# Detecting dark matter-nucleus scattering through molecular excitations

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

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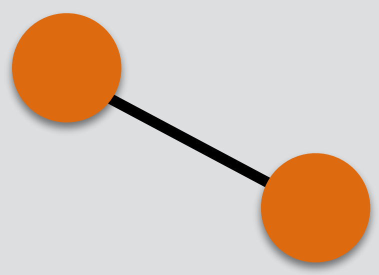
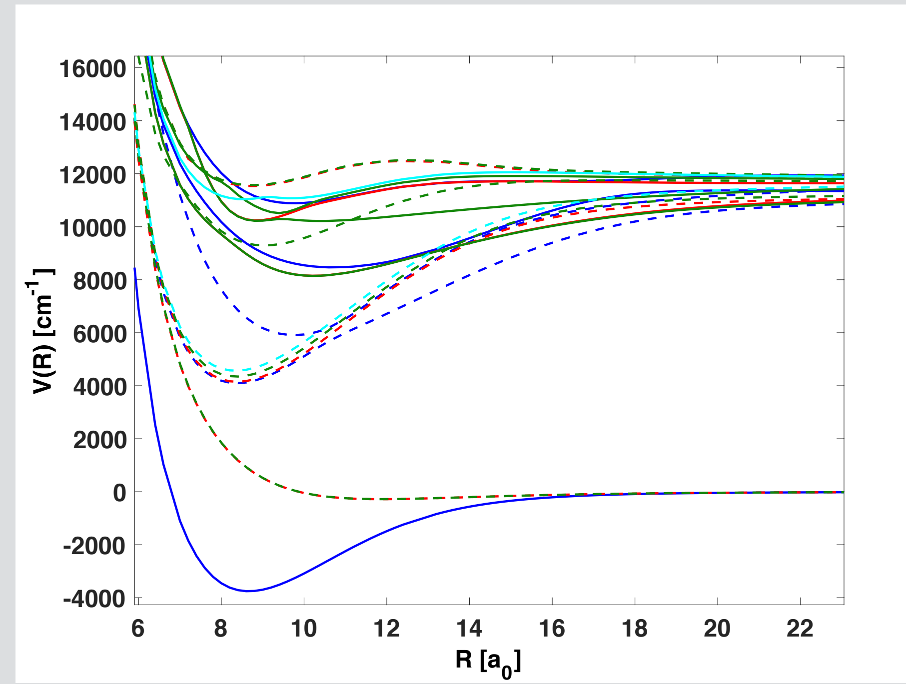
[3]Department of Physics and Astronomy, Stony Brook University, USA

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

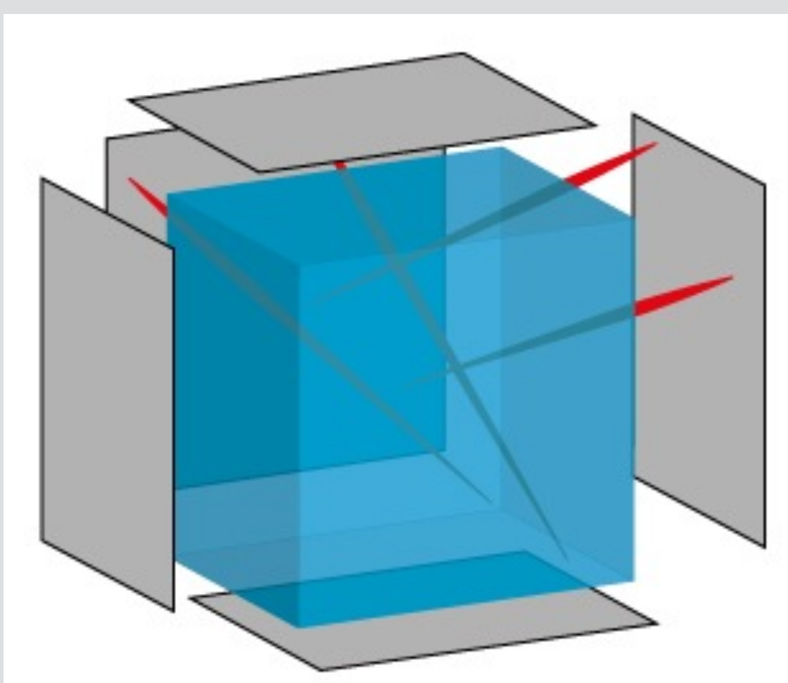
# Outlook

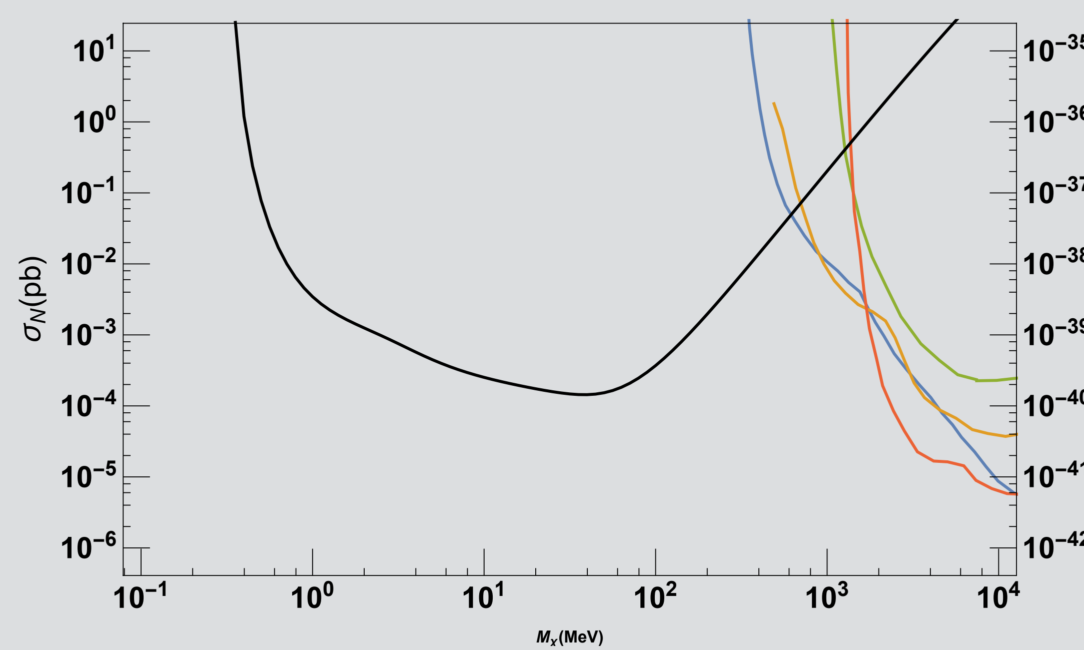
## Molecules as a probe of DM?






## Our approach for DM detection





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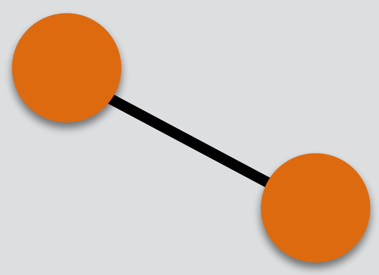

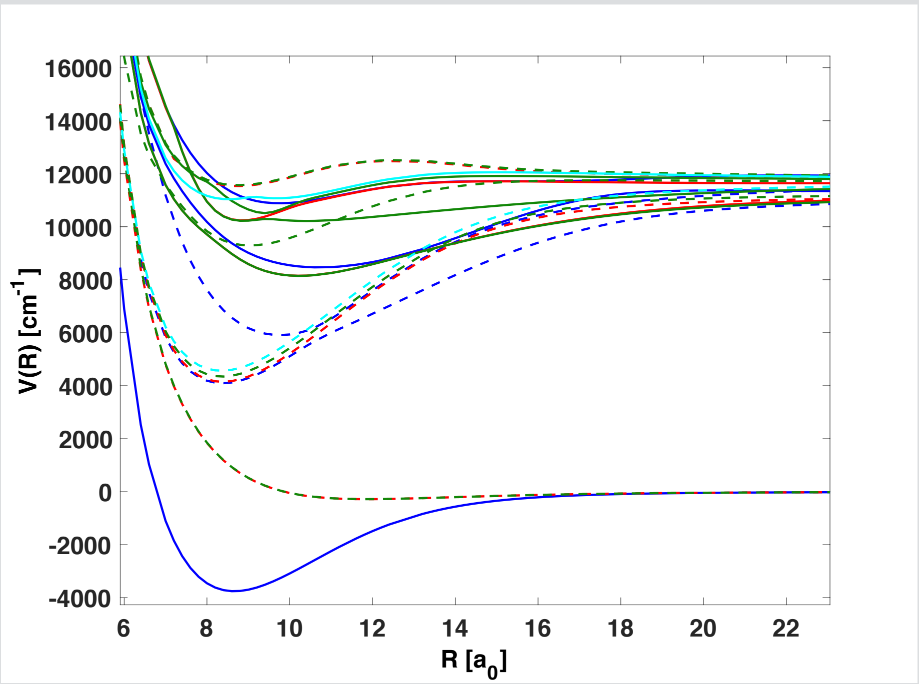


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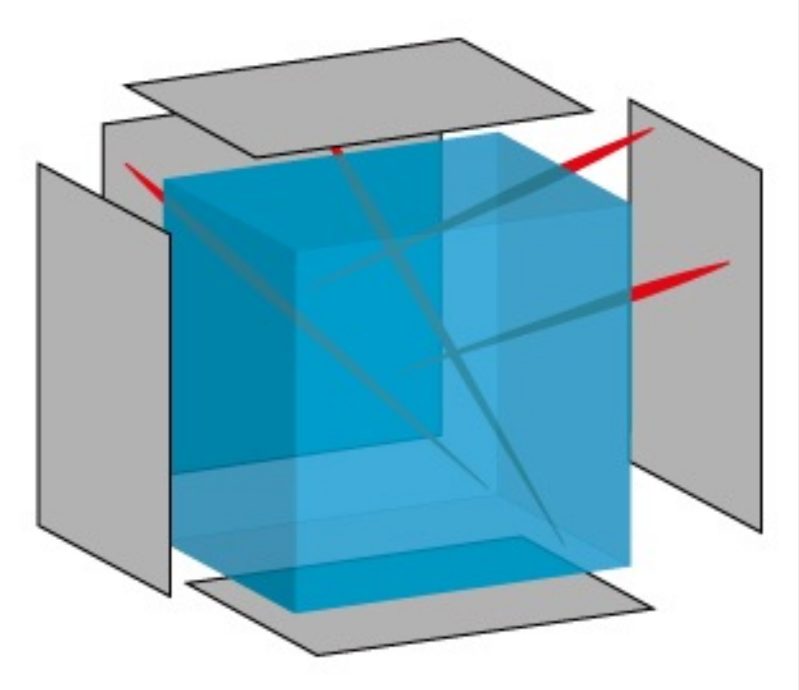

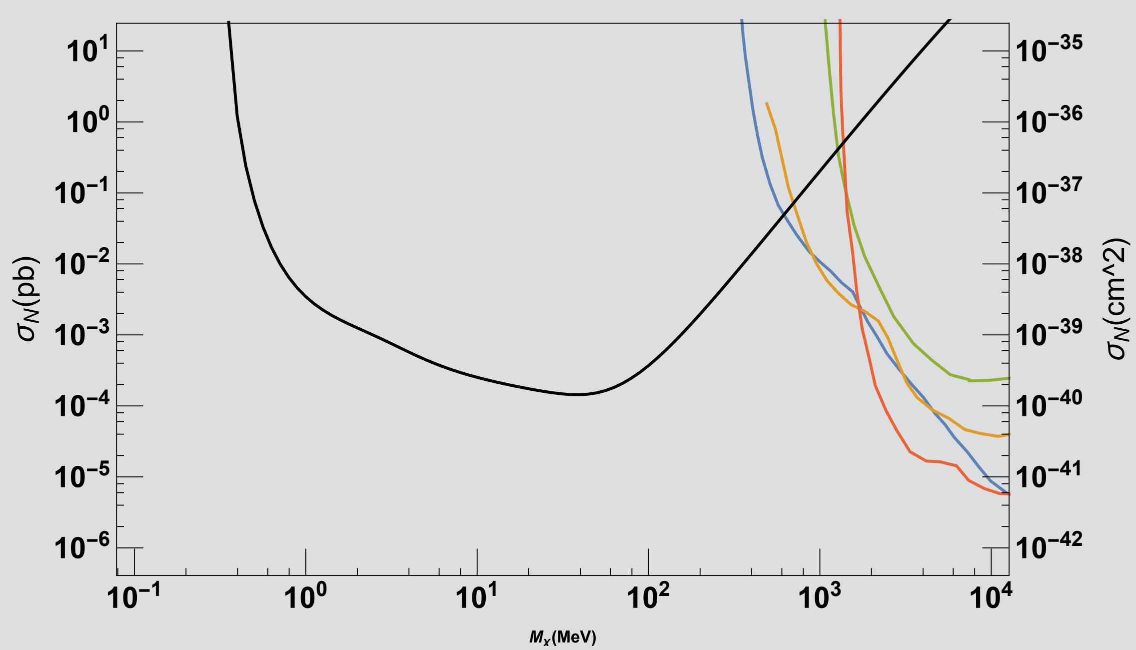

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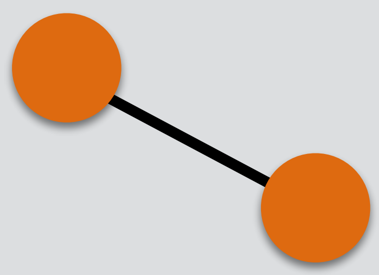

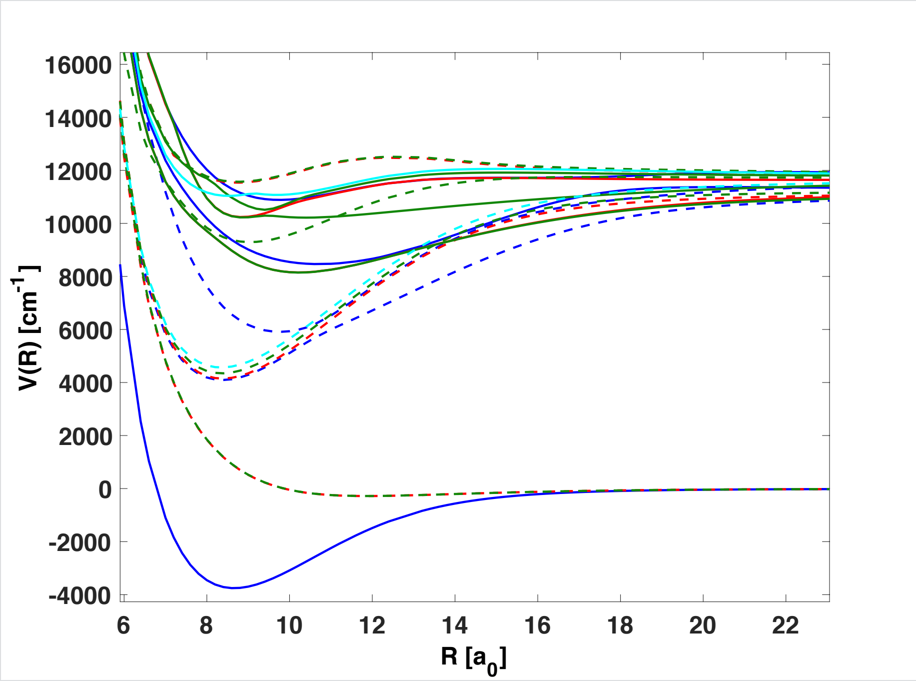


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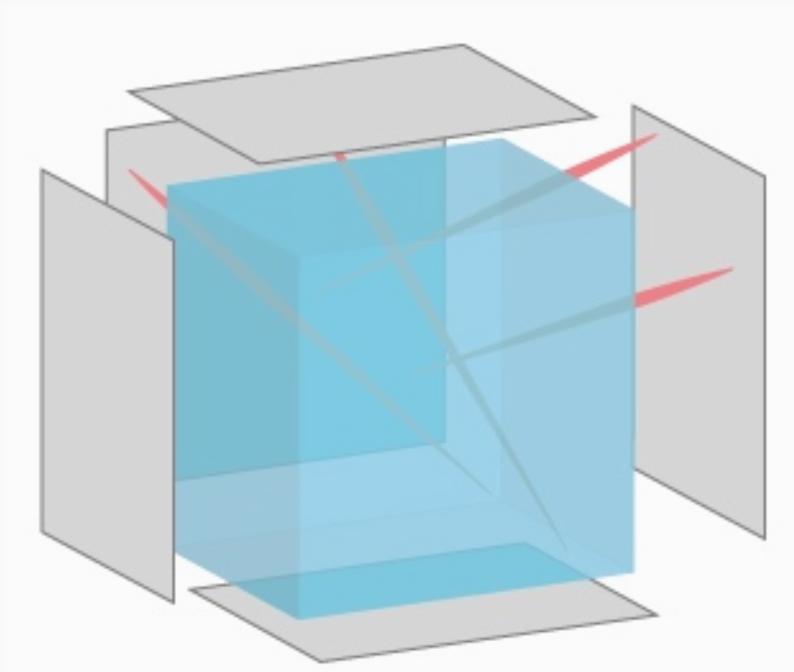
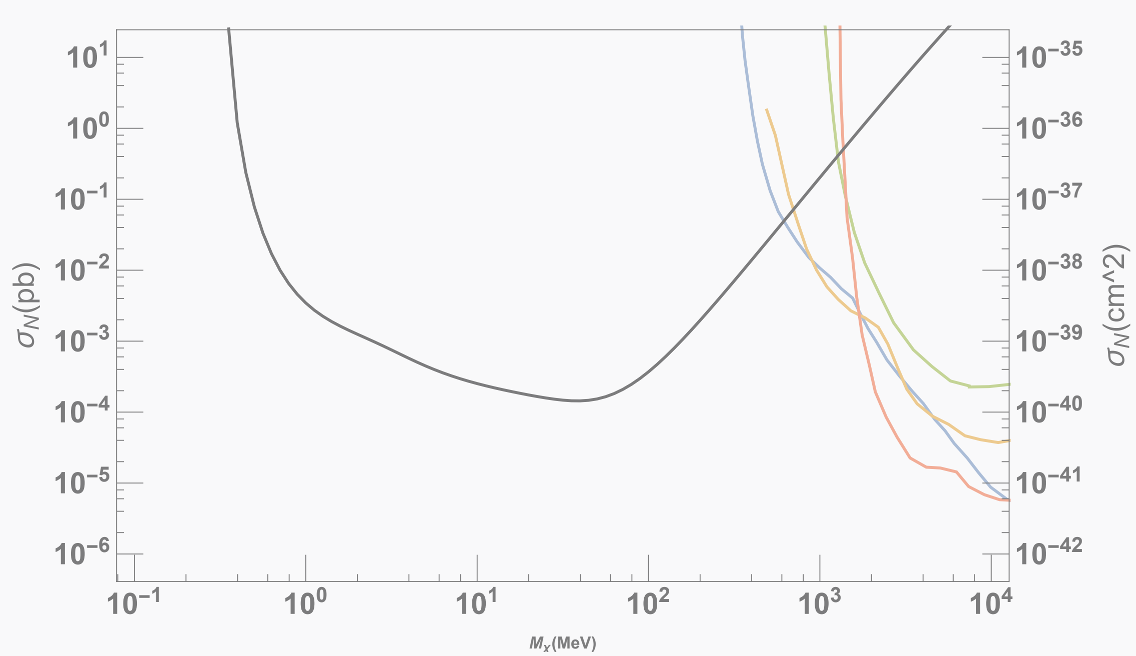
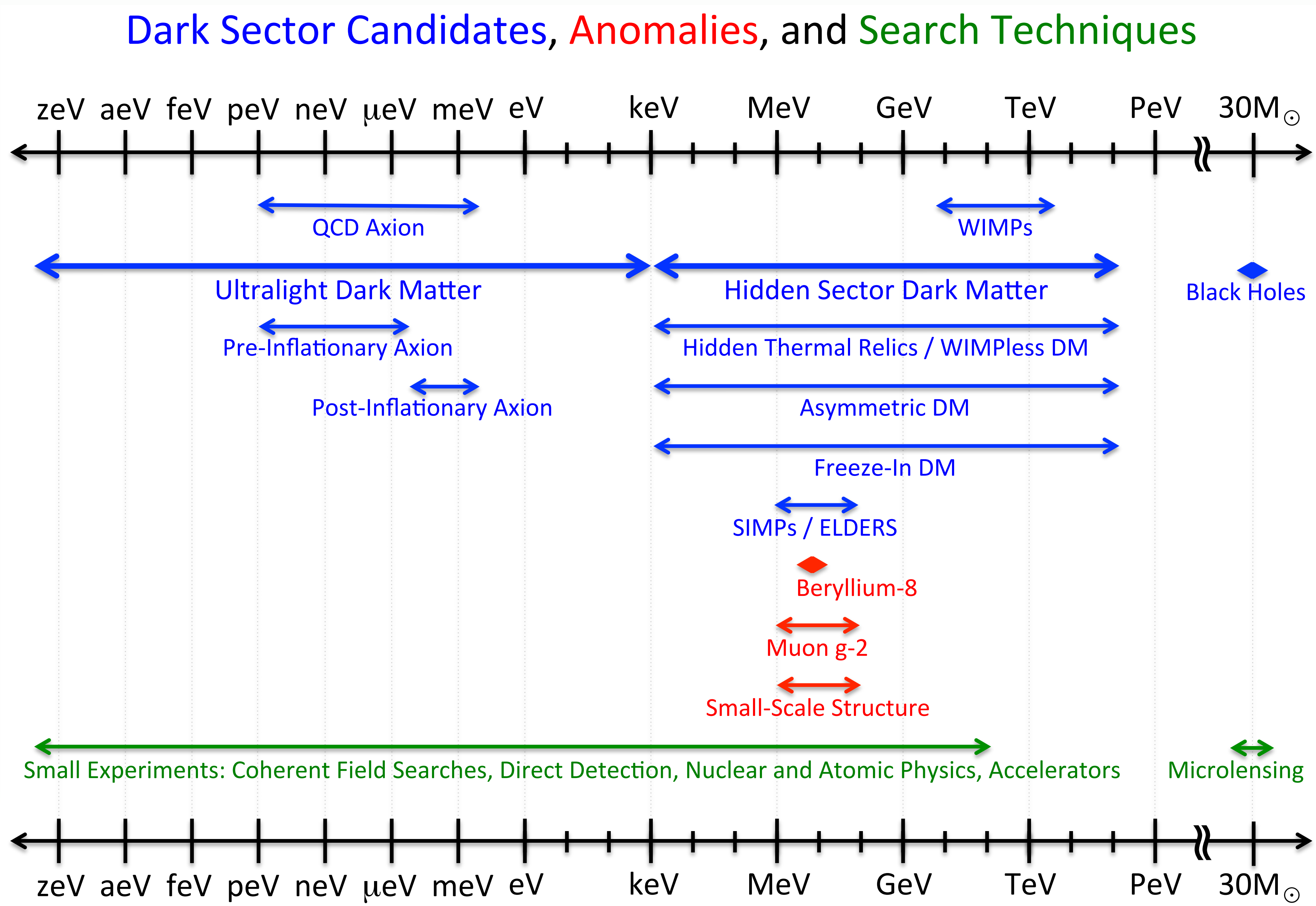




