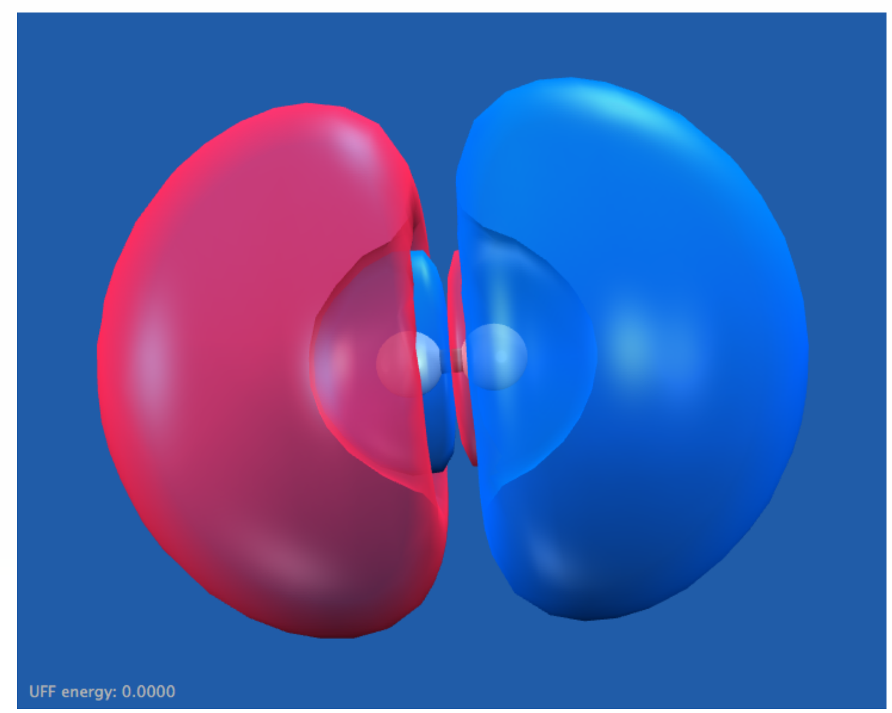

Molecules

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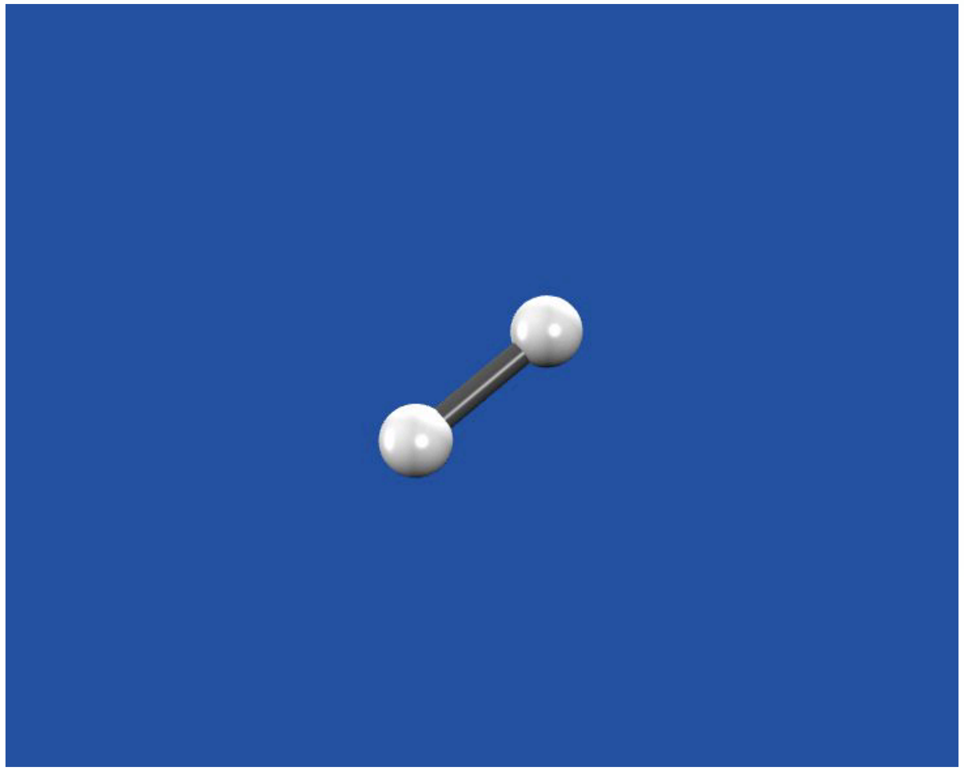
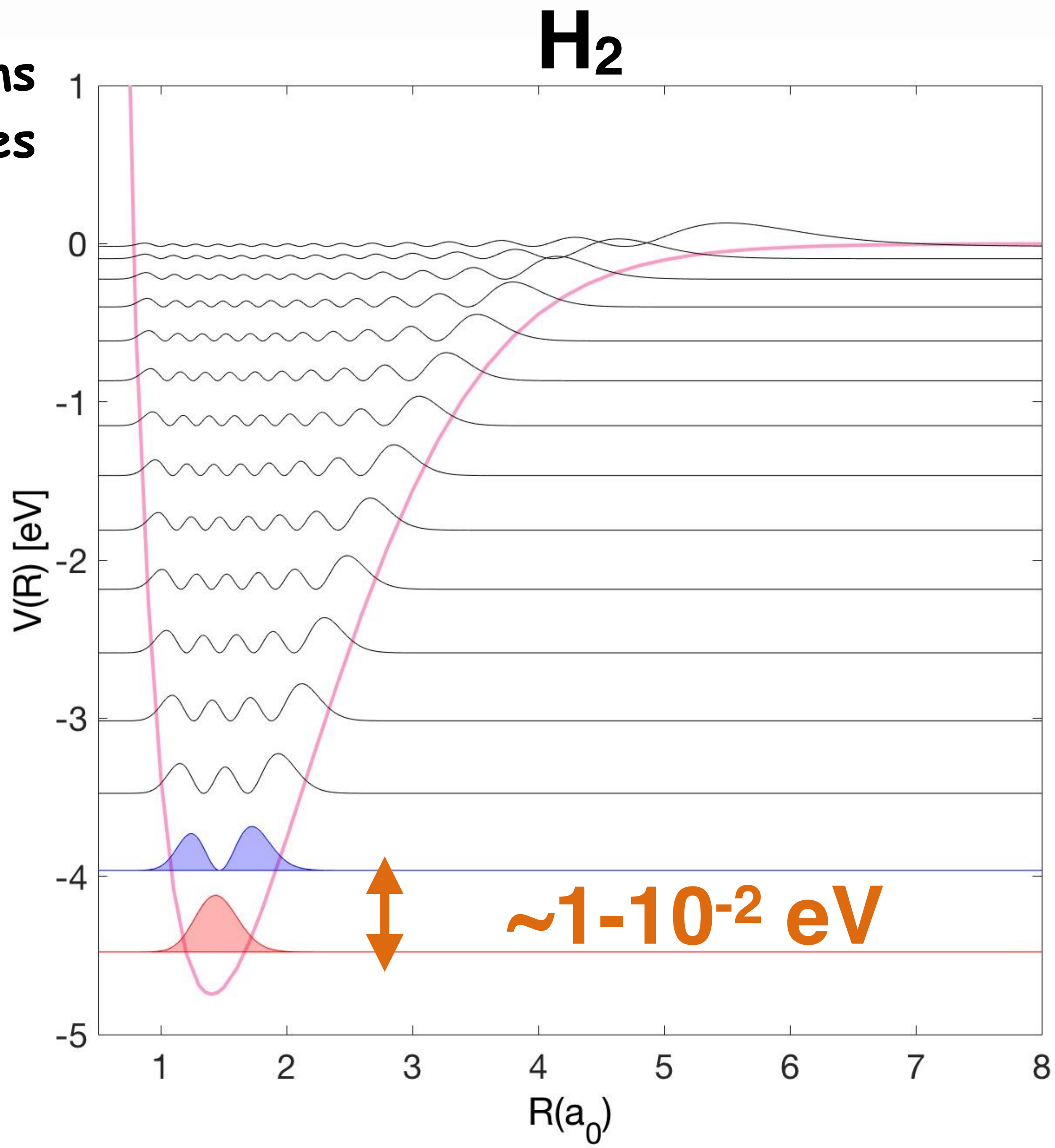
Molecules are more versatile than atoms thanks to the presence of internal degrees of freedom:

- Electronic
- Vibrational
- Rotational





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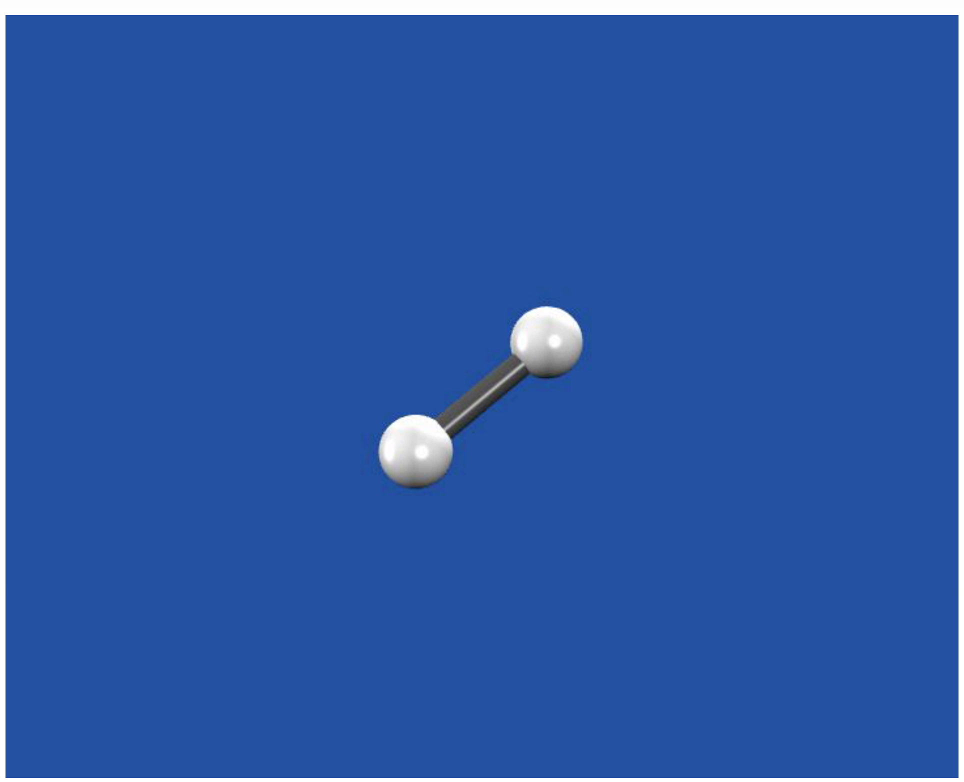
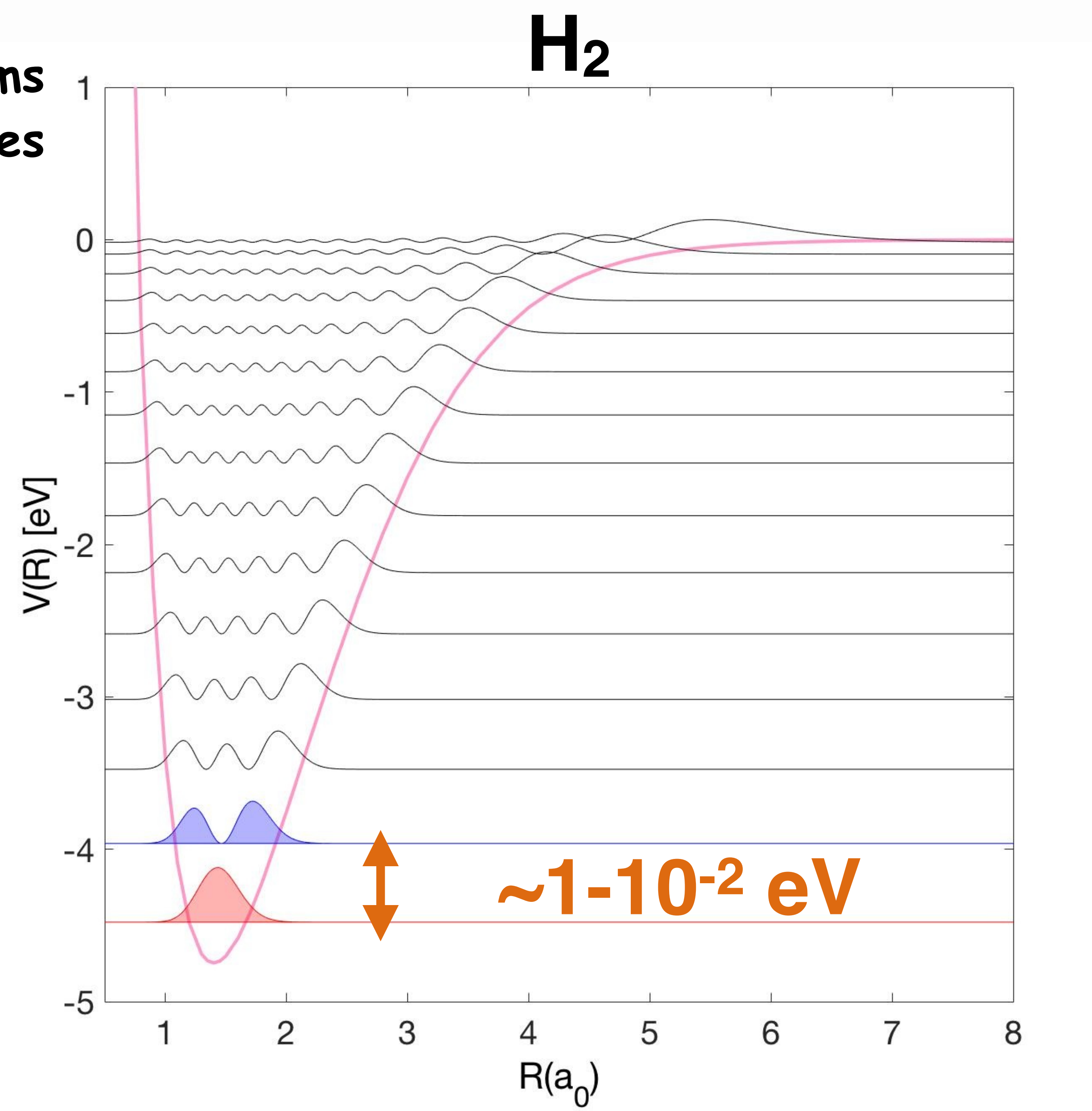
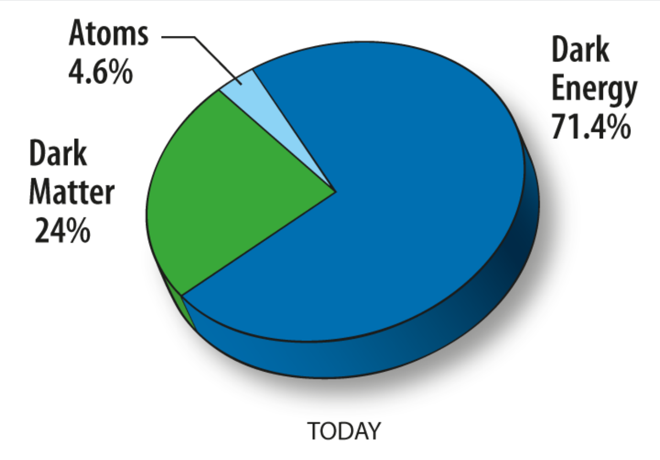




Outlook

Dark Matter



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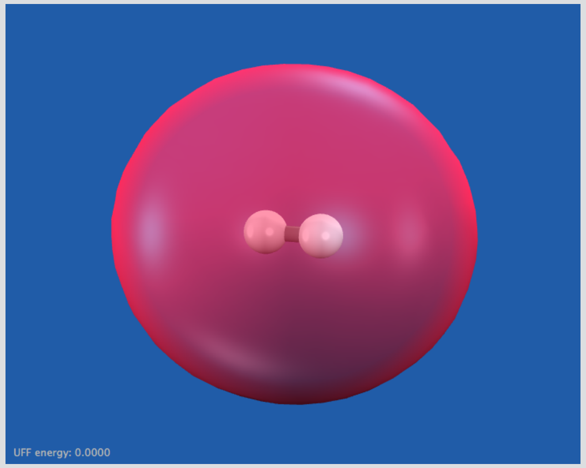
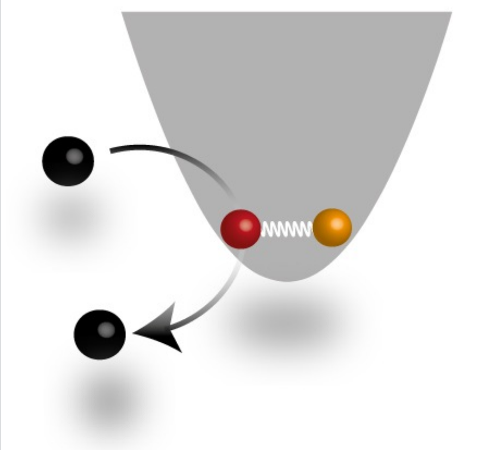


Molecules as a probe of DM?



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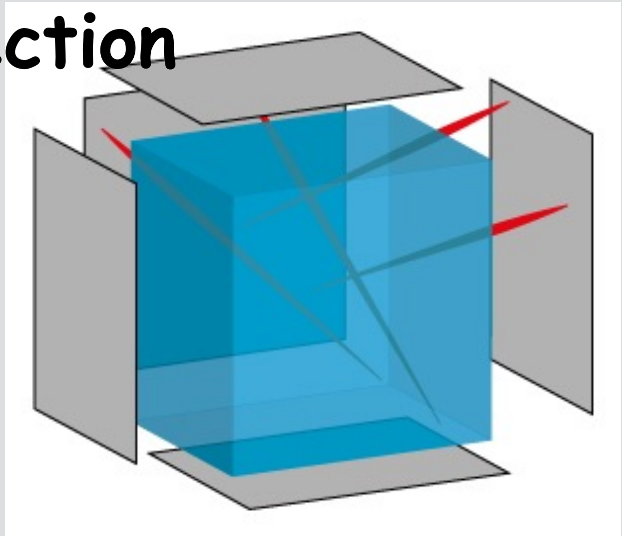

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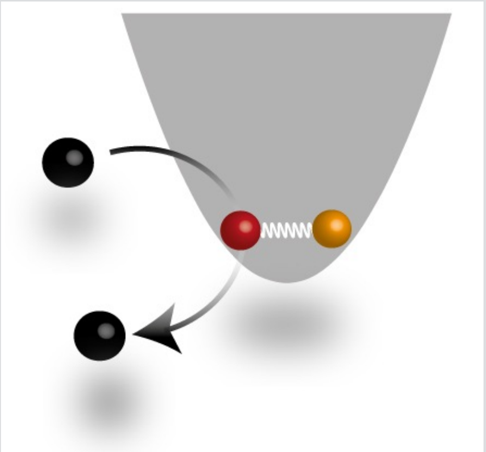

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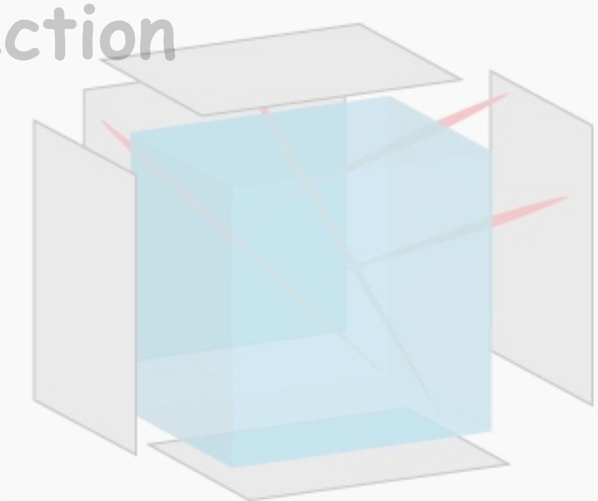

Molecules as a probe of DM?

PHYSICAL REVIEW D **85,** 076007 (2012)

Direct detection of sub-GeV dark matter

Rouven Essig,[1] Jeremy Mardon,[2,3,4] and Tomer Volansky[2,3]

[1] *SLAC National Accelerator Laboratory, Stanford University, Menlo Park, California 94025, USA*
[2] *Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, California 94720, USA*
[3] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4] *Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
(Received 2 October 2011; published 9 April 2012)

$$E_{tot} = m_{DM} v^2/2 = 50 \text{ eV} \times (m_{DM}/100 \text{ MeV})$$

Molecules as a probe of DM?

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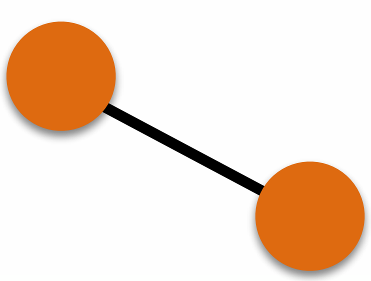
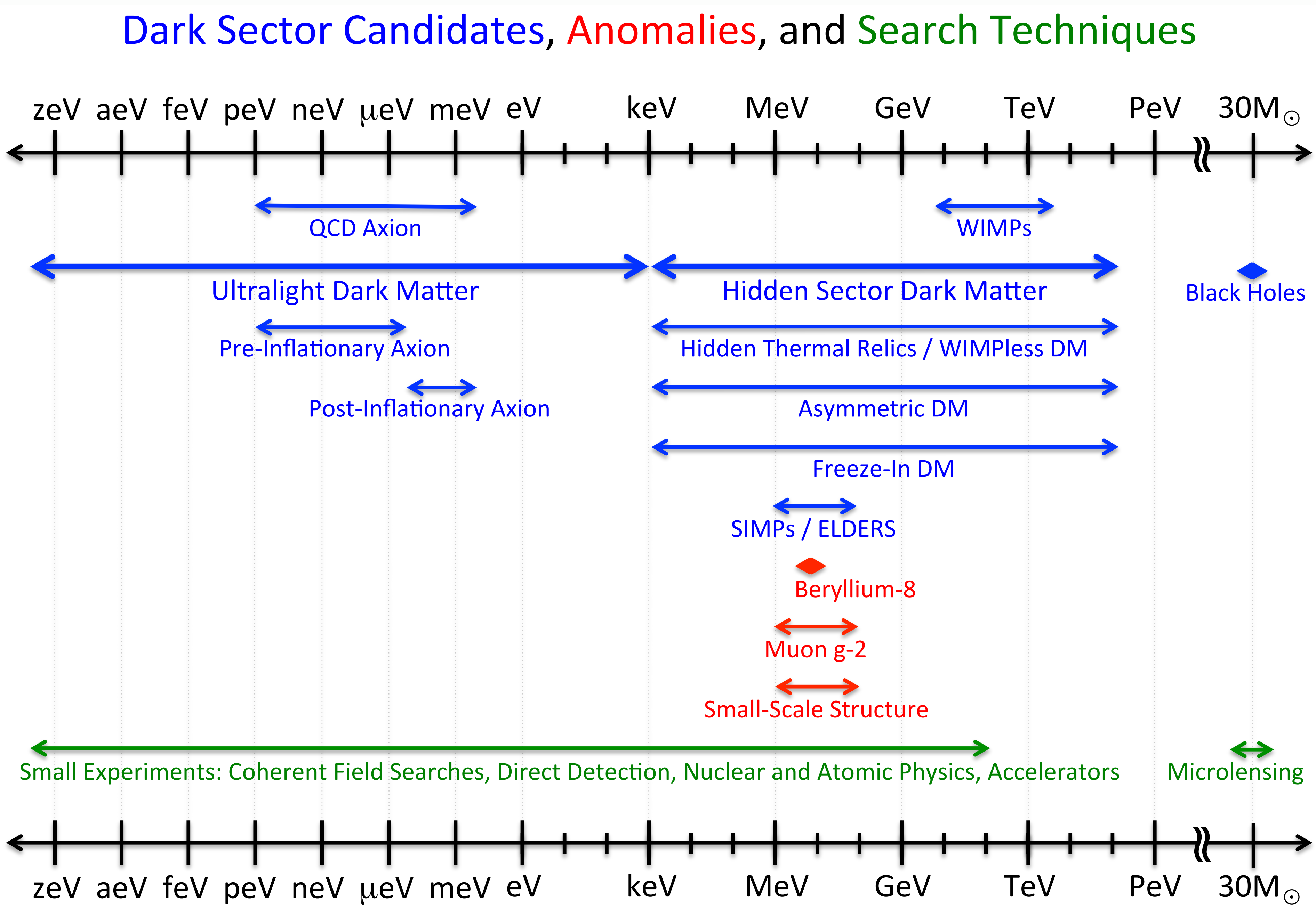


Vibration of molecules
$m_{DM} \sim$ MeV

Molecules as a probe of DM?

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017



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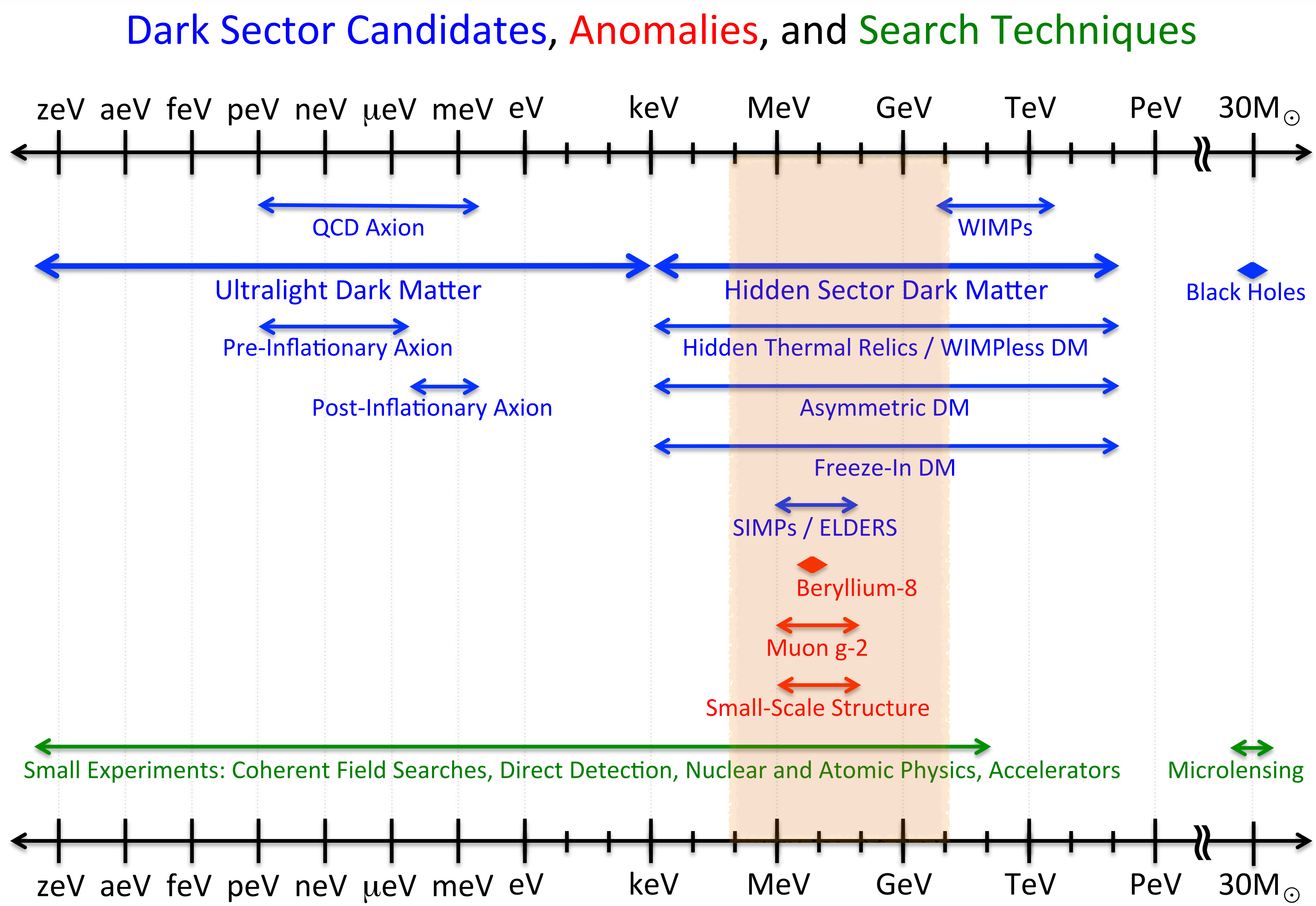


Molecules as a probe of DM?

PHYSICAL REVIEW D **95,** 056011 (2017)

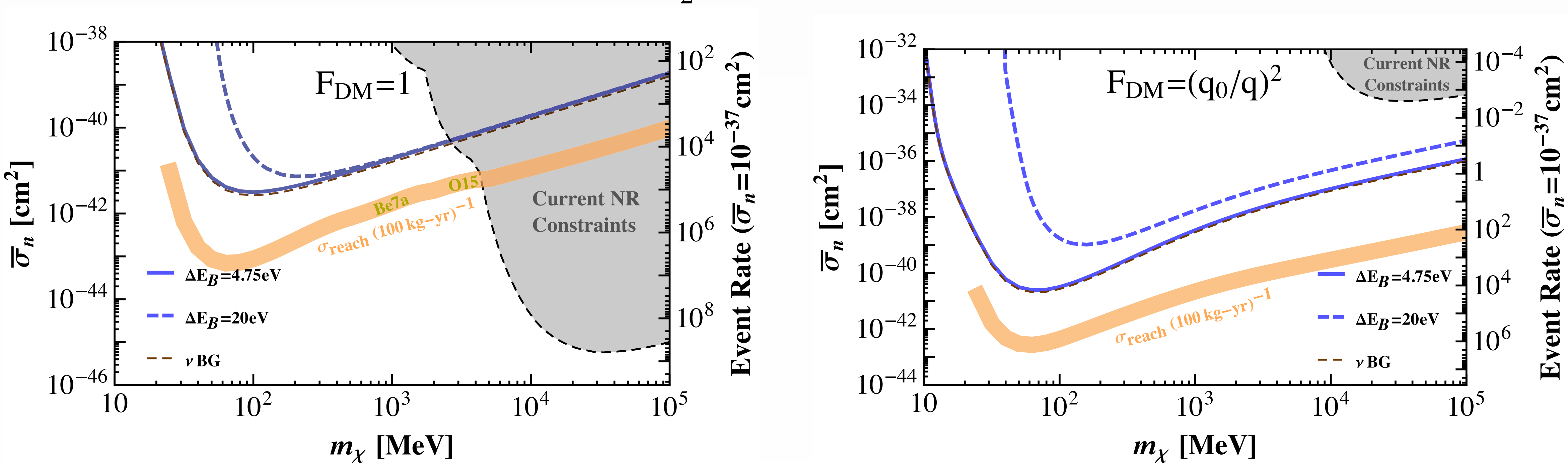
Detection of sub-GeV dark matter and solar neutrinos via chemical-bond breaking

Rouven Essig,[1,*] Jeremy Mardon,[2,†] Oren Slone,[3,‡] and Tomer Volansky[3,§]

[1]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
[3]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel*

(Received 11 December 2016; published 8 March 2017)

H_2-like Molecule



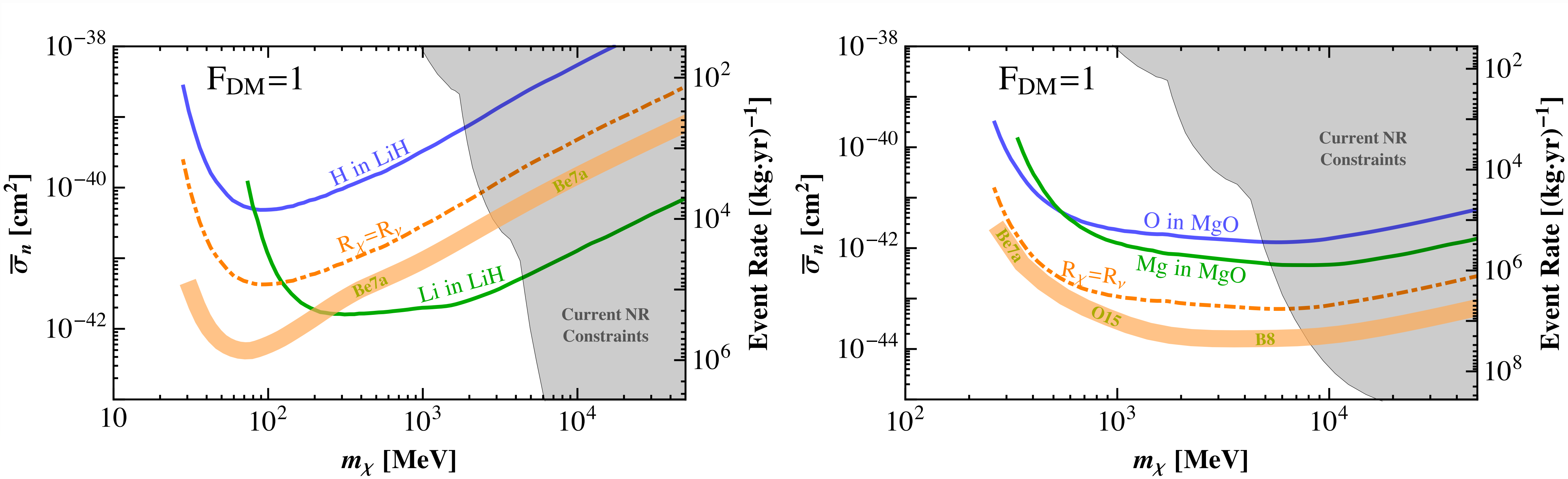
Molecules as a probe of DM?

Direct Detection of Light Dark Matter and Solar Neutrinos via Color Center Production in Crystals

Ranny Budnik
*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel**

Ori Chesnovsky
Raymond and Beverly Sackler School of Chemistry, Tel-Aviv University, Tel-Aviv, Israel†

Oren Slone and Tomer Volansky
Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv, Israel‡



Molecules as a probe of DM?

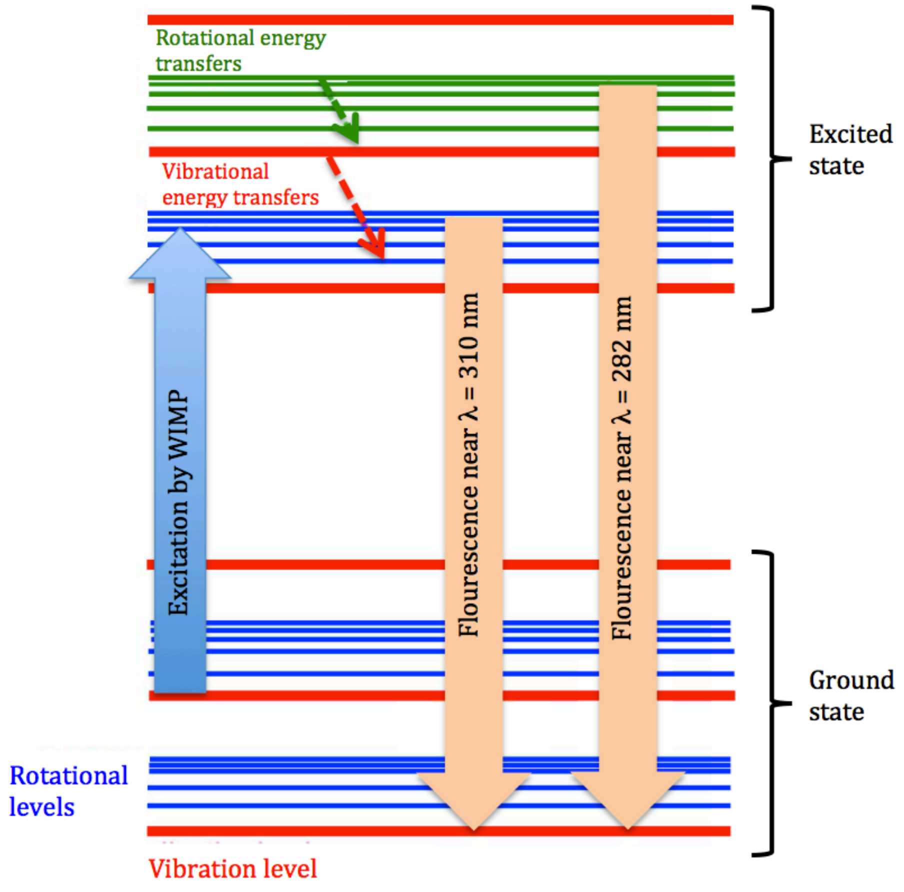
Molecular excitations: a new way to detect Dark matter

J.Va'vra

SLAC, Stanford University, CA94309, U.S.A.
e-mail: jjv@slac.stanford.edu

Table 1. A simple calculation of the transition wavelength for several frequency overtones of the OH-radicals. The last two modes correspond to visible wavelengths. Higher modes can reach the UV regime [6].

OH-band identity	Transition	Calculated wavelength [nm]
ν_1	$0 \rightarrow 1$	2803
$2\nu_1$	$0 \rightarrow 2$	1436
$3\nu_1$	$0 \rightarrow 3$	980
$4\nu_1$	$0 \rightarrow 4$	755
$5\nu_1$	$0 \rightarrow 5$	619.5

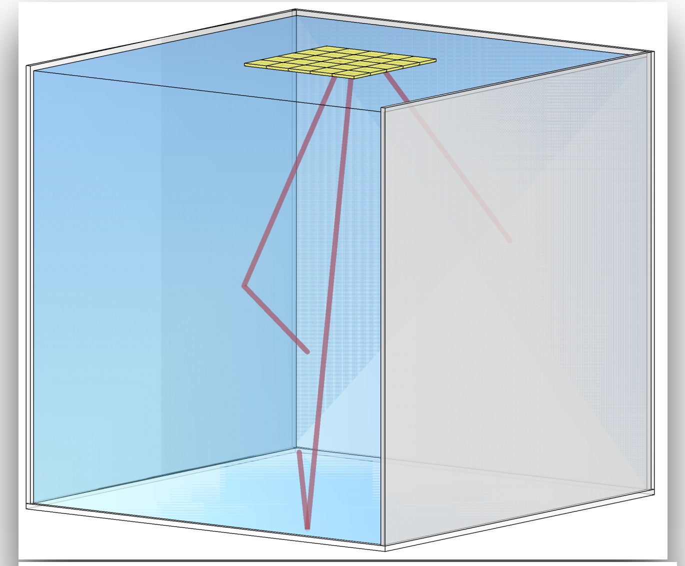


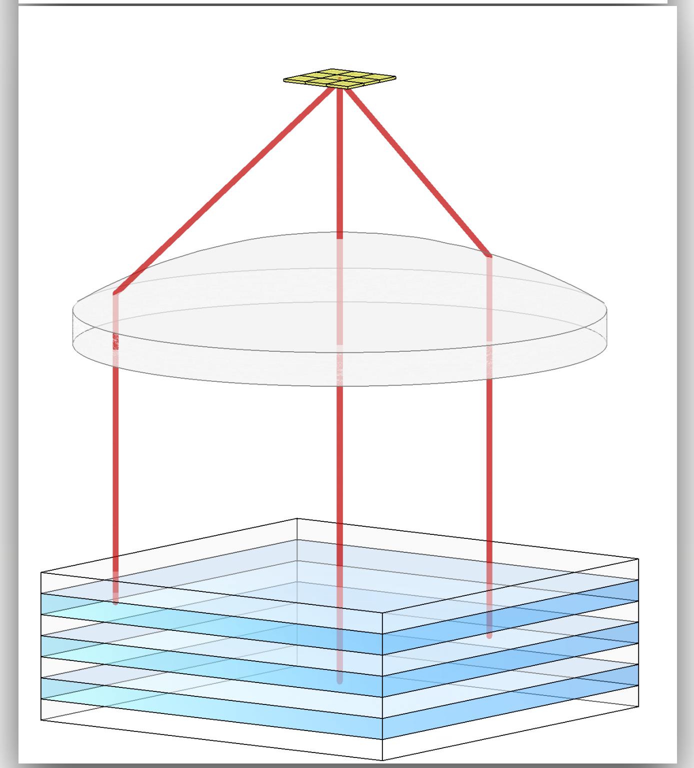
Molecules as a probe of DM?

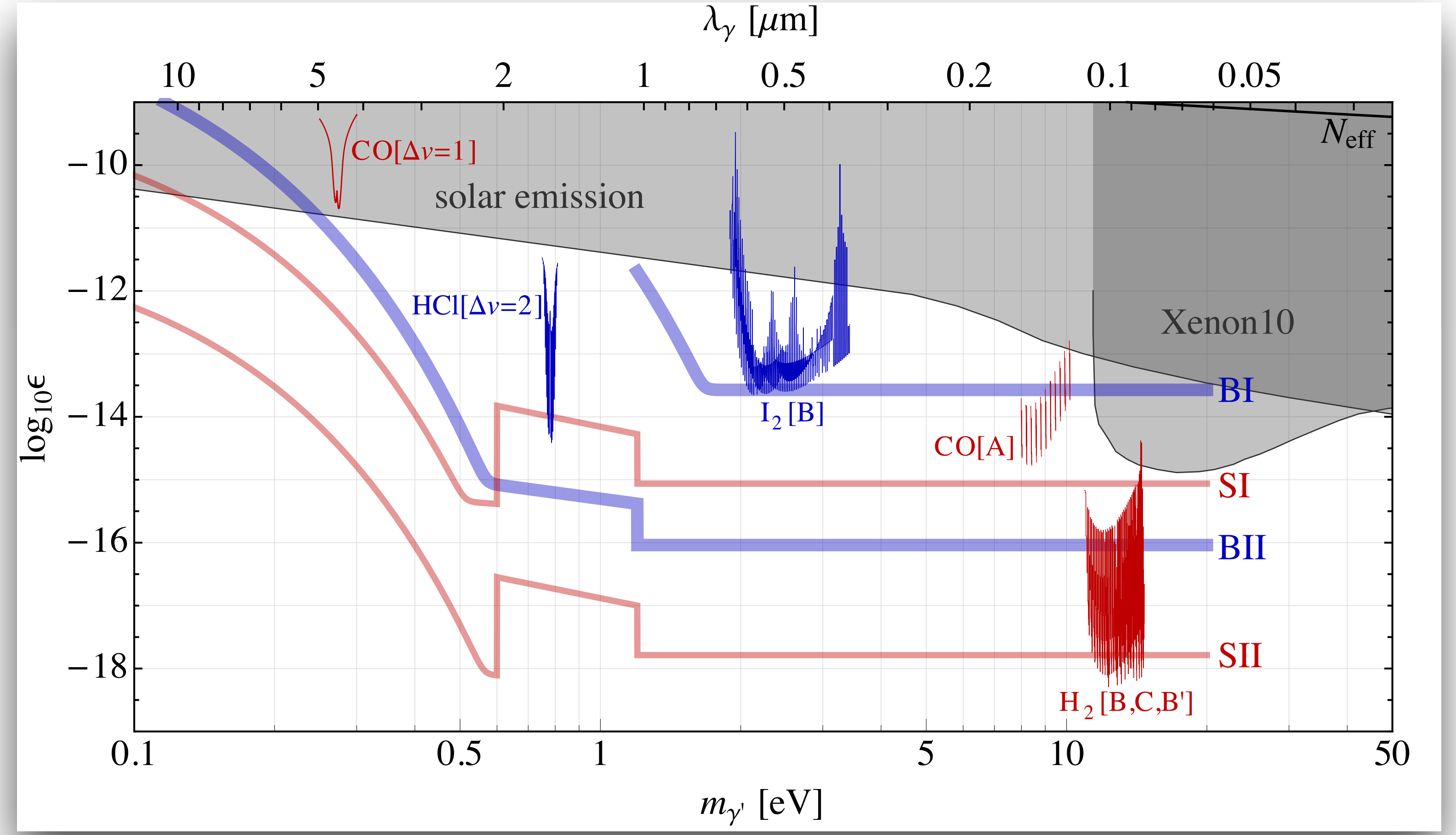
Resonant absorption of bosonic dark matter in molecules

Asimina Arvanitaki,[1,*] Savas Dimopoulos,[2,†] and Ken Van Tilburg[3,4,‡]

[1] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[2] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*
[3] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA*
[4] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*







Molecules as a probe of DM?

Kinematic constrains

$$q^2_{\mathrm{min/max}} = \mu^2_{\chi N} v^2_{max} [1 \mp \sqrt{1 - \frac{2\Delta E}{\mu_{\chi N} v^2_{max}}}]^2$$

Molecules as a probe of DM?

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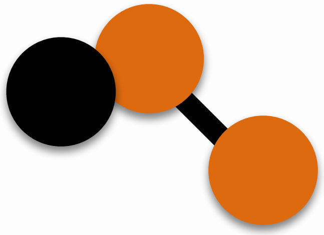

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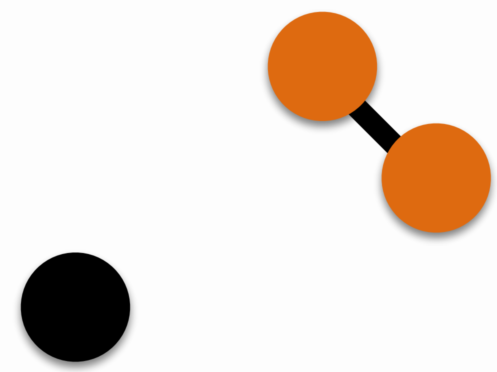

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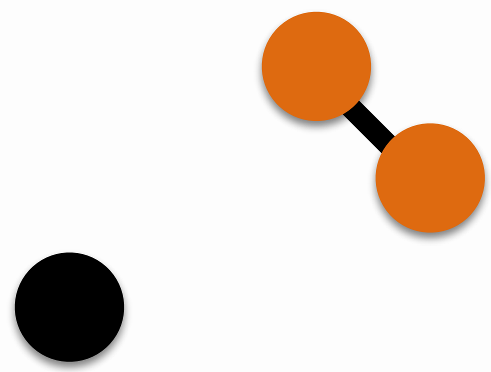


$$v_{\max} = v_{\mathrm{SS}} + v_{\mathrm{esc}}$$

$$q^2_{\mathrm{min/max}} = \mu^2_{\chi N} v^2_{max} [1 \mp \sqrt{1 - \frac{2\Delta E}{\mu_{\chi N} v^2_{max}}}]^2$$

Molecules as a probe of DM?

$$|F_{DM}(\vec{q})|^2 = \frac{|\mathcal{M}_{free}(q)|^2}{|\mathcal{M}_{free}(q_0)|^2}$$

DM-nucleon cross section

DM velocity distribution

$$\frac{dR}{d\ln E_r} = (f_P Z + f_N(A-Z))^2 N_T \frac{\rho_\chi}{m_\chi} \frac{\sigma_N}{8\mu_{\chi n}^2} q^2 |F_{DM}(\vec{q})|^2 |\mathcal{F}_{ij}(\vec{q})|^2 \eta(v_{min})$$

Recoil energy

DM form factor

Molecules as a probe of DM?

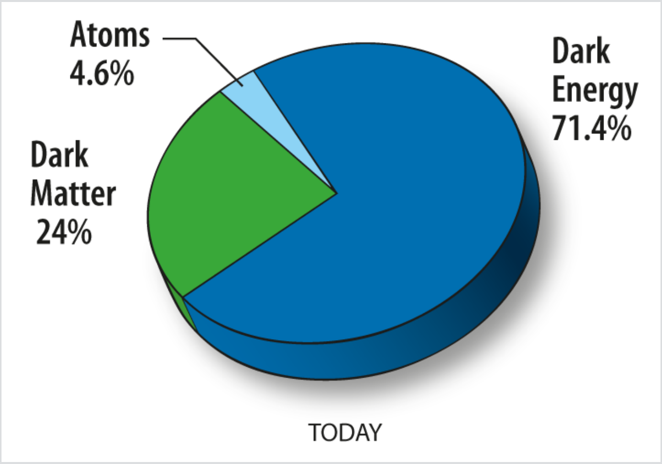
$$\frac{dR}{d\ln E_r} = (f_P Z + f_N(A-Z))^2 N_T \frac{\rho_\chi}{m_\chi} \frac{\sigma_N}{8\mu_{\chi n}^2} q^2 |F_{DM}(\vec{q})|^2 |\mathcal{F}_{ij}(\vec{q})|^2 \eta(v_{min})$$

Molecular form factor

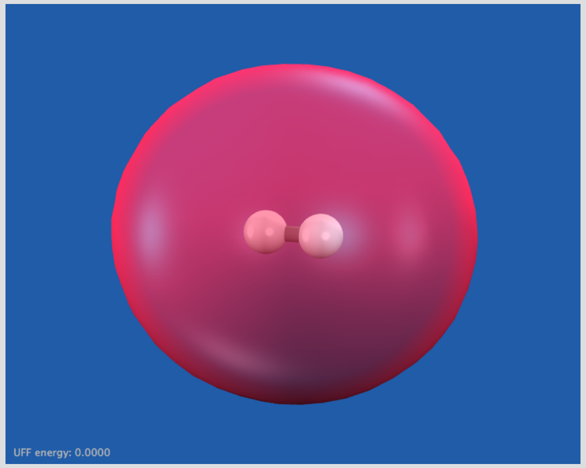
$$|\mathcal{F}_{ij}(q)|^2 = |\int d^3\vec{r} e^{\frac{\imath\mu_{12}}{m_A}\vec{q}.\vec{r}} \Psi_i^J(\vec{r}) \Psi_j^{J'}(\vec{r})|^2$$

Outlook

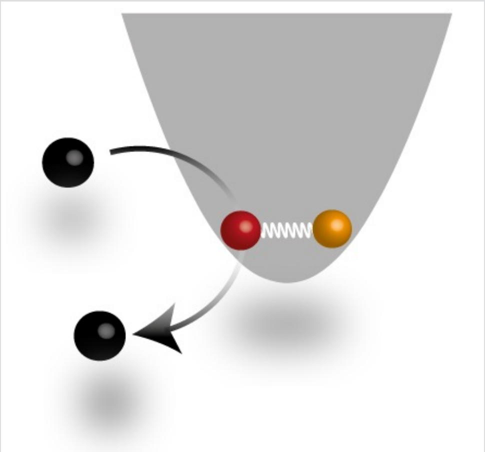
Dark Matter



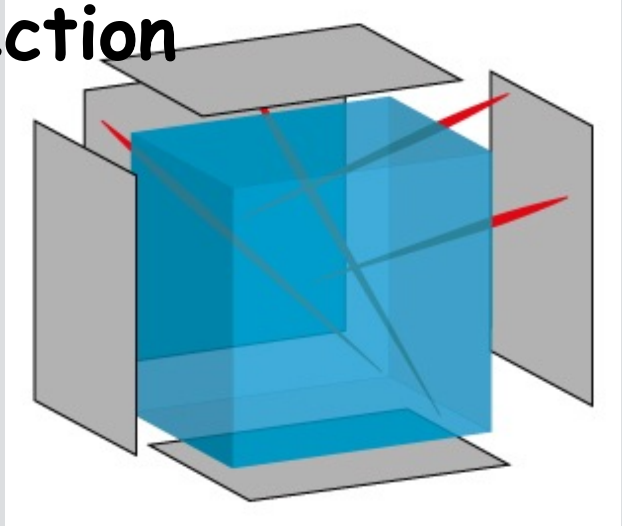
Molecules



Molecules as a probe of DM?

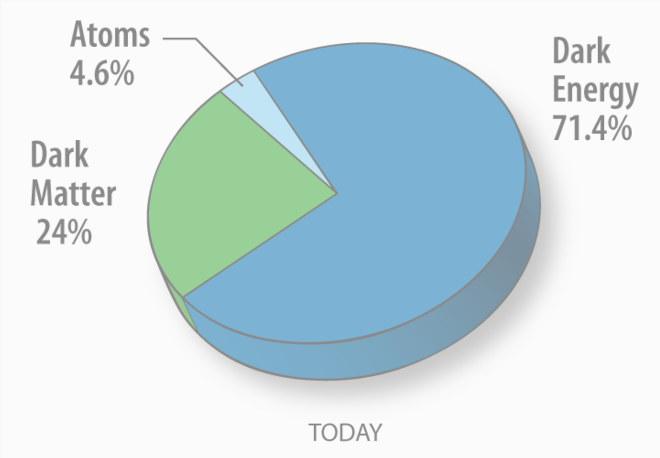


A novel approach for DM detection



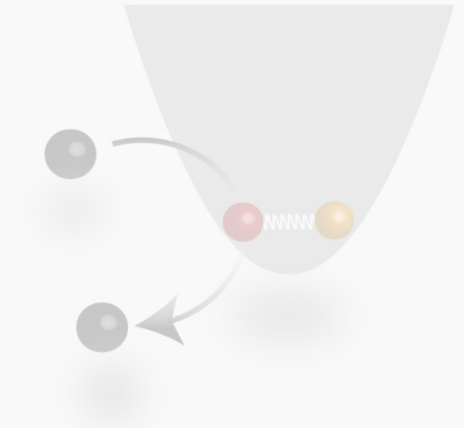
Outlook

Dark Matter



Molecules

Molecules as a probe of DM?



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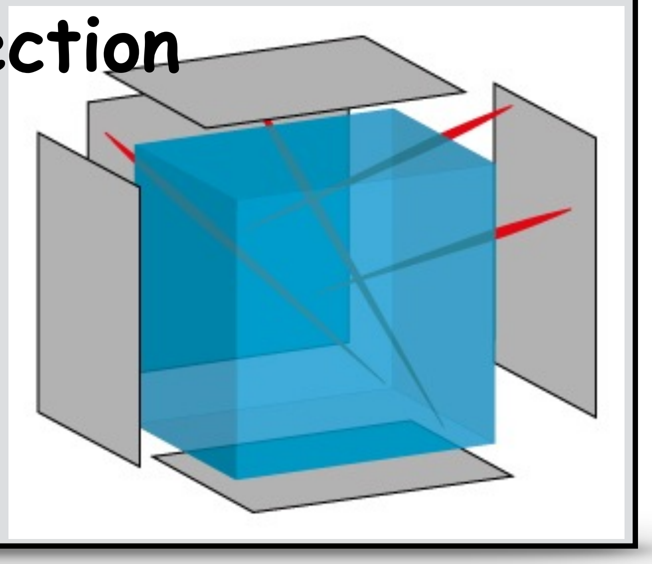

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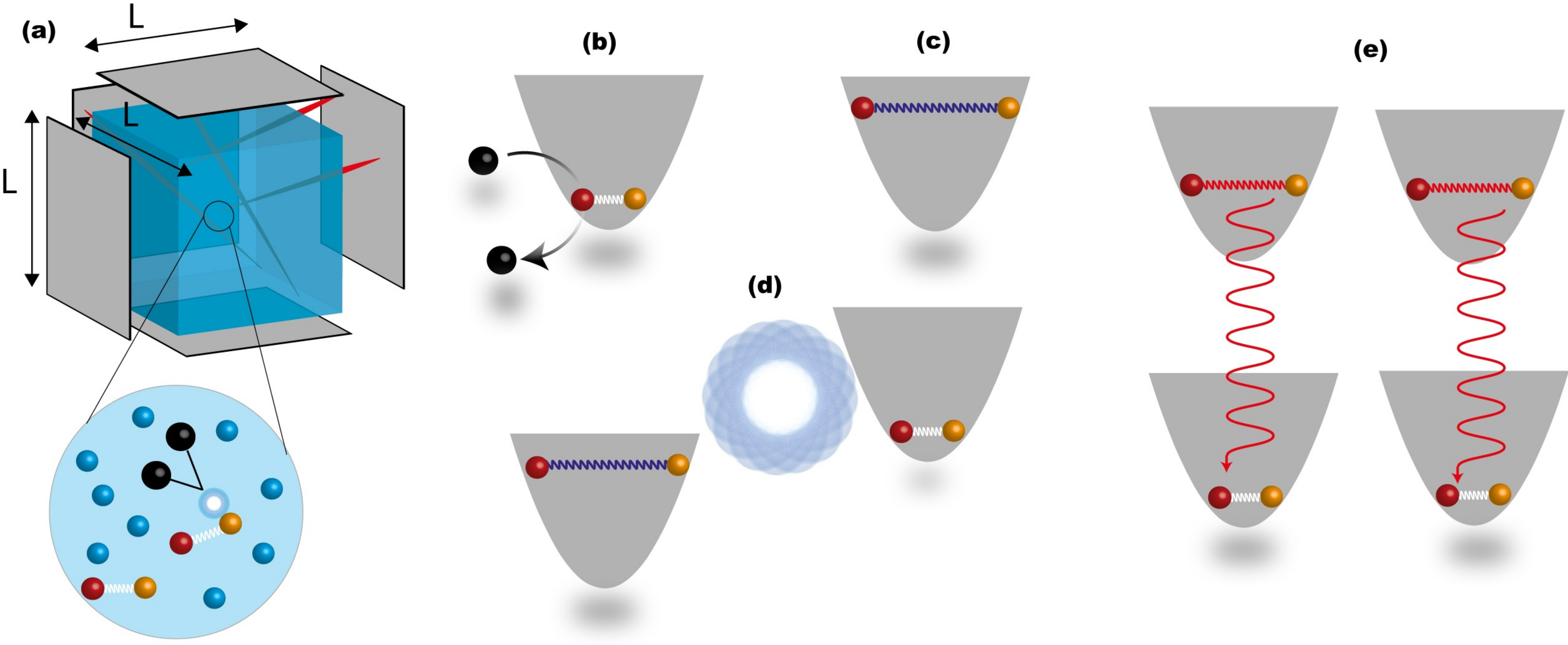

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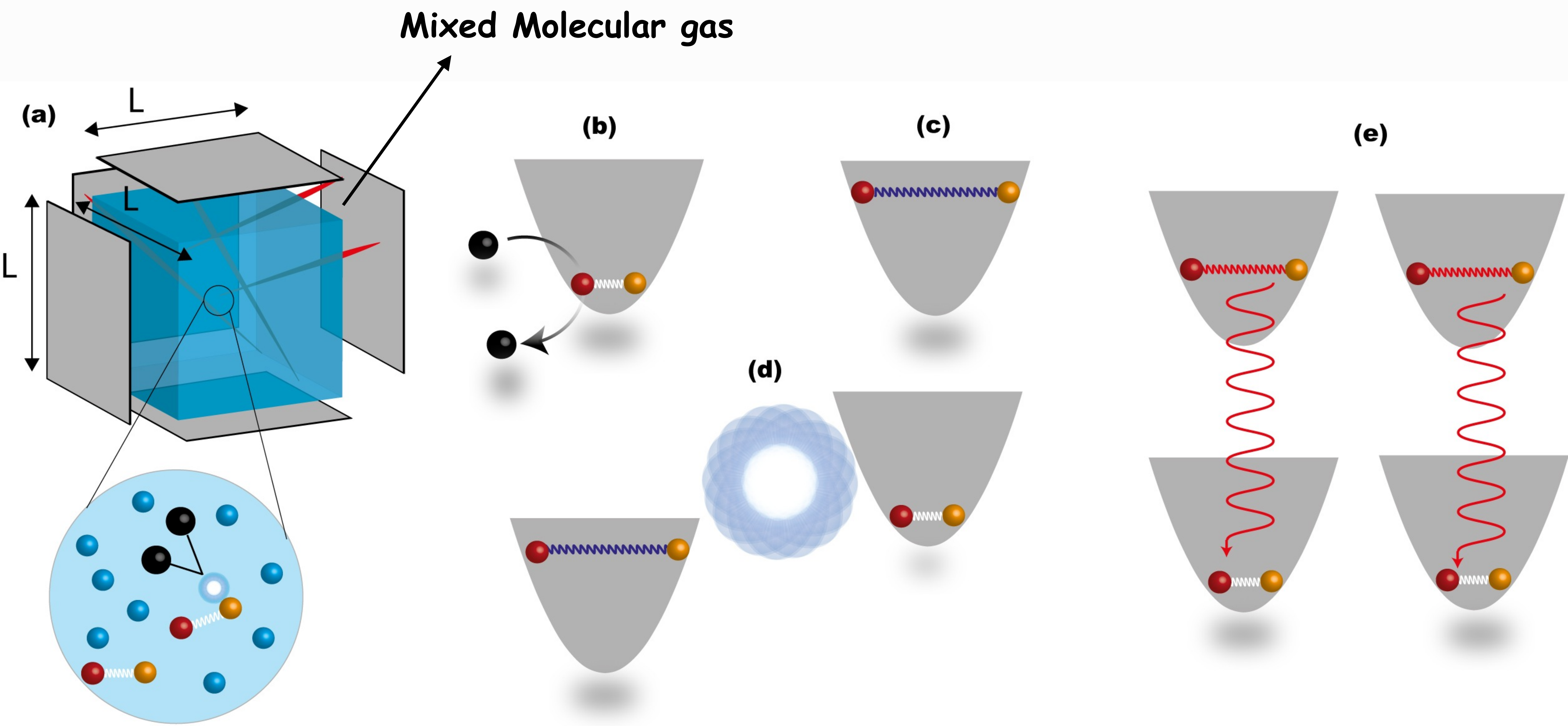

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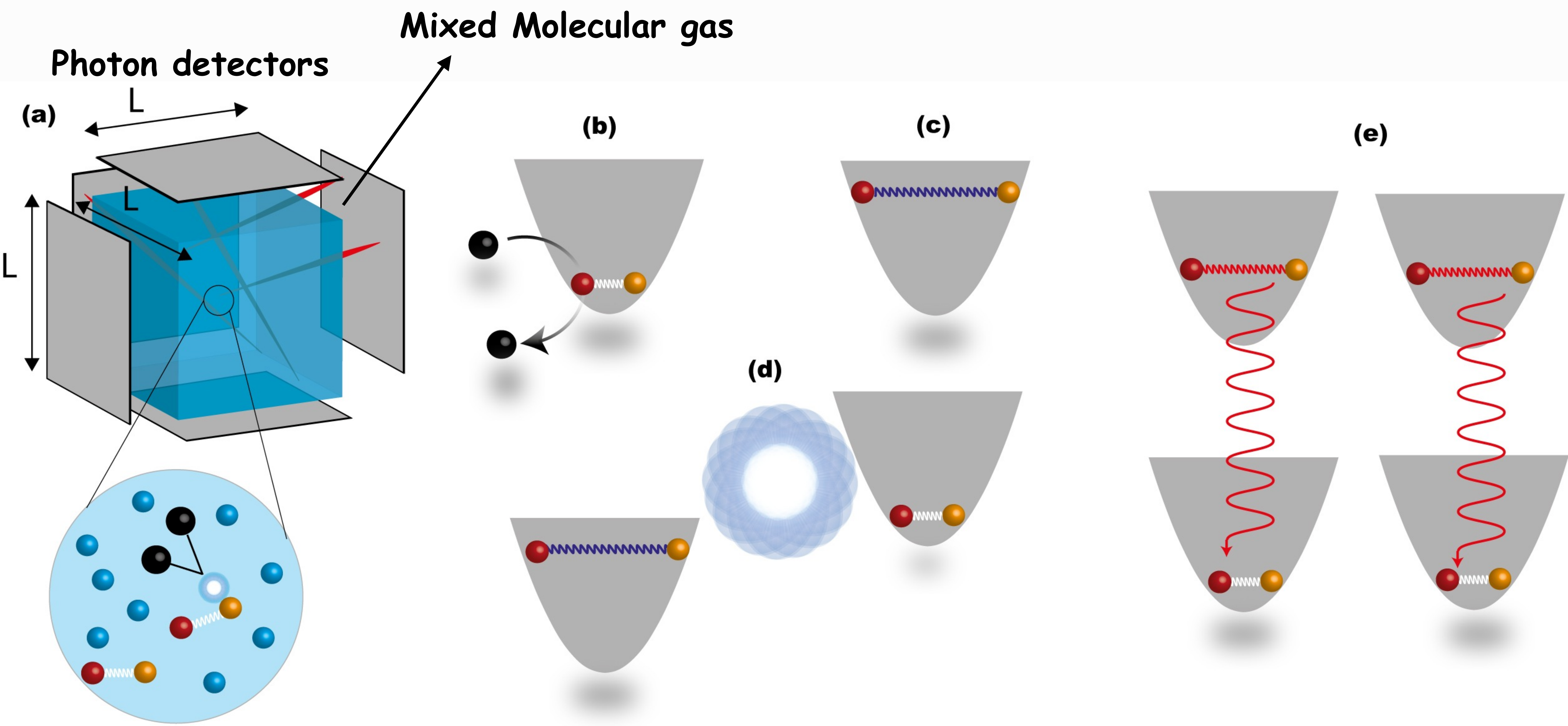
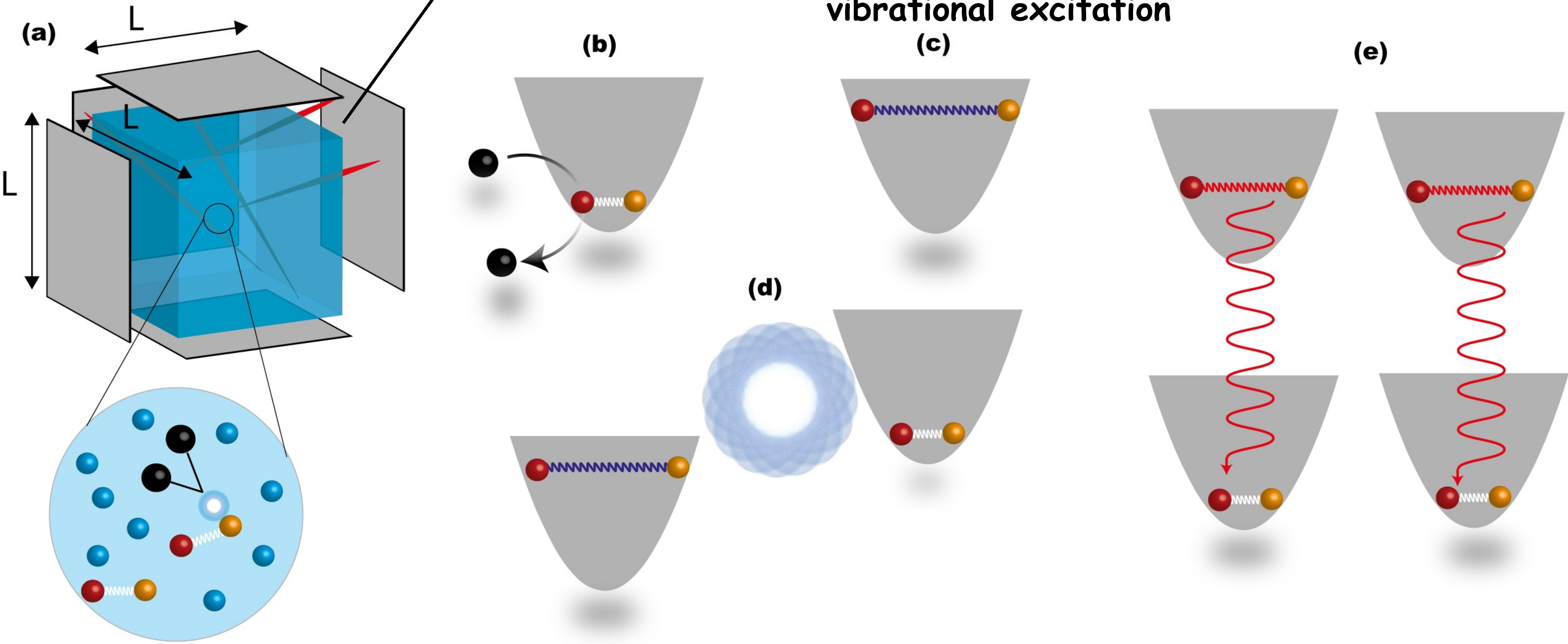