# Molecules as a probe of DM?

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

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



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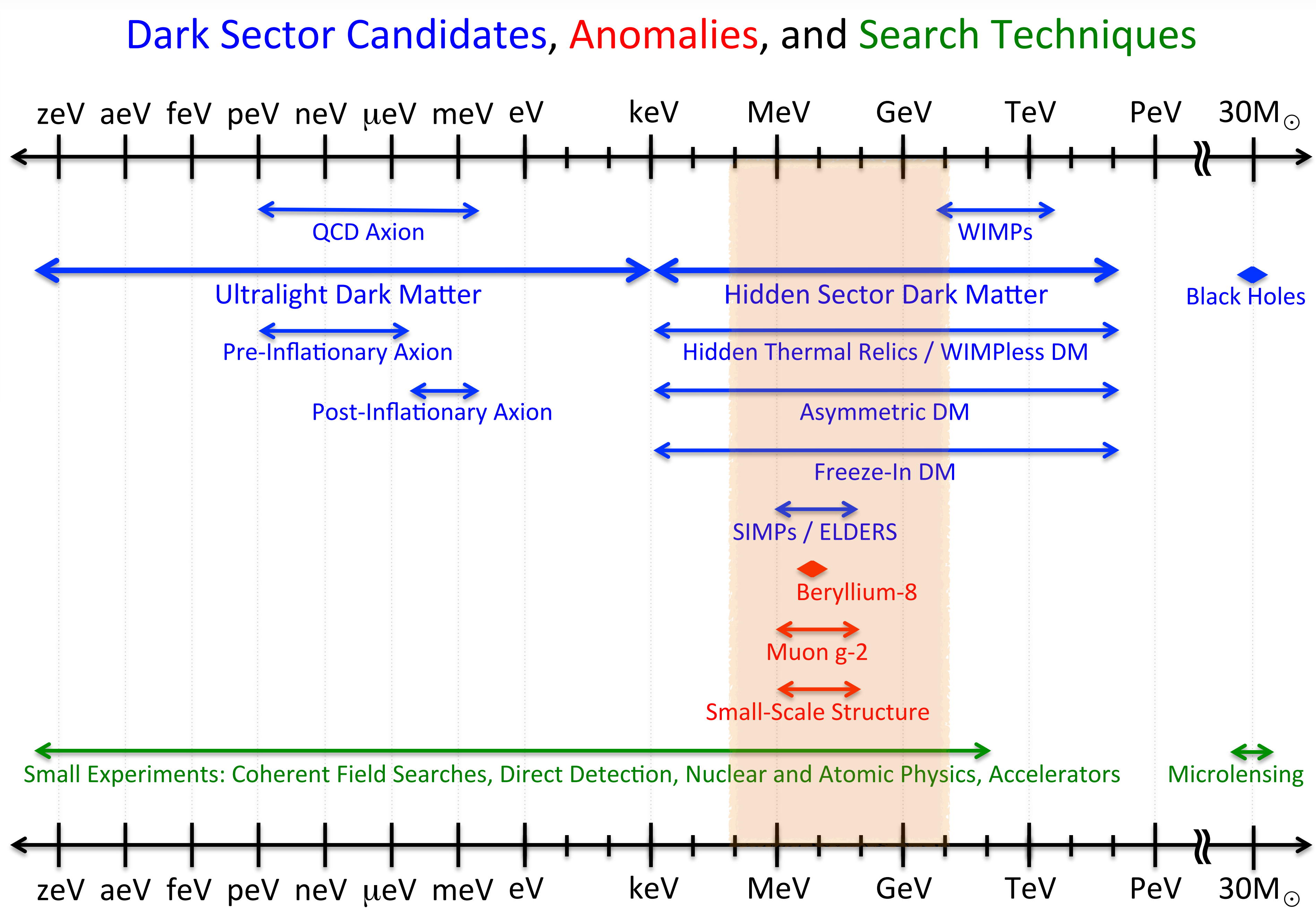
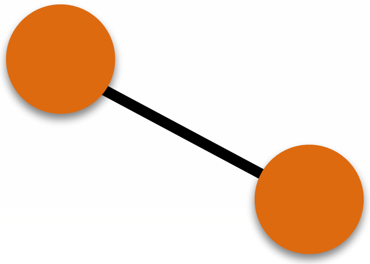


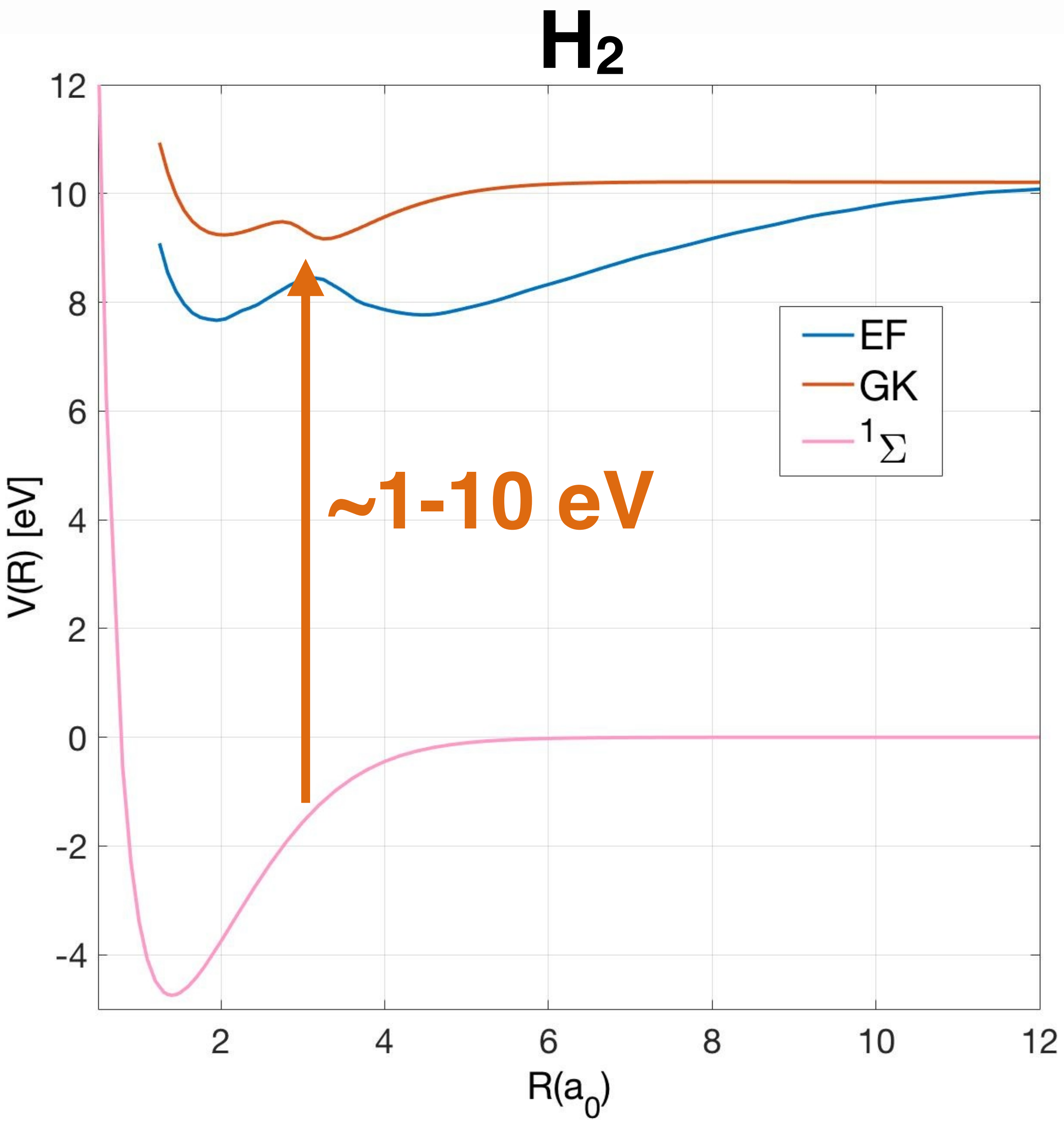
# Molecules as a probe of DM?

Molecules are fun!!!!

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

- Electronic
- Vibrational
- Rotational





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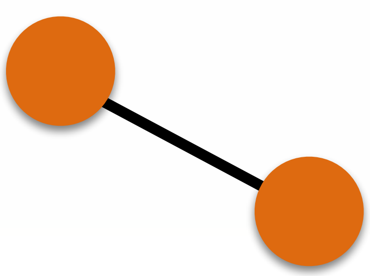

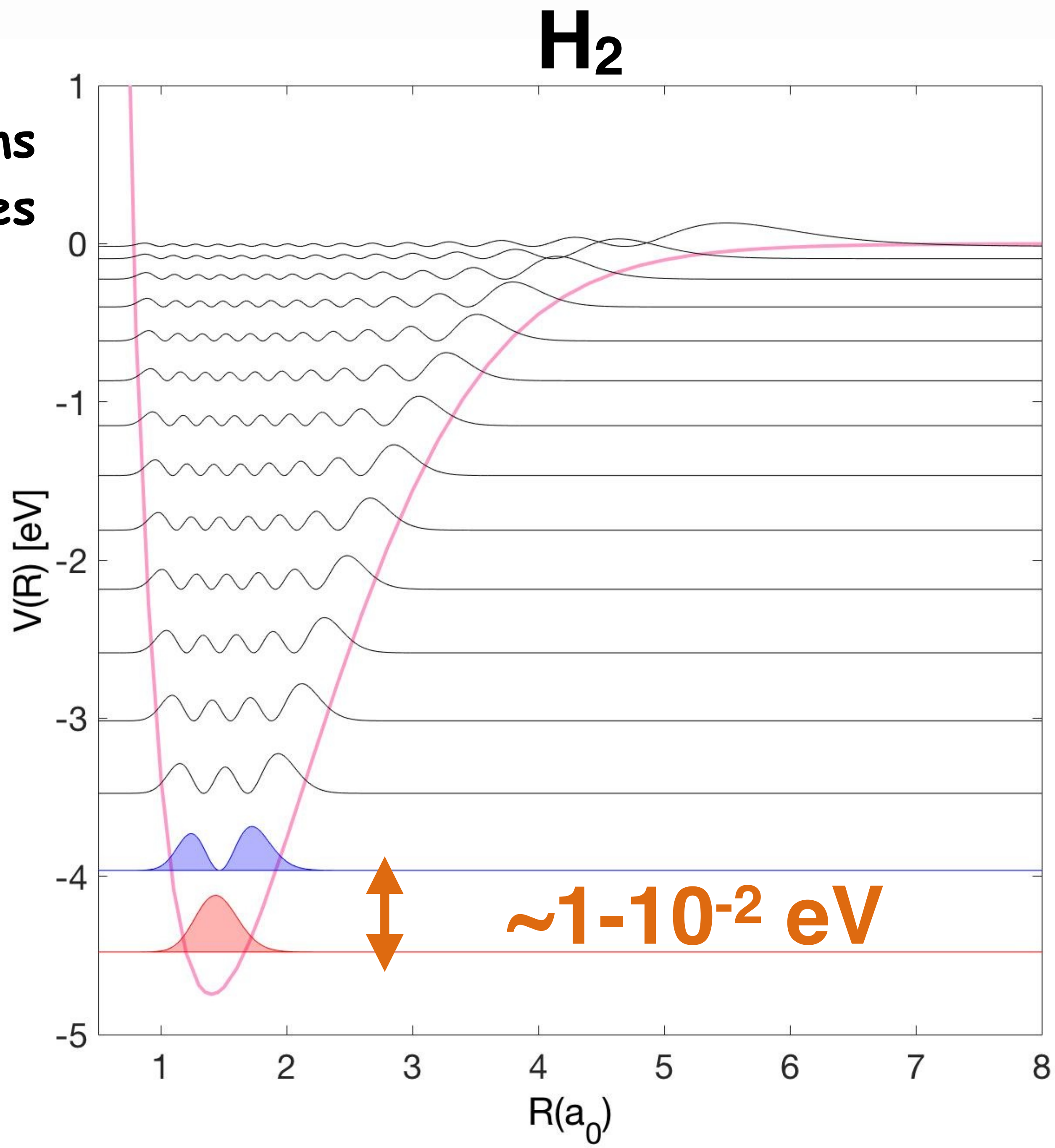

# Molecules as a probe of DM?

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)

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

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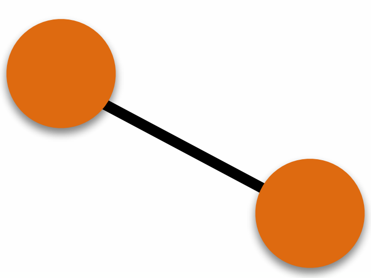


Vibration of molecules
$m_{DM} \sim$ MeV

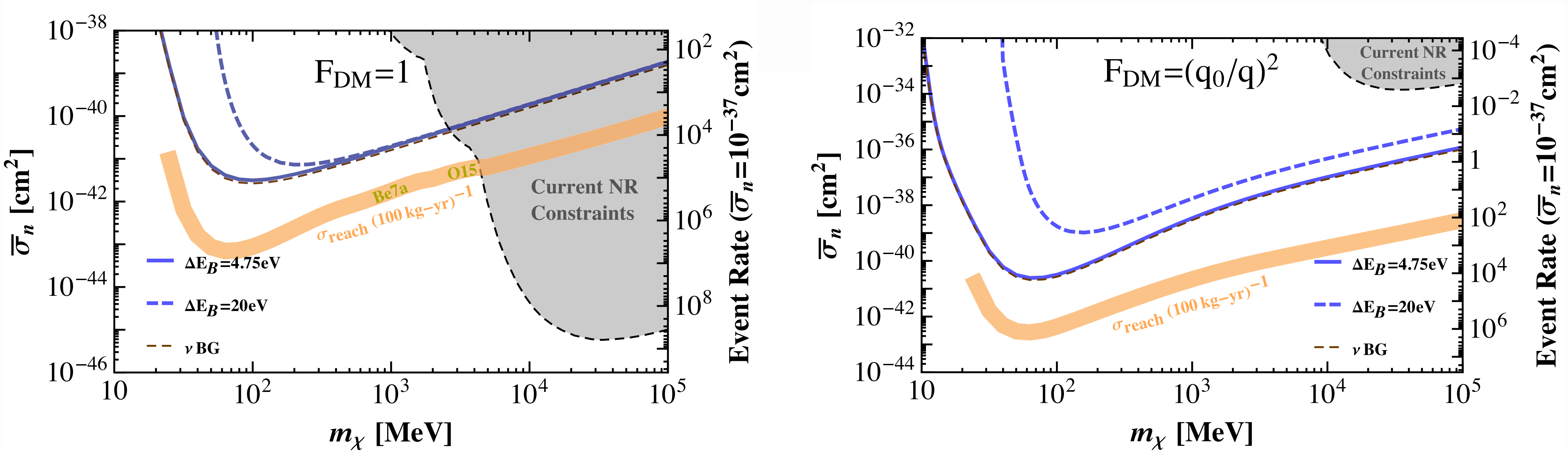
# Molecules as a probe of DM?

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?

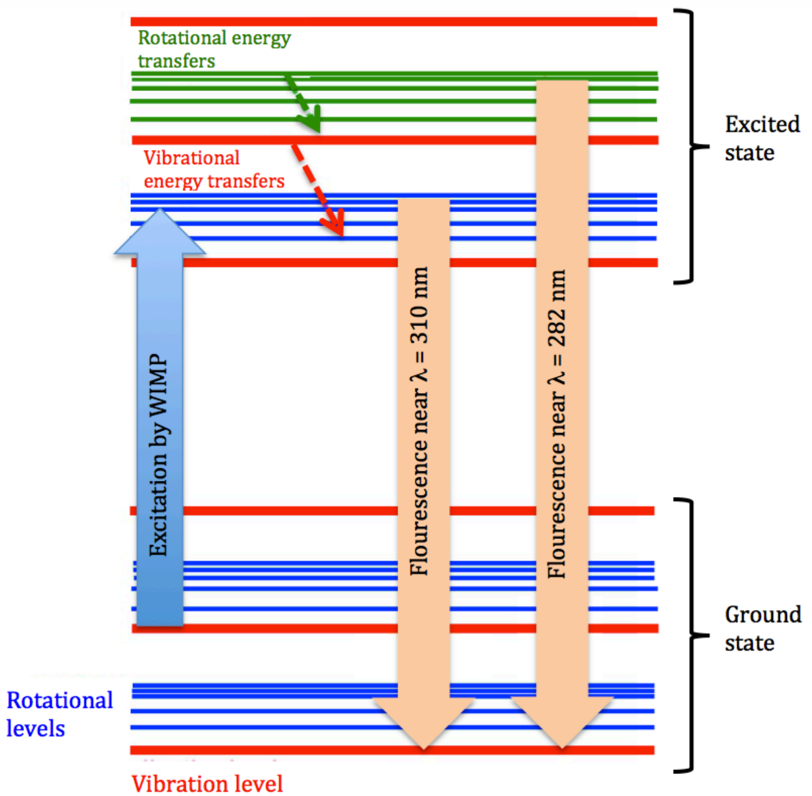
## Molecular excitations: a new way to detect Dark matter

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].