A novel approach for DM detection

Photon detectors

Mixed Molecular gas

DM particle collisions with molecules induce vibrational excitation



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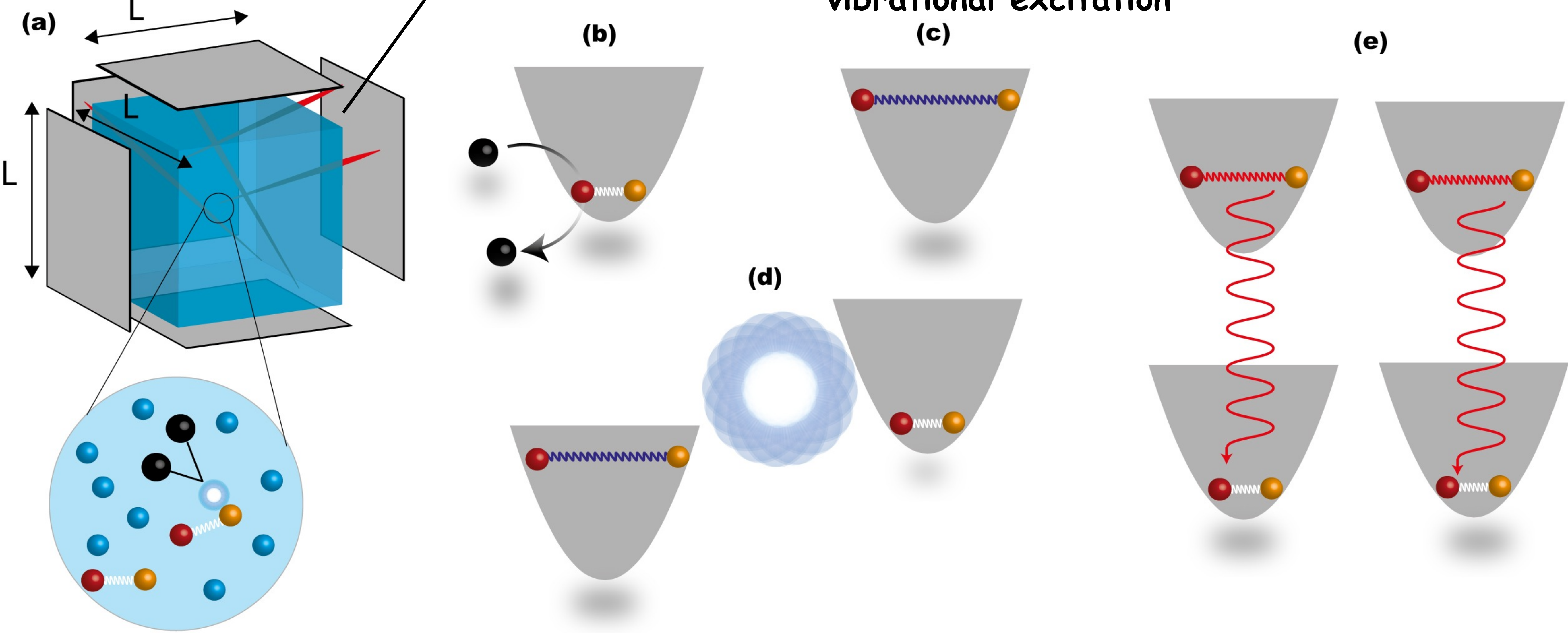
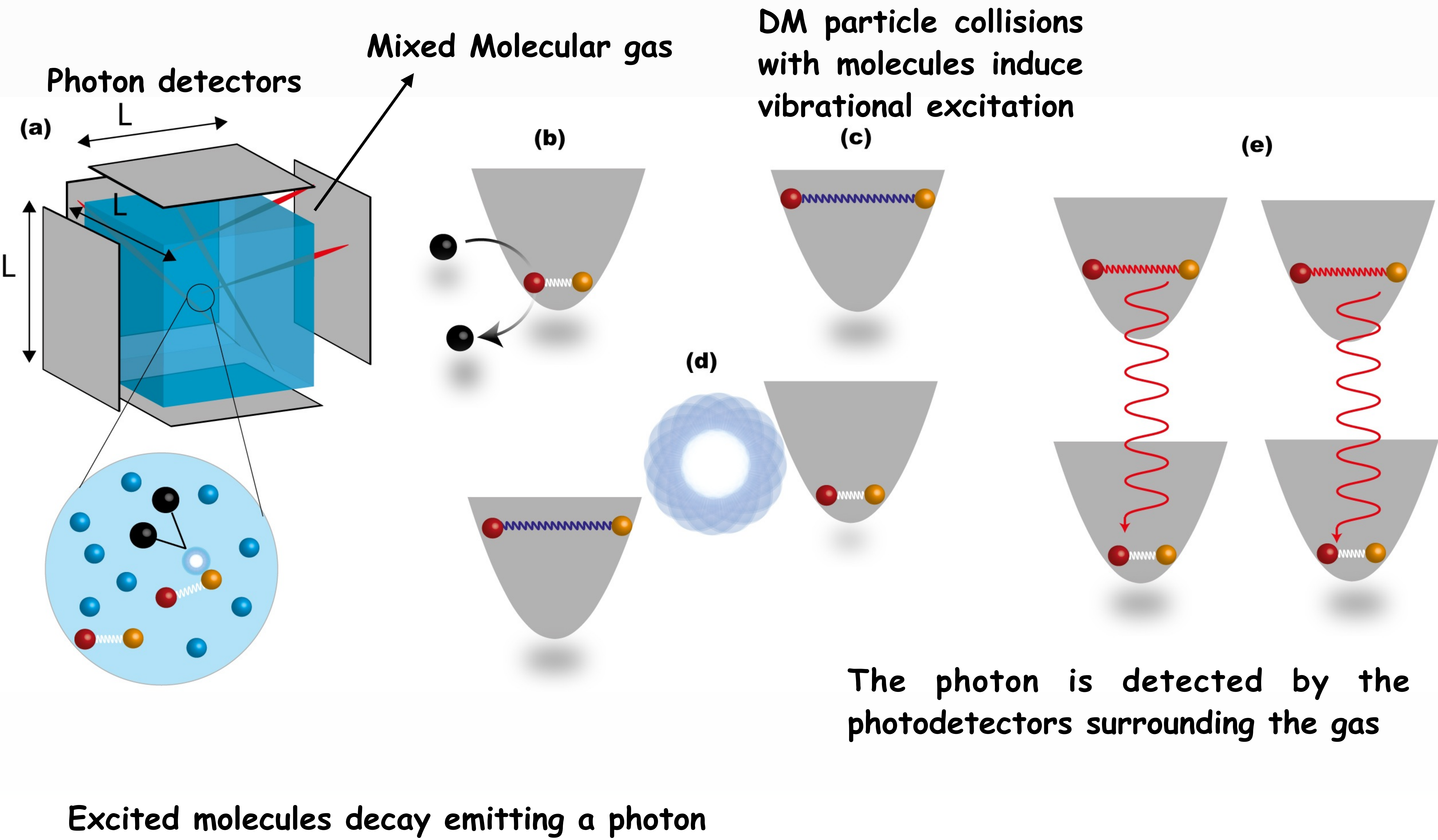


Excited molecules decay emitting a photon

A novel approach for DM detection



A novel approach for DM detection

Four points to take care of

1. Spontaneous emission rate

2. Thermal population of vibrational states

3. Black Body radiation background

4. Collisional de-excitation rate

A novel approach for DM detection

Four points to take care of

1. Spontaneous emission rate
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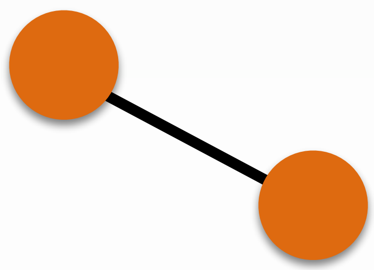
Bonus: Photon absorption

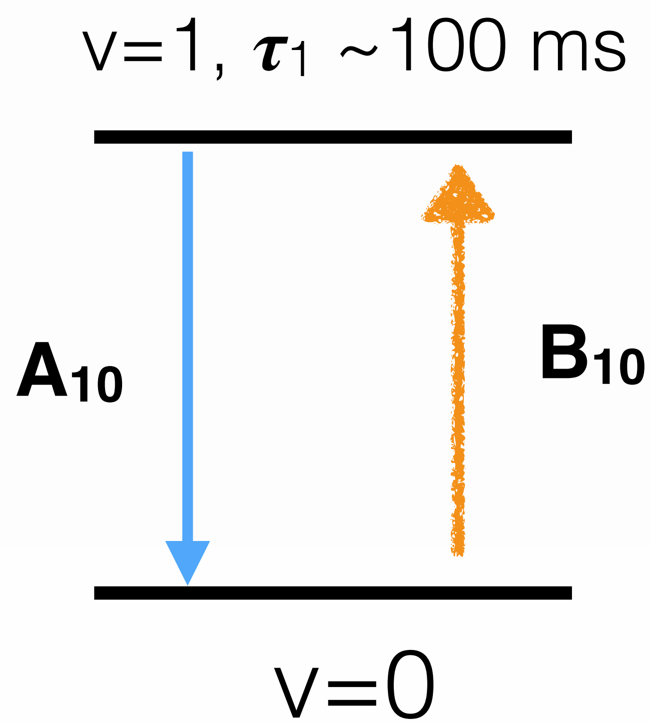
1. Spontaneous emission rate

Homonuclear

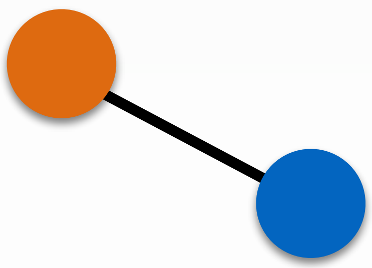


$$\frac{d\Gamma_{ij}}{d\Omega} = \frac{\alpha\omega_{ij}^5}{8\pi c^4}|Q|^2$$

A_{10}~10^{-7} s^{-1}



Heteronuclear



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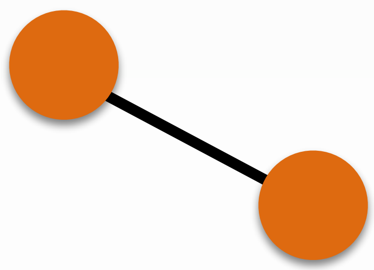
1. Spontaneous emission rate

Homonuclear



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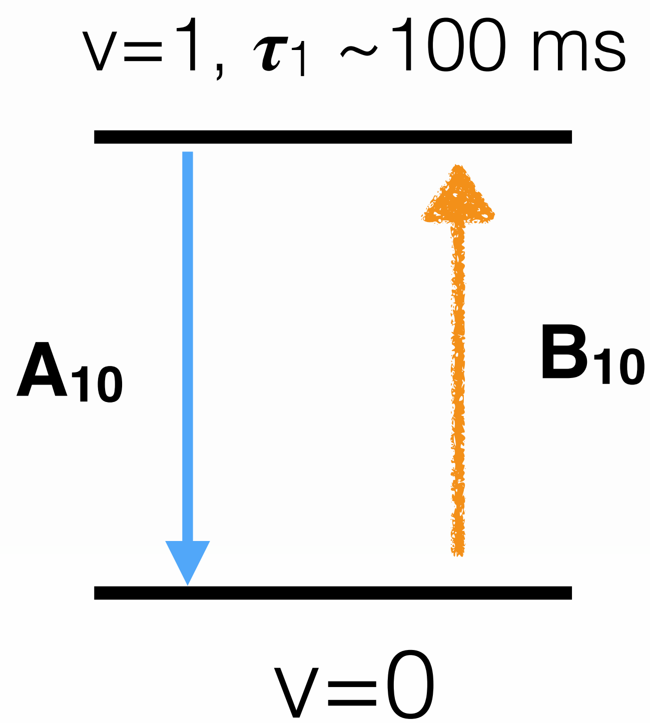

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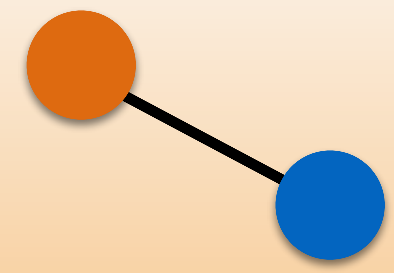

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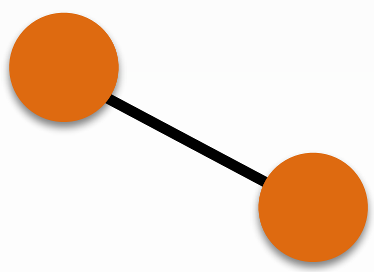

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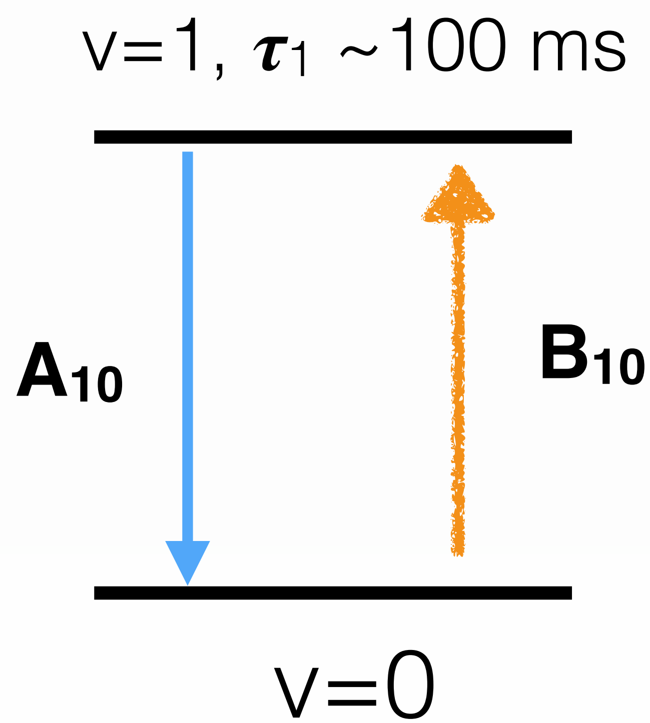

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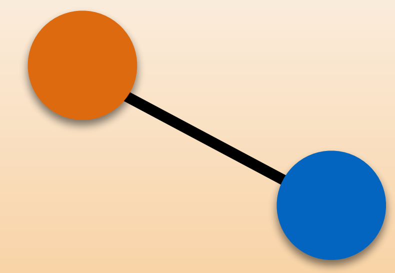

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A_{10}~10 s^{-1}

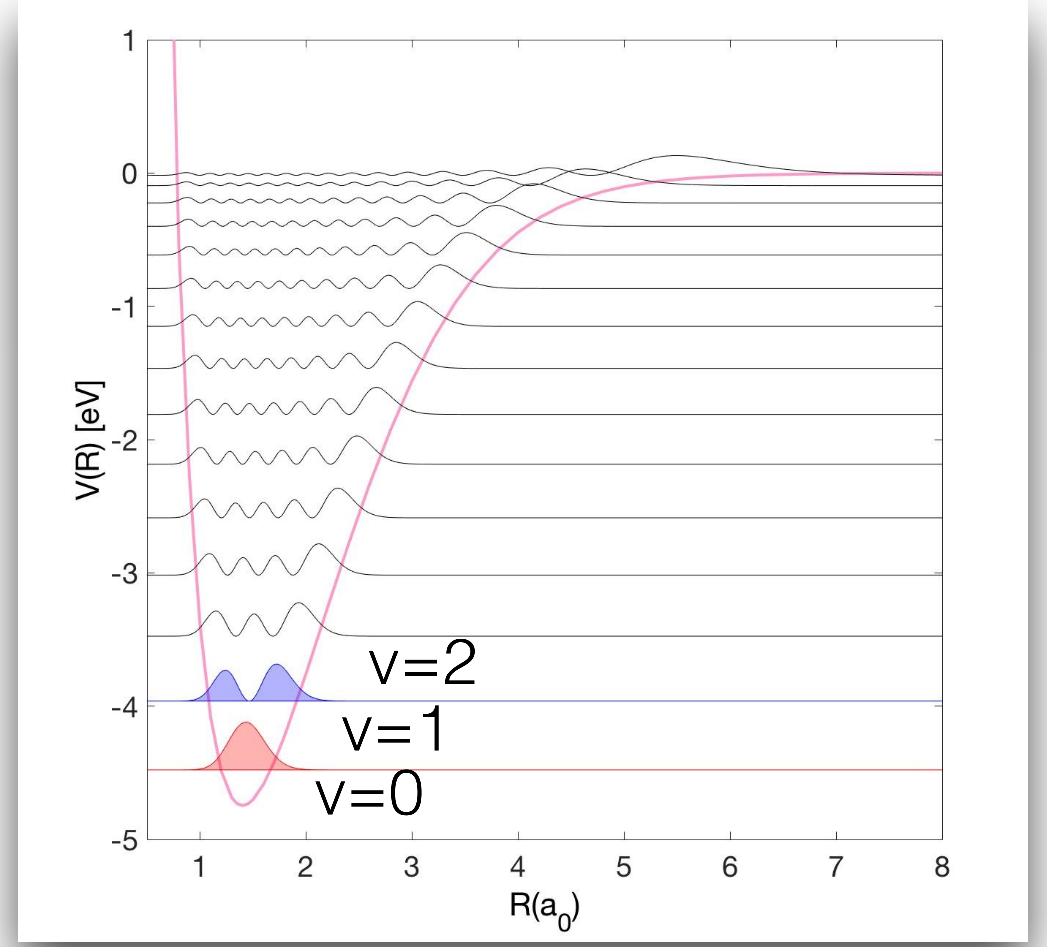
A fee to pay

Permanent dipole moment -> **faster collisional rates**
-> **BBR**

2. Thermal population

$$Z_{\text{vib}} = \sum_{\nu} e^{-\hbar\omega(\nu+1/2)/k_b T}$$

$$P_{\nu} = \frac{e^{-\hbar\omega(\nu+1/2)/k_b T}}{Z_{\text{vib}}}$$



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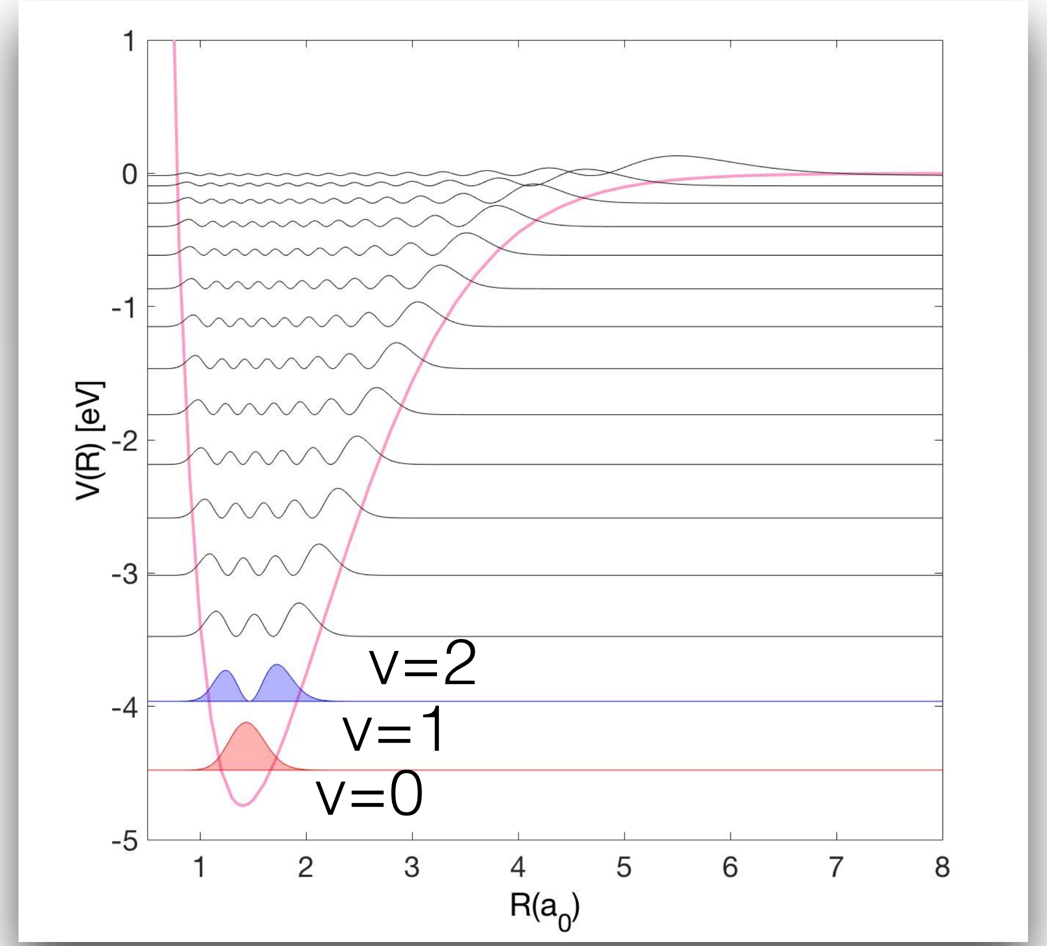

The temperature has to be low enough to ensure that almost every single molecule is in the vibrational ground state

→ The lower the temperature the lower the pressure to avoid clustering of the gas, i.e, formation of droplets on the gas

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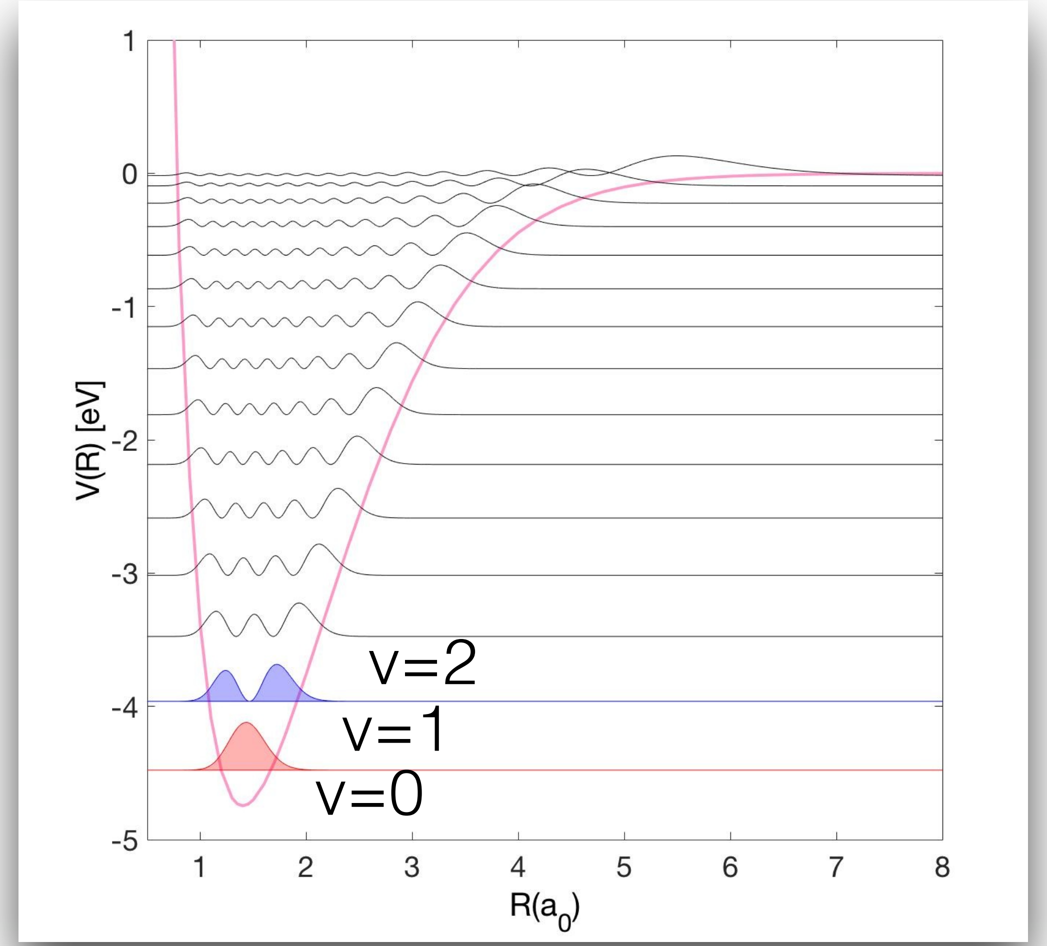


We prefer lighter molecules, i.e., large vibrational spacing

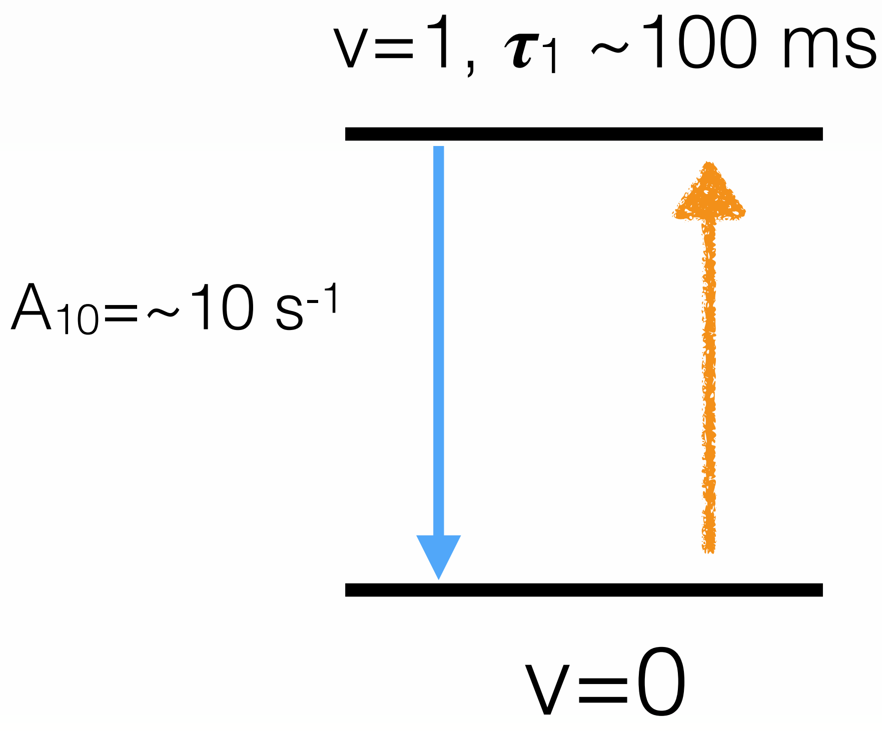
The **temperature has to be low** enough to ensure that almost every single molecule is in the vibrational ground state

→

The lower the temperature the lower the pressure to avoid clustering of the gas, i.e, formation of droplets on the gas

3. Black body radiation

$$\Gamma_{ij}^{BBR} = \frac{8\pi^2 |d_{ij}|^2}{3\epsilon_o \hbar c^3} \frac{\nu^3}{\exp \frac{h\nu}{k_B T} - 1}$$



3. Black body radiation

Dipole matrix element

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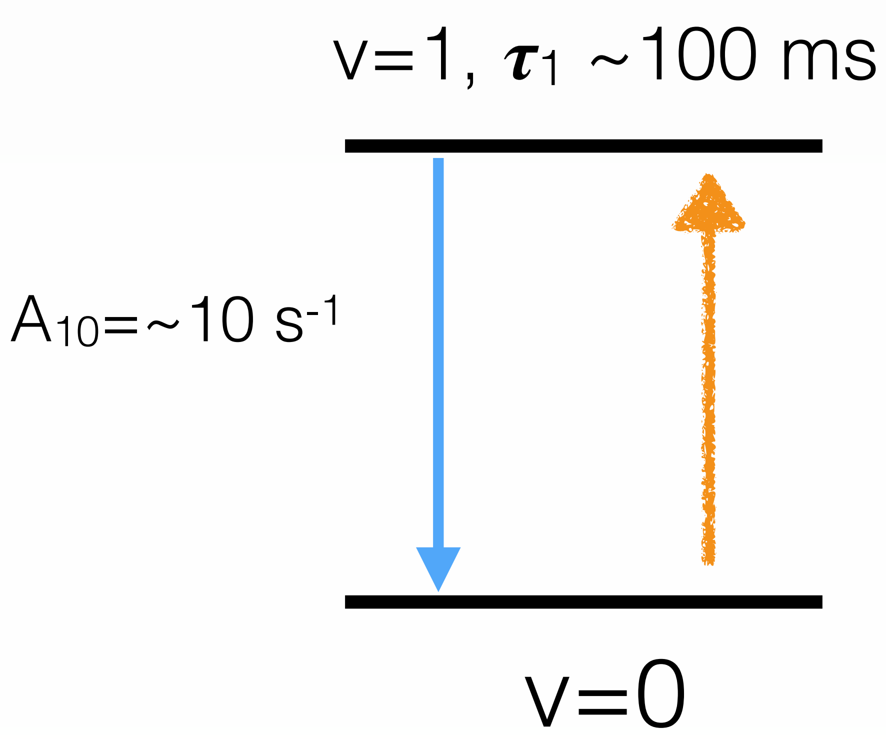

3. Black body radiation

Dipole matrix element — Vibrational frequency

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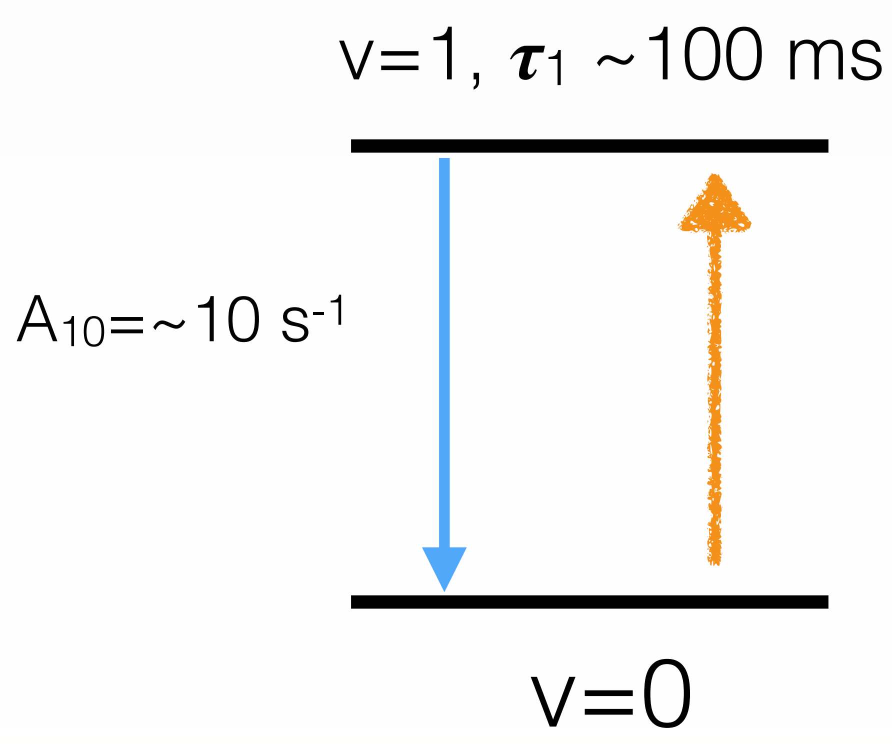

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Dipole matrix element **Vibrational frequency**

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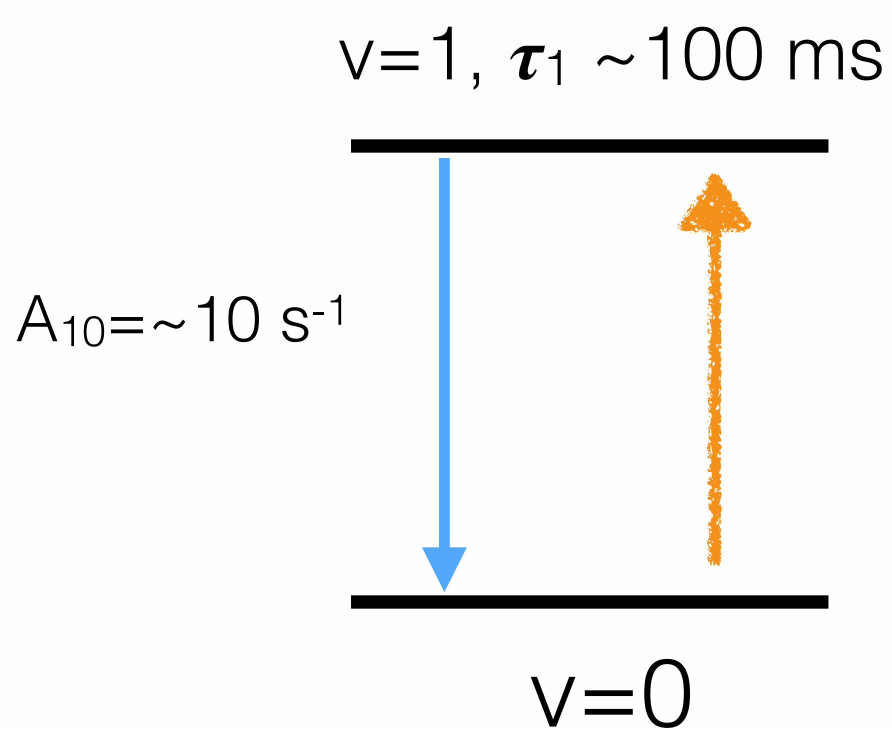

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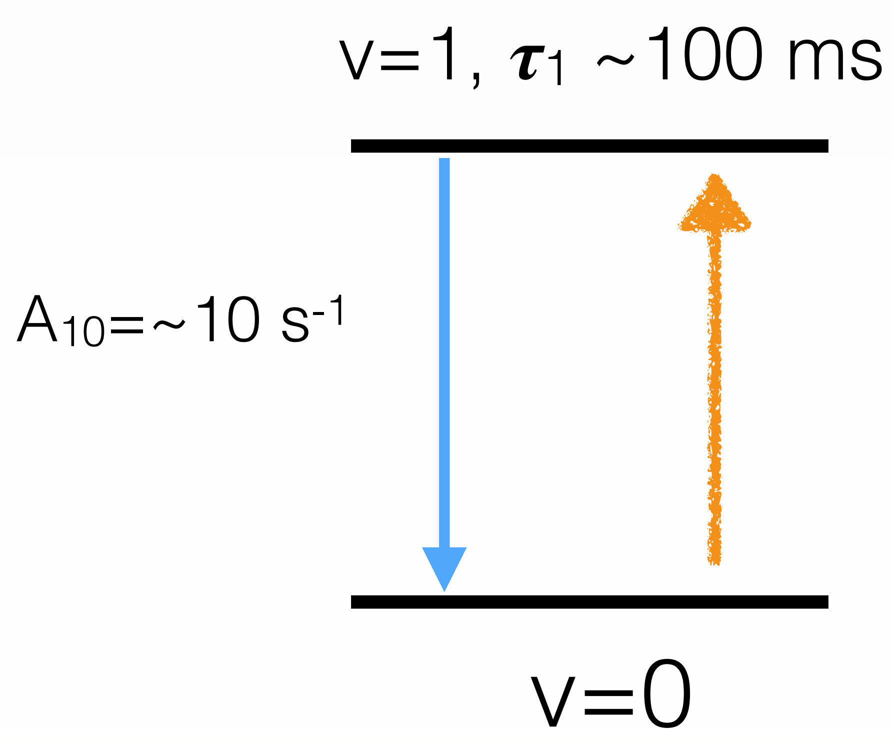

We prefer lighter molecules, i.e., large vibrational spacing

Molecules with smaller dipole moment will have smaller BBR rate

Low temperatures are better!!!

3. Black body radiation

Dipole matrix element

Vibrational frequency

$$\Gamma_{ij}^{BBR} = \frac{8\pi^2 \boxed{|d_{ij}|^2}}{3\epsilon_o \hbar c^3} \frac{\nu^3}{\exp \frac{h\nu}{k_B T} - 1}$$

	H	HF	CO	NO	HCl
r		1.7	2.1	2.2	2.4
ω	453 198 466	513	269	236	371
d(D)	1.80	1.98	0.12	0.16	1.03

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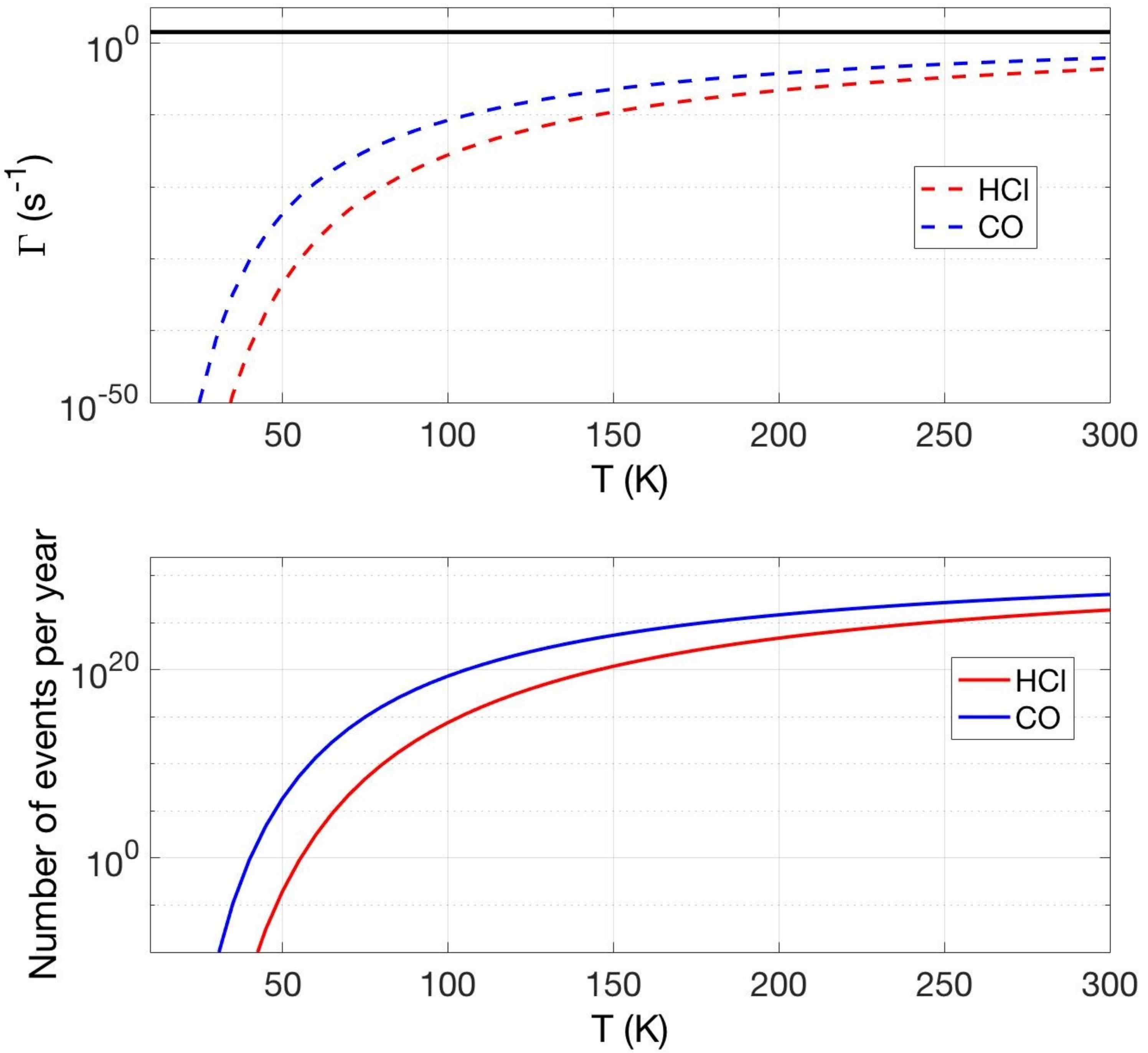

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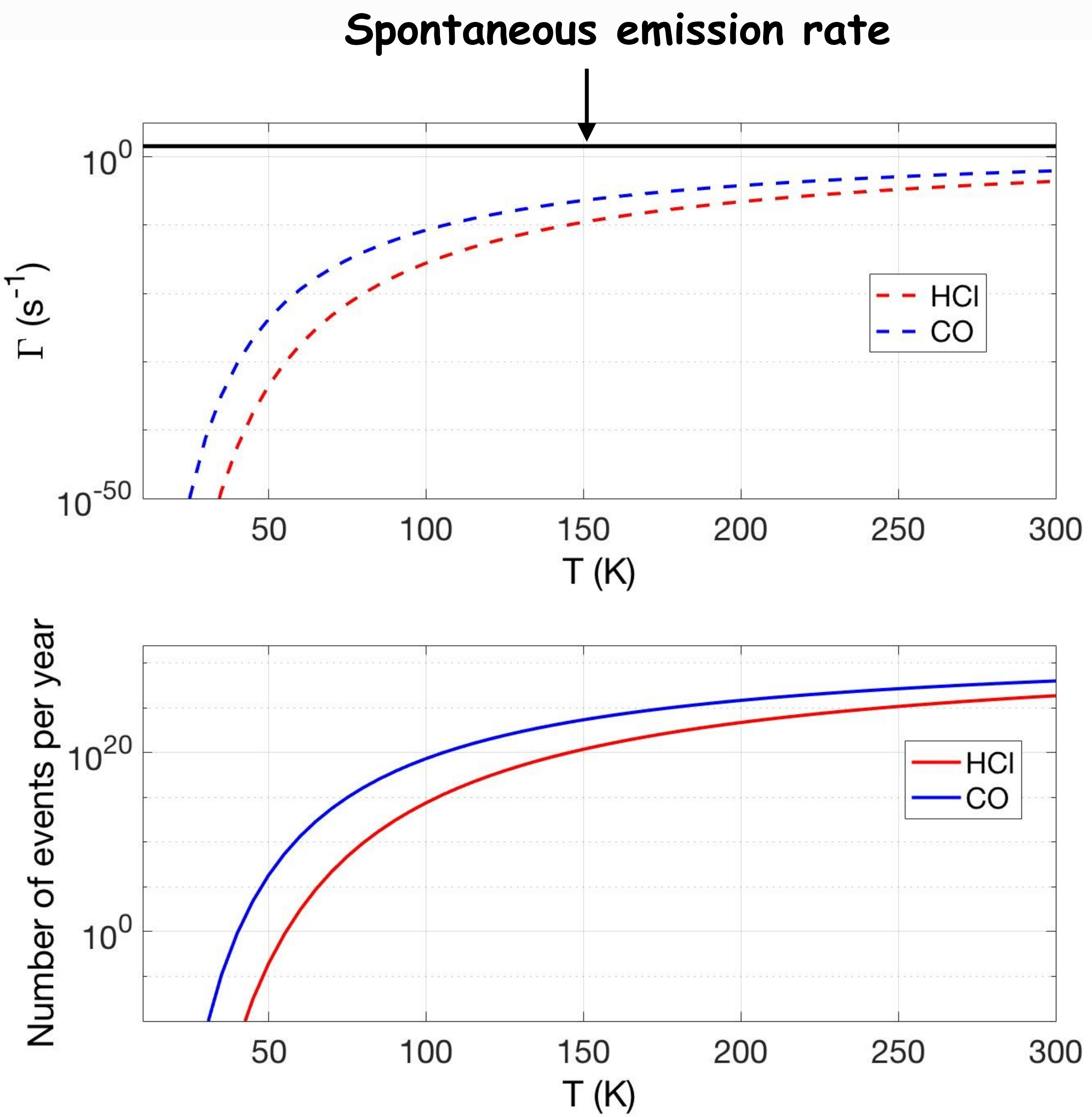

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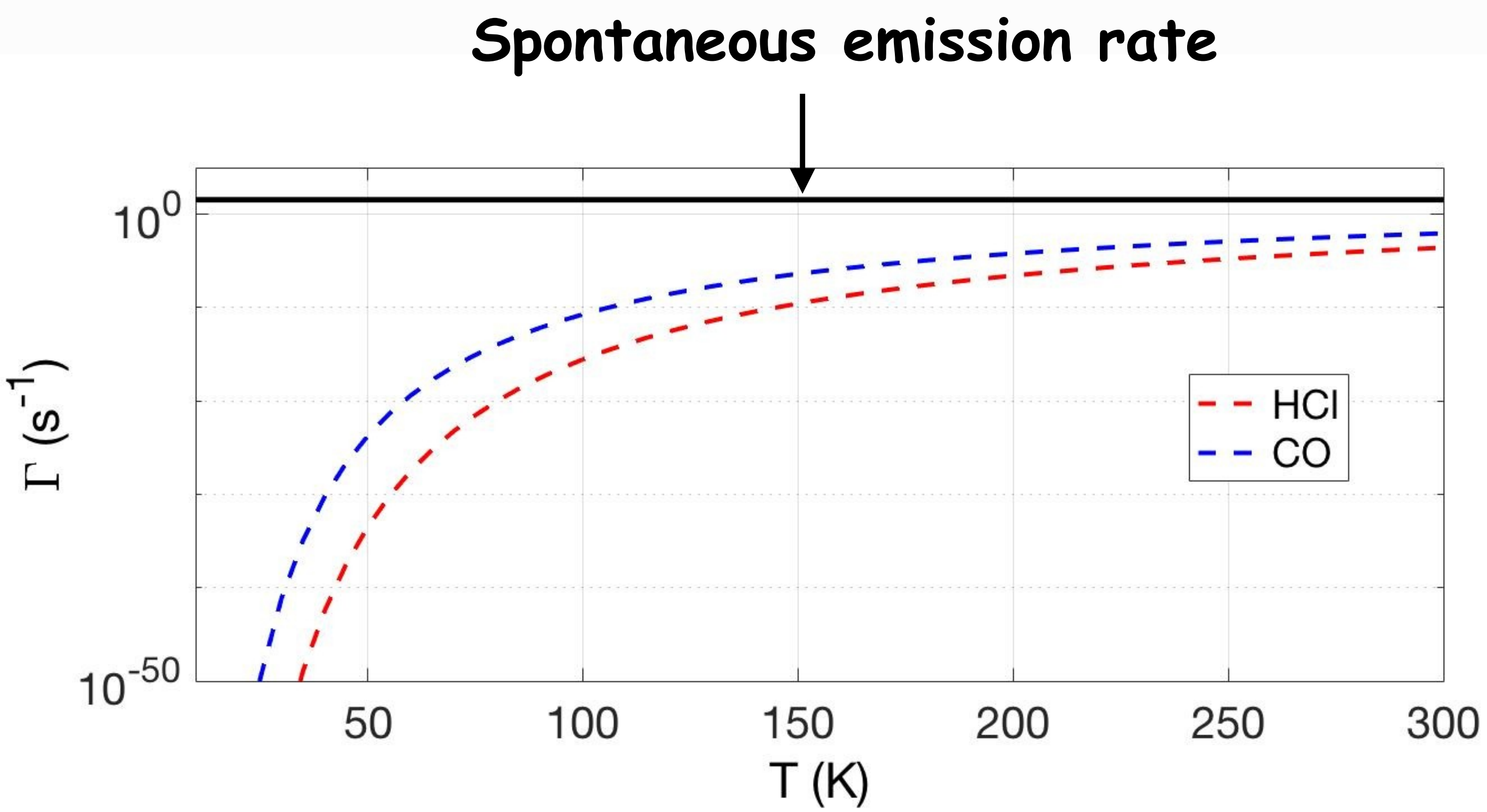
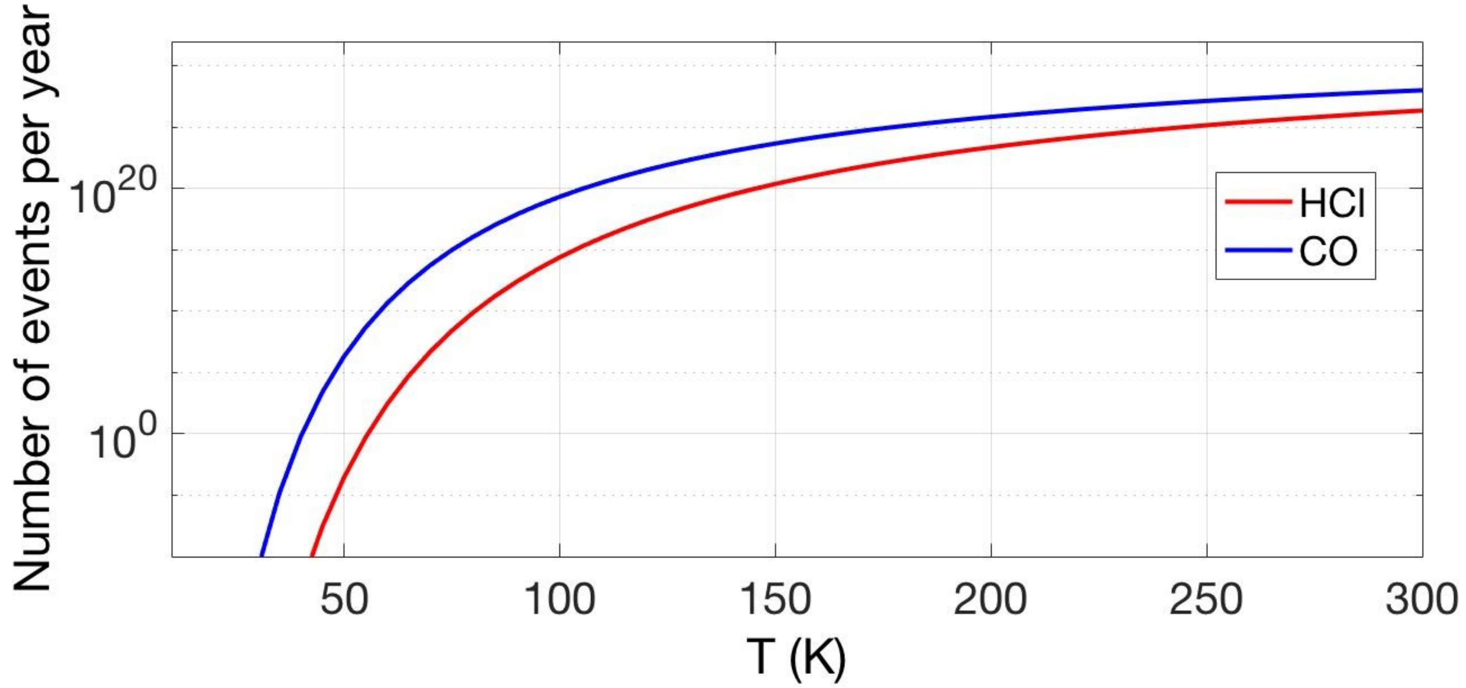


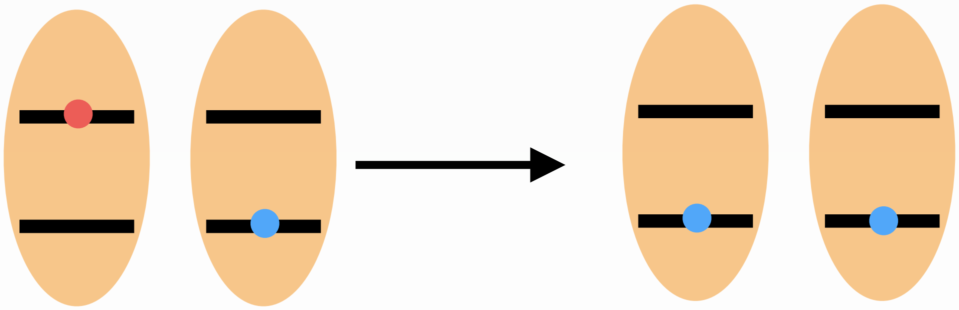
We need

Molecules with large vibrational energy spacing

Low temperatures T≲ 60 K



4. Collisional de-excitation

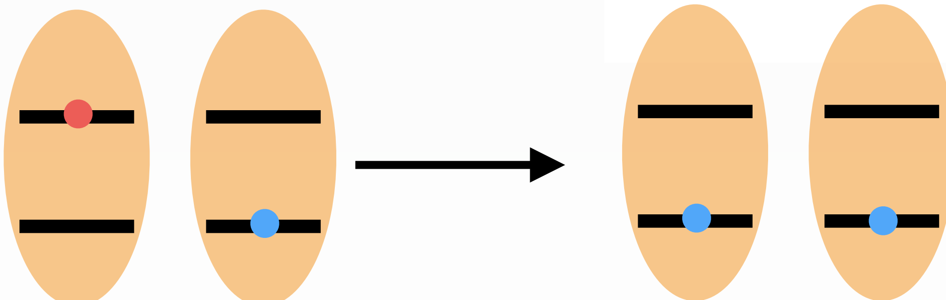


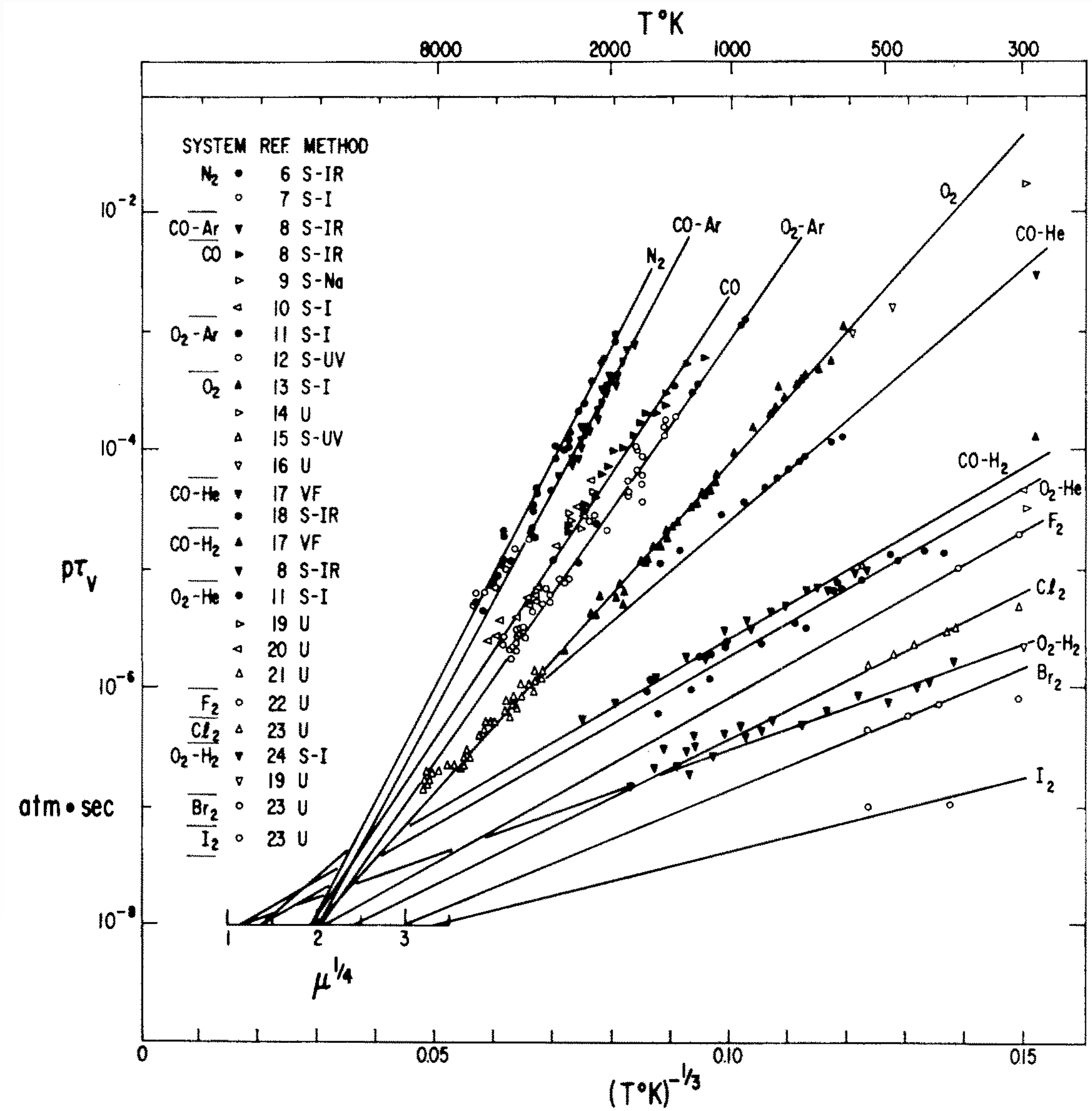
4. Collisional de-excitation

THE JOURNAL OF CHEMICAL PHYSICS VOLUME 39, NUMBER 12 15 DECEMBER 1963

Systematics of Vibrational Relaxation*

Roger C. Millikan and Donald R. White
General Electric Research Laboratory, Schenectady, New York





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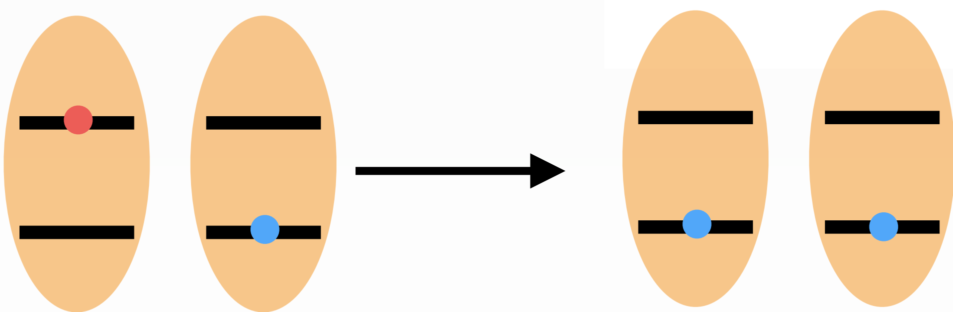
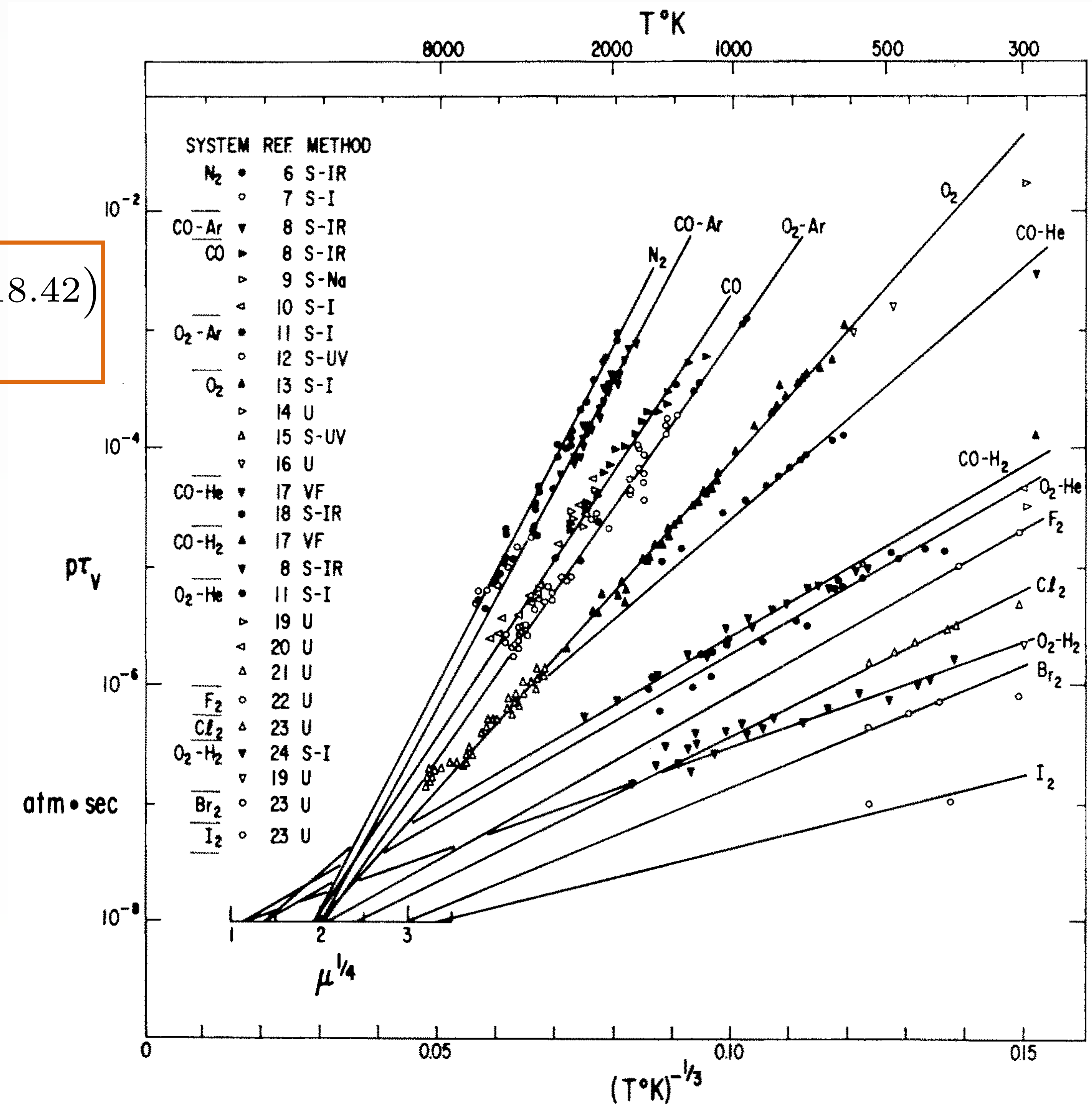


$$p\tau_v = e^{\left(1.16\times10^{-3}\mu^{1/2}\omega^{4/3}(T^{-1/3}-0.015\mu^{1/4})-18.42\right)}$$



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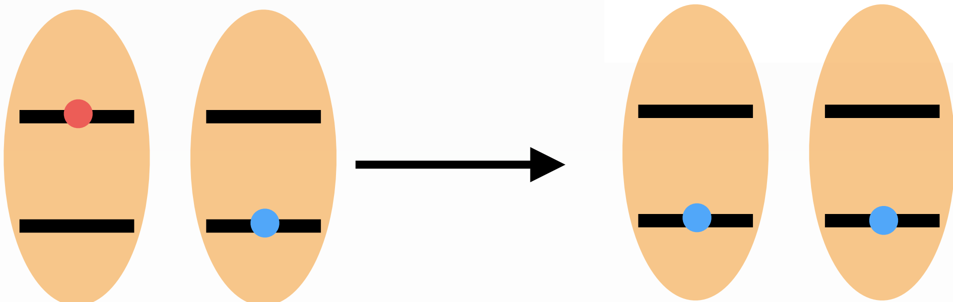

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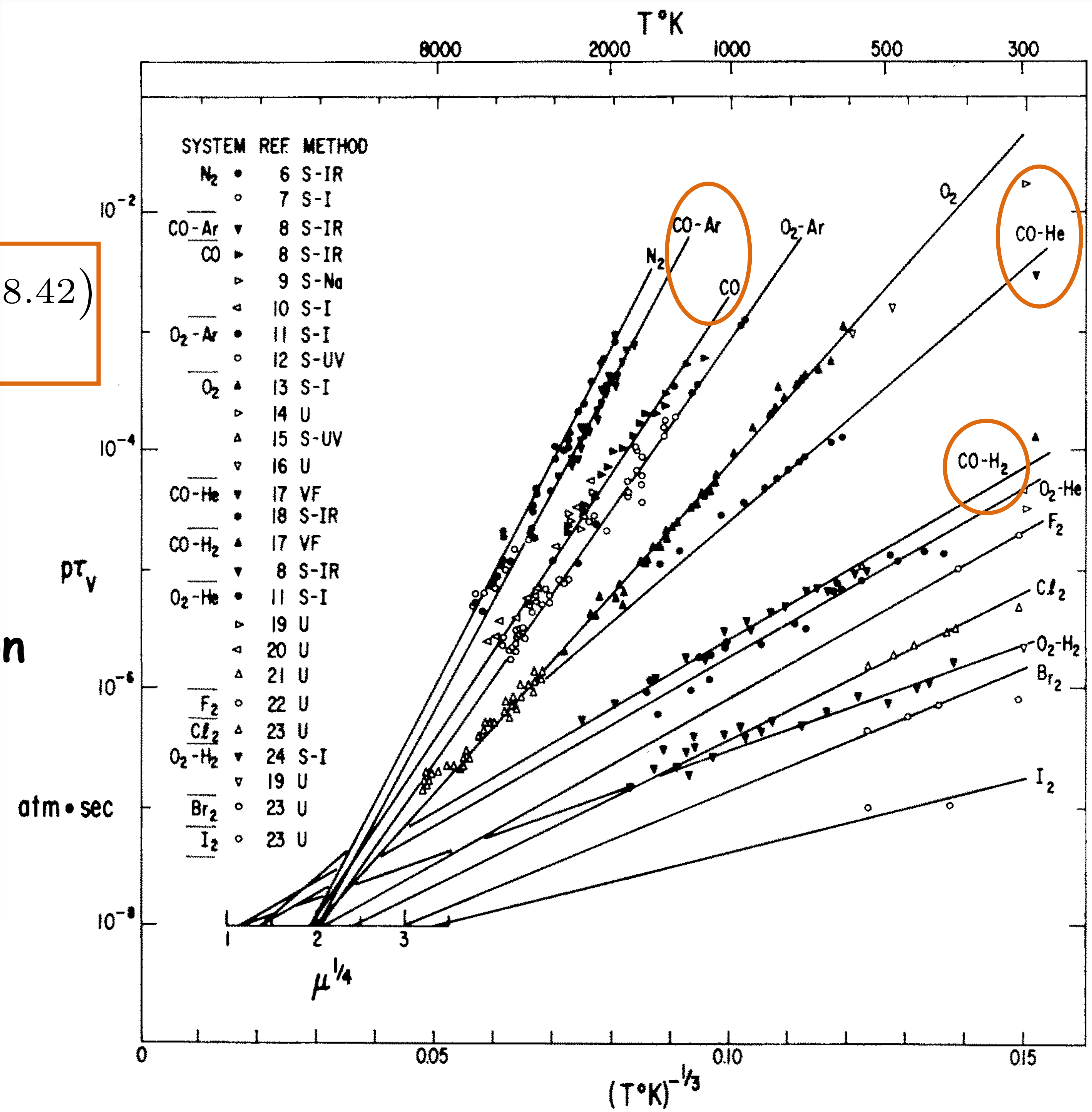