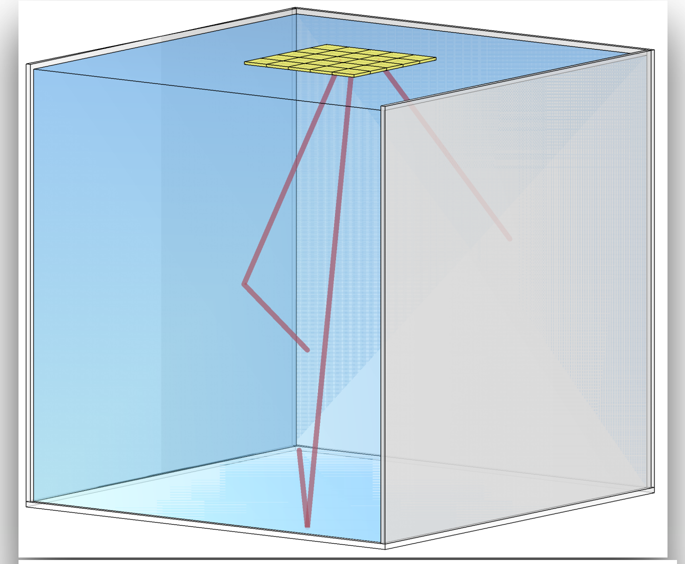
| OH-band identity | Transition | Calculated wavelength [nm] |
|---|---|---|
| $v_1$ | $0 \to 1$ | 2803 |
| $2v_1$ | $0 \to 2$ | 1436 |
| $3v_1$ | $0 \to 3$ | 980 |
| $4v_1$ | $0 \to 4$ | 755 |
| $5v_1$ | $0 \to 5$ | 619.5 |

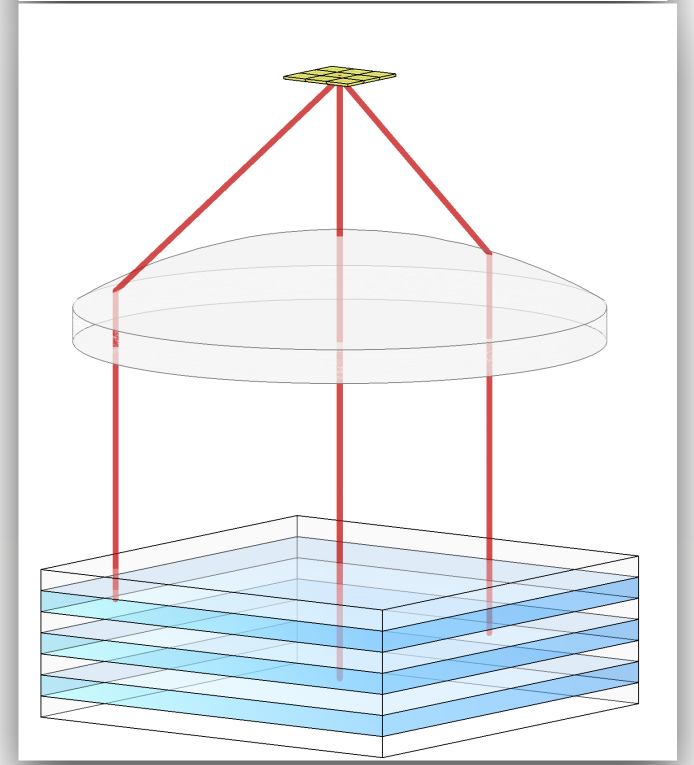


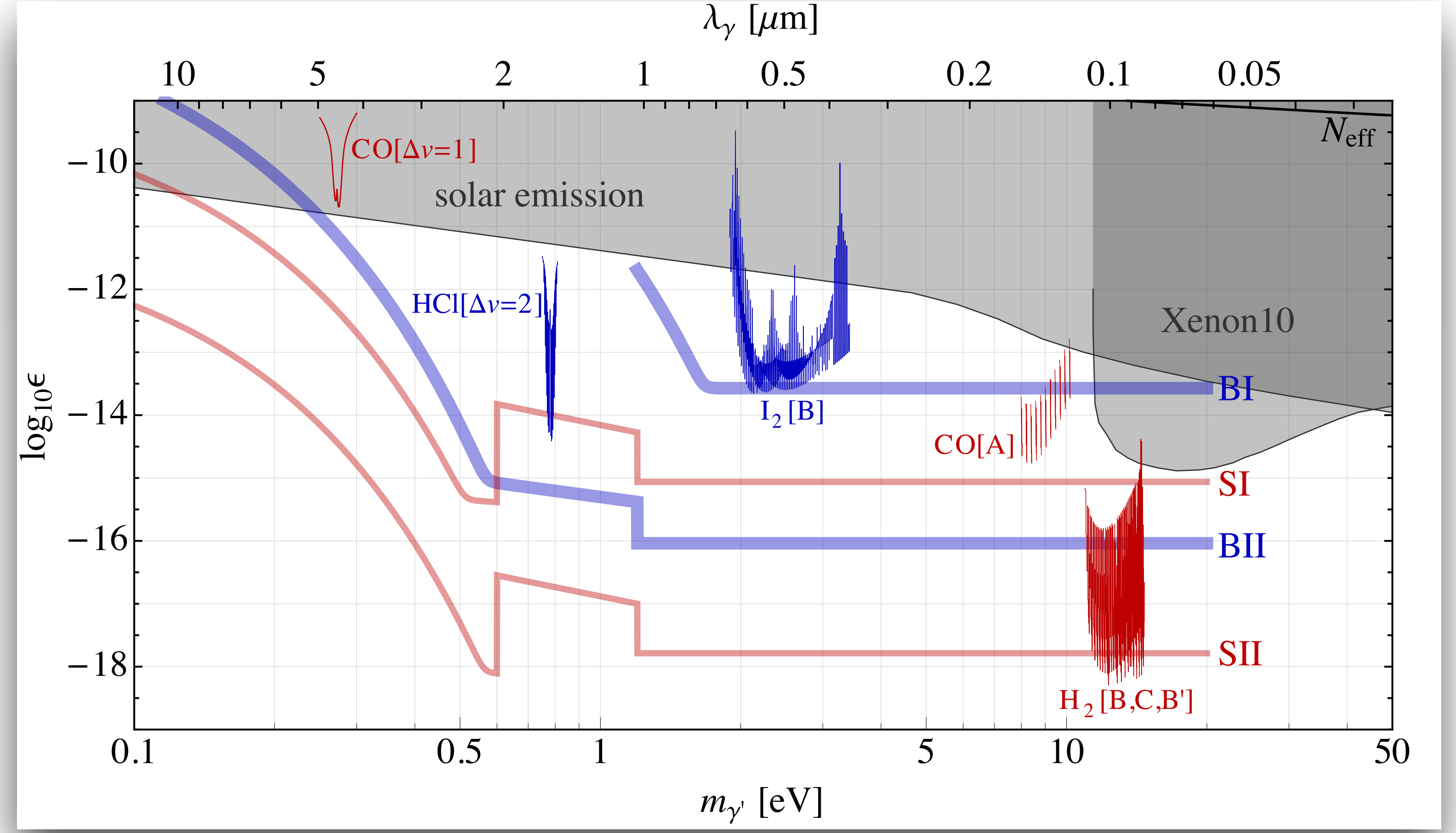
# Molecules as a probe of DM?

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







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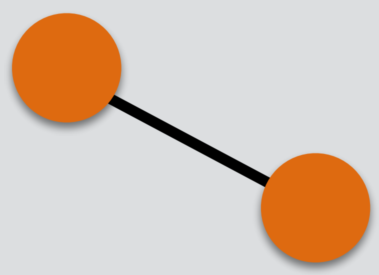

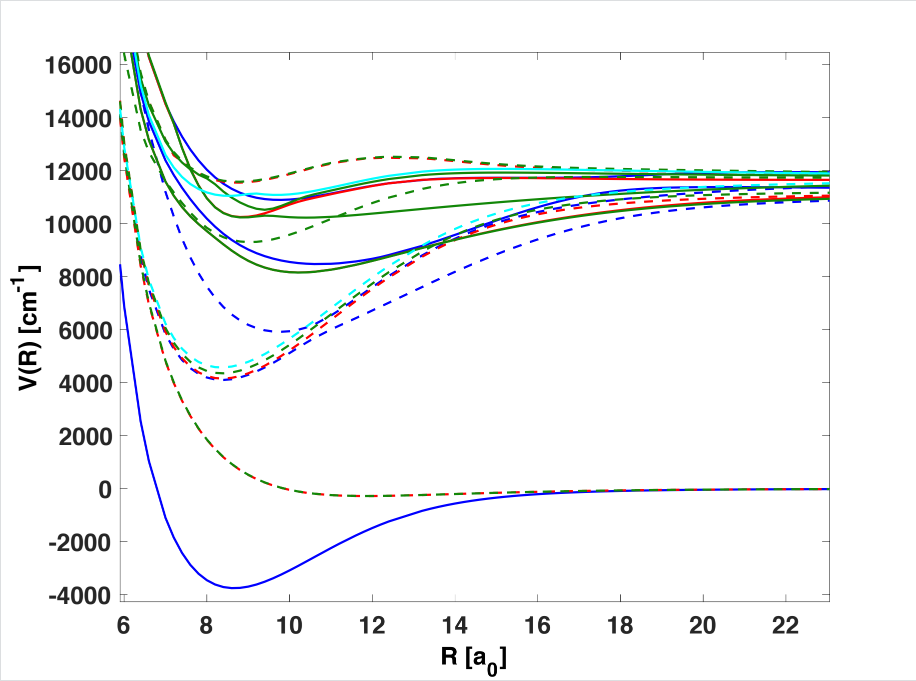


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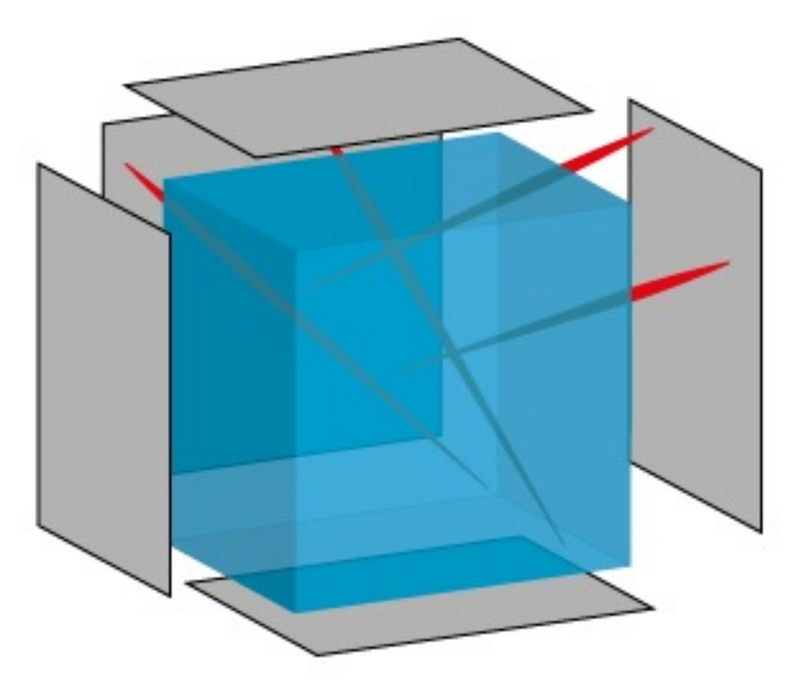

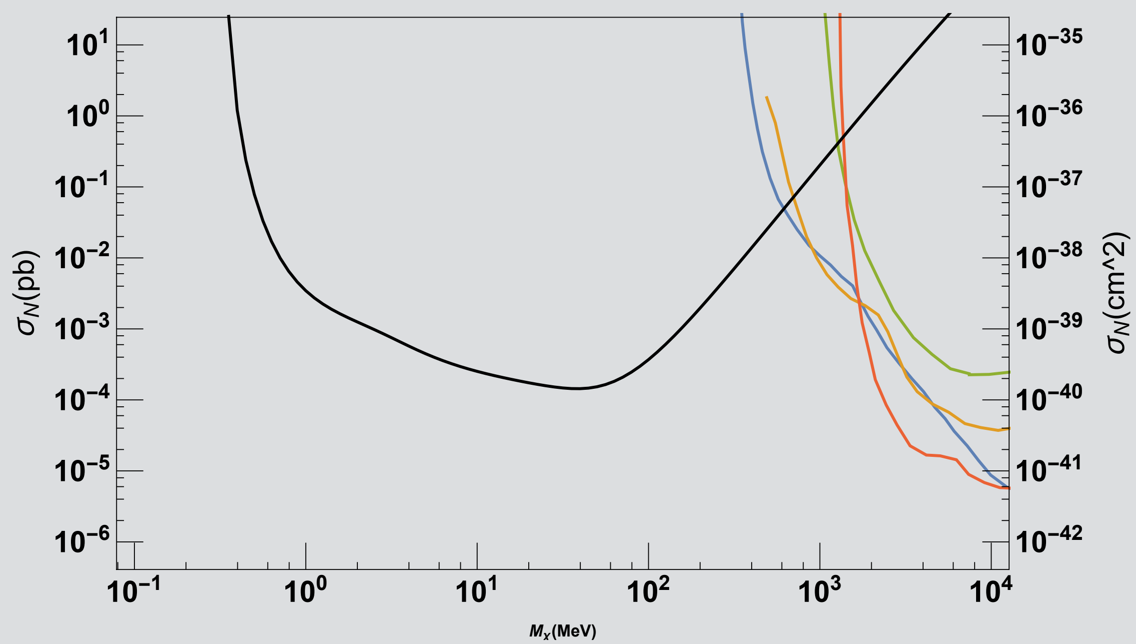

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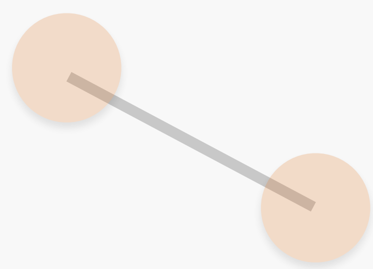

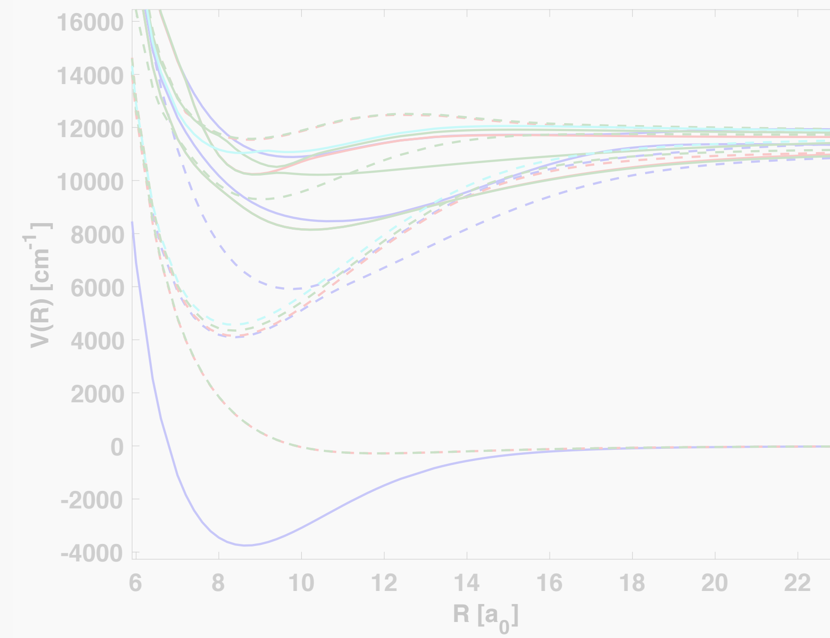


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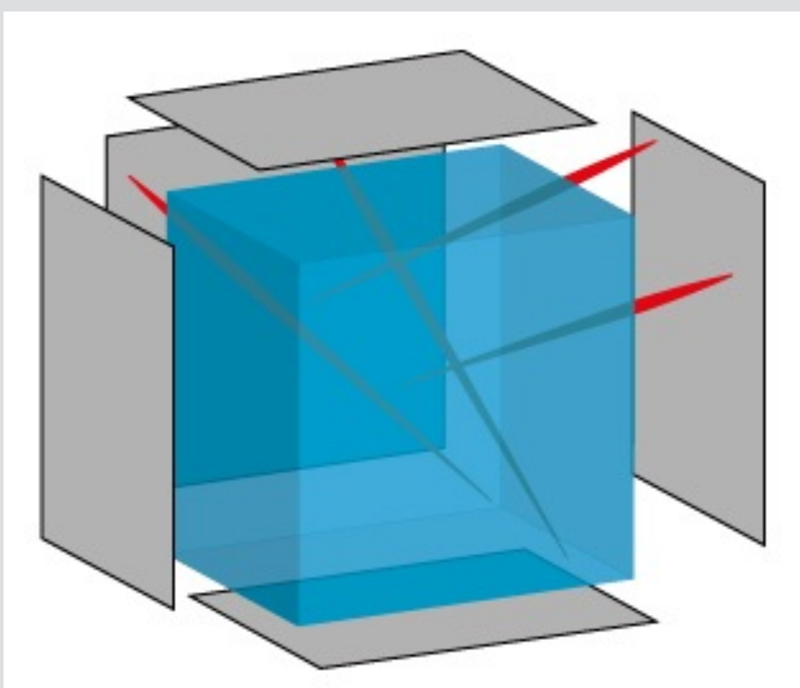
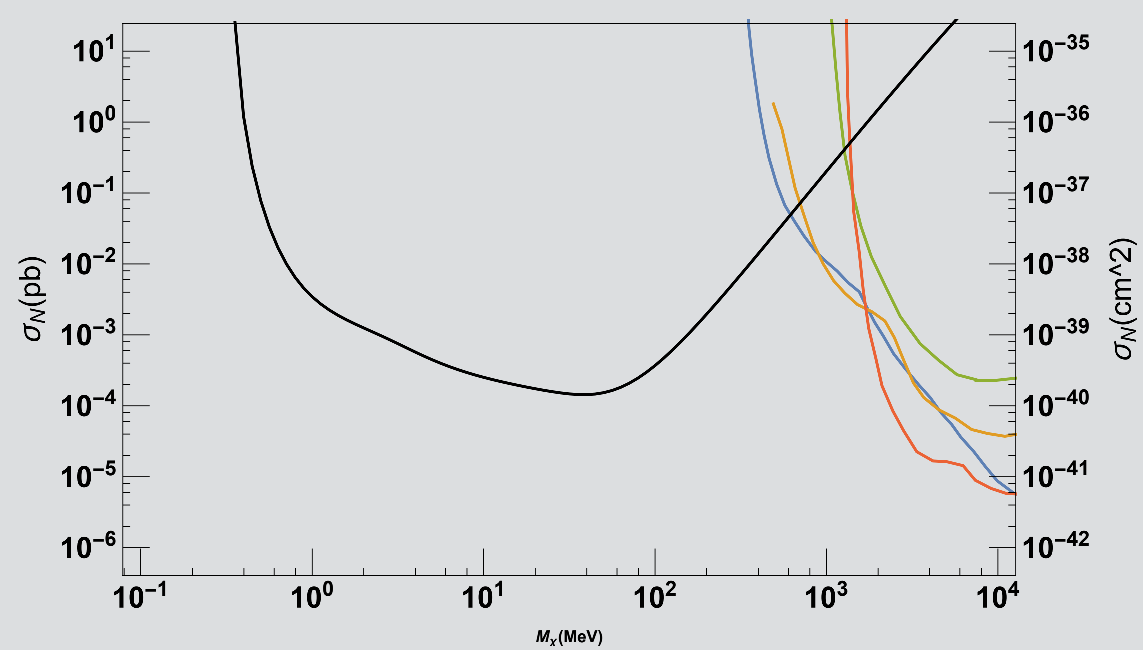
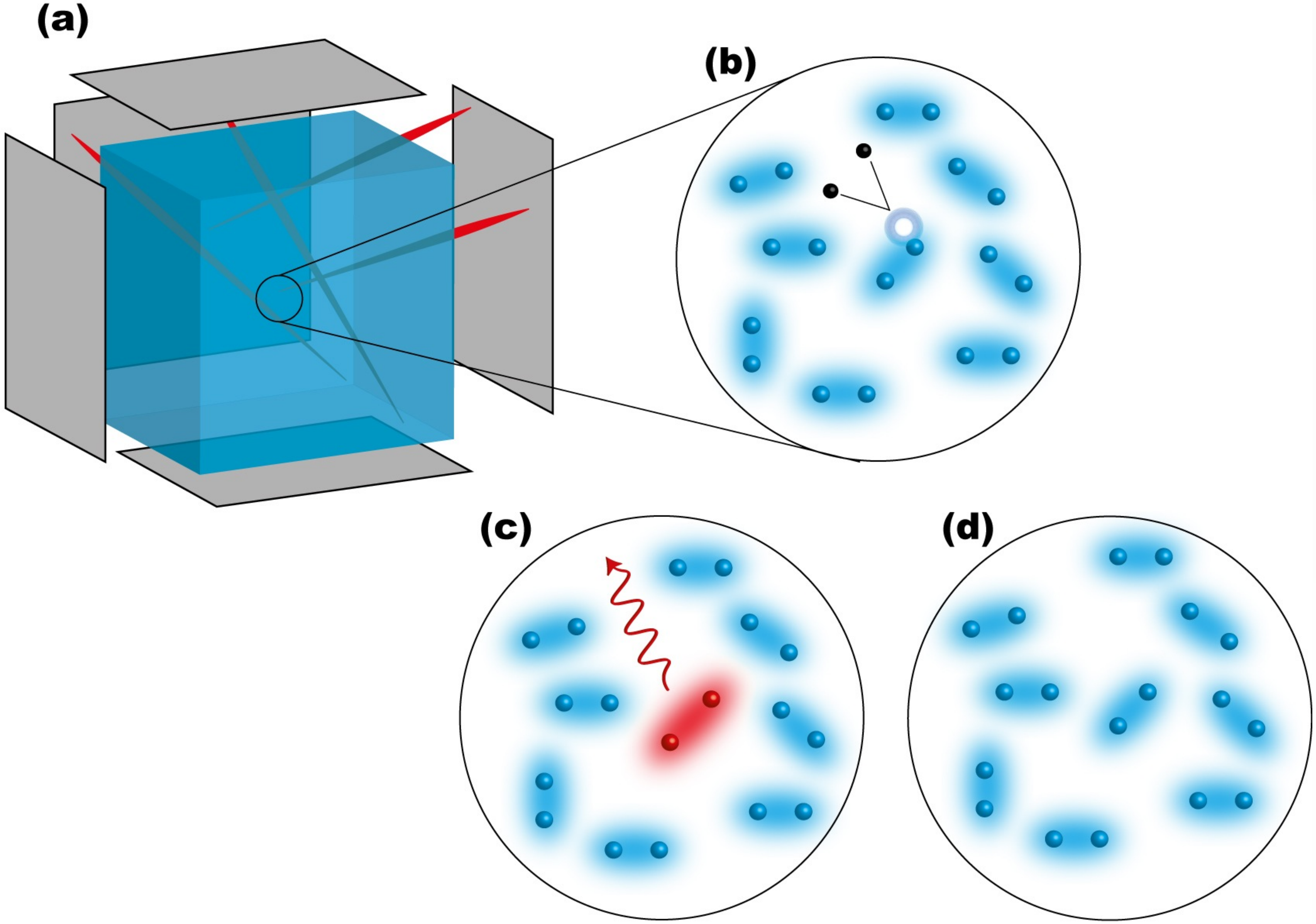