CO shows larger vibrational quenching time
CO has a decent vibrational spacing
CO shows a regular BBR rate absorption spectra at low temperatures

4. Collisional de-excitation

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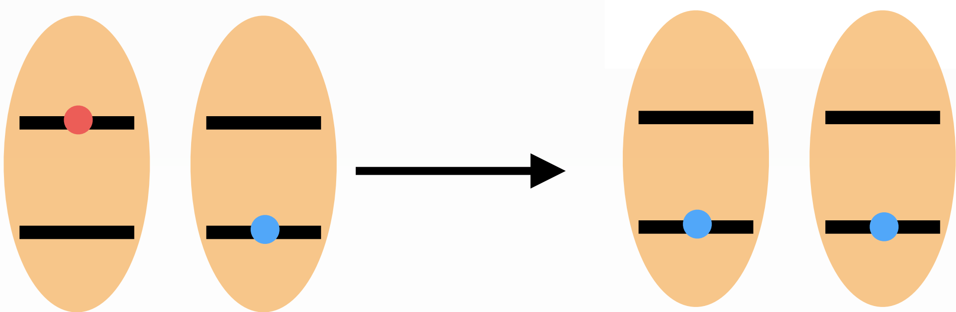

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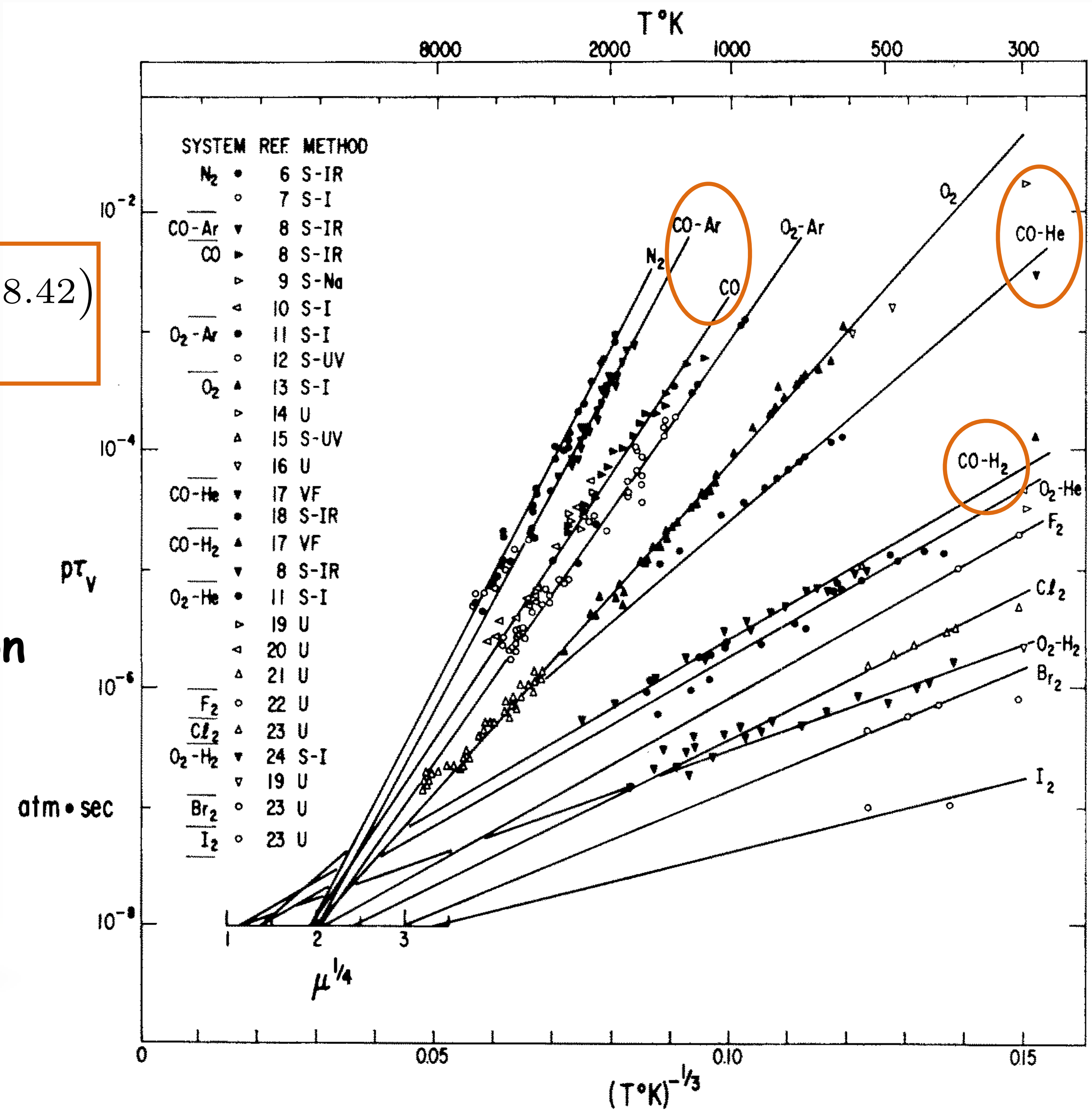
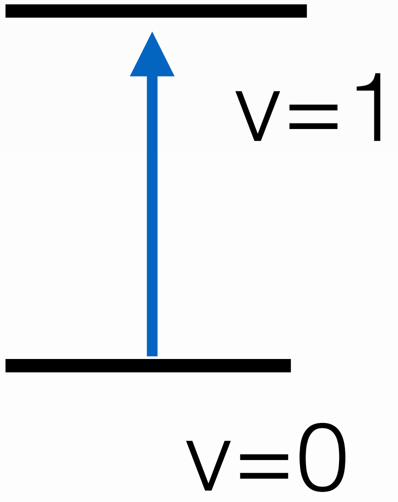


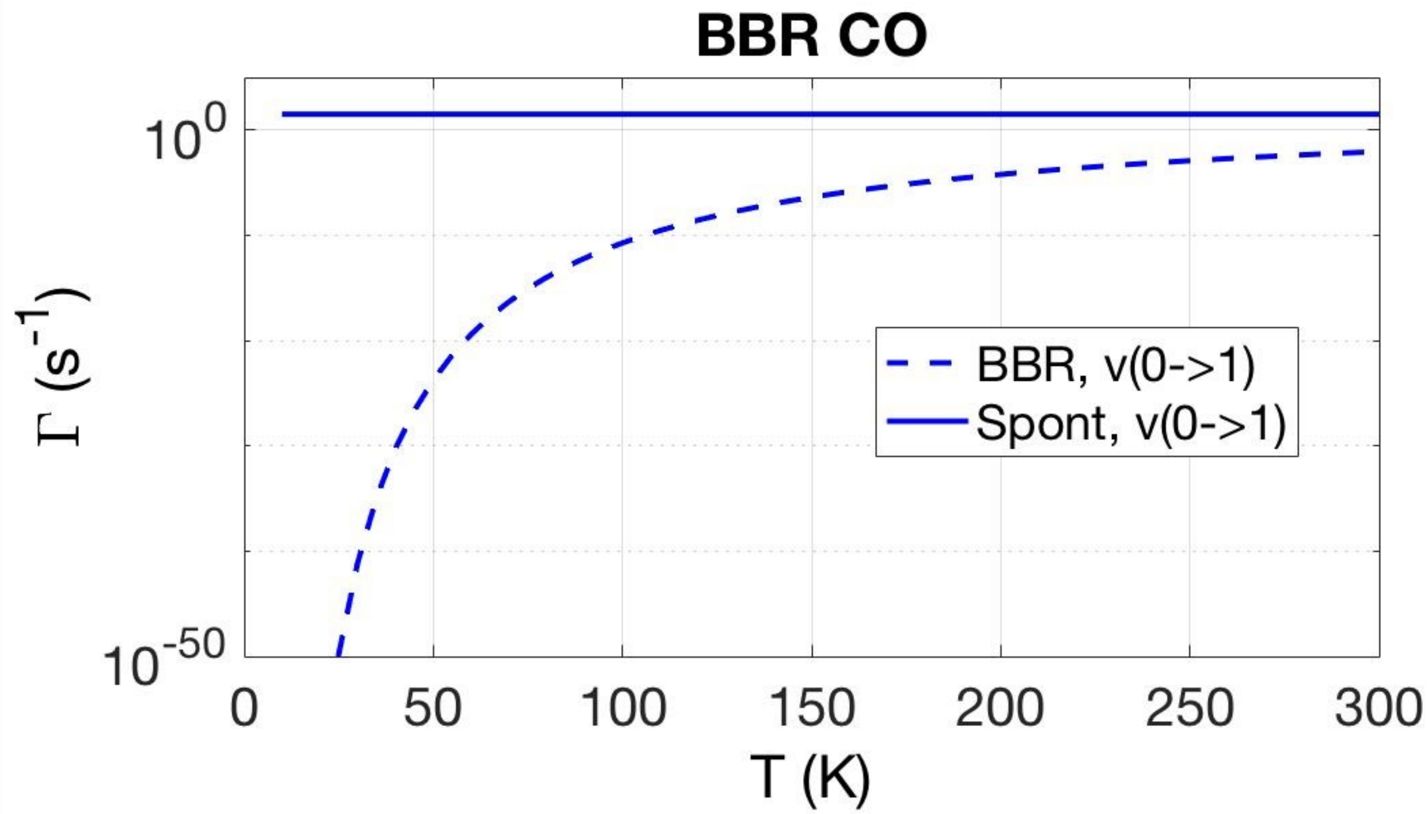
CO shows larger vibrational quenching time
CO has a decent vibrational spacing
CO shows a regular BBR rate absorption spectra at low temperatures

CO is a great candidate

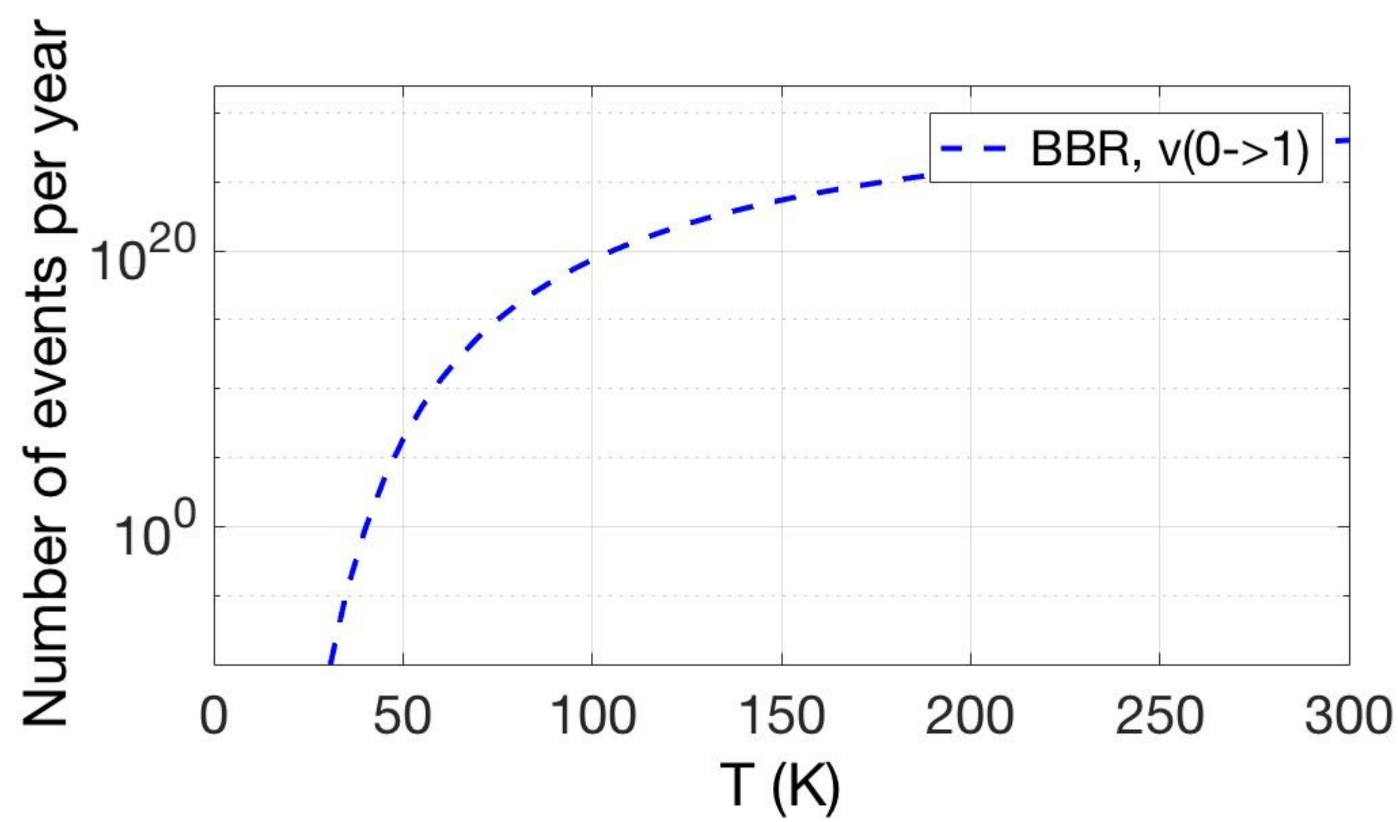
CO in detail (BBR)

A_{10}=32.5 s^{-1}

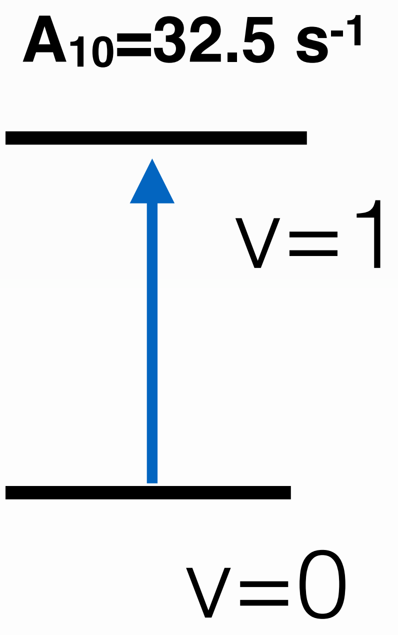




$$\Gamma_{ij}^{BBR} = \frac{8\pi^2 |d_{ij}|^2}{3\epsilon_o \hbar c^3} \frac{\nu^3}{\exp \frac{h\nu}{k_B T} - 1}$$



CO in detail (BBR)



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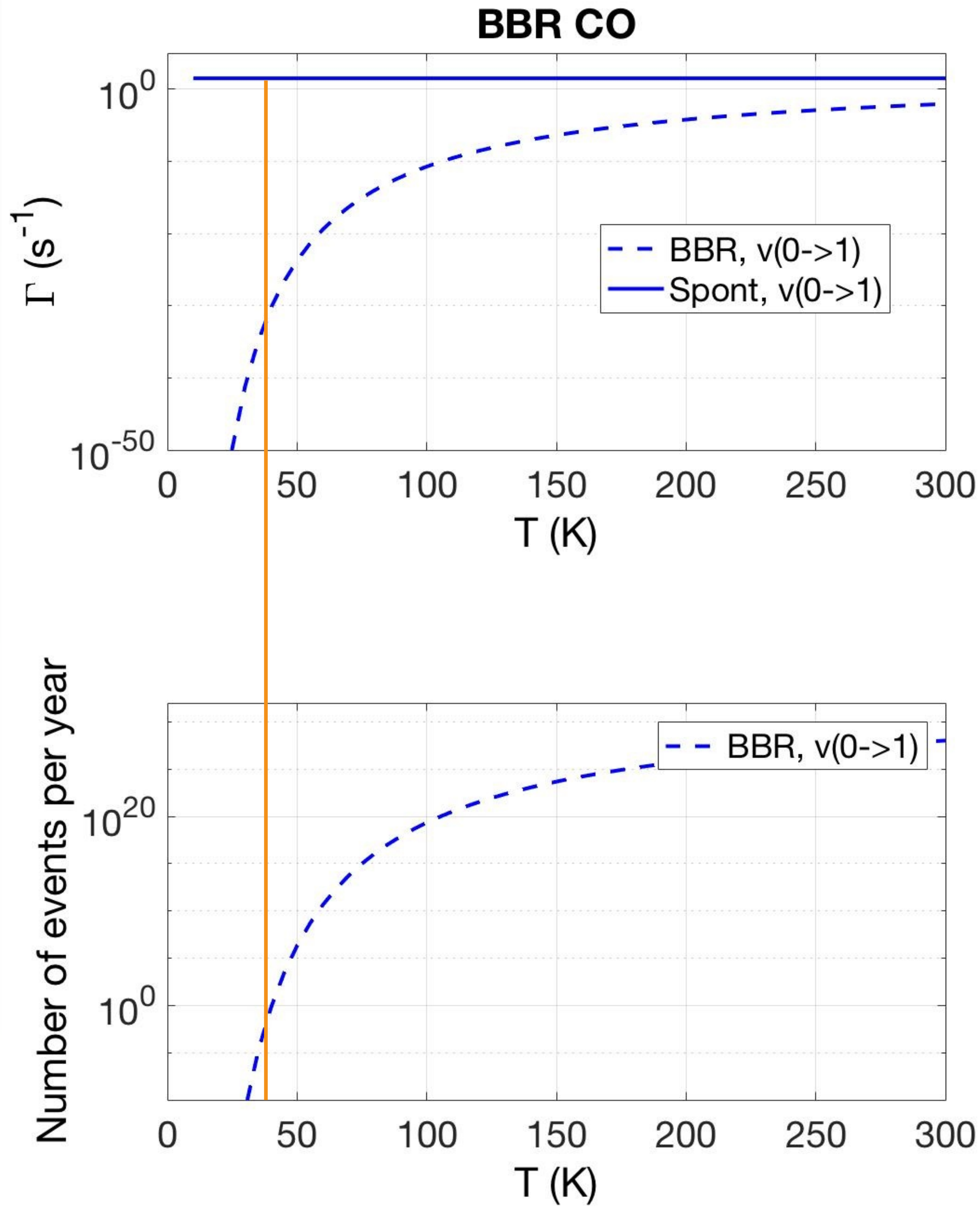

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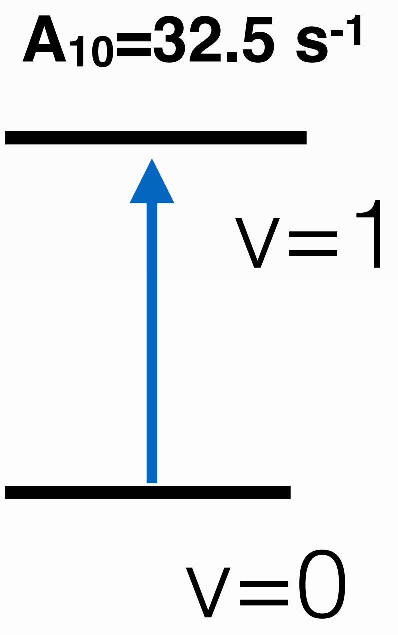

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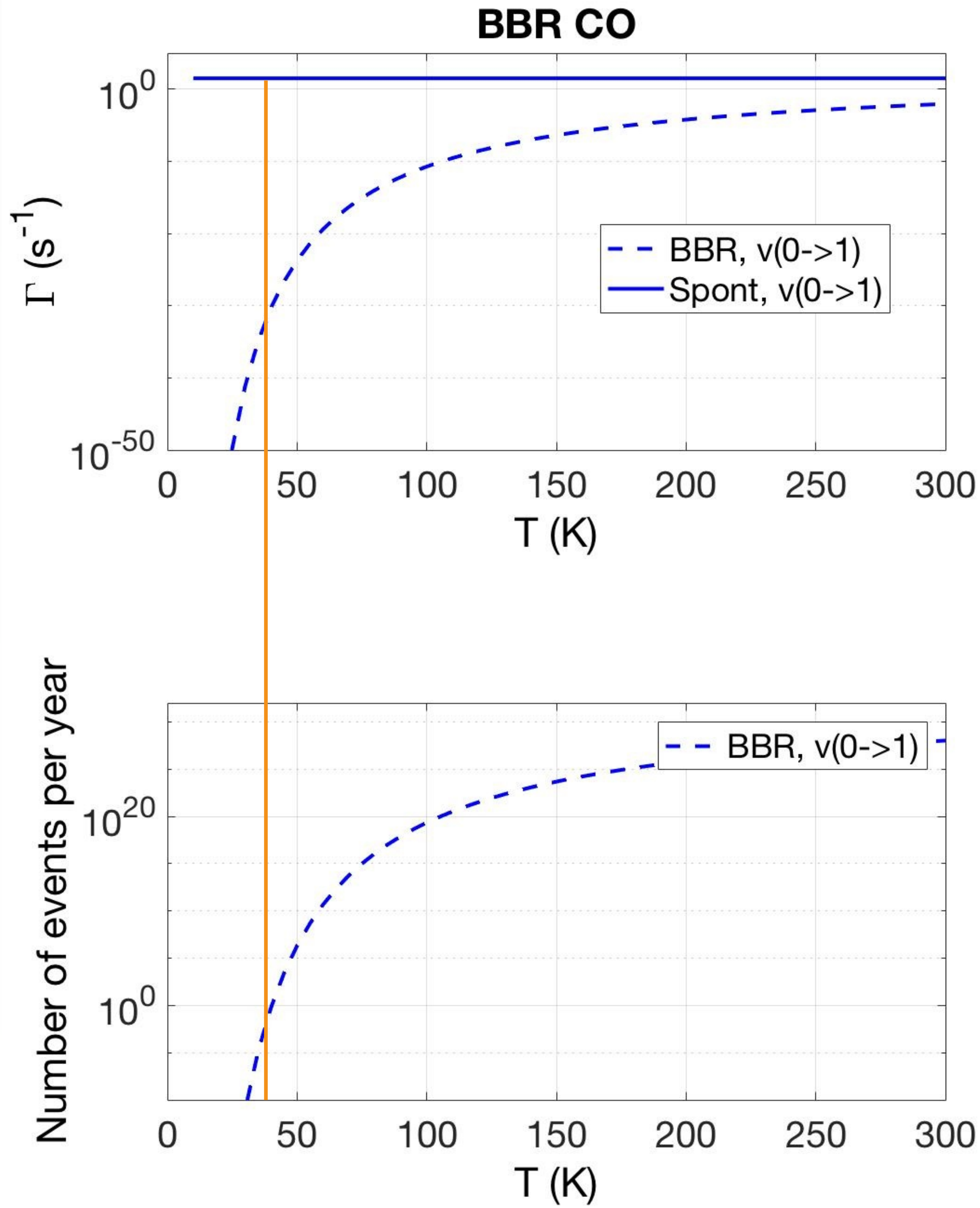
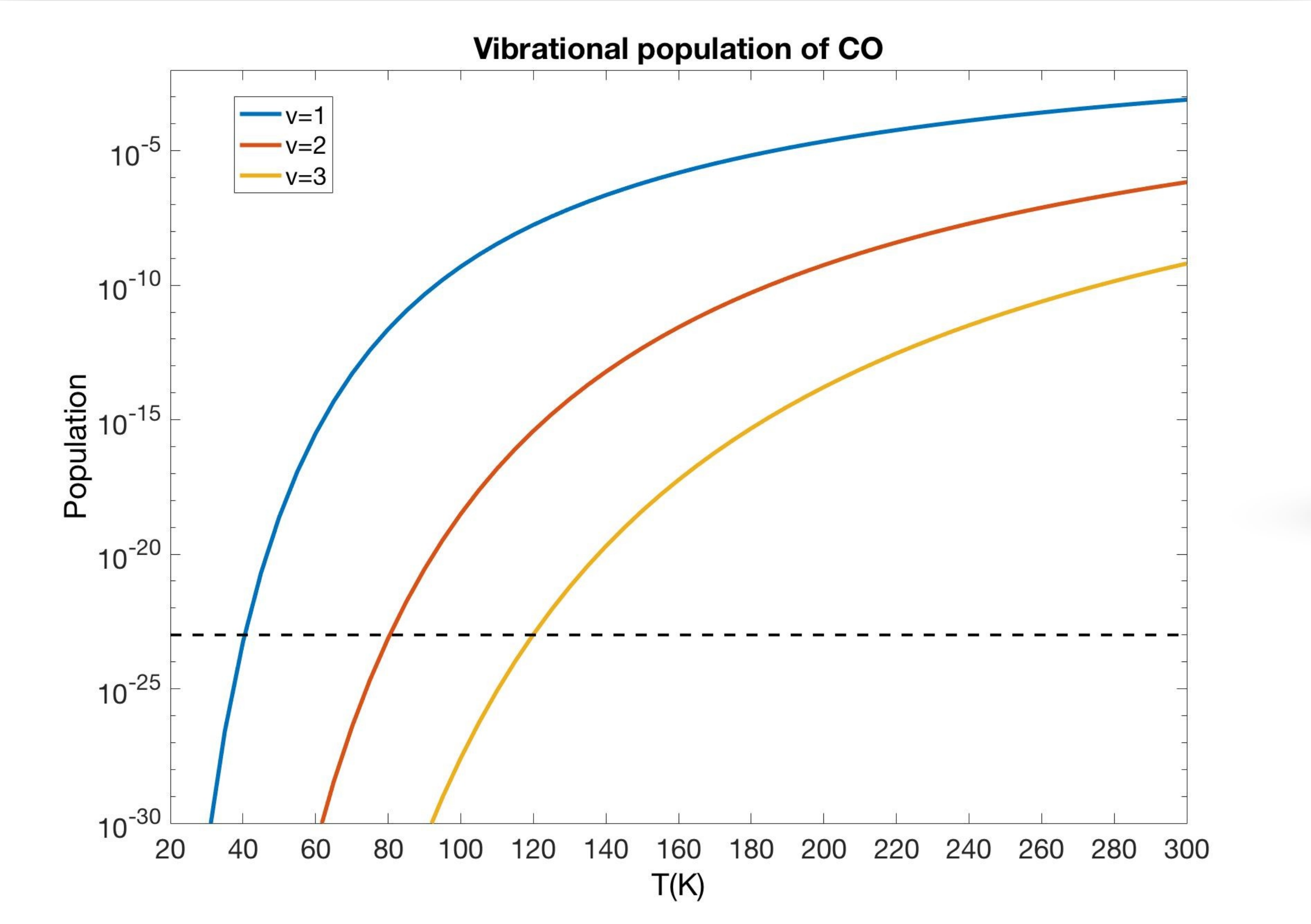
CO @ 40K

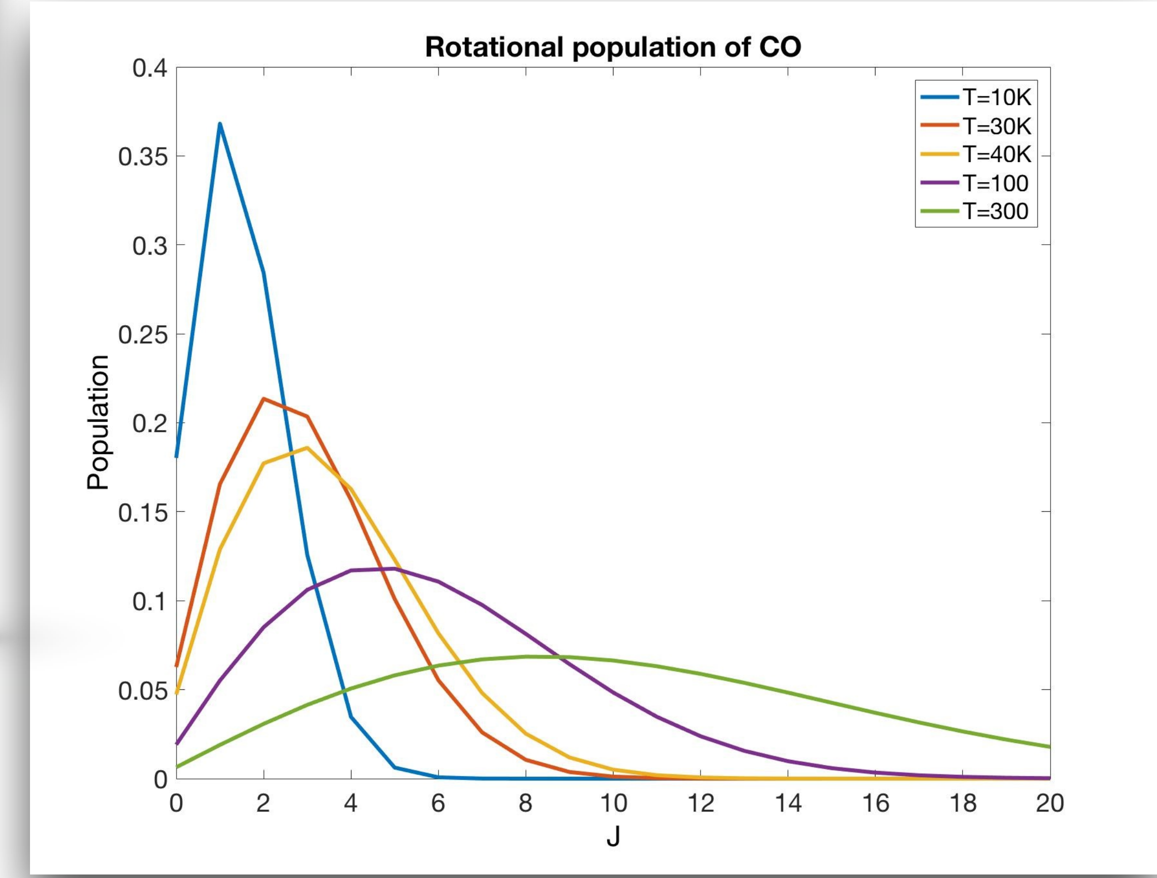


CO in detail (Rovibrational population)



For CO @ 40 K the <u>pressure must be ≲ 0.1 mbar</u> to have all the molecules in gas phase

The rotational level distribution is accounted for in the rate calculation



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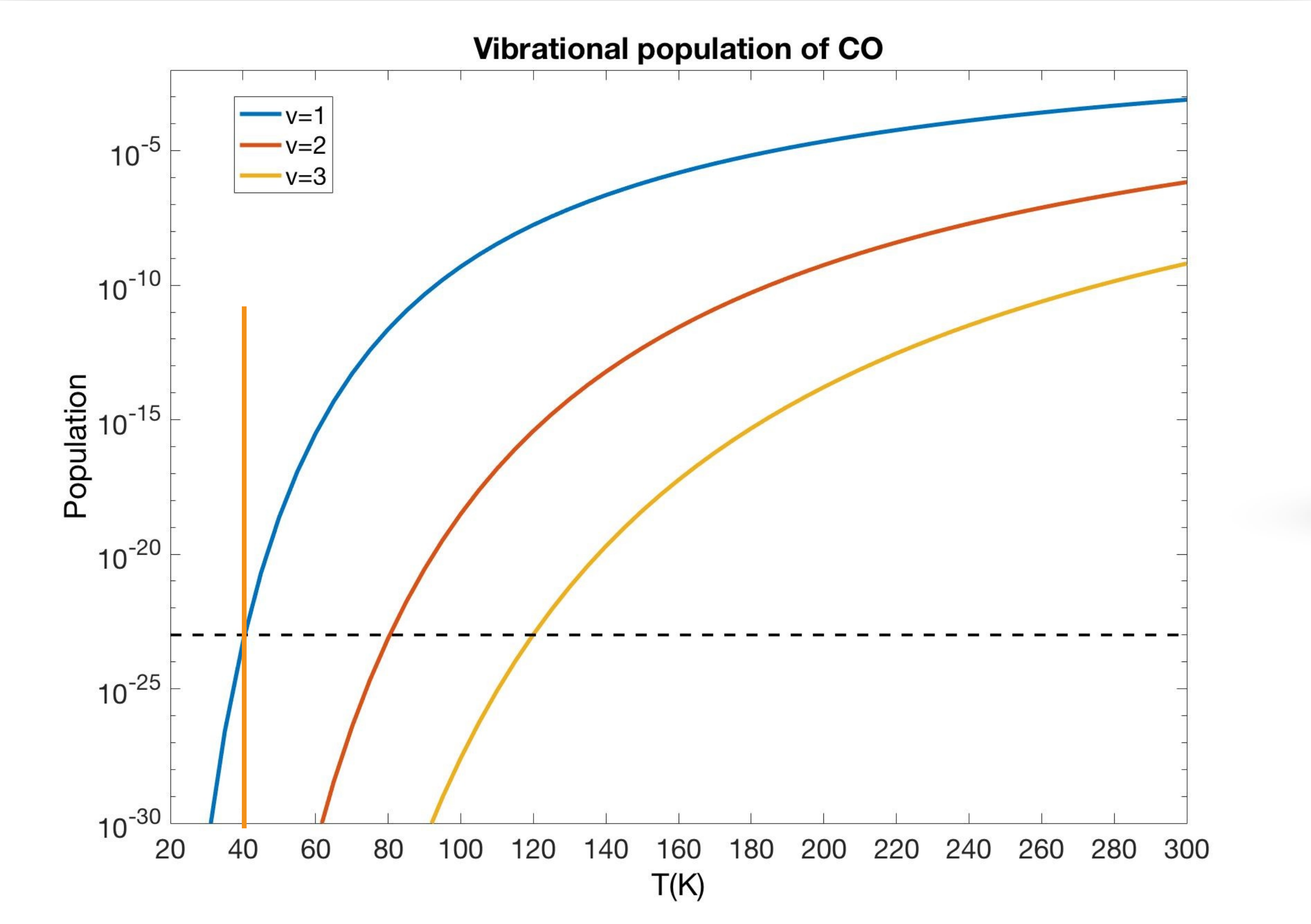

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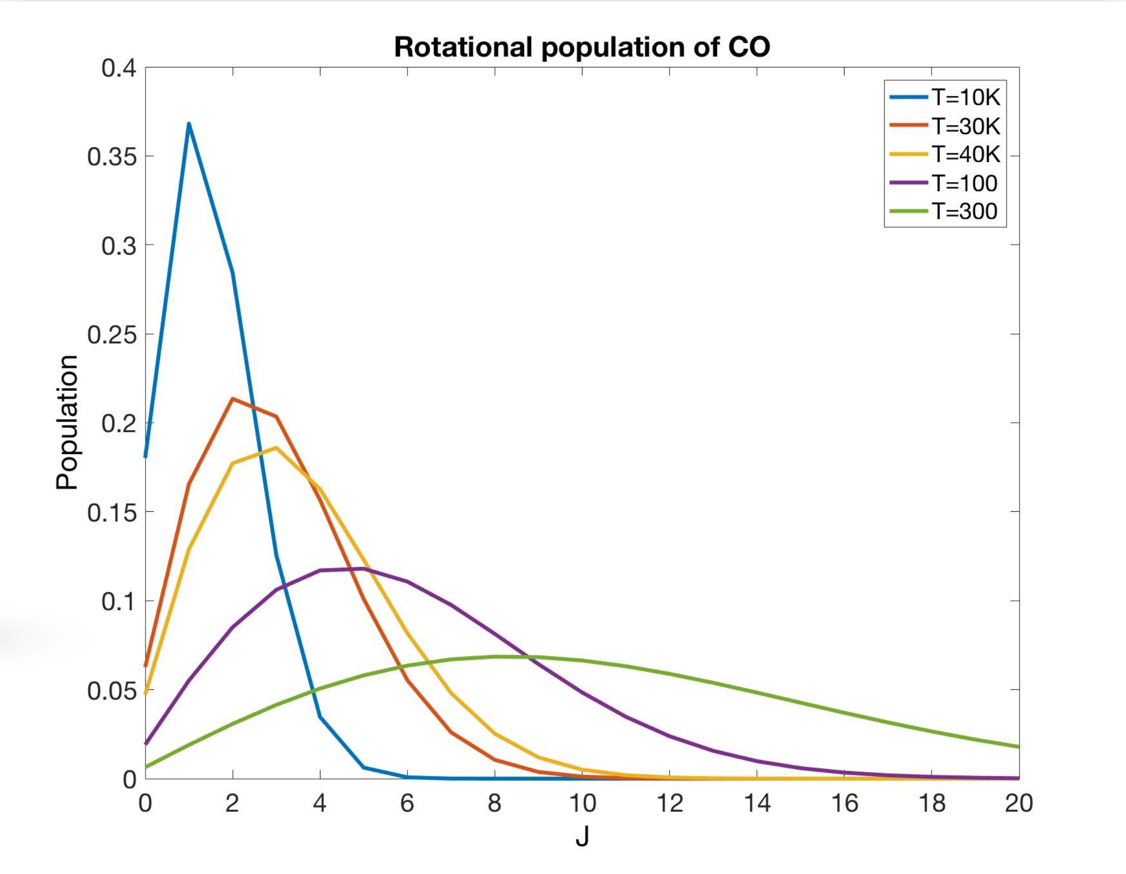
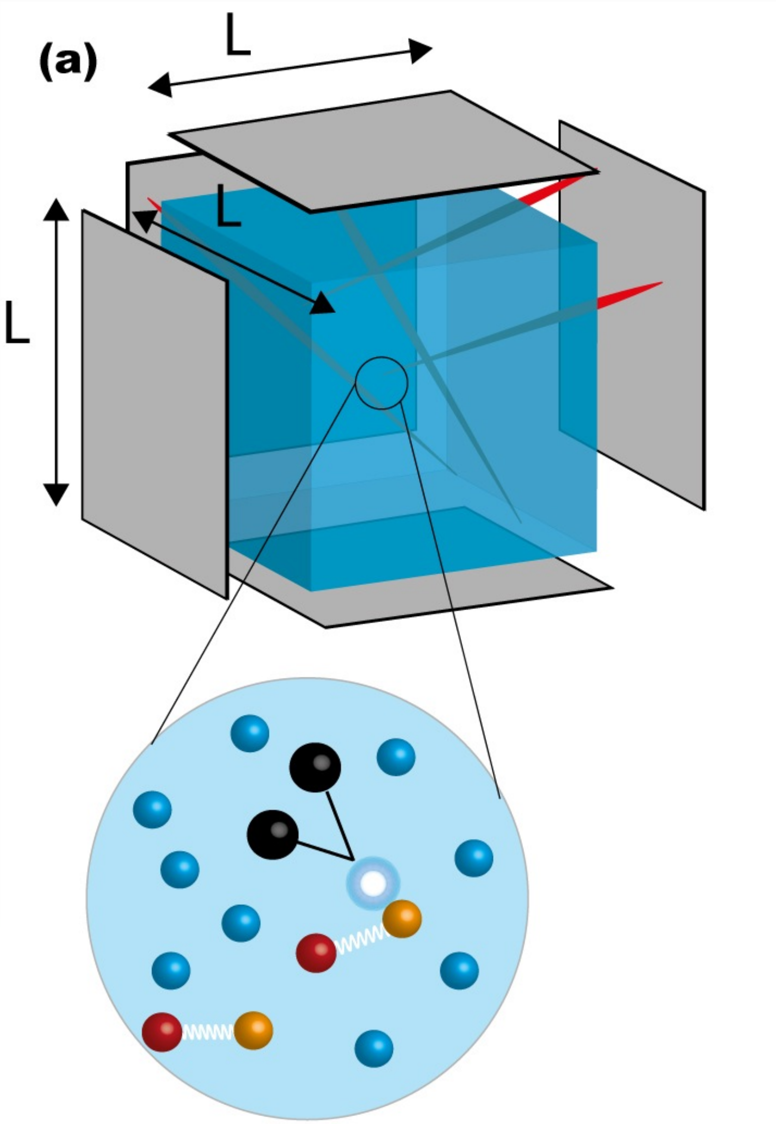


The rotational level distribution is accounted for in the rate calculation

CO in detail (bonus as I promised)



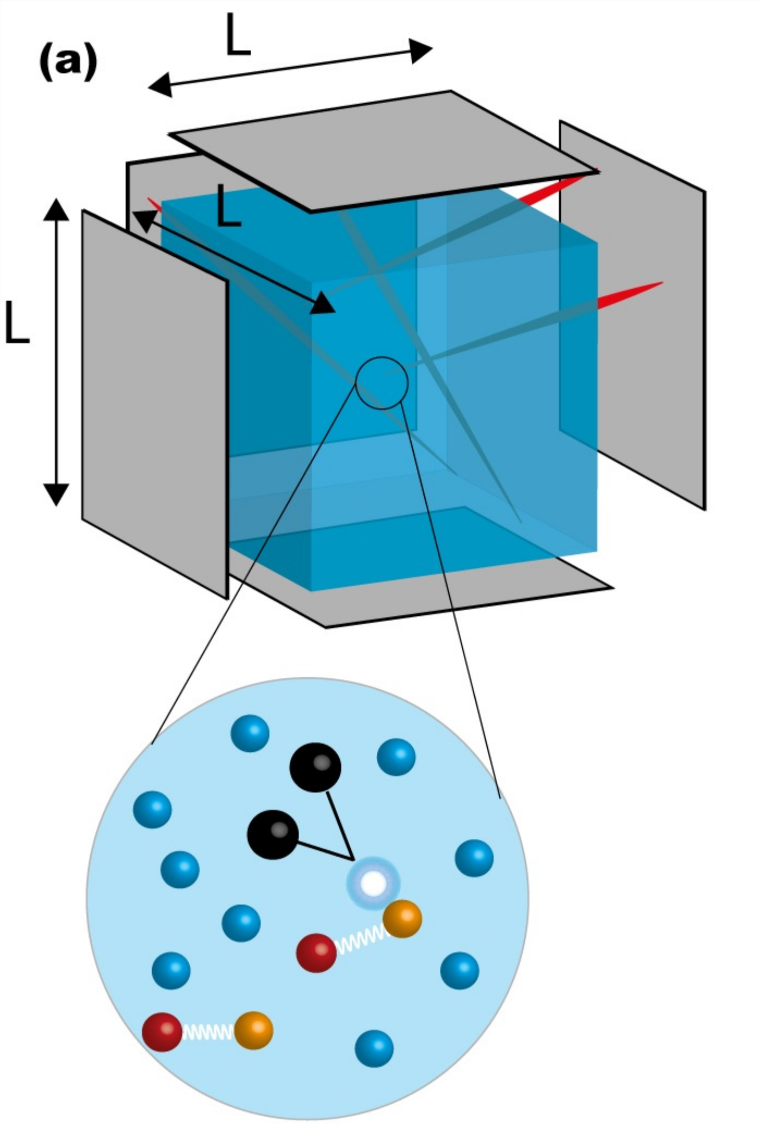
$$\sigma_{\rm abs}(\omega) = \hbar\omega B_{ij} g(\omega)$$

$$g(\omega) = \frac{1}{2\pi}\frac{\gamma_{\rm el}}{\gamma_{\rm el}^2 + (\omega - \omega_0)^2}$$

$$\gamma_{\rm el} = \rho_{\rm He}\langle \sigma_{\rm el}(v) v \rangle$$

CO in detail (bonus as I promised)

The emitted photon can be absorbed by another molecule before it reaches the detector



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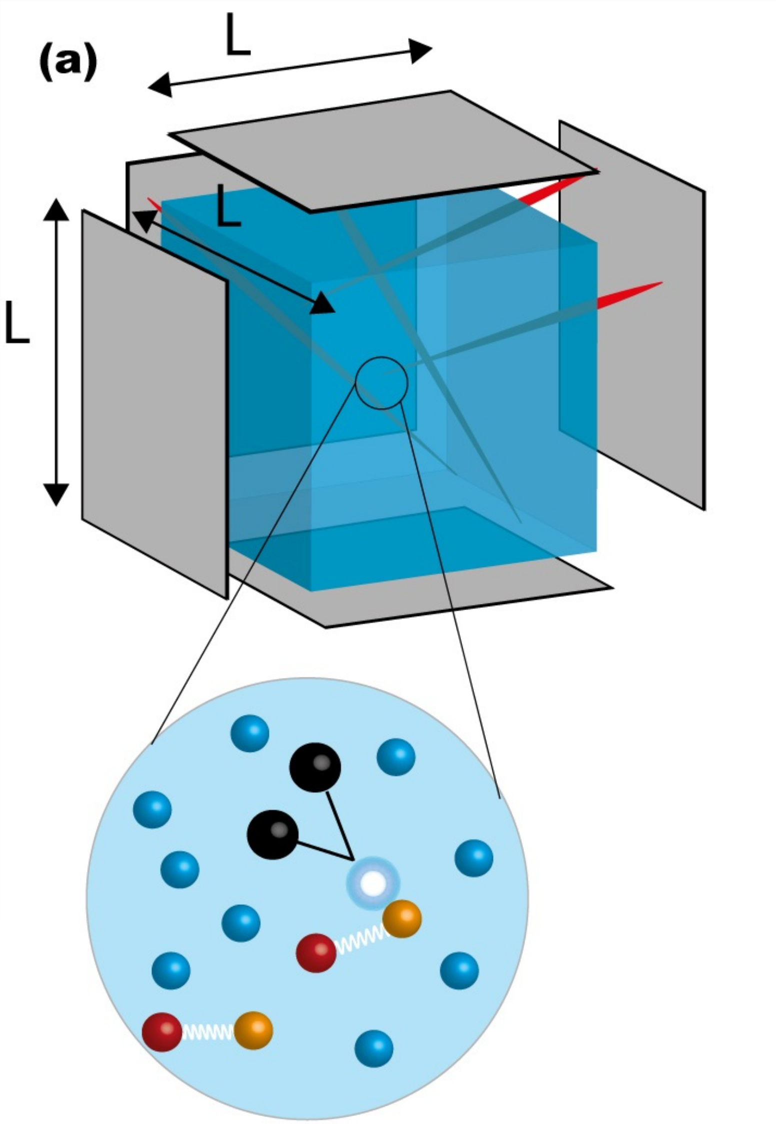

Absorption cross section

$$\sigma_{\mathrm{abs}}(\omega) = \hbar\omega B_{ij} g(\omega)$$

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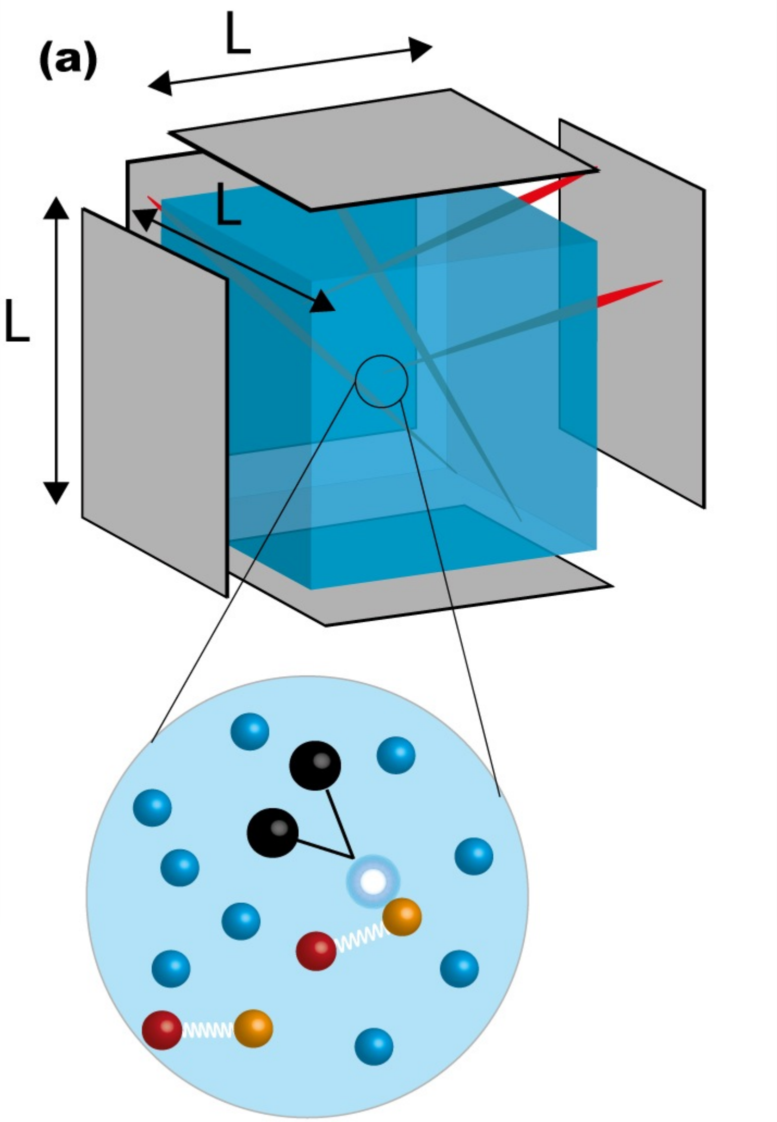

$$\sigma_{\rm abs}(\omega) = \hbar\omega B_{ij} g(\omega)$$

$$B_{ij} = \frac{\lambda^3}{8\pi hc} A_{ij}$$

$$l(\omega) = \frac{1}{\rho_{\rm CO}\sigma_{\rm abs}(\omega)}$$

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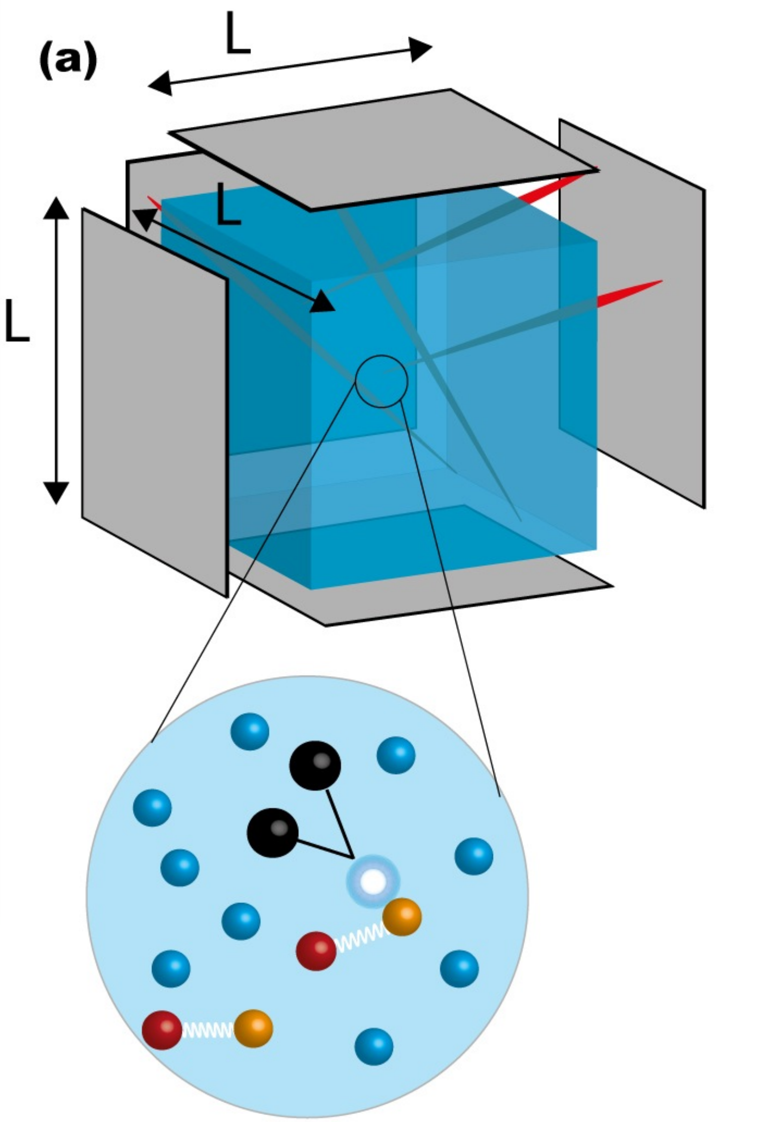

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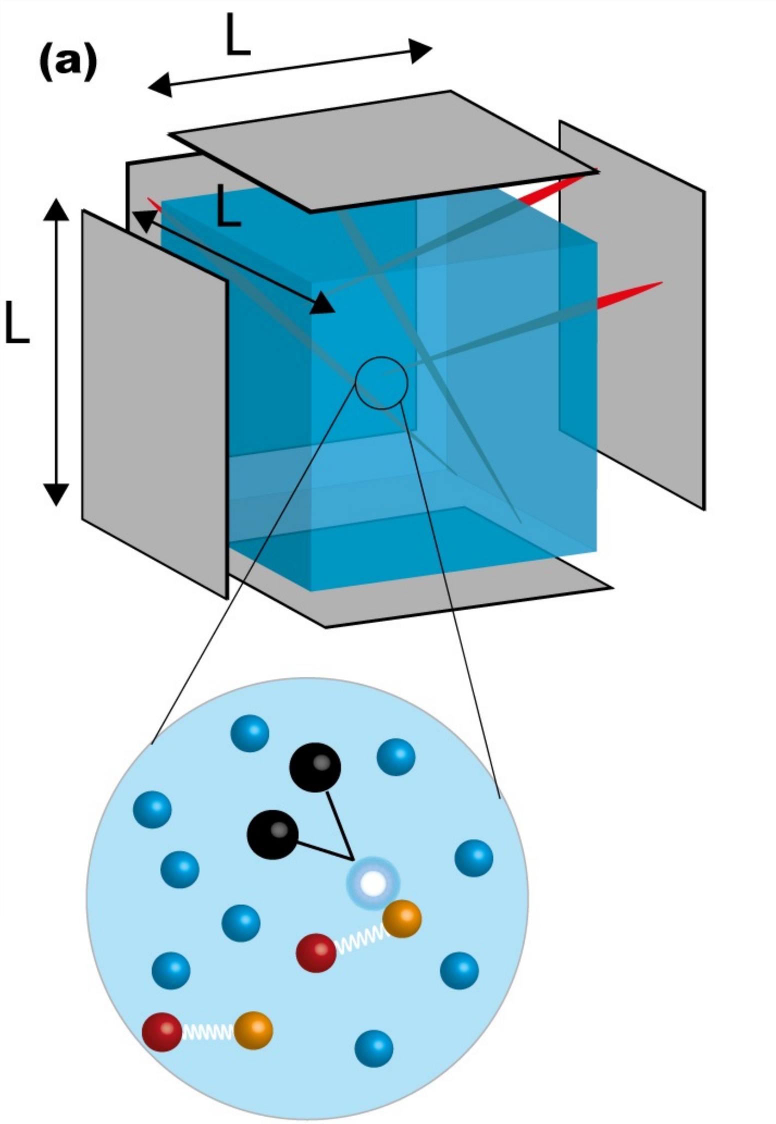

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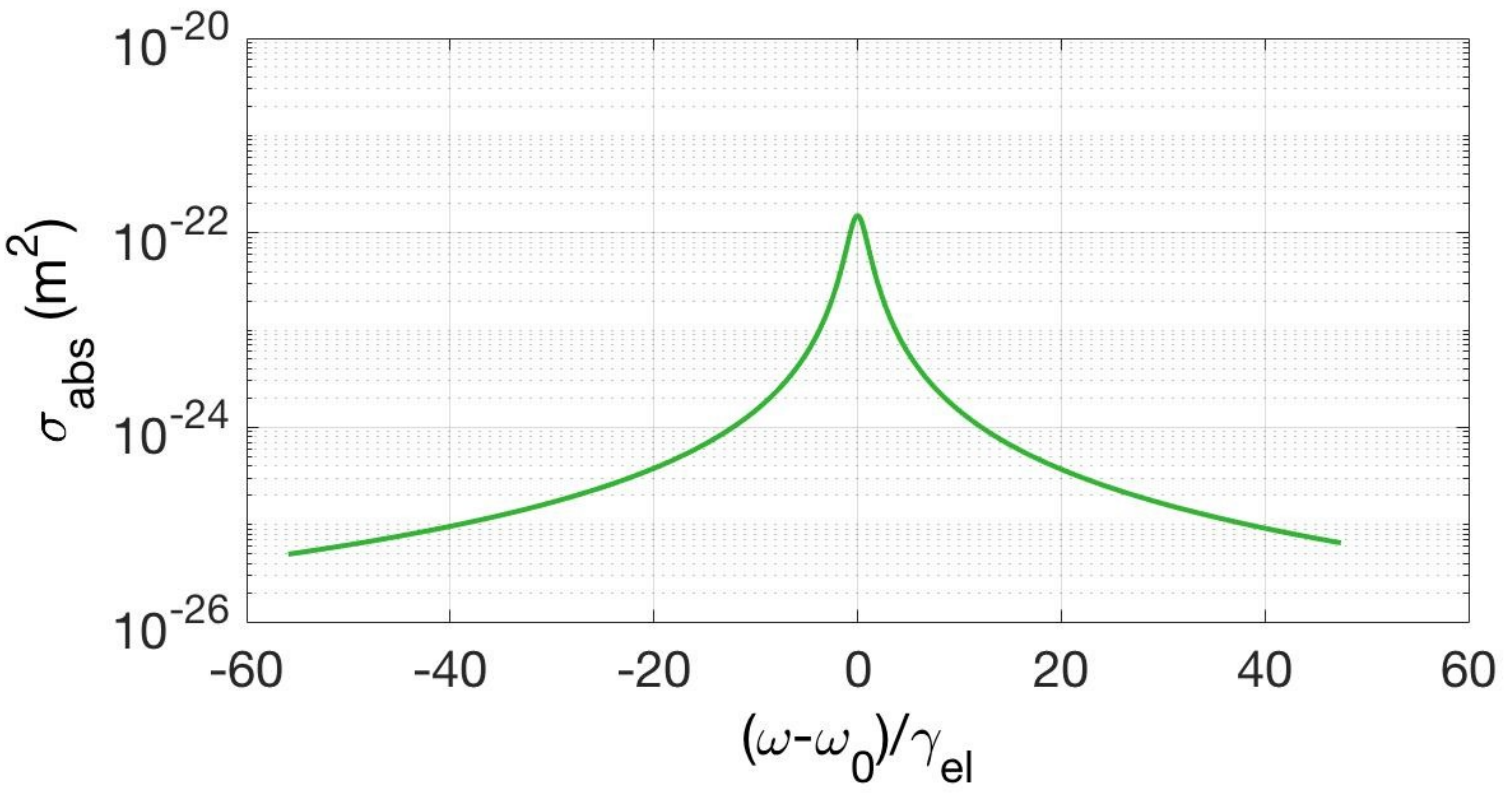

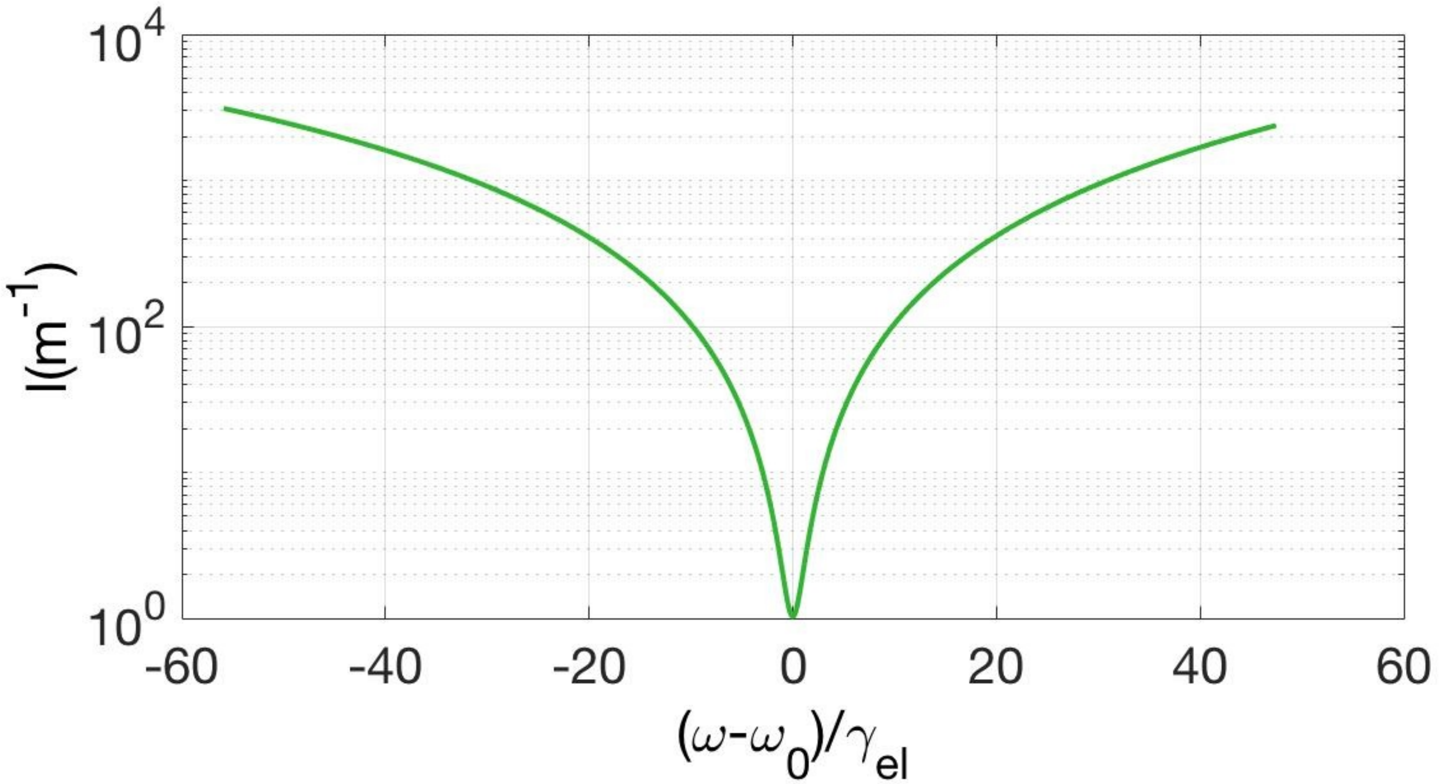

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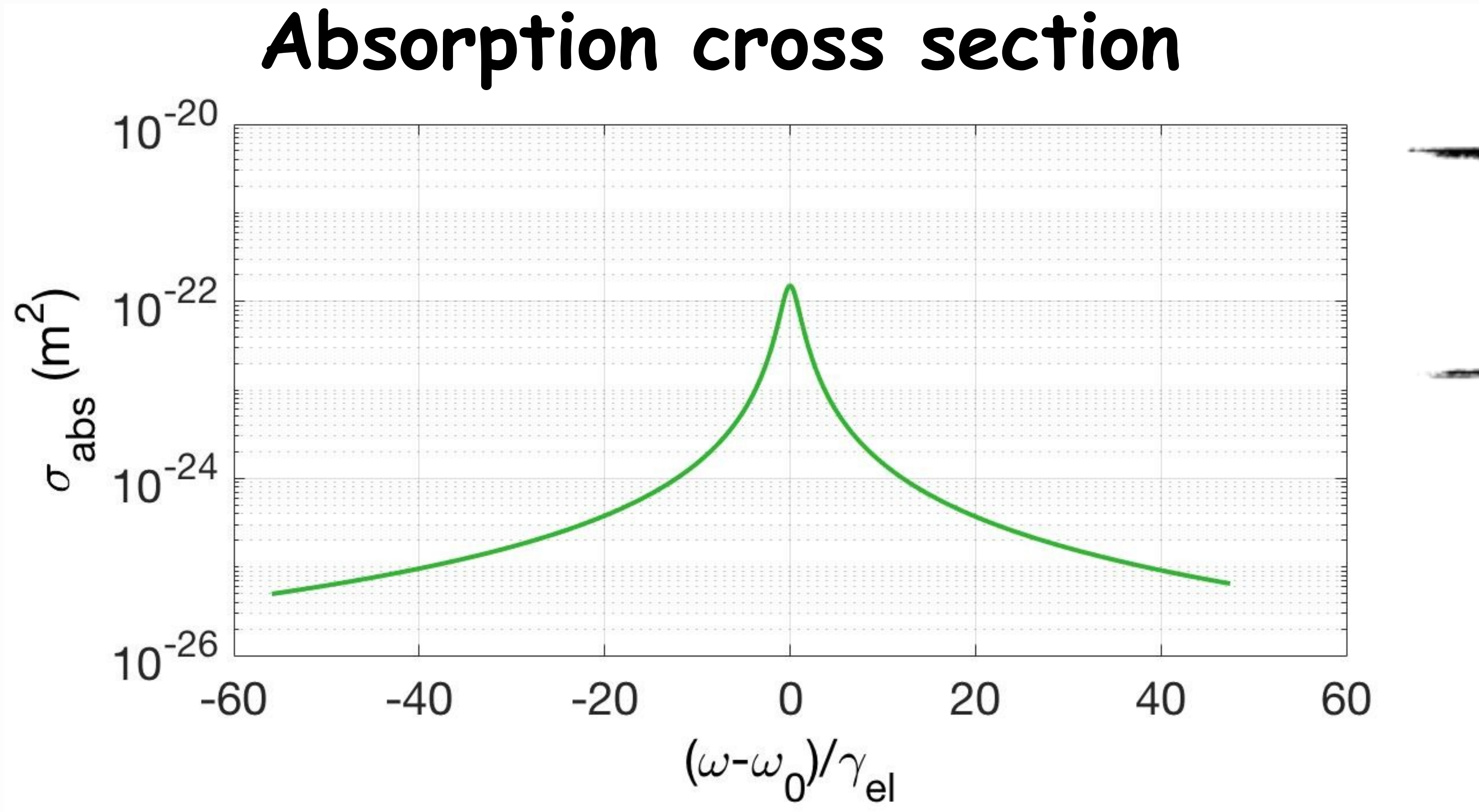
P_{CO}=2.3x10^{-5} bar