# A novel approach for DM detection



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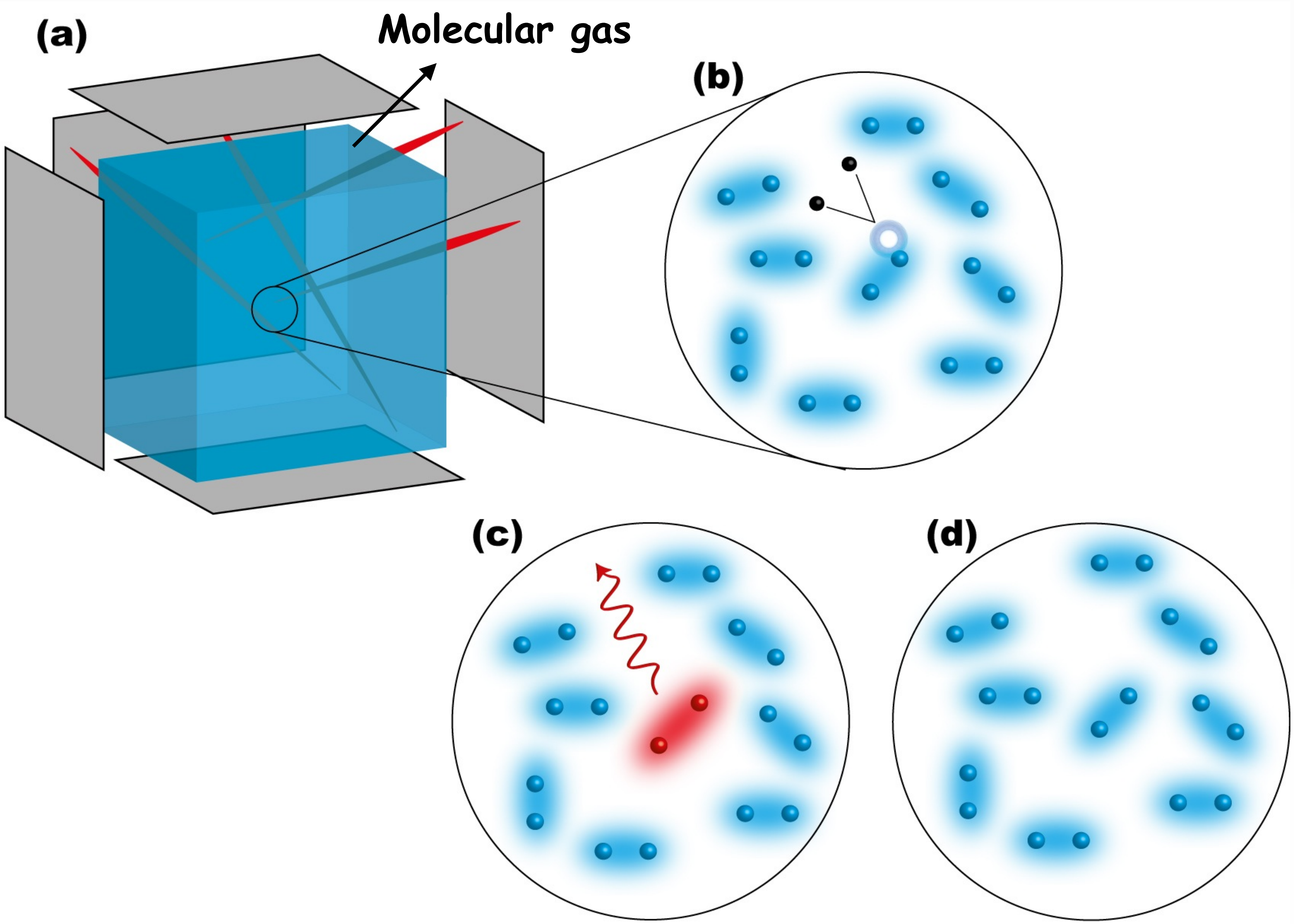

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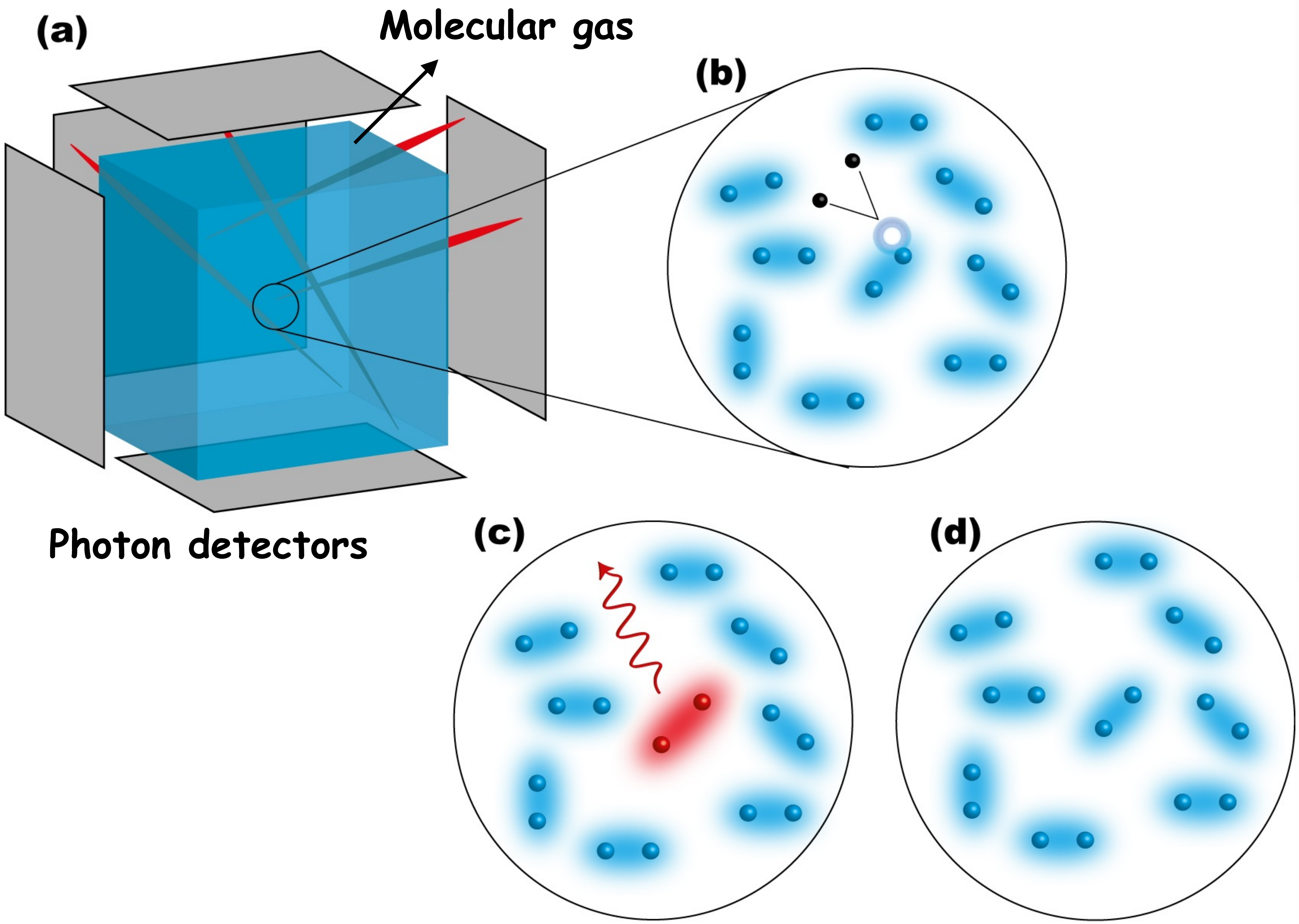

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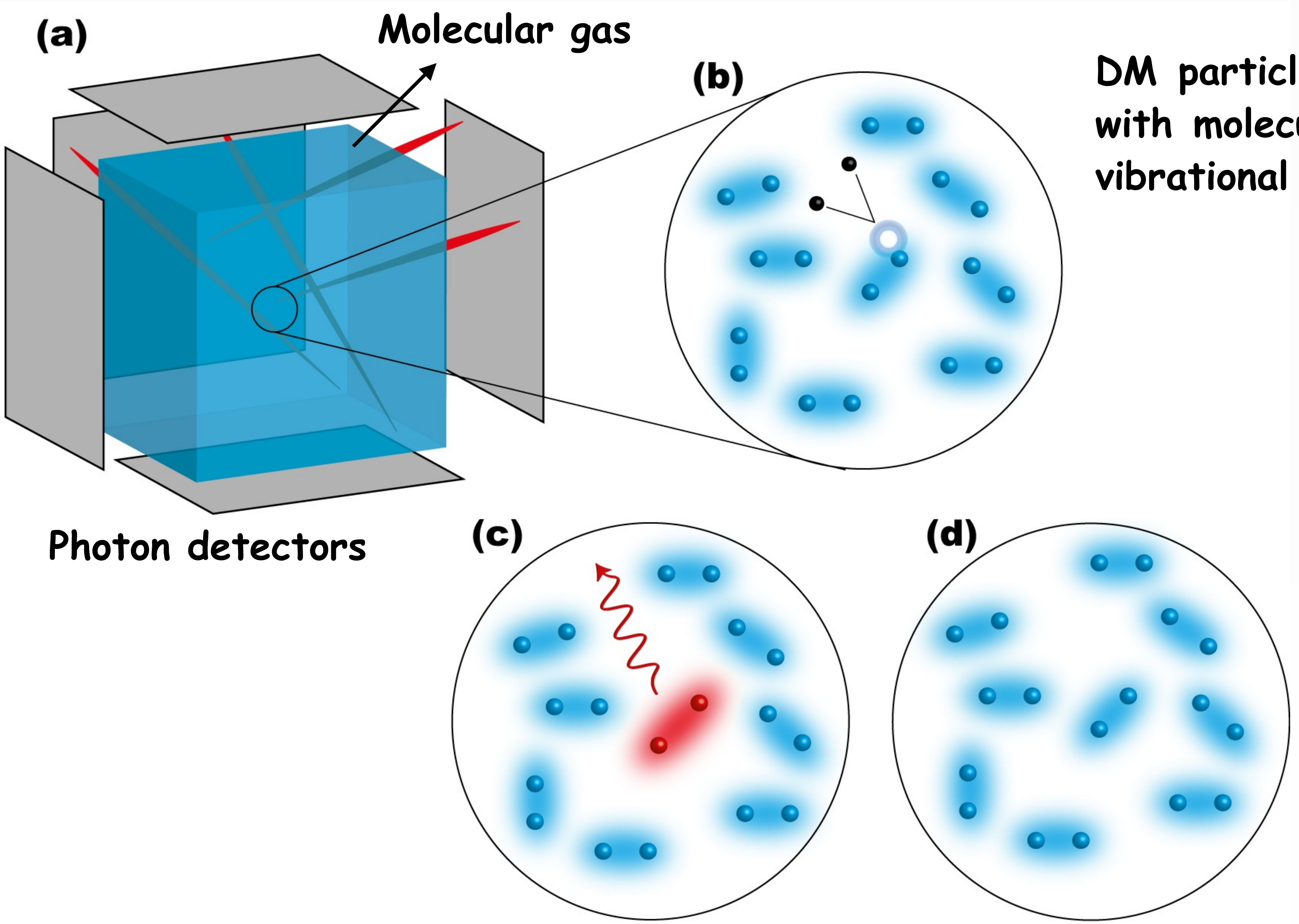
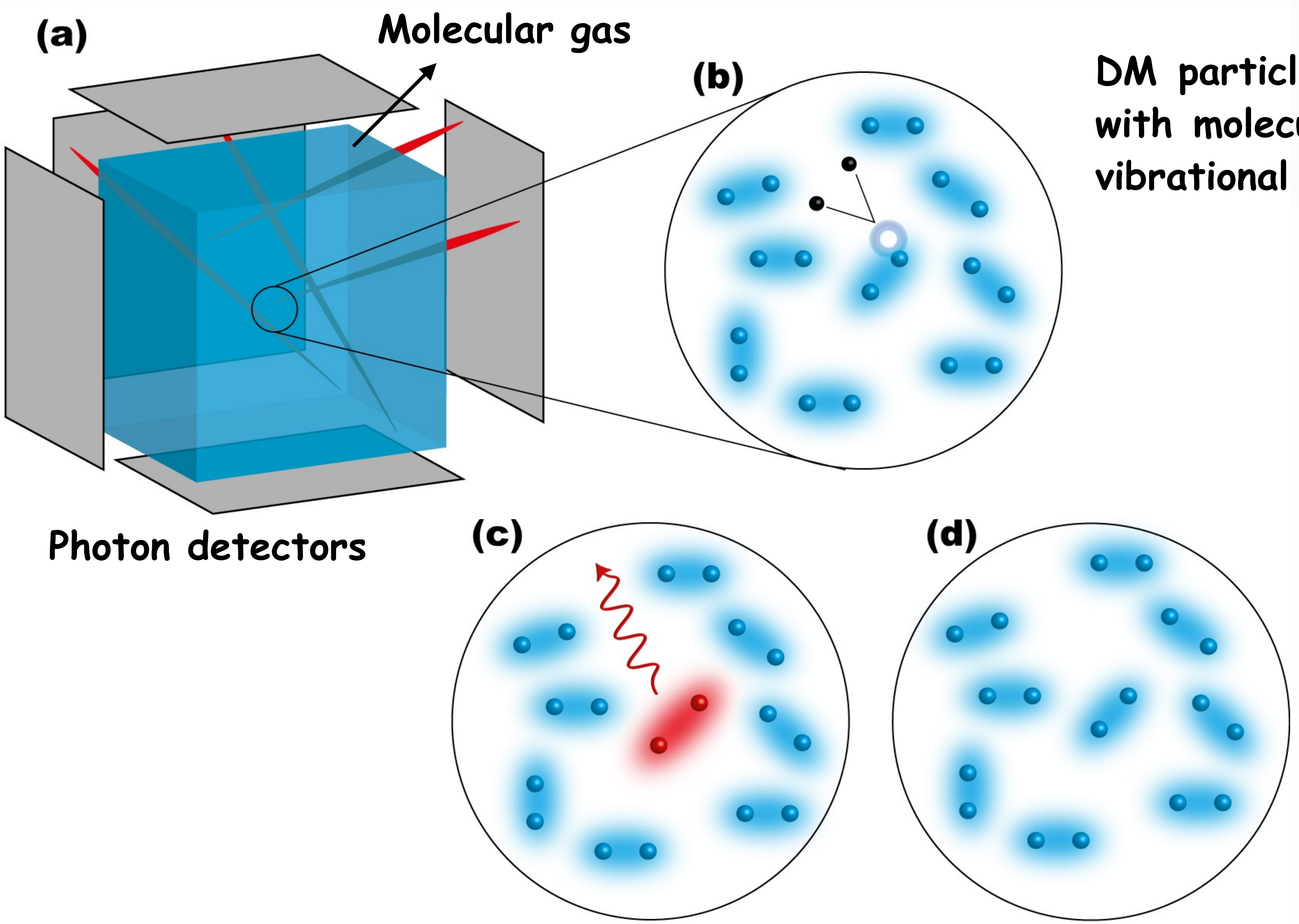



DM particle collisions with molecules induce vibrational excitation

# A novel approach for DM detection

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Excited molecules decay emitting a photon

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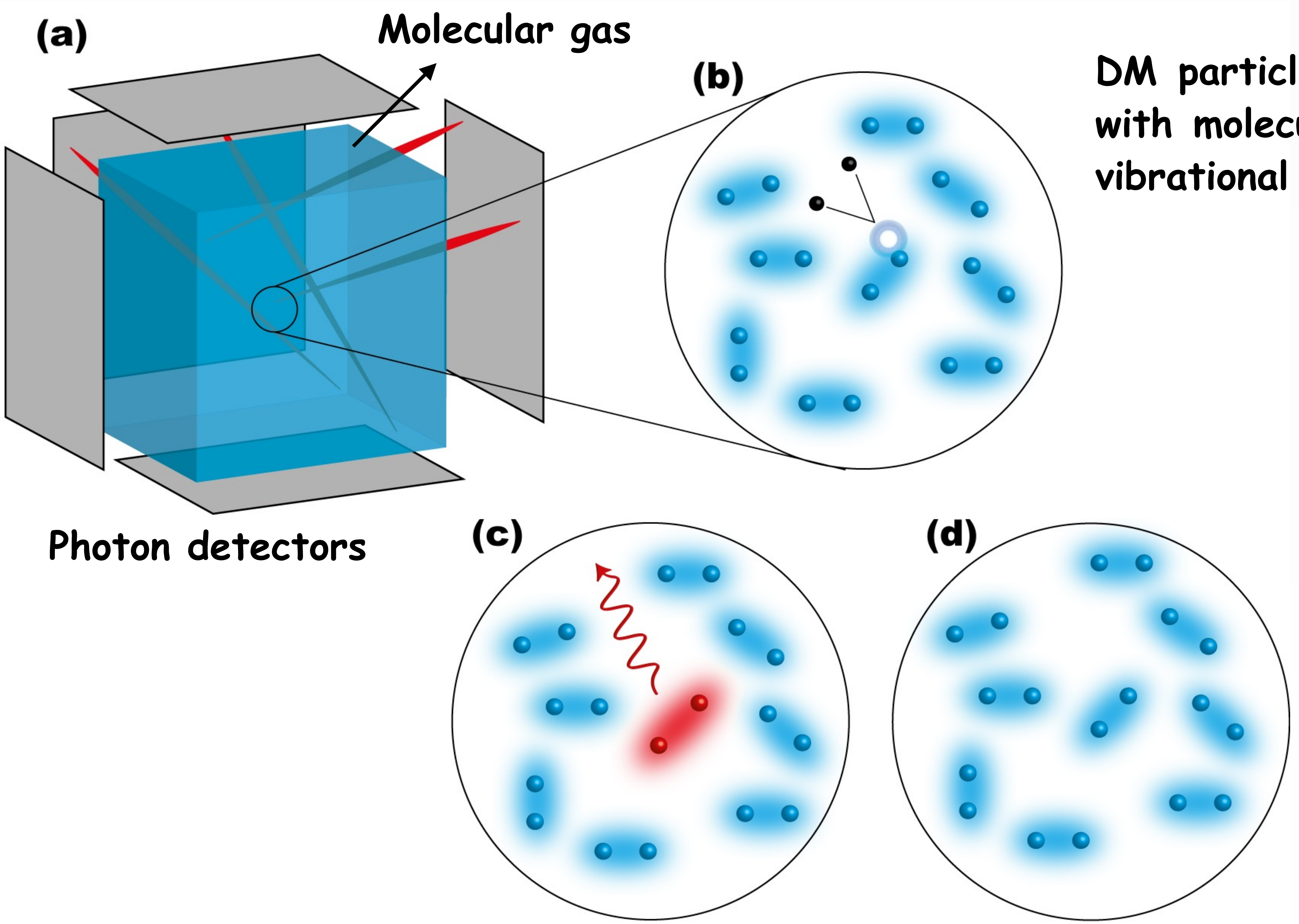



DM particle collisions with molecules induce vibrational excitation

Excited molecules decay emitting a photon

The photon is detected by the photodetectors surrounding the gas

# A novel approach for DM detection

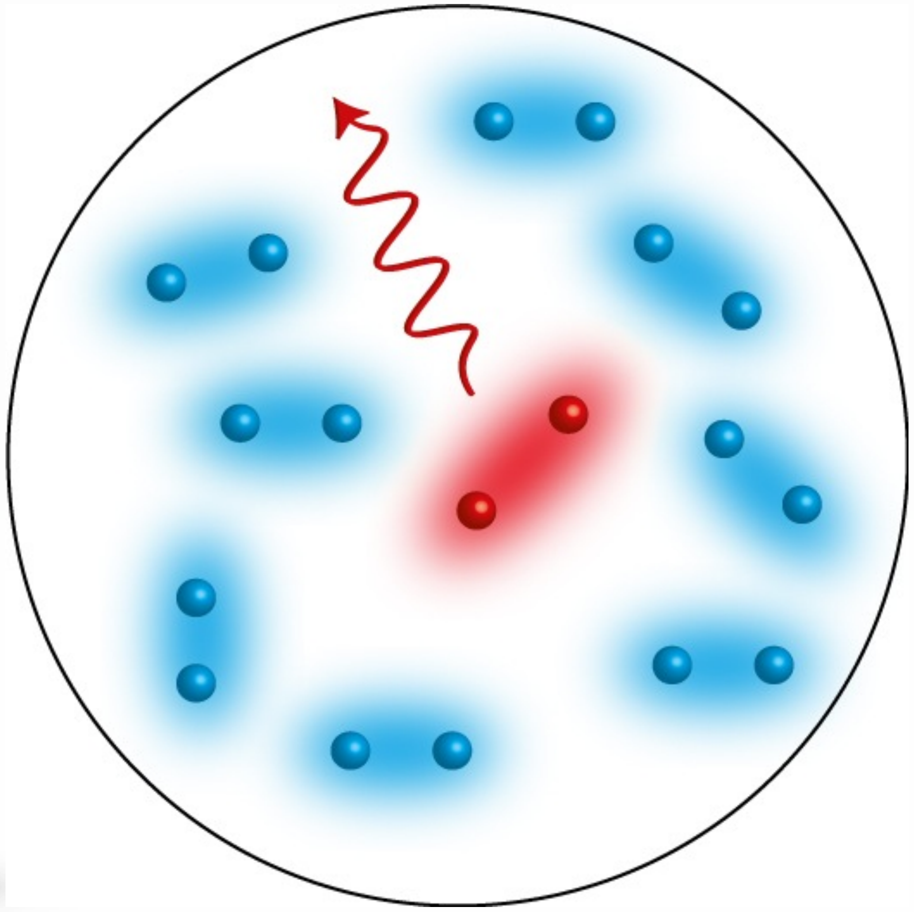
**Four points to take care of**

1. Spontaneous emission rate

2. Thermal population of vibrational states

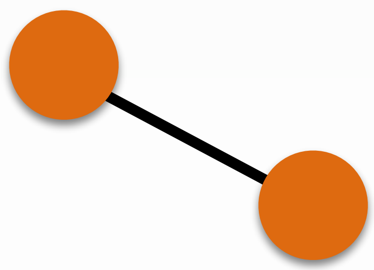
3. Black Body radiation background

4. Collisional de-excitation rate



# 1. Spontaneous emission rate

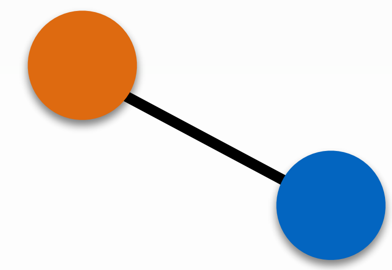
**Homonuclear**



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

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

**Heteronuclear**



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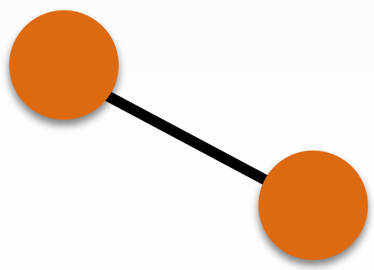
# 1. Spontaneous emission rate

## Homonuclear



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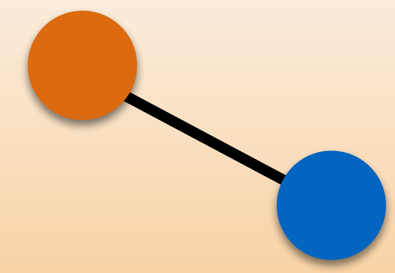
## Heteronuclear



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# 1. Spontaneous emission rate

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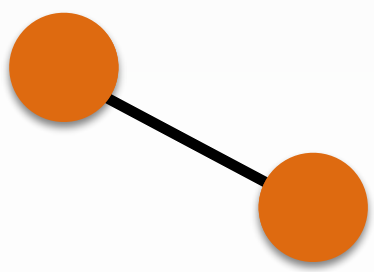

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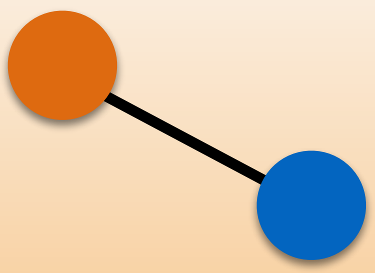


$$\frac{d\Gamma_{ij}}{d\Omega} = \frac{\alpha\omega_{ij}^3}{2\pi c^2}|d|^2$$

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

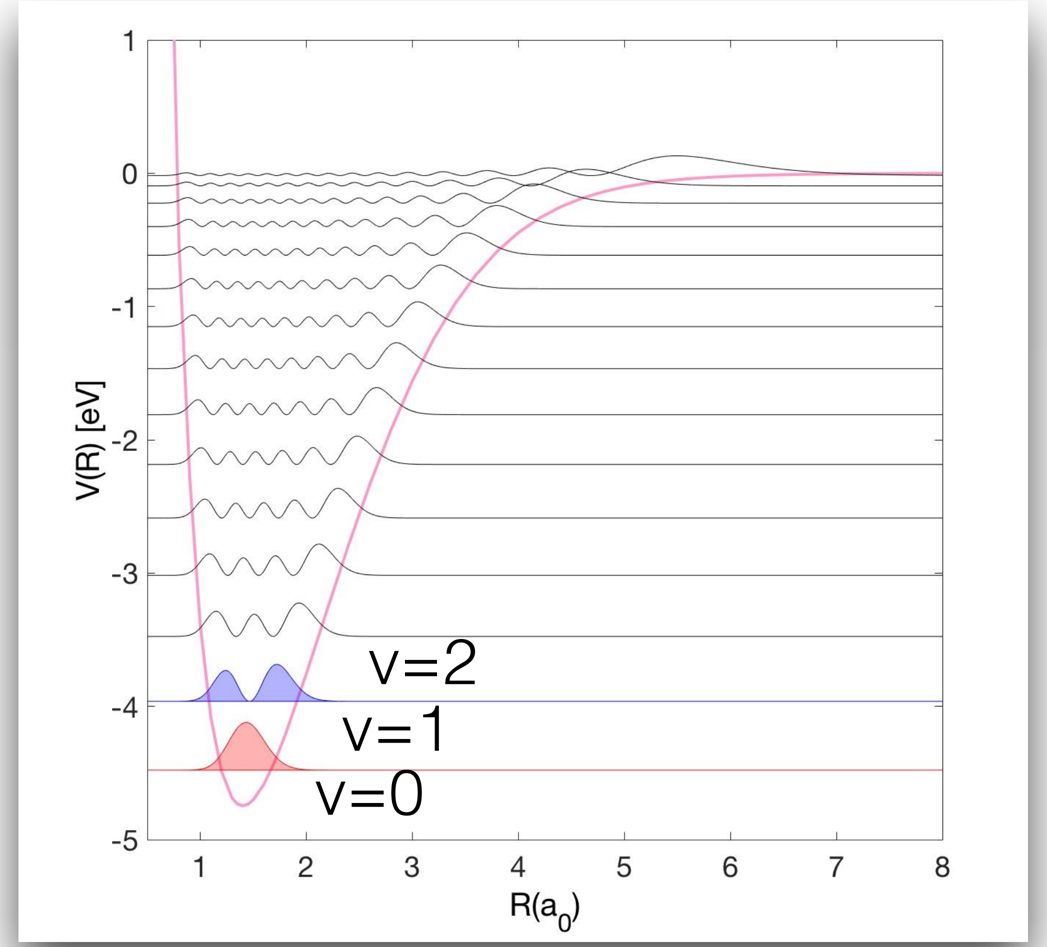
A fee to pay

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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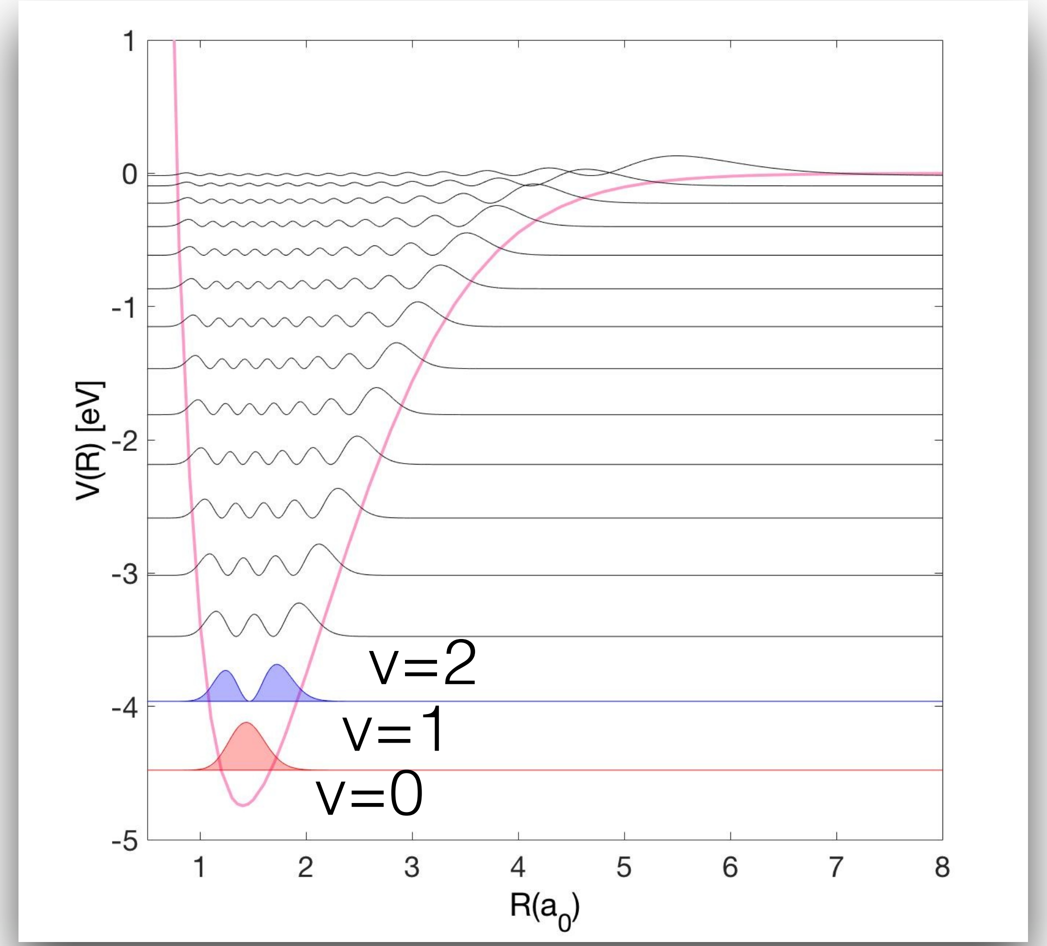


The temperature has to be low enough to ensure that almost every single molecule is in the vibrational ground state

→ 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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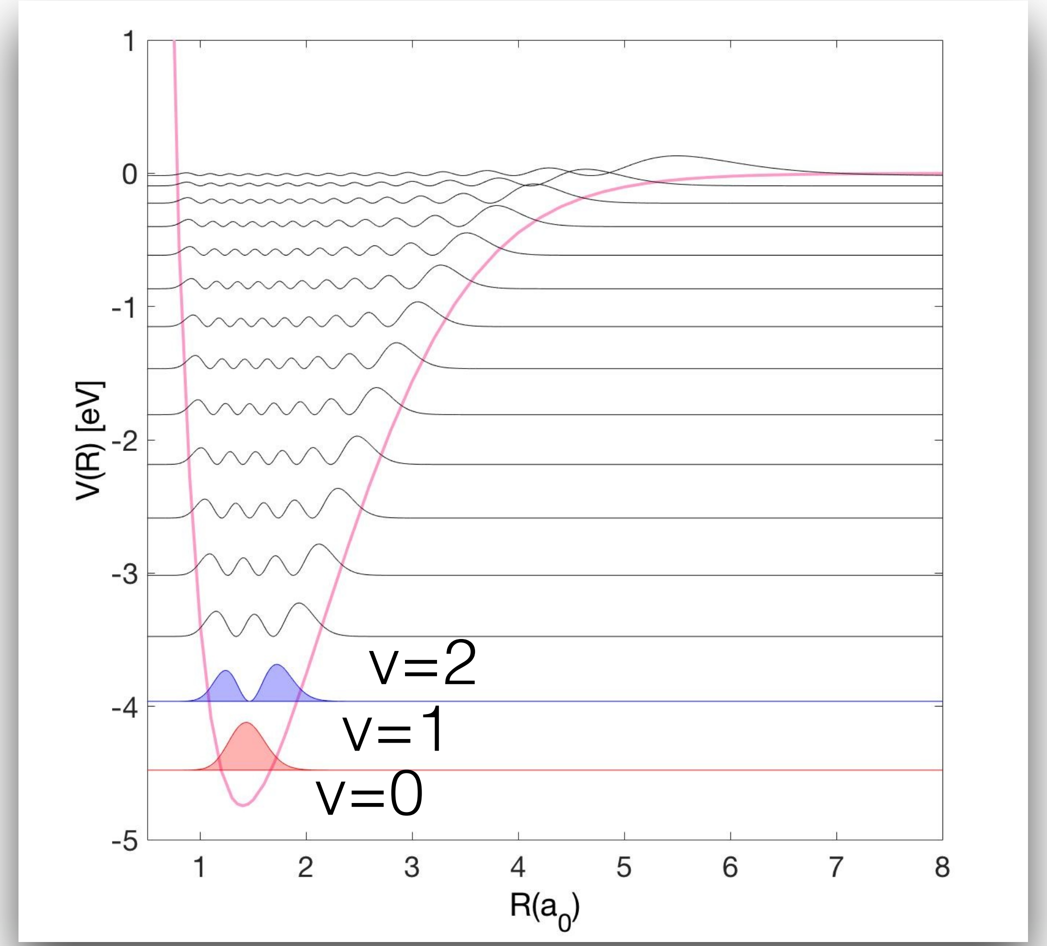


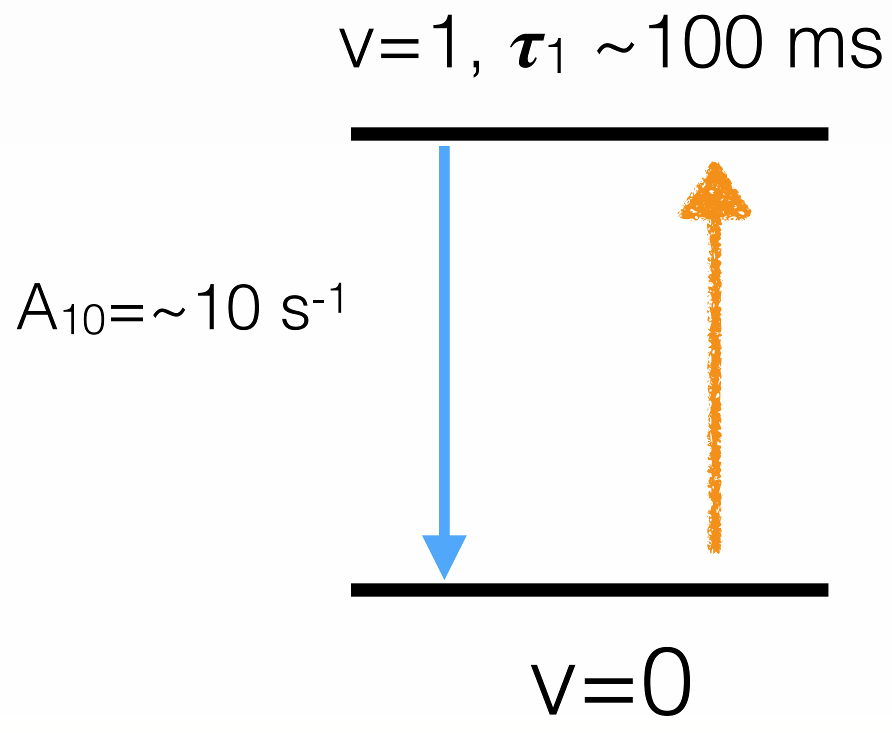

We prefer lighter molecules, i.e., large vibrational spacing

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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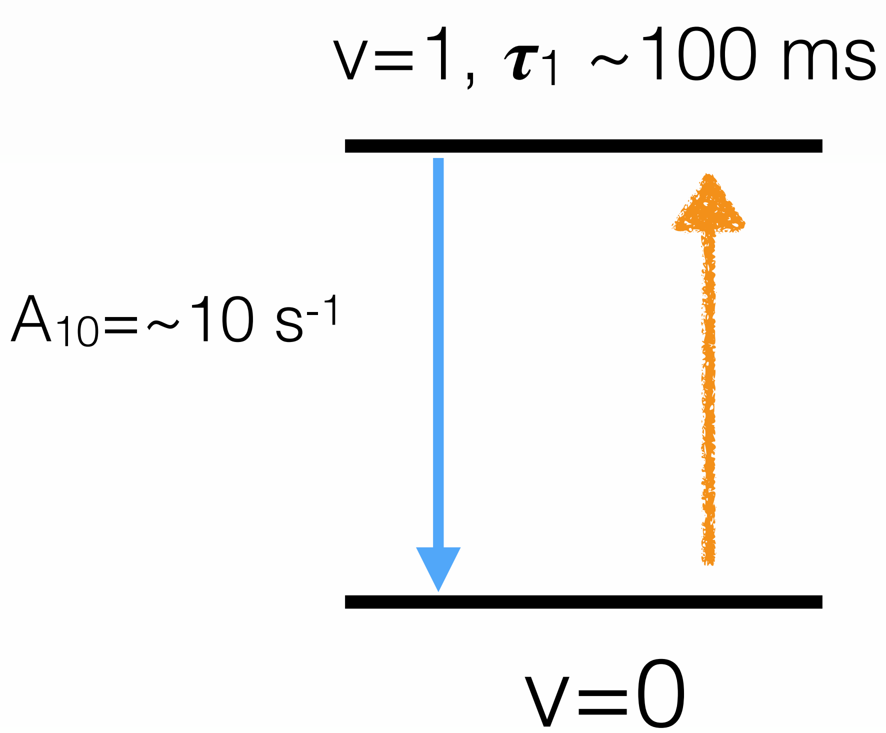