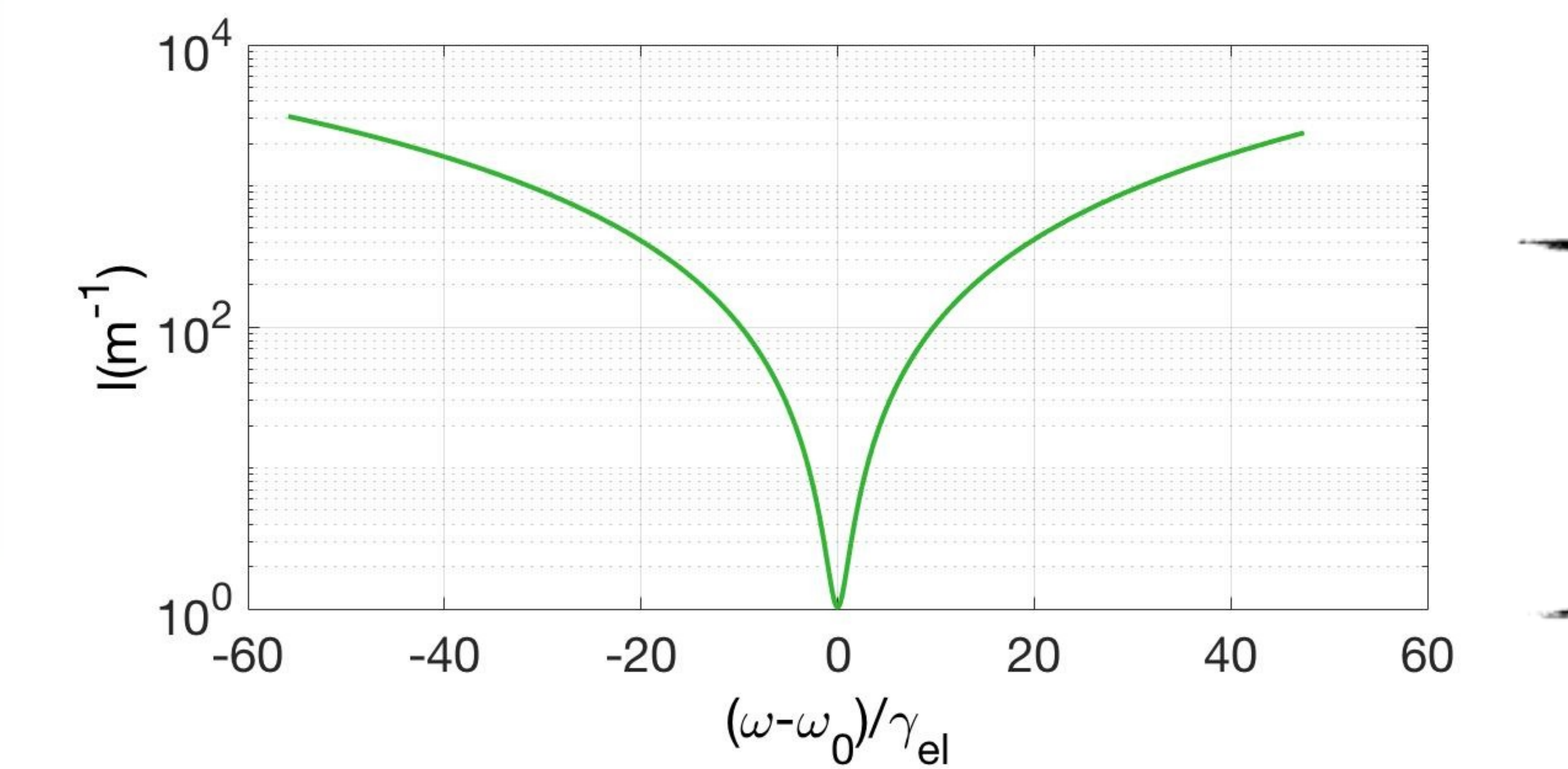
P_{He}=0.99998 bar

$$l(\omega) = \frac{1}{\rho_{\mathrm{CO}}\sigma_{\mathrm{abs}}(\omega)}$$

CO in detail (bonus as I promised)

Absorption cross section





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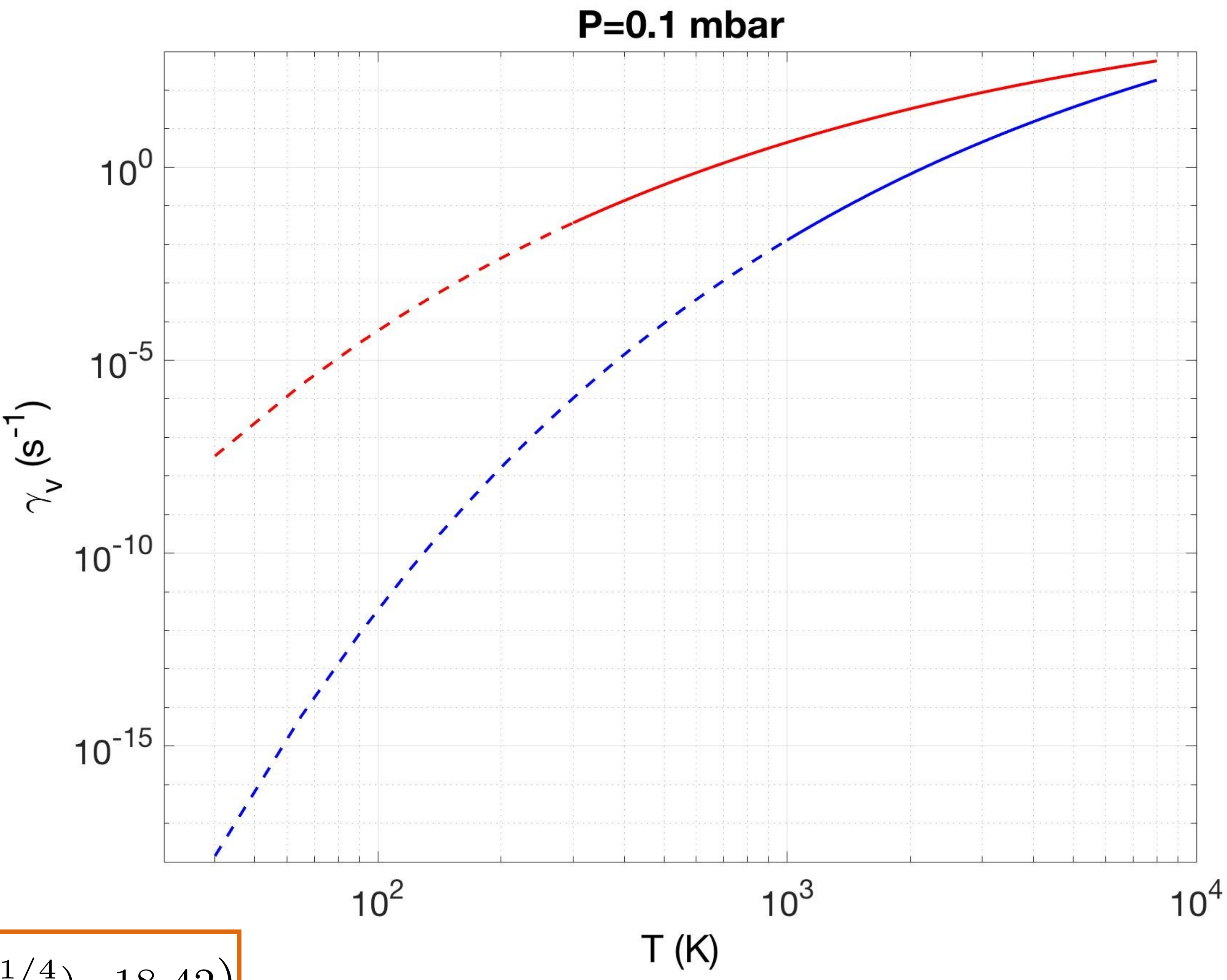
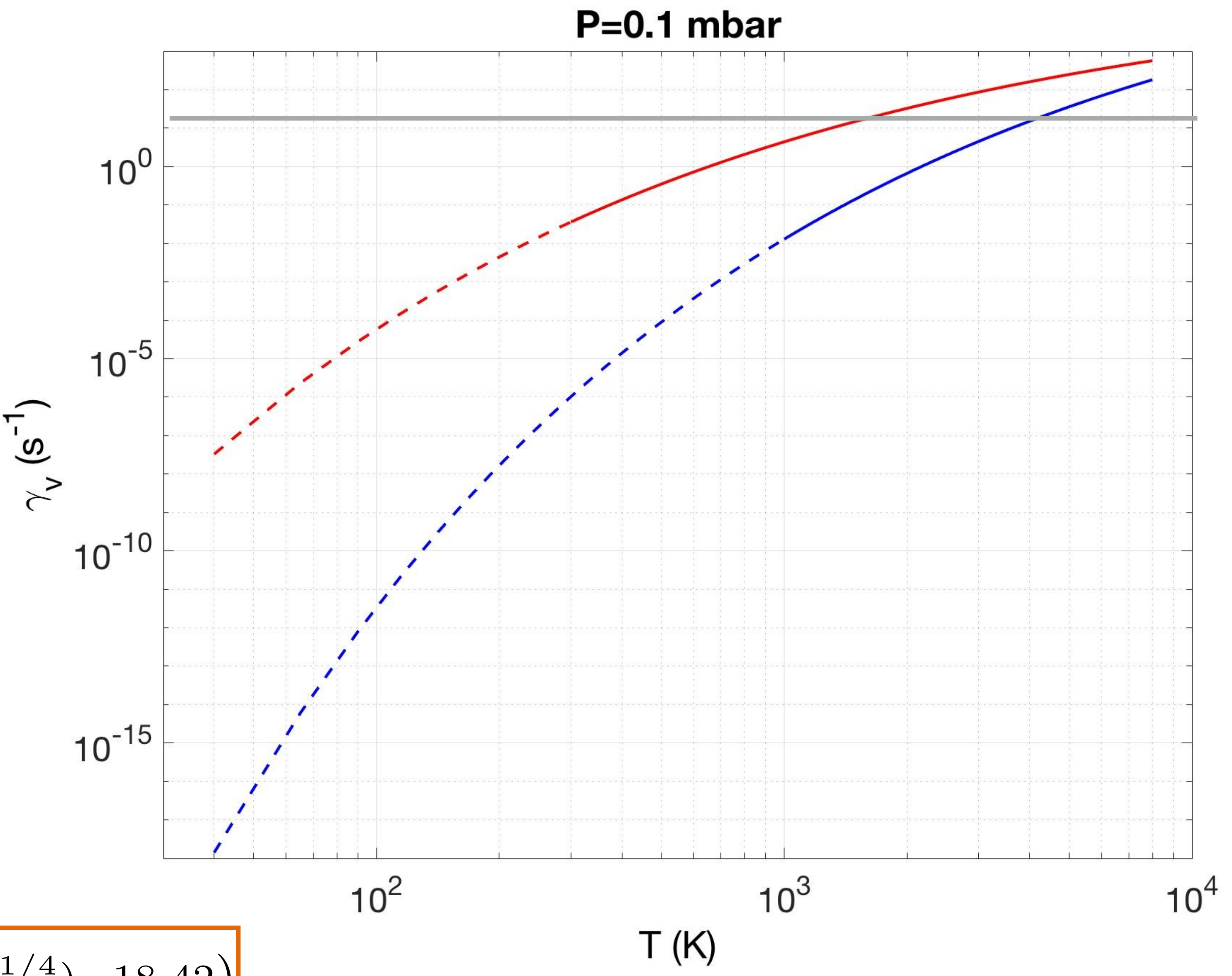
CO in detail (collisions)



$$p\tau_v = e^{\left(1.16\times10^{-3}\mu^{1/2}\omega^{4/3}(T^{-1/3}-0.015\mu^{1/4})-18.42\right)}$$

CO in detail (collisions)



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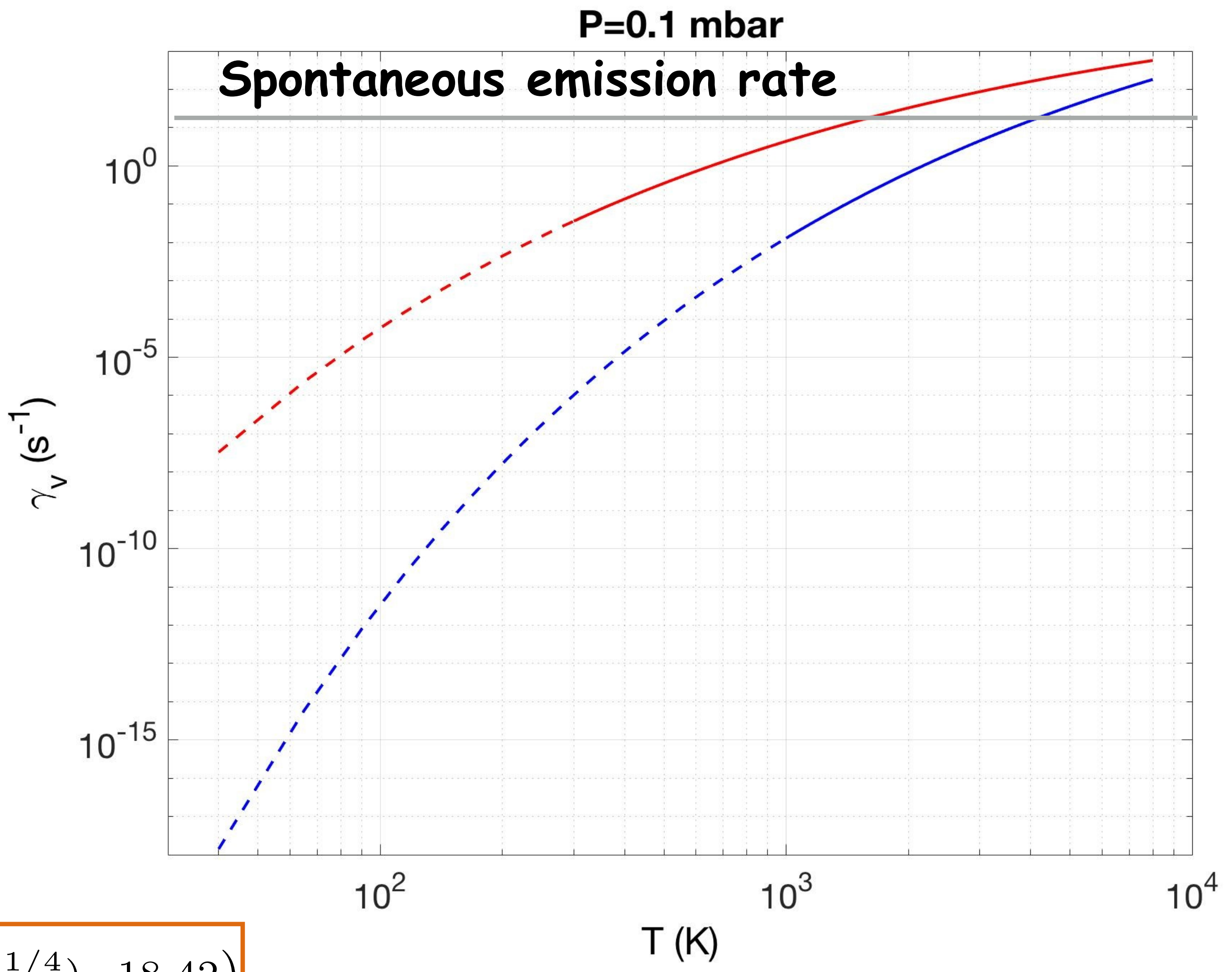

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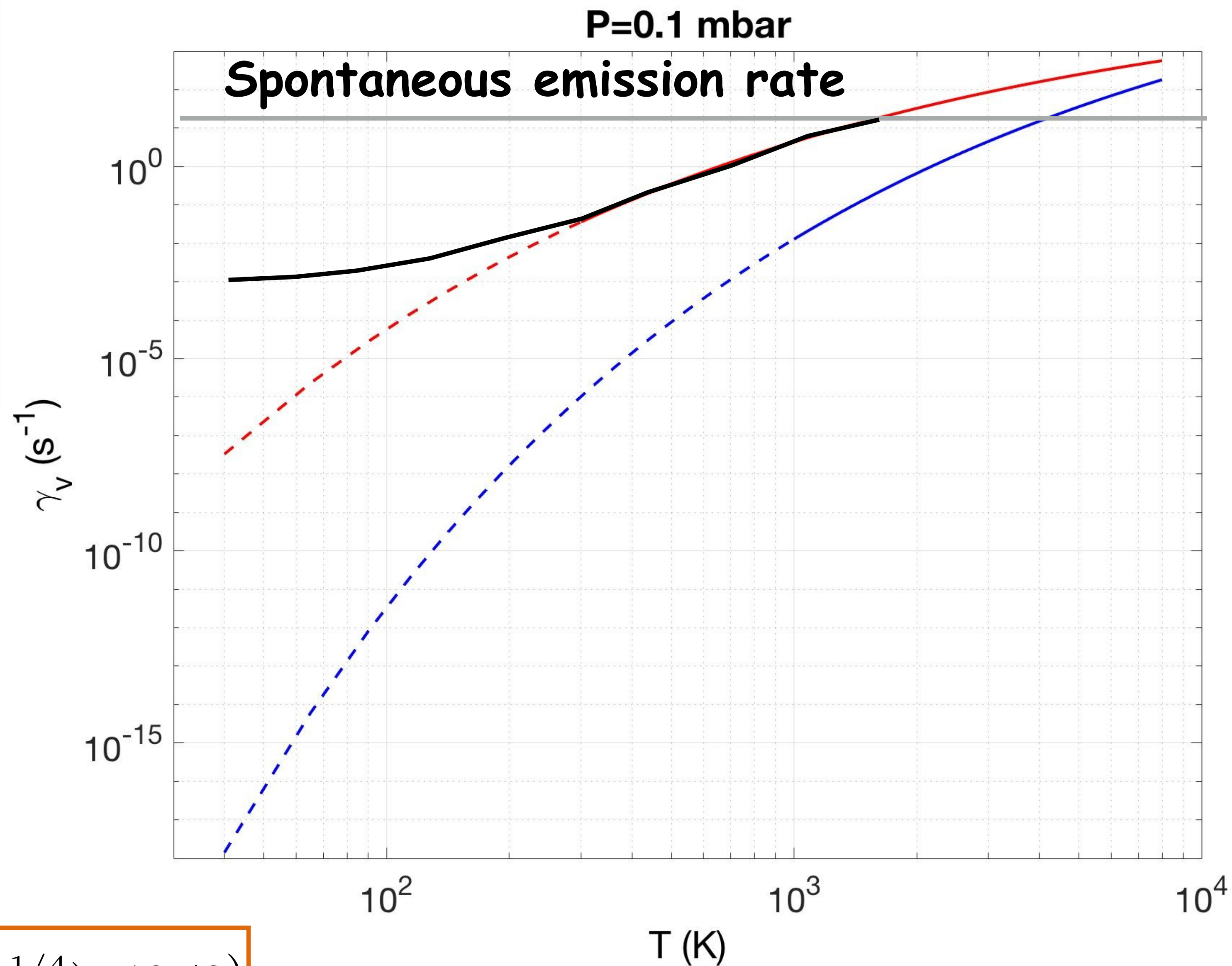
JOURNAL OF CHEMICAL PHYSICS VOLUME 116, NUMBER 11 15 MARCH 2002

Vibrational relaxation of vibrationally and rotationally excited CO molecules by He atoms

Roman V. Krems[a)]
Department of Chemistry, Physical Chemistry, Göteborg University, SE-412 96, Göteborg, Sweden



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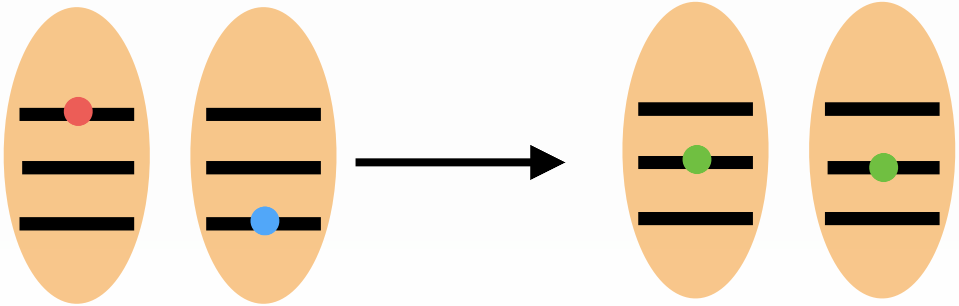
CO in detail (collisions)

Vibrational energy exchange in CO–CO collisions at low temperature

M. C. Gower, G. Srinivasan, and K. W. Billman

Citation: The Journal of Chemical Physics **63**, 4206 (1975);
View online: https://doi.org/10.1063/1.431190
View Table of Contents: http://aip.scitation.org/toc/jcp/63/10
Published by the American Institute of Physics



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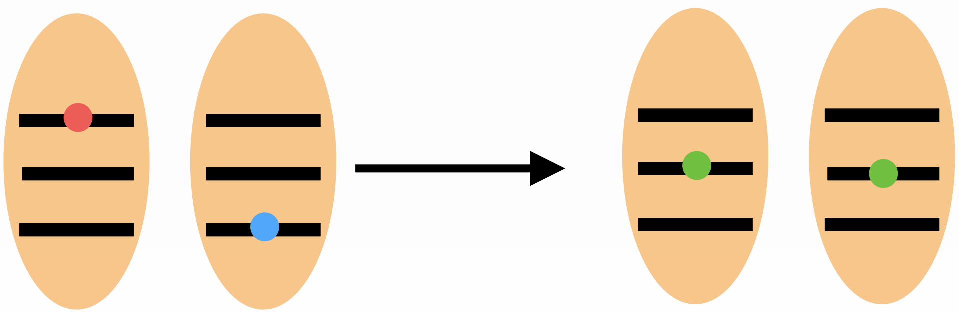
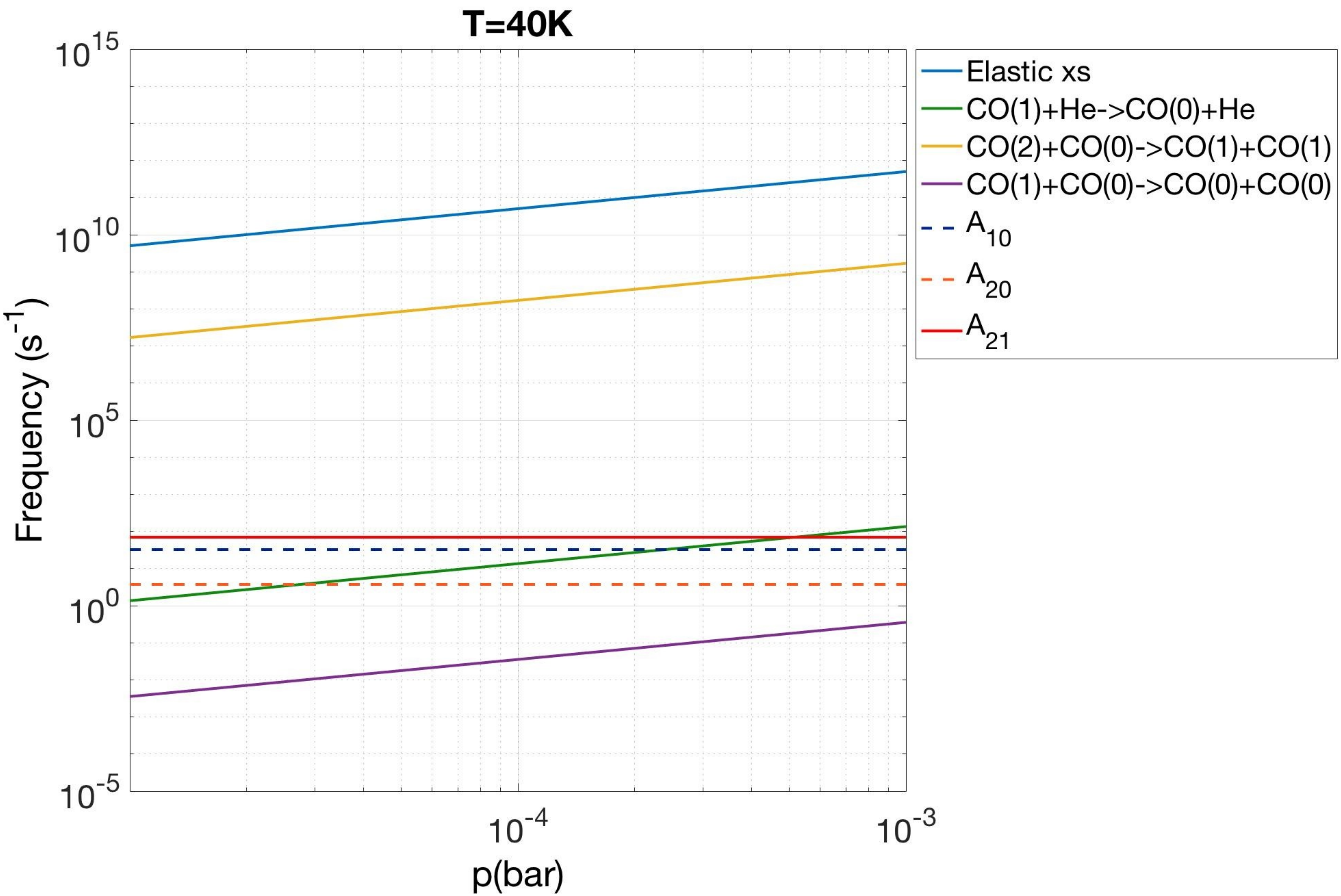


CO @ 40 K

$$k_{v,v-1}=1.8\times10^{-12}\ cm^3/s$$

CO in detail (collisions)



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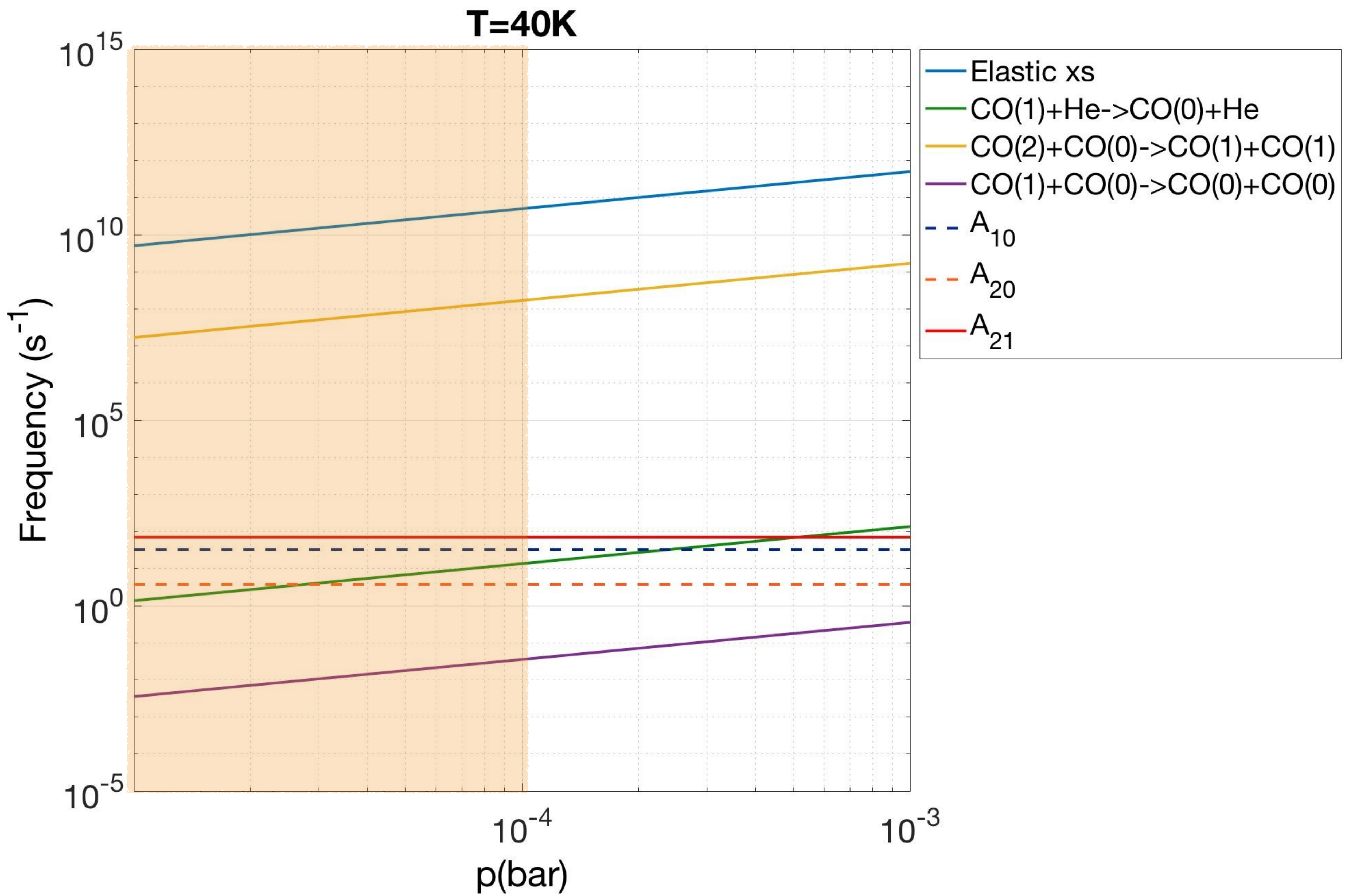
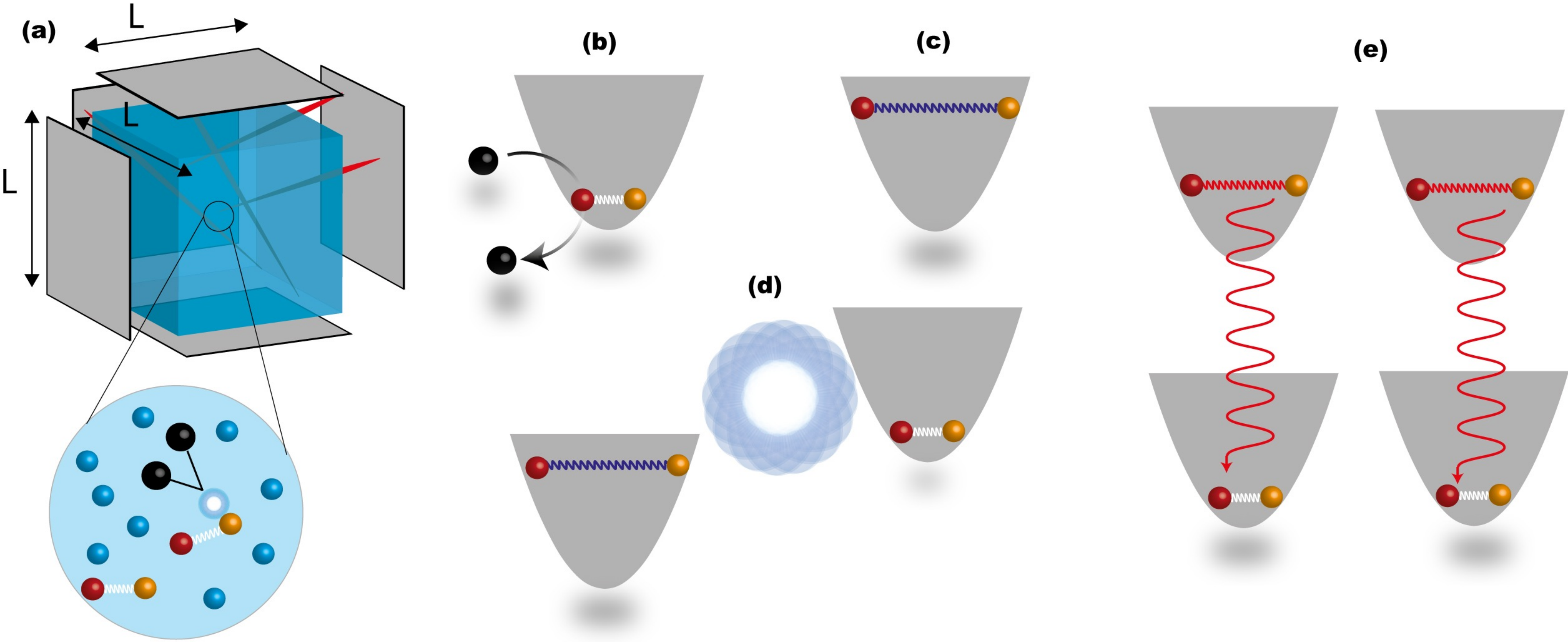
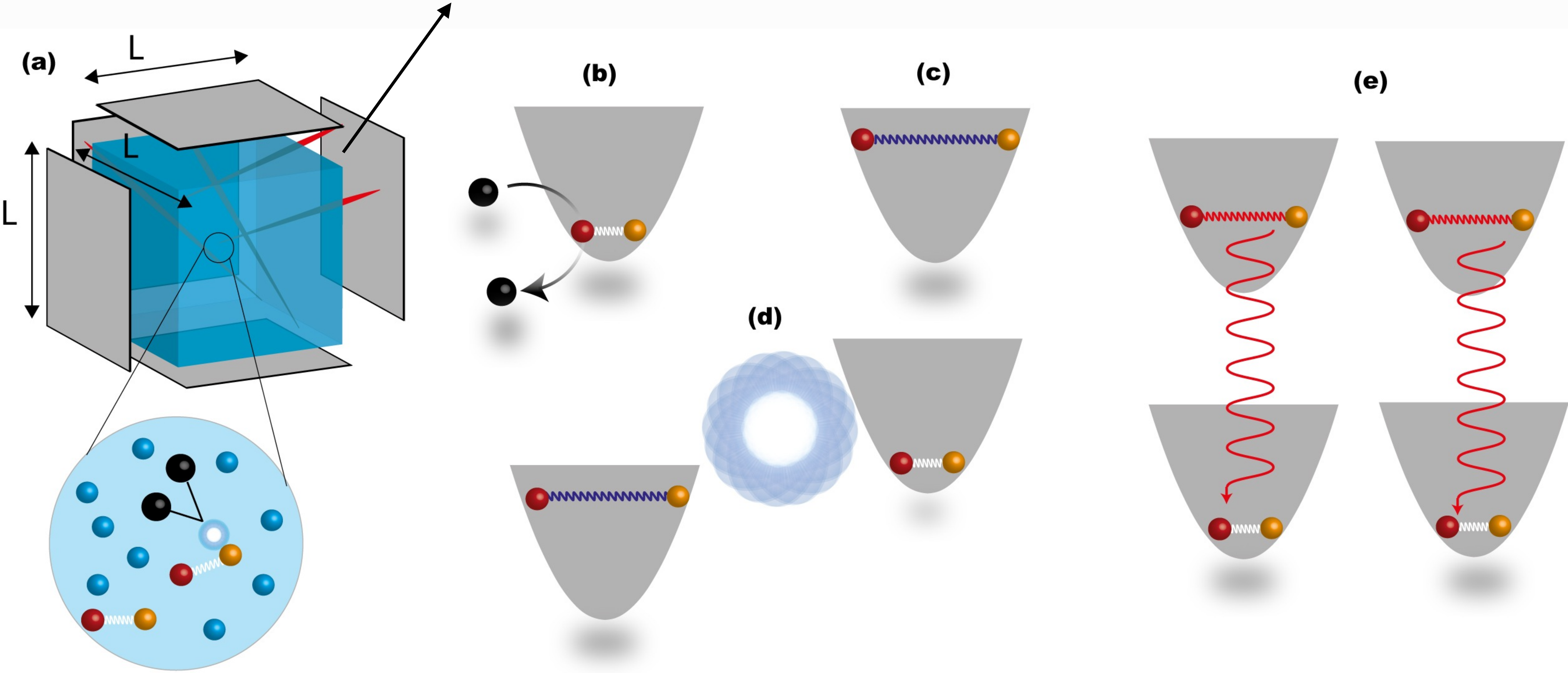