# 3. Black body radiation

Dipole matrix element

Vibrational frequency

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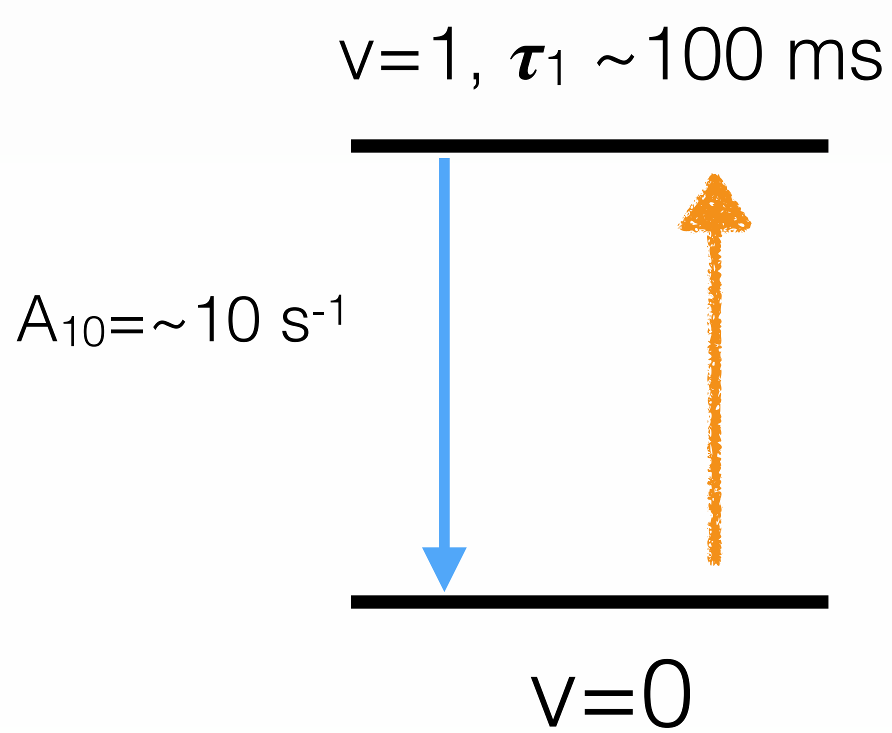

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**Dipole matrix element** | **Vibrational frequency**

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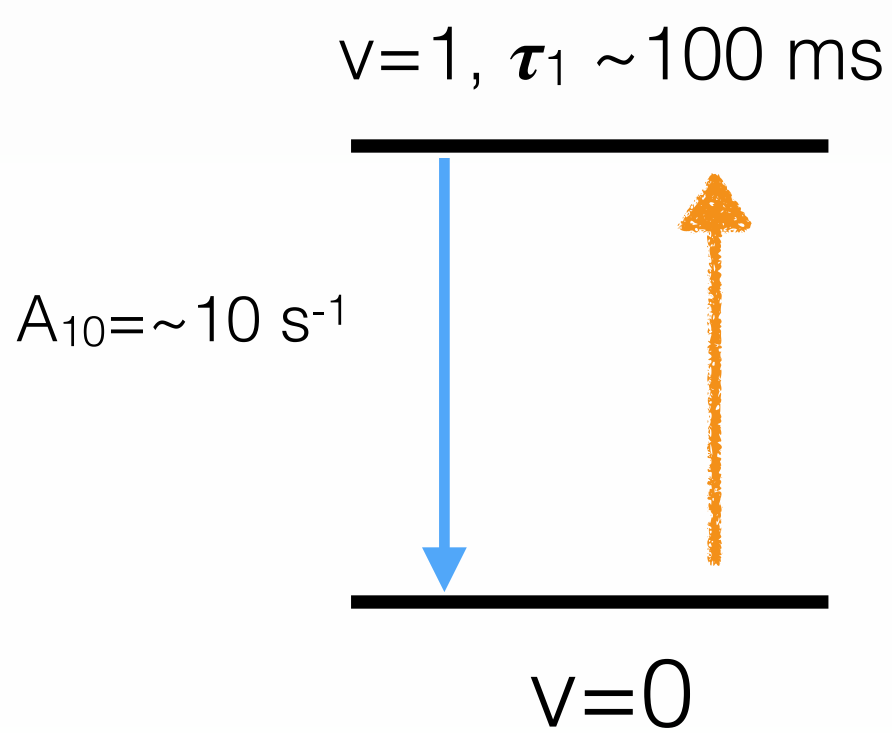
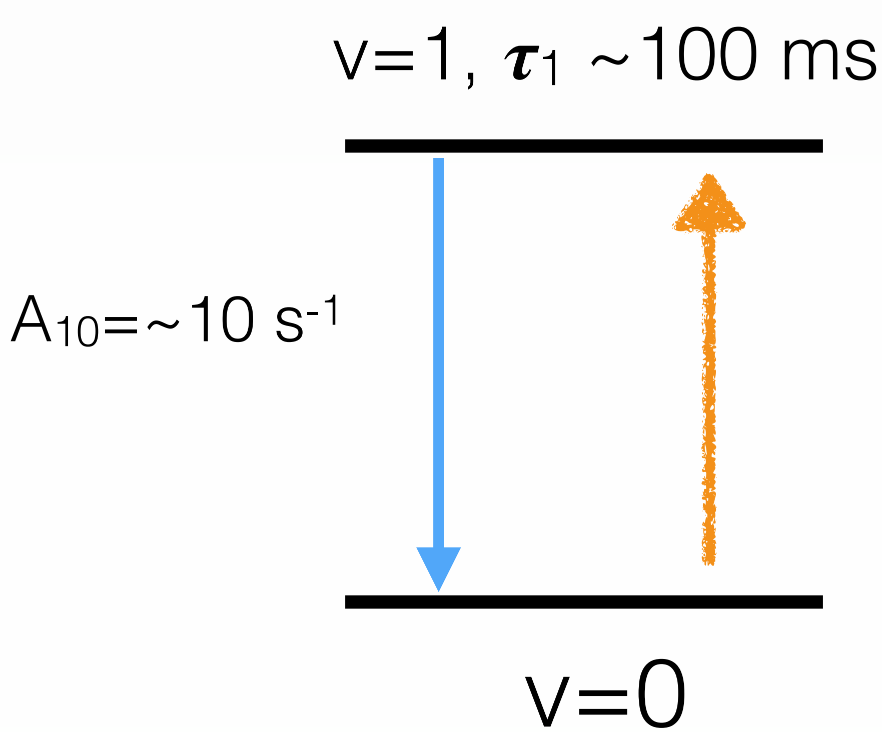



**We prefer lighter molecules, i.e., large vibrational spacing**

# 3. Black body radiation

**Dipole matrix element** **Vibrational frequency**

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




**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<br>198<br>466 | 513 | 269 | 236 | 371 |
| d(D) | 1.80 | 1.98 | 0.12 | 0.16 | 1.03 |

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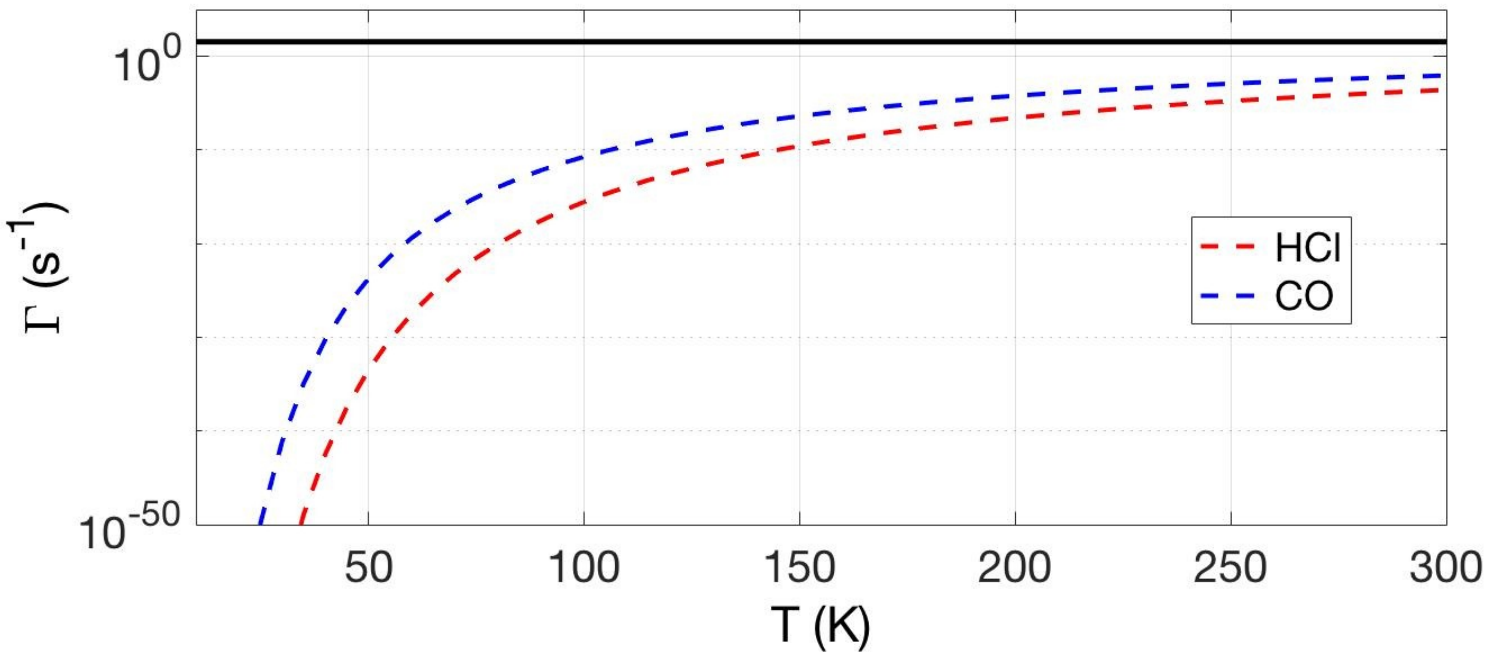


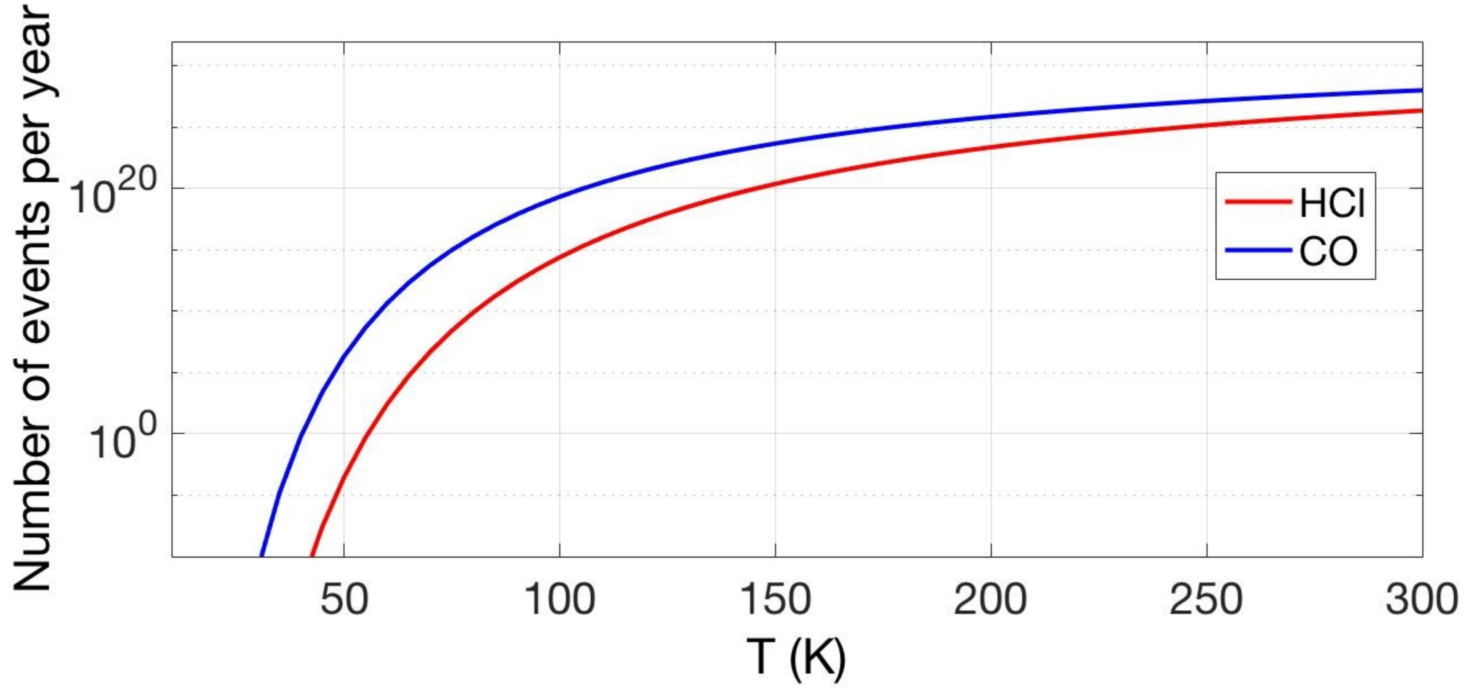

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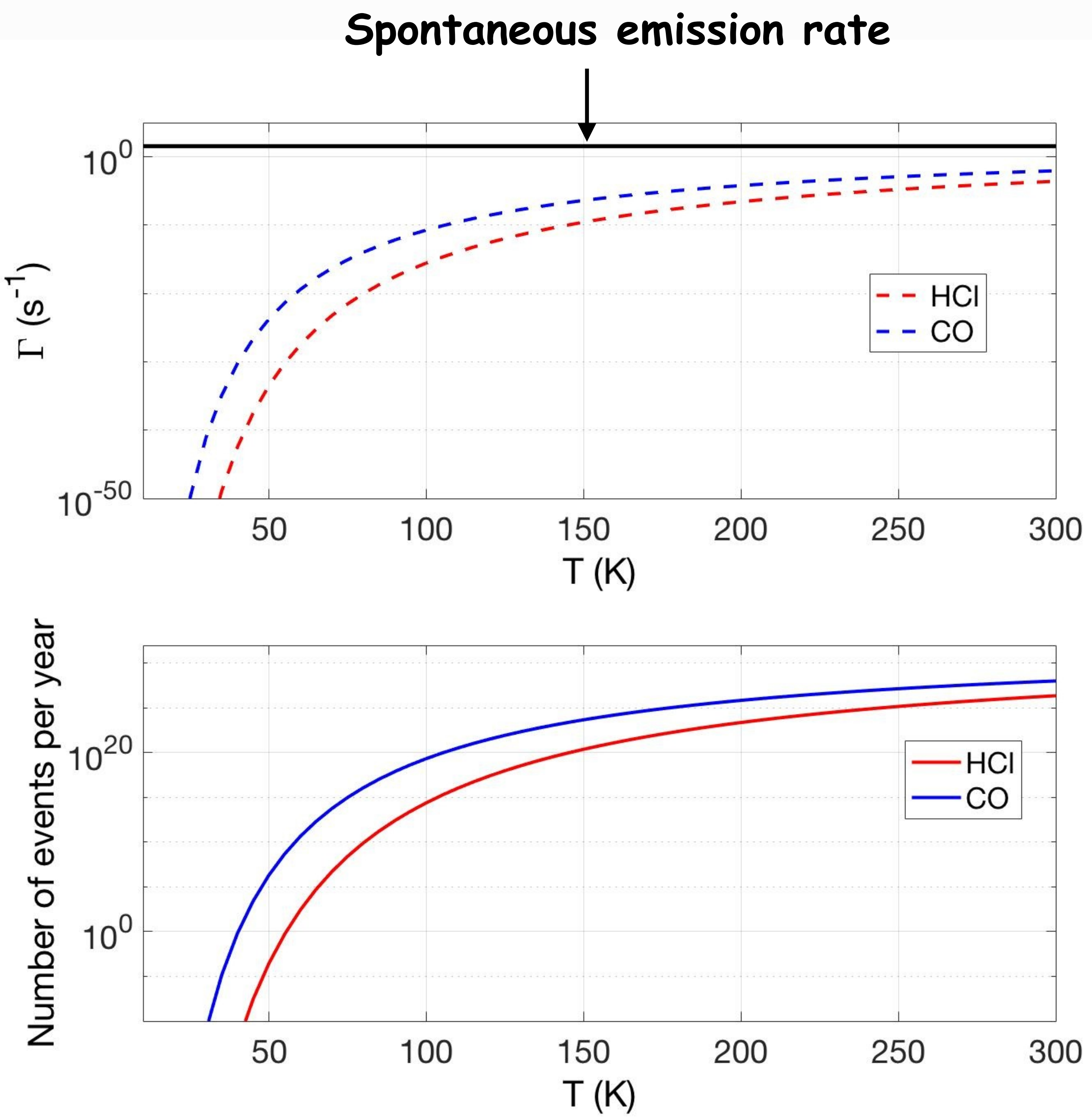

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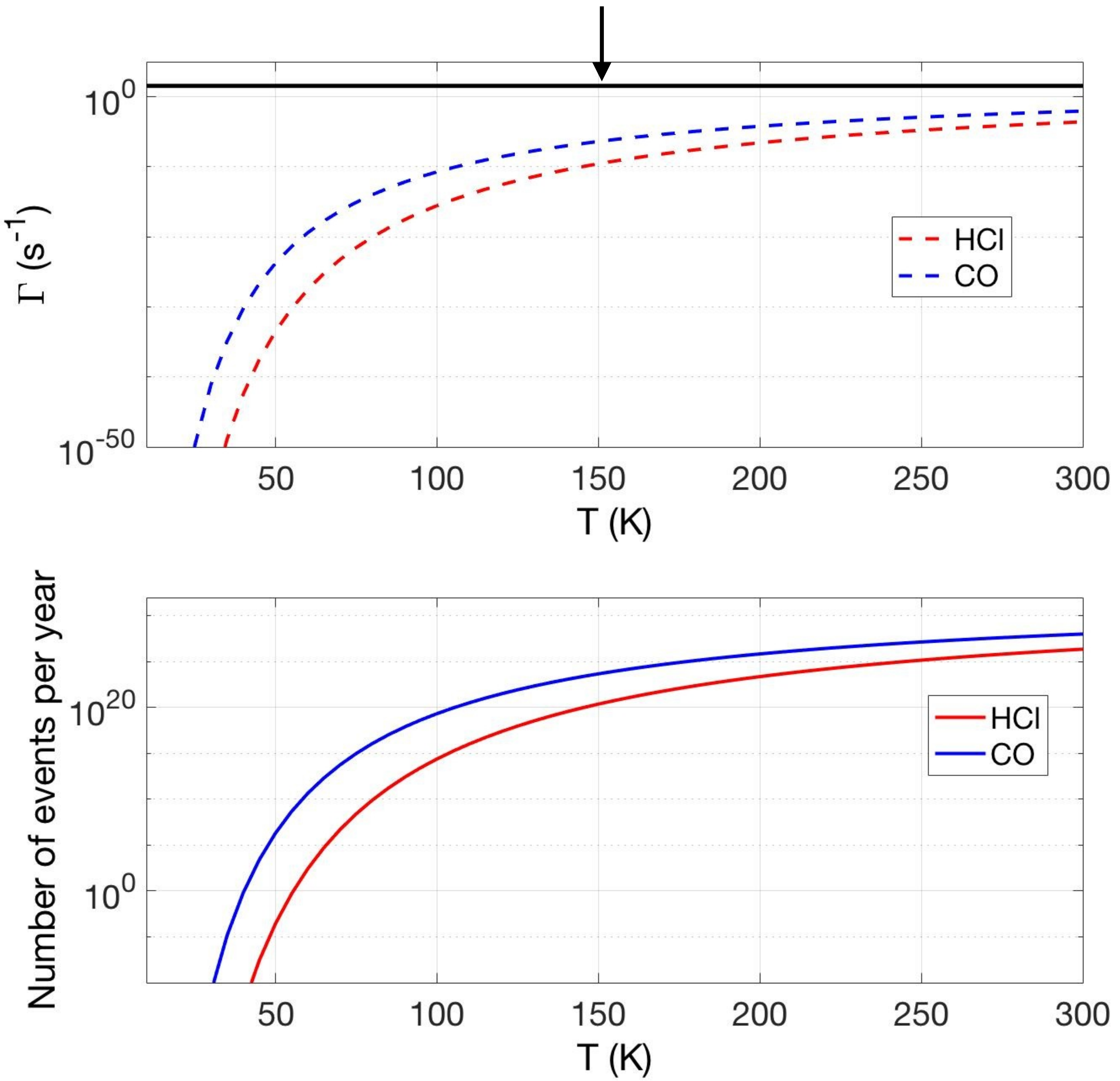
Spontaneous emission rate

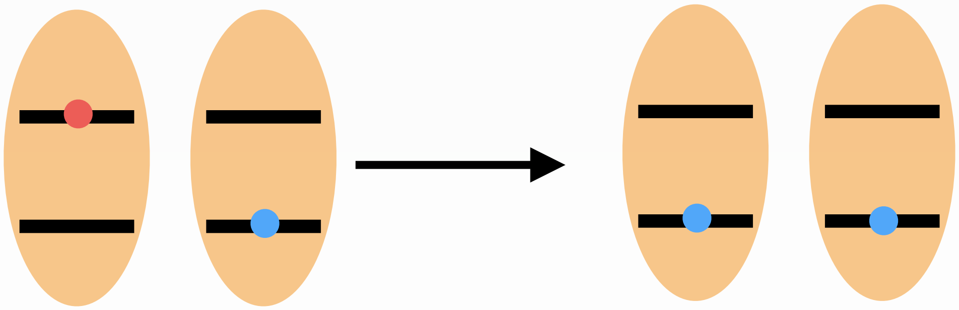



We need

**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

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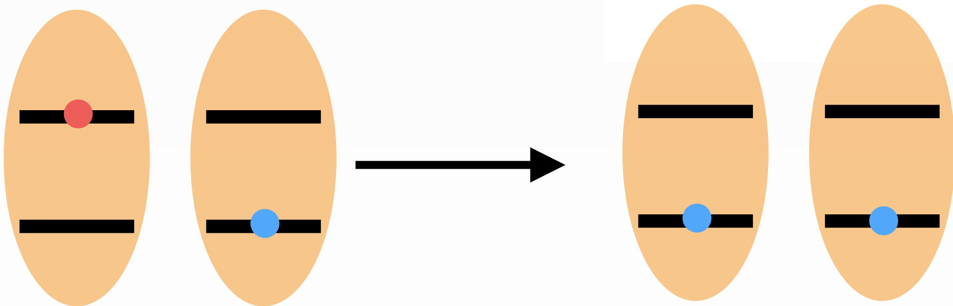
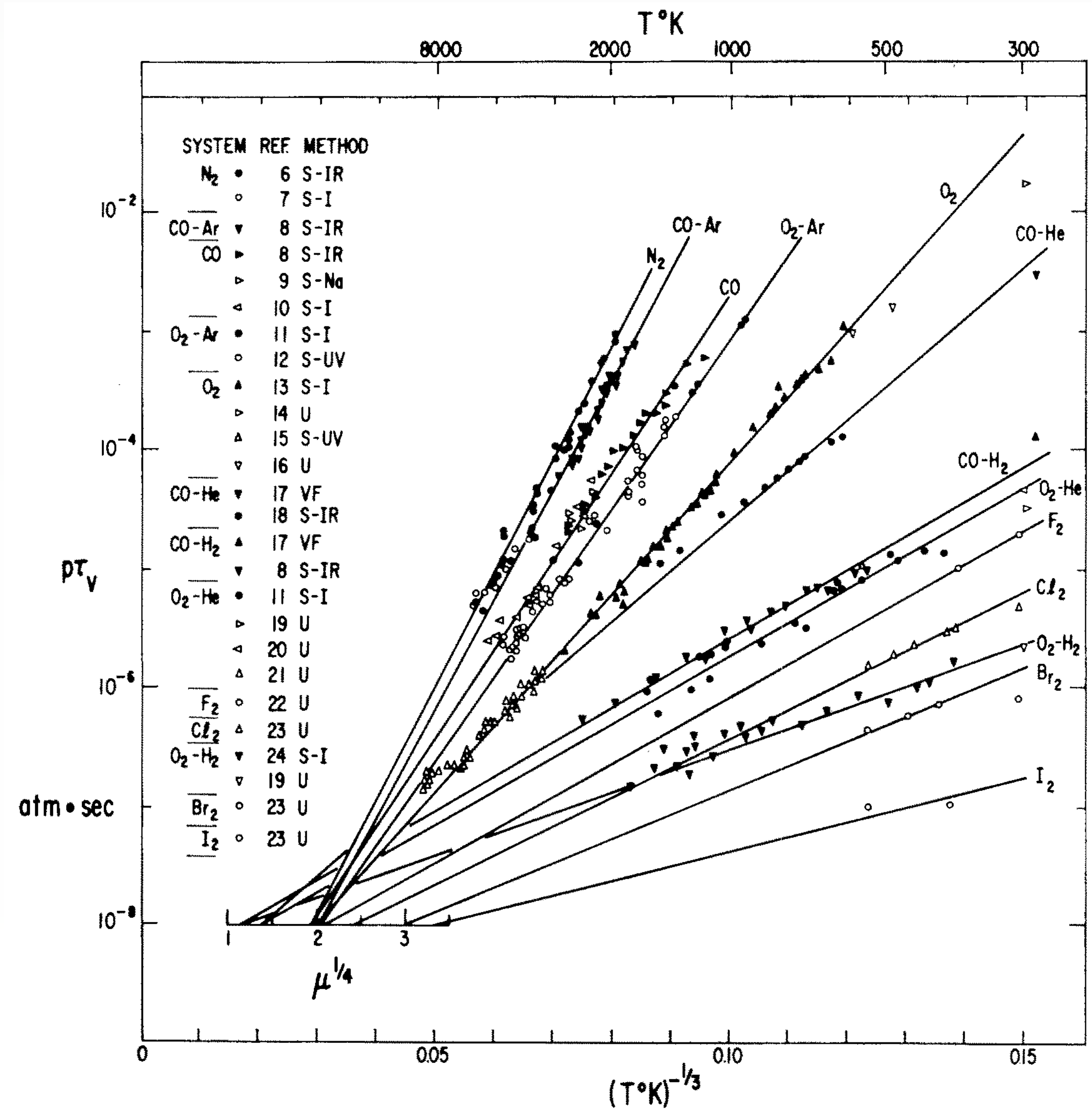
Roger C. Millikan and Donald R. White
*General Electric Research Laboratory, Schenectady, New York*





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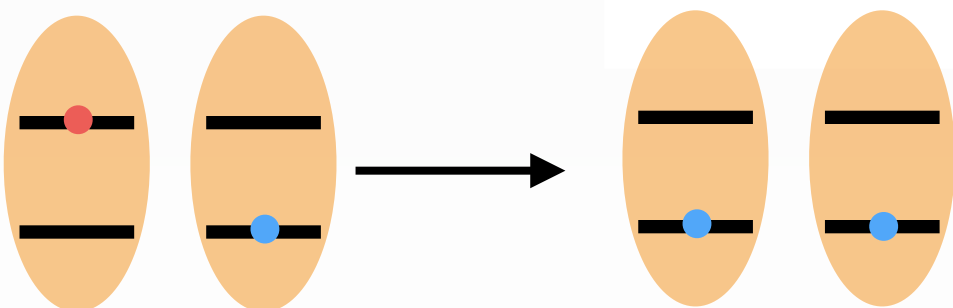

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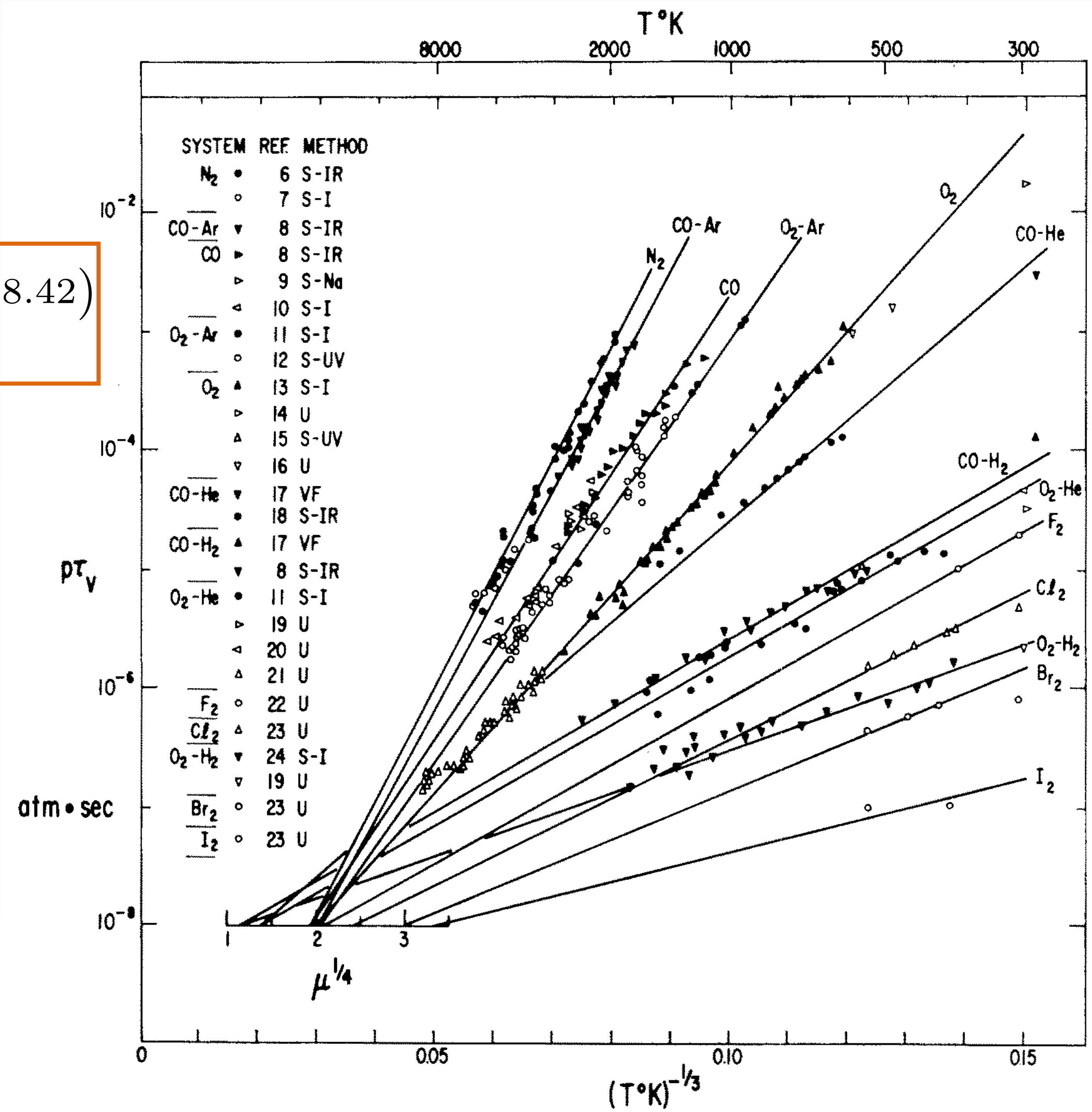

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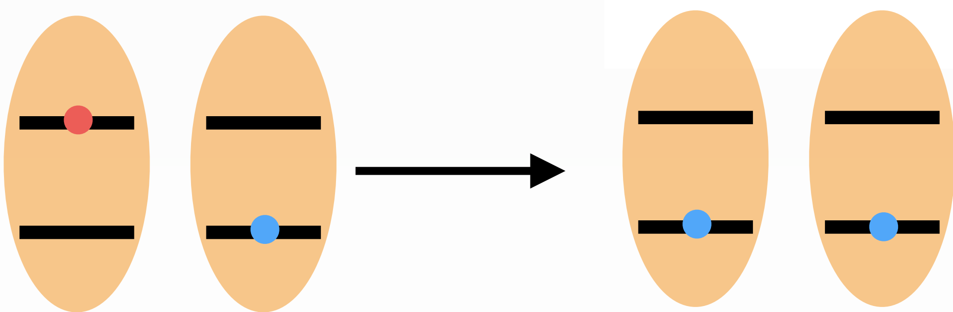

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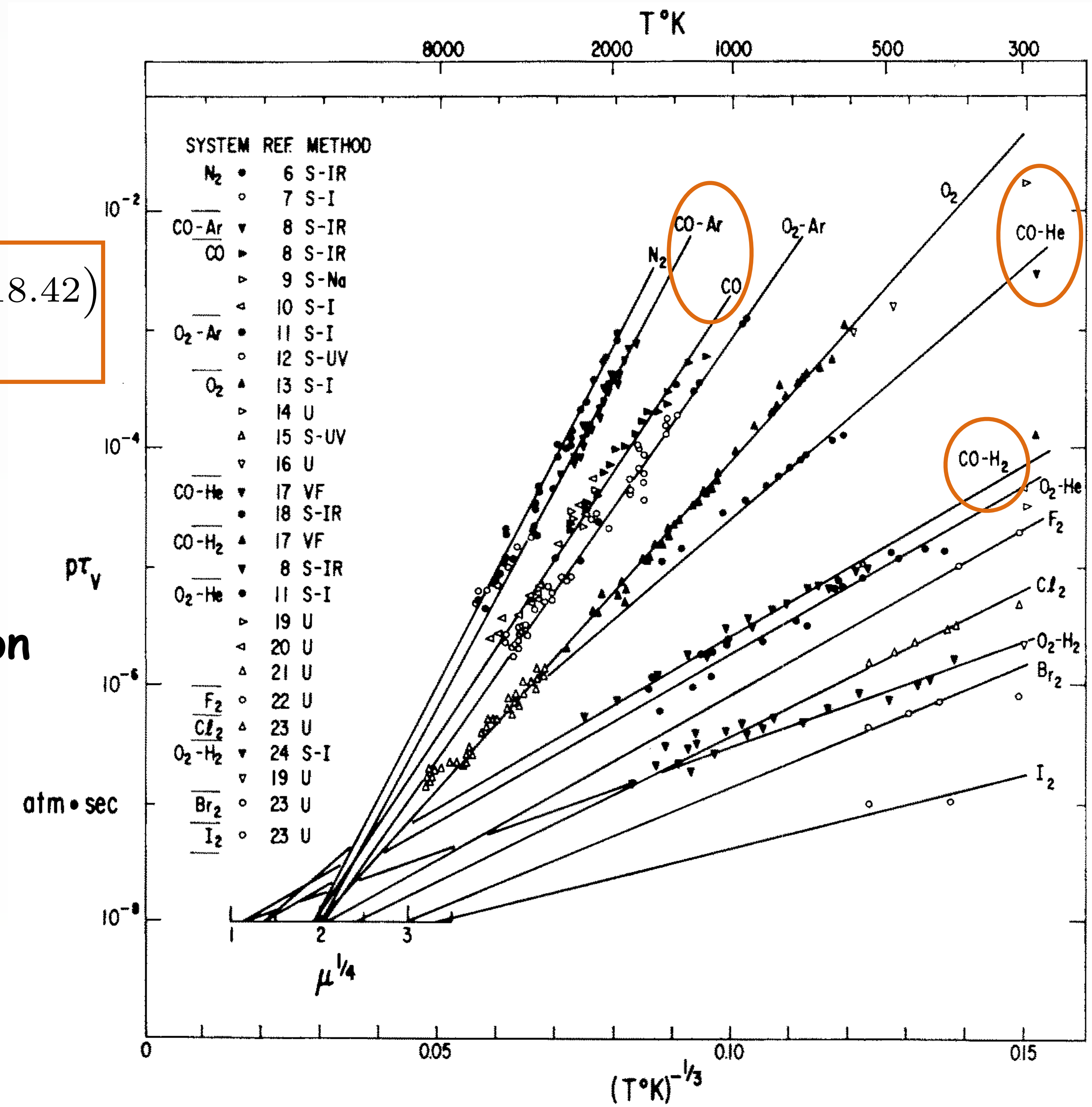


CO shows larger vibrational quenching time
CO has a decent vibrational spacing
CO shows a regular BBR rate absorption spectra at low temperatures

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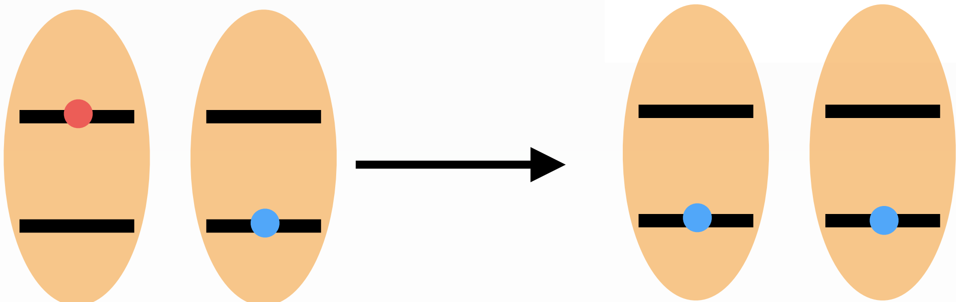