A novel approach for DM detection



A novel approach for DM detection

Mixed Molecular gas



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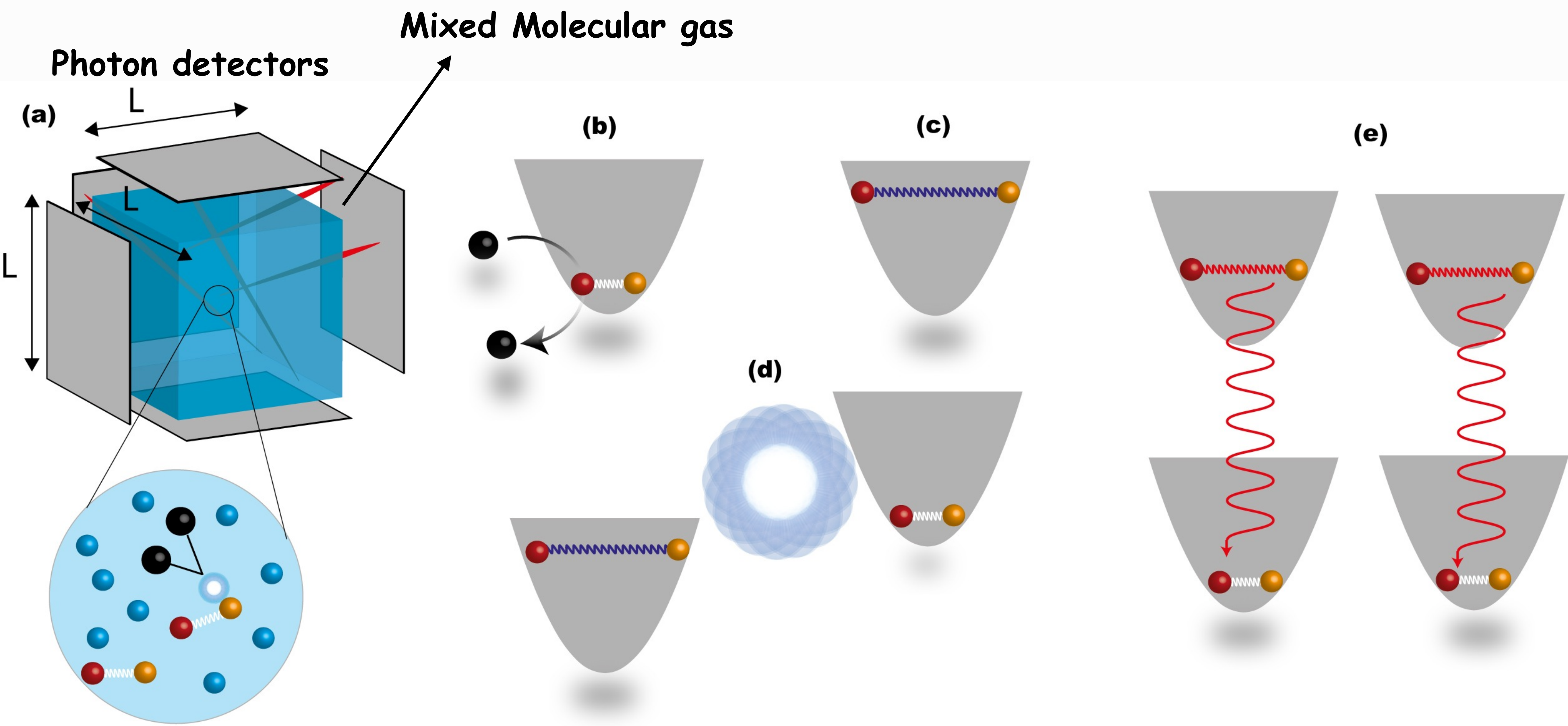

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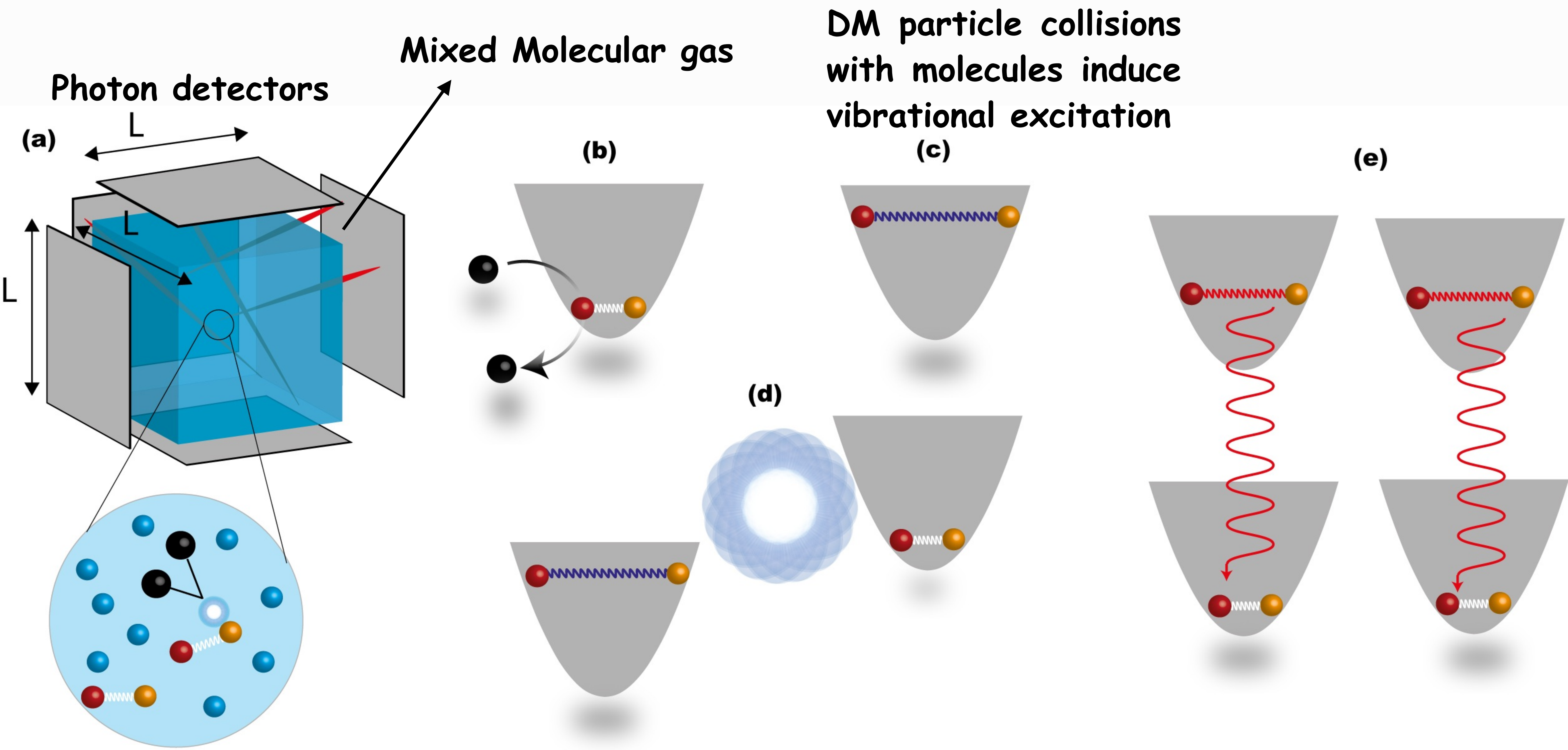
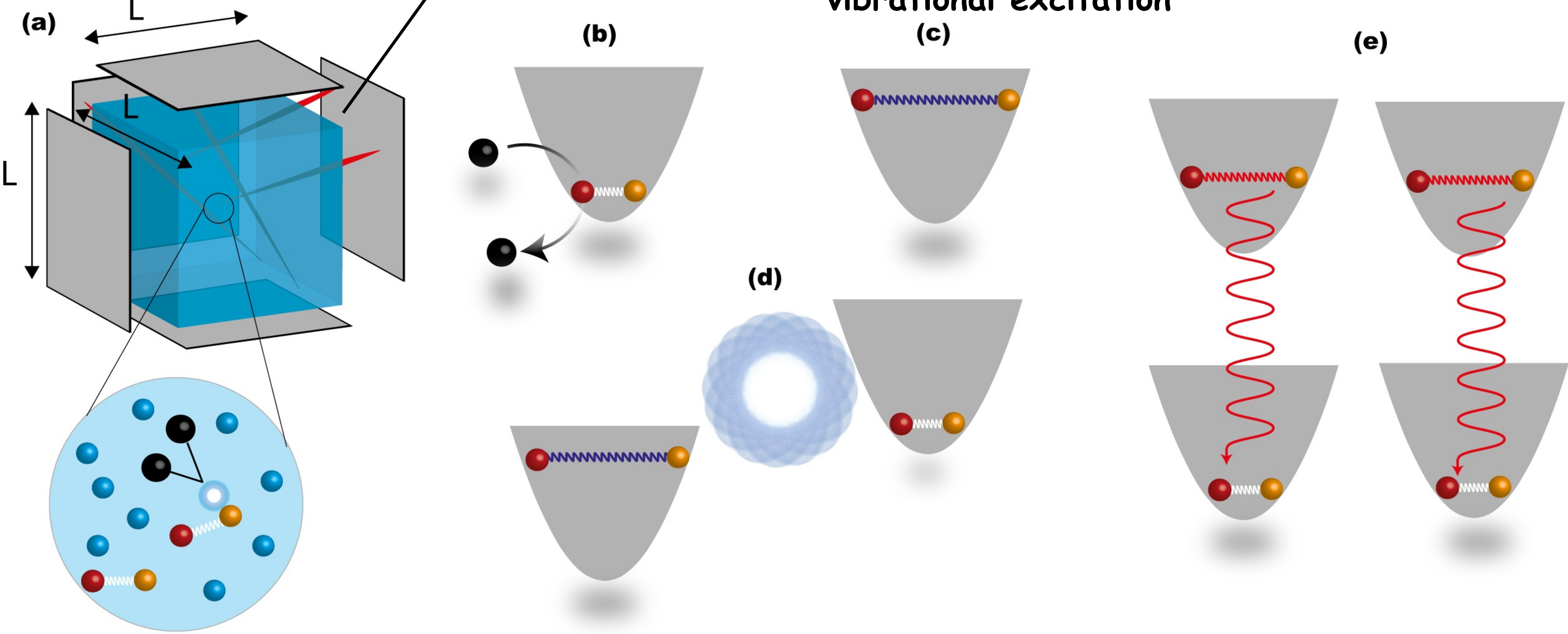


A novel approach for DM detection

Photon detectors

Mixed Molecular gas

DM particle collisions with molecules induce vibrational excitation



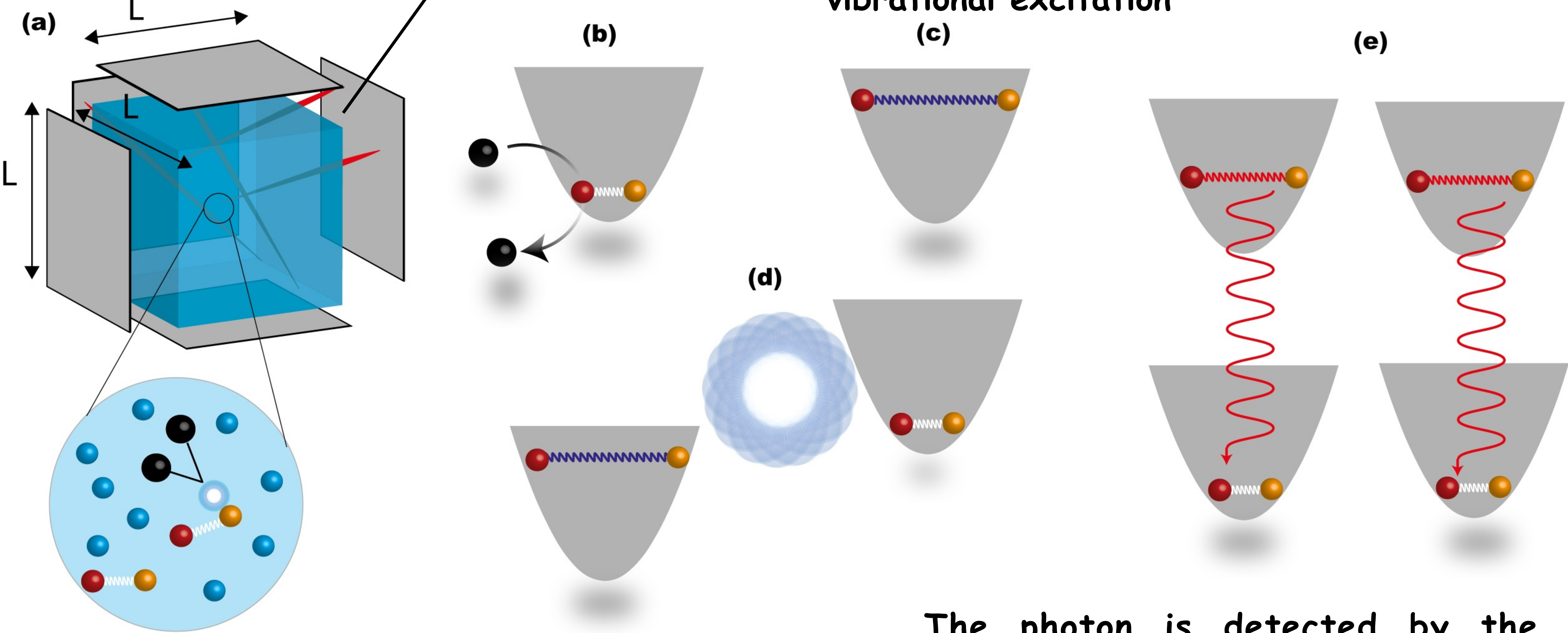
Excited molecules decay emitting a photon

A novel approach for DM detection

Photon detectors

Mixed Molecular gas

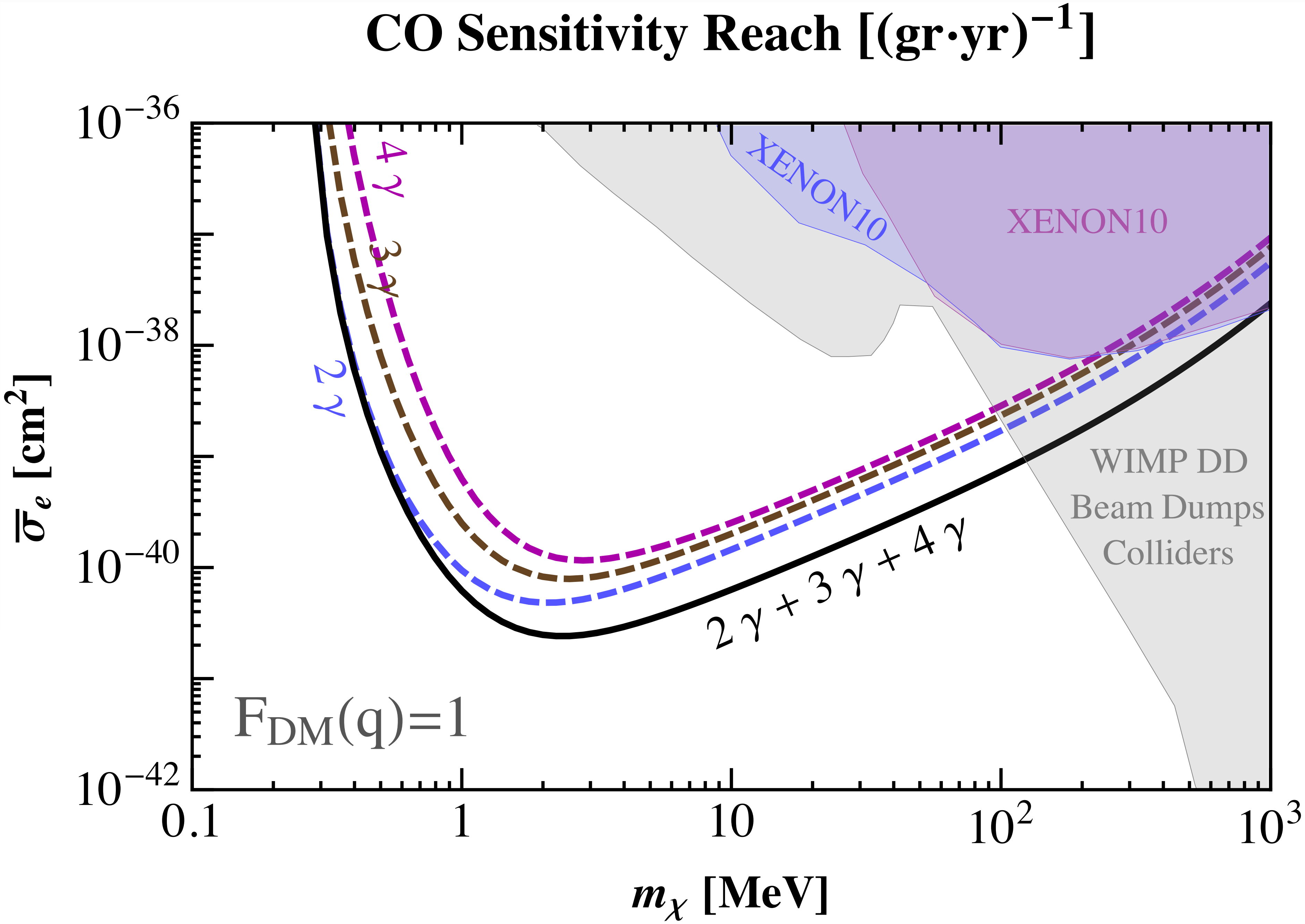
DM particle collisions with molecules induce vibrational excitation

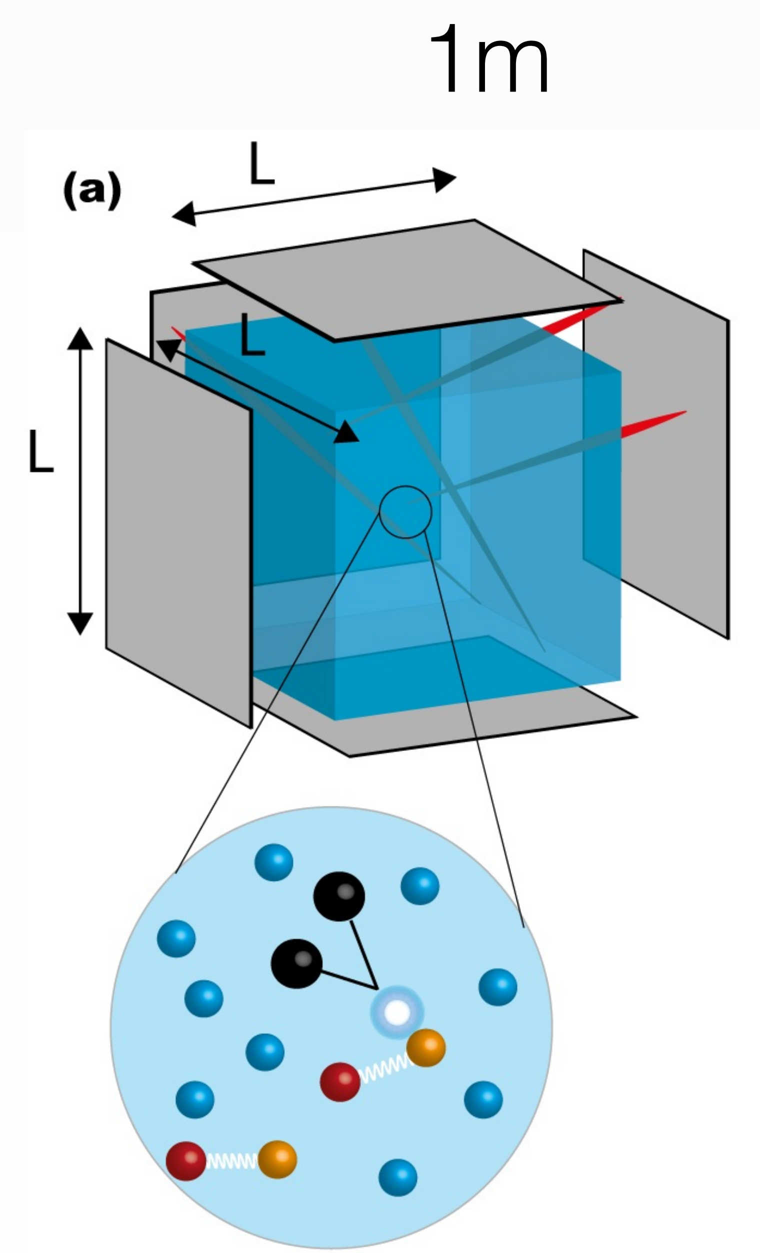


The photon is detected by the photodetectors surrounding the gas

Excited molecules decay emitting a photon

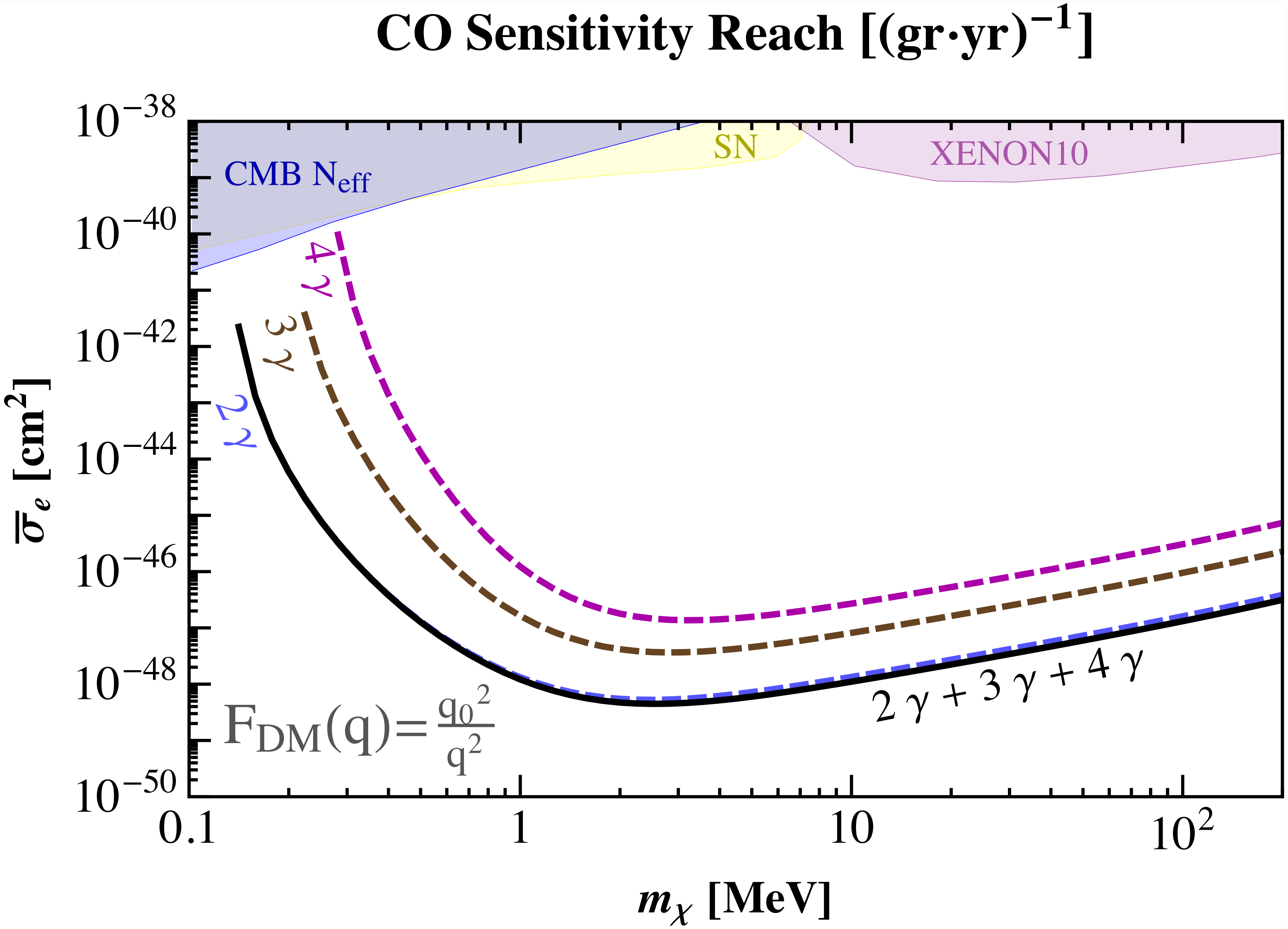
CO in detail

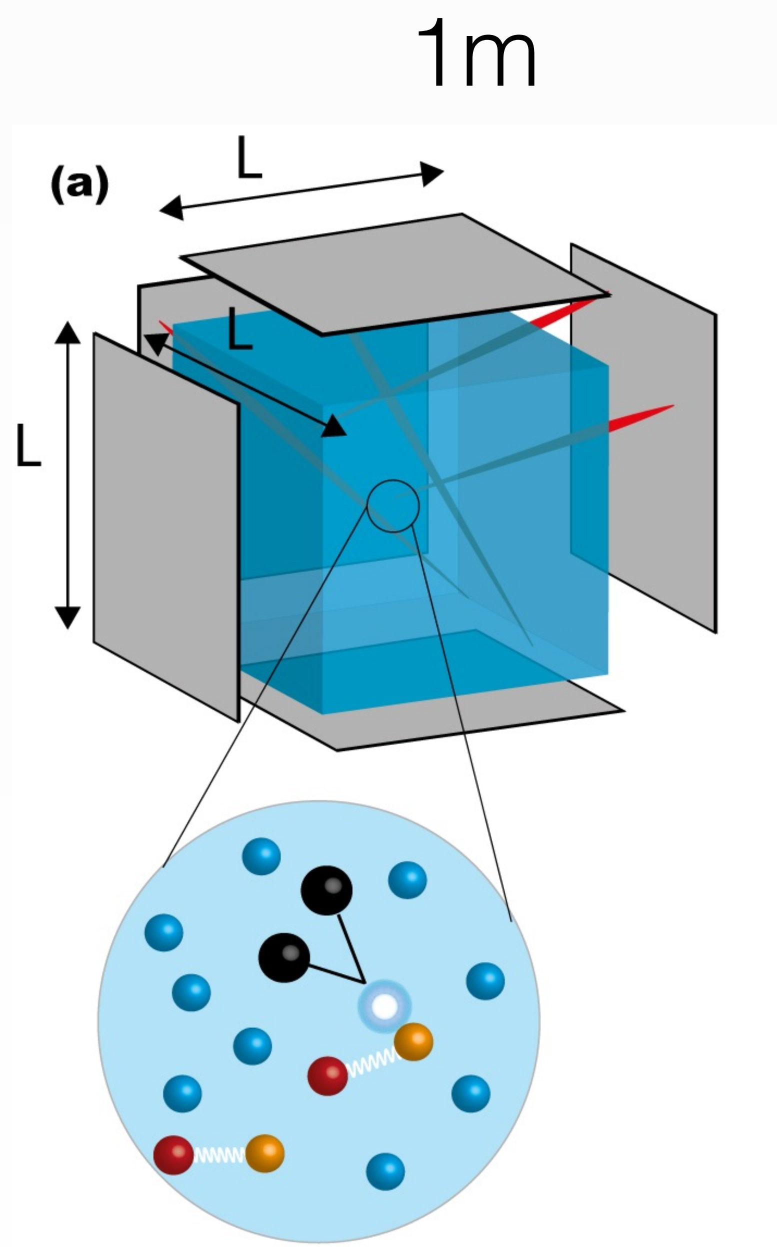




We will be able to explore DM particles in a mass range of almost 3 orders of magnitude, from 100 keV to 100 MeV.

CO in detail





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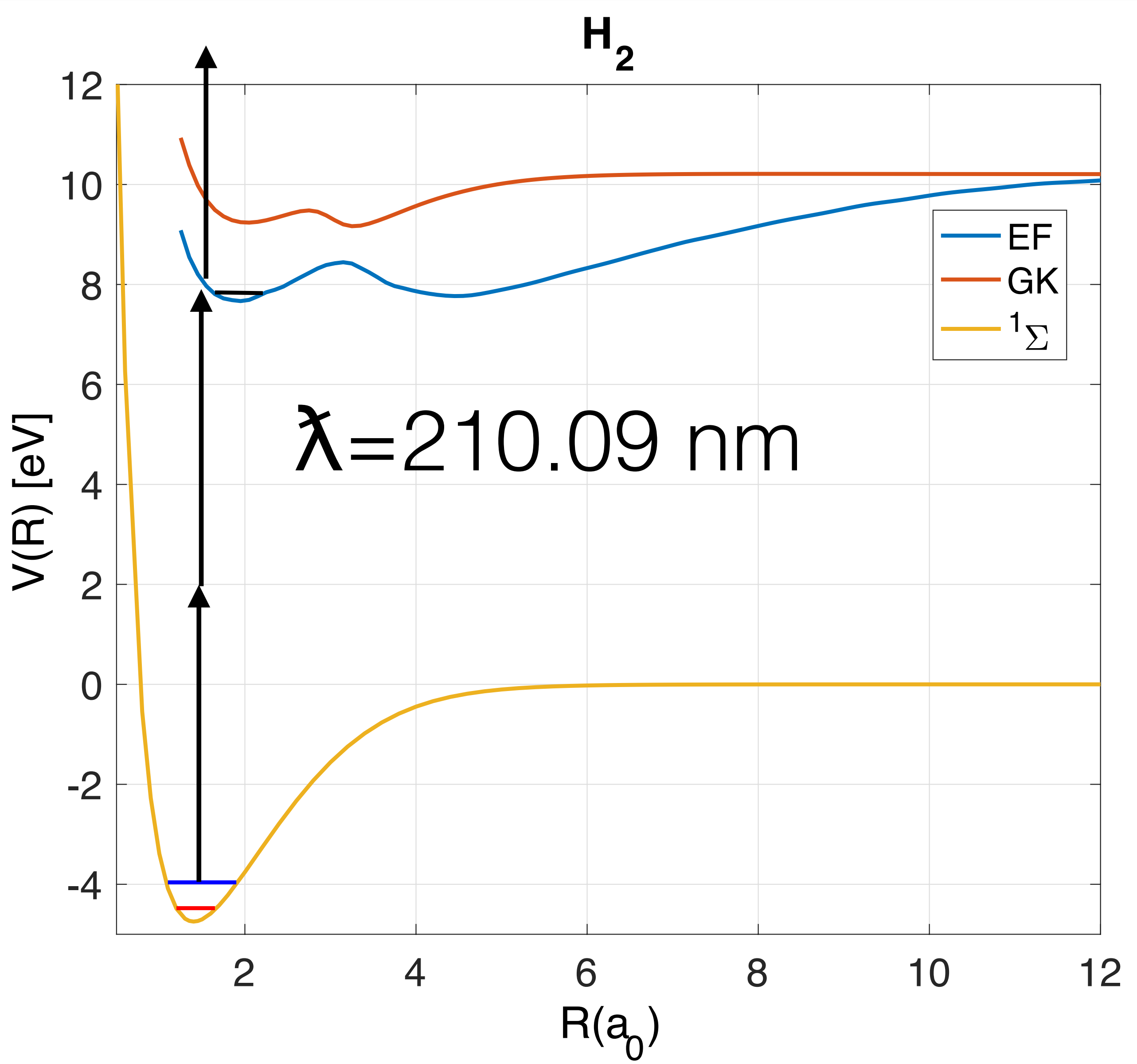
Some future work

Electronic excitations?

REMPI through a dark state



That´s all folks

Thank you so much for your attention!!!!!!!!