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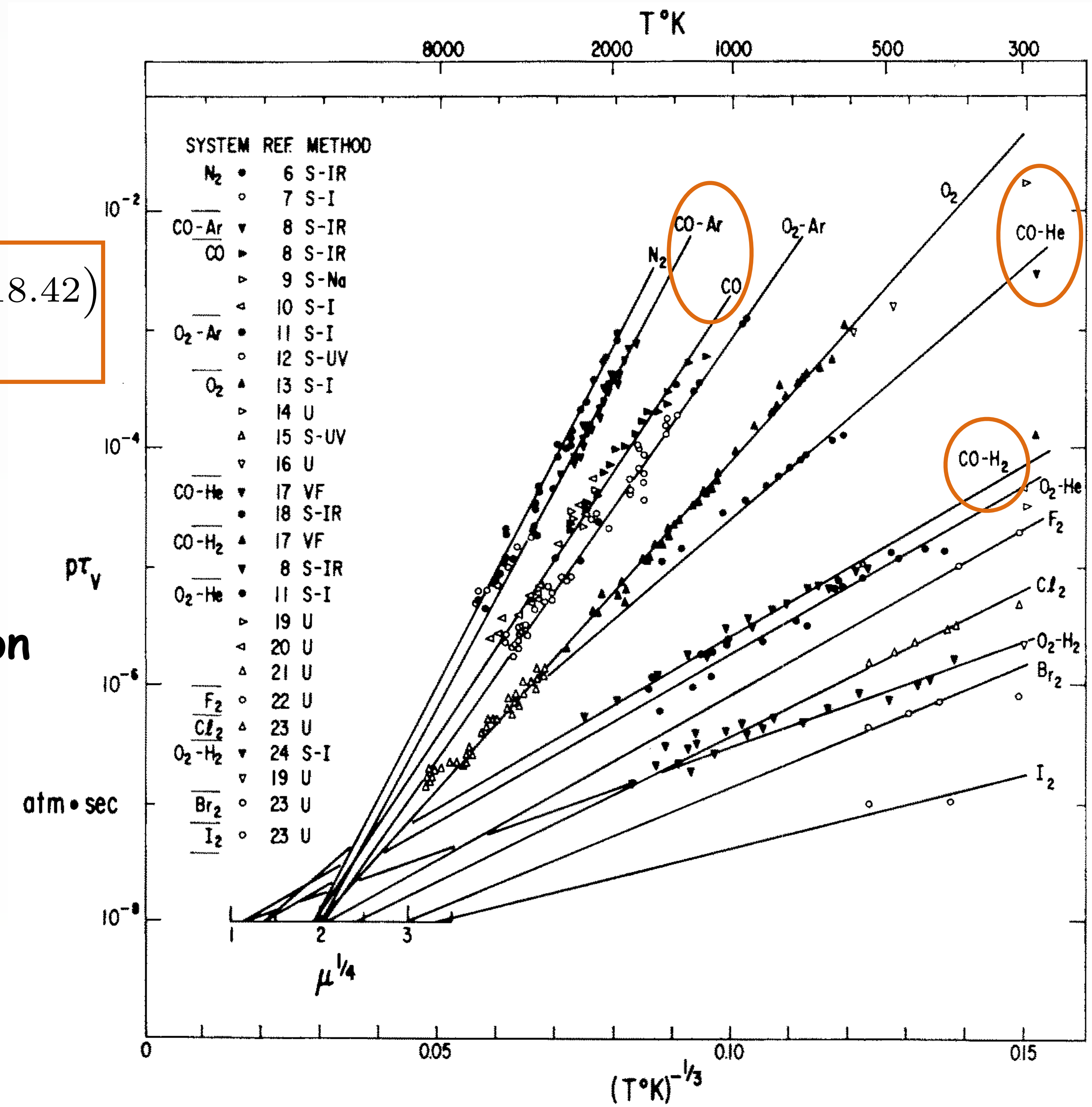
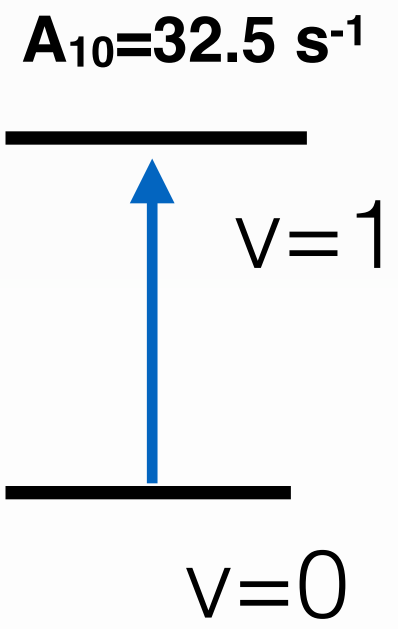



CO shows larger vibrational quenching time
CO has a decent vibrational spacing
CO shows a regular BBR rate absorption spectra at low temperatures

**CO is our guy**

# CO in detail

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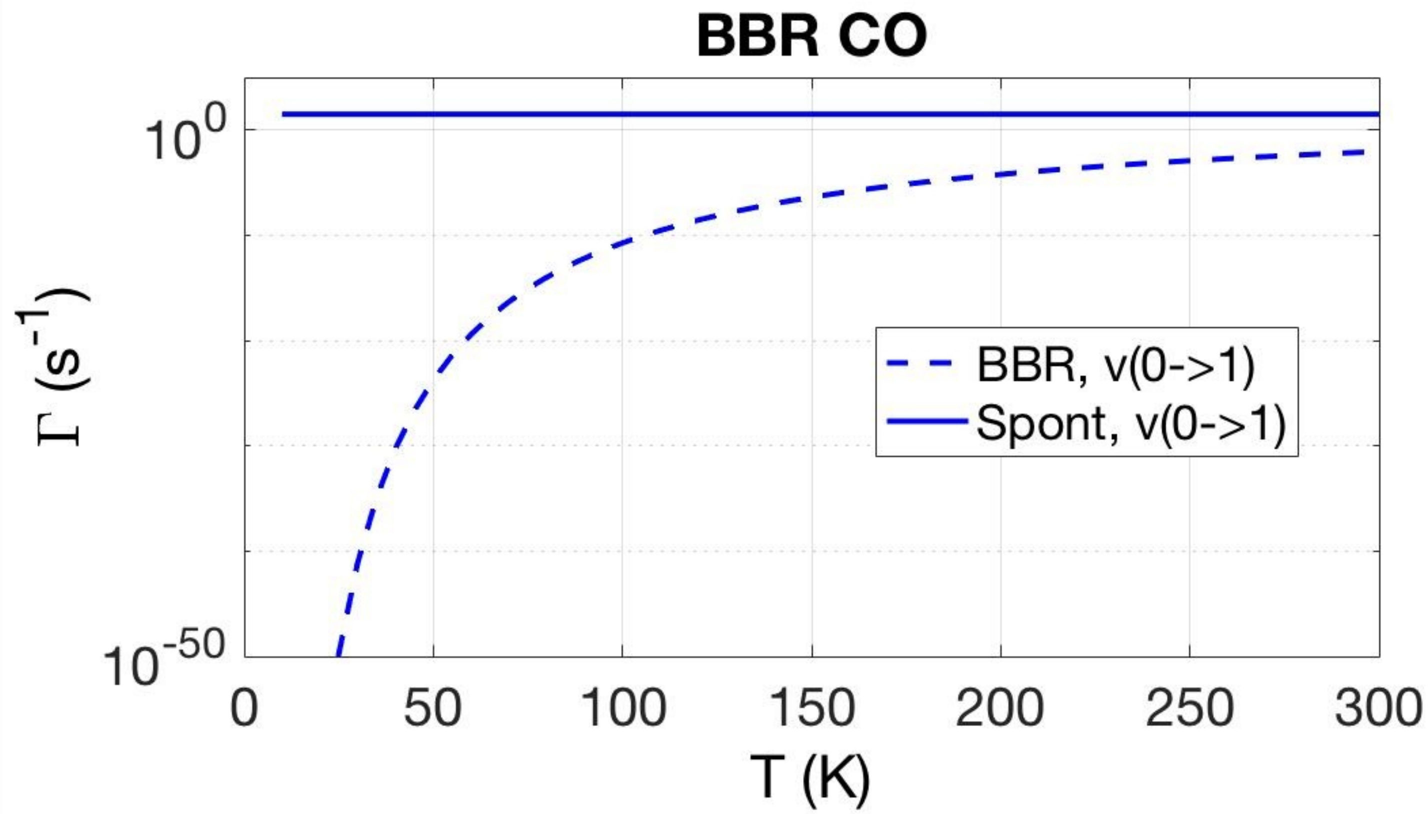


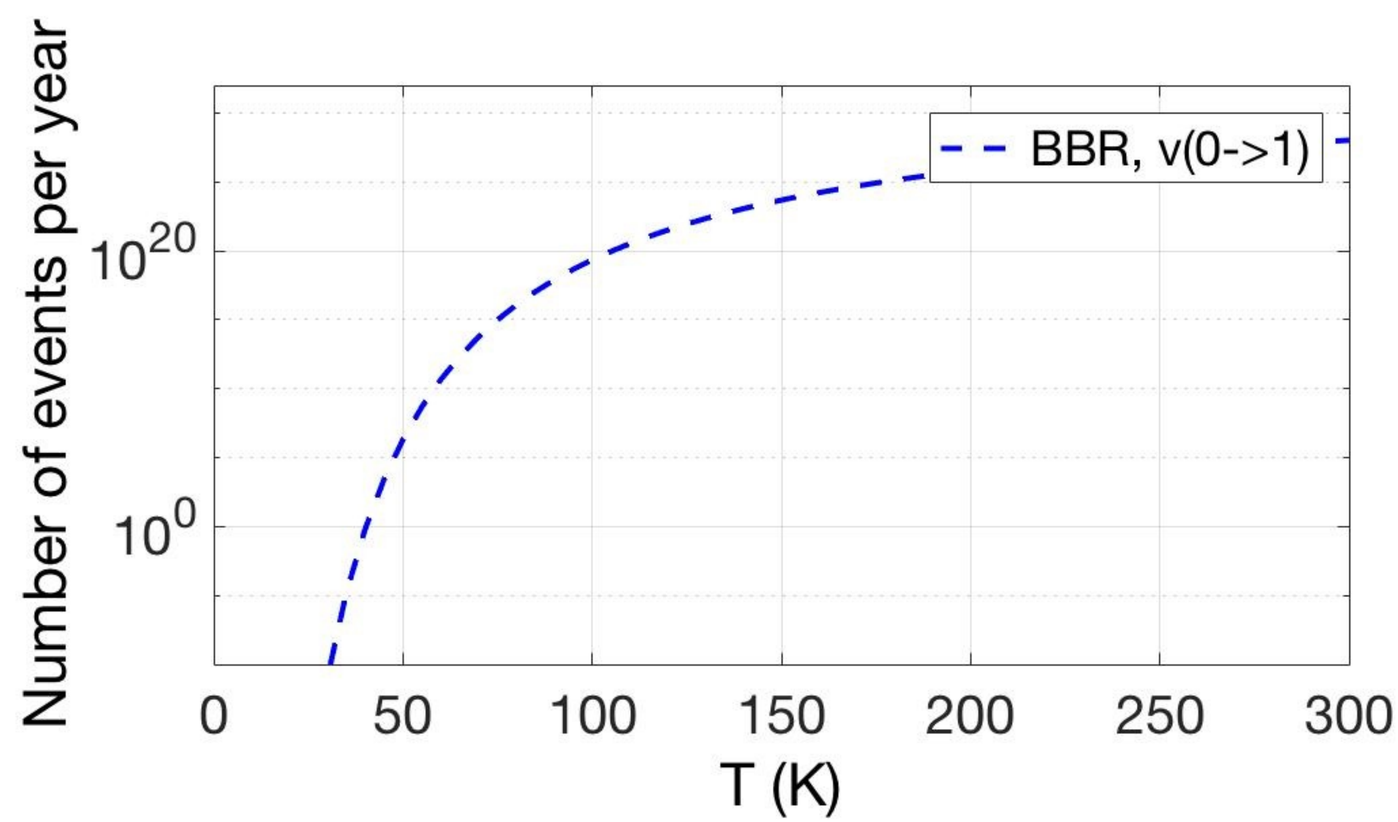

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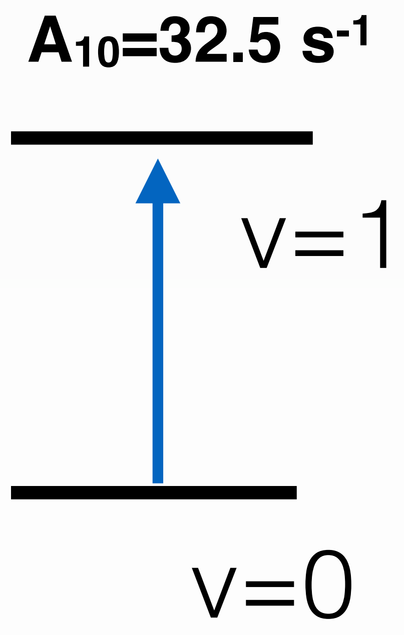


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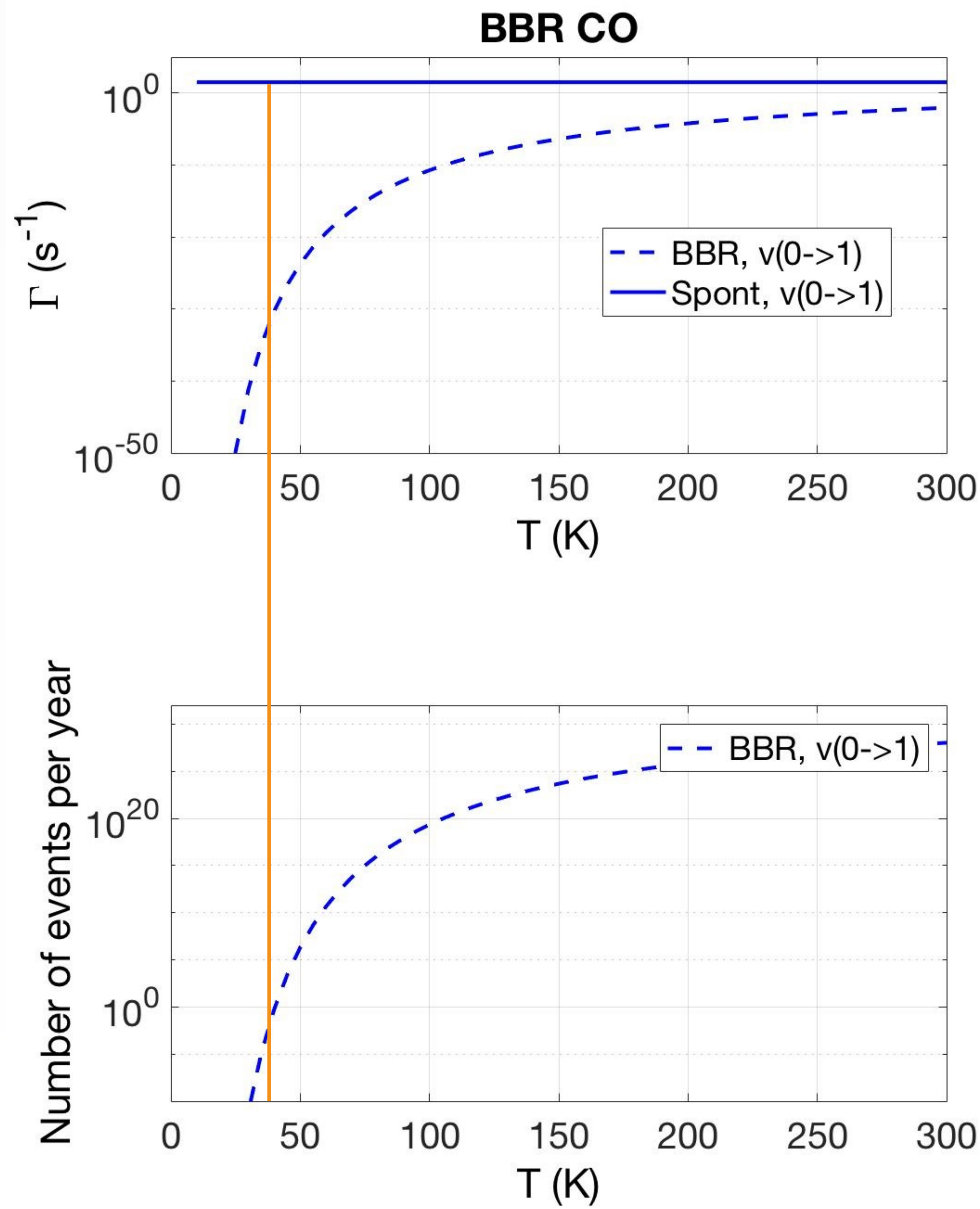

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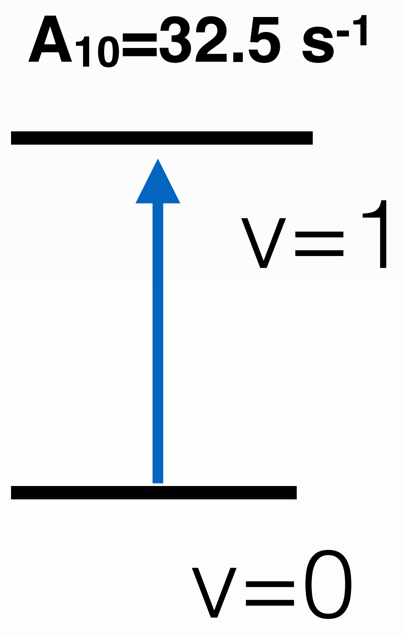


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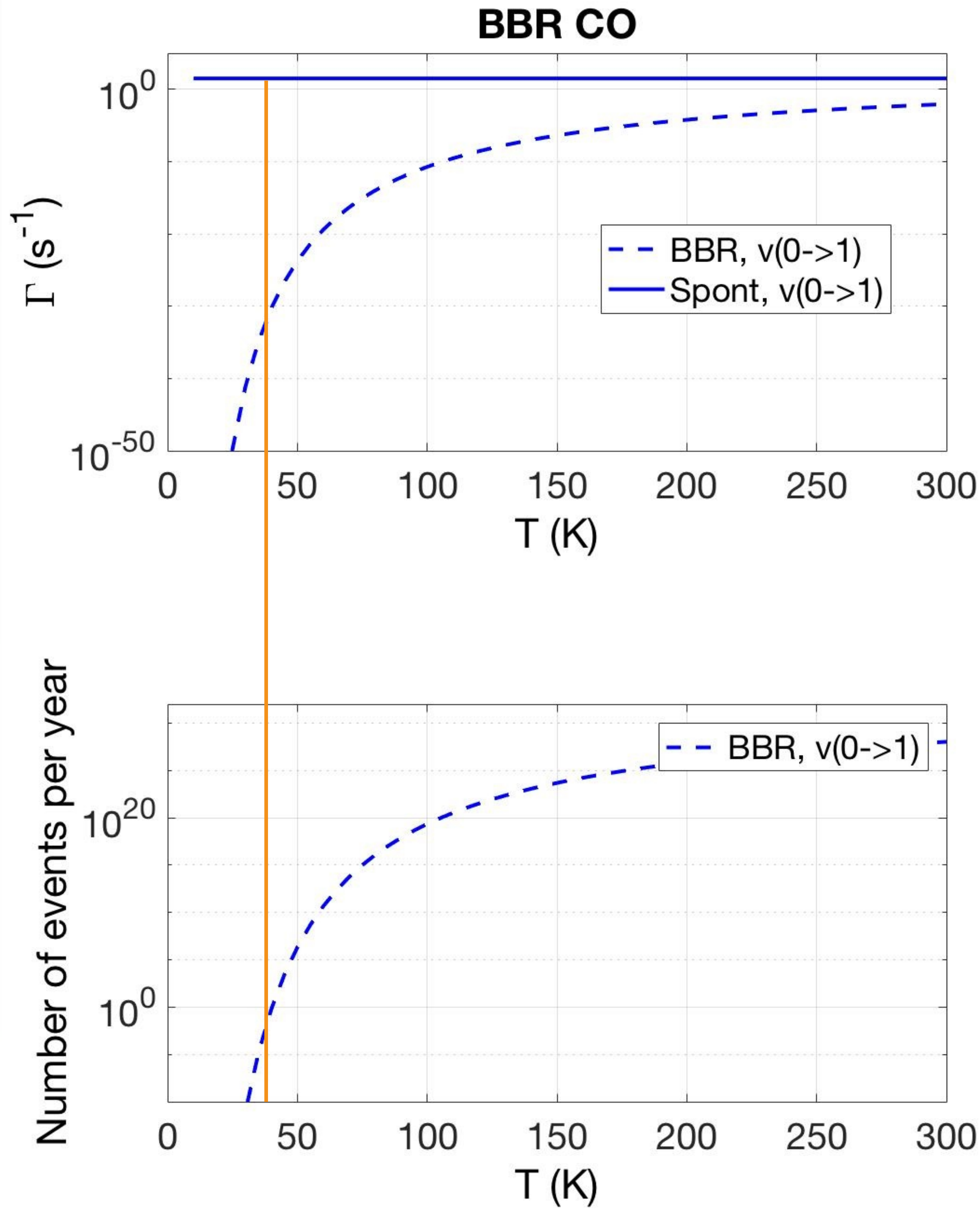
**CO @ 40K**



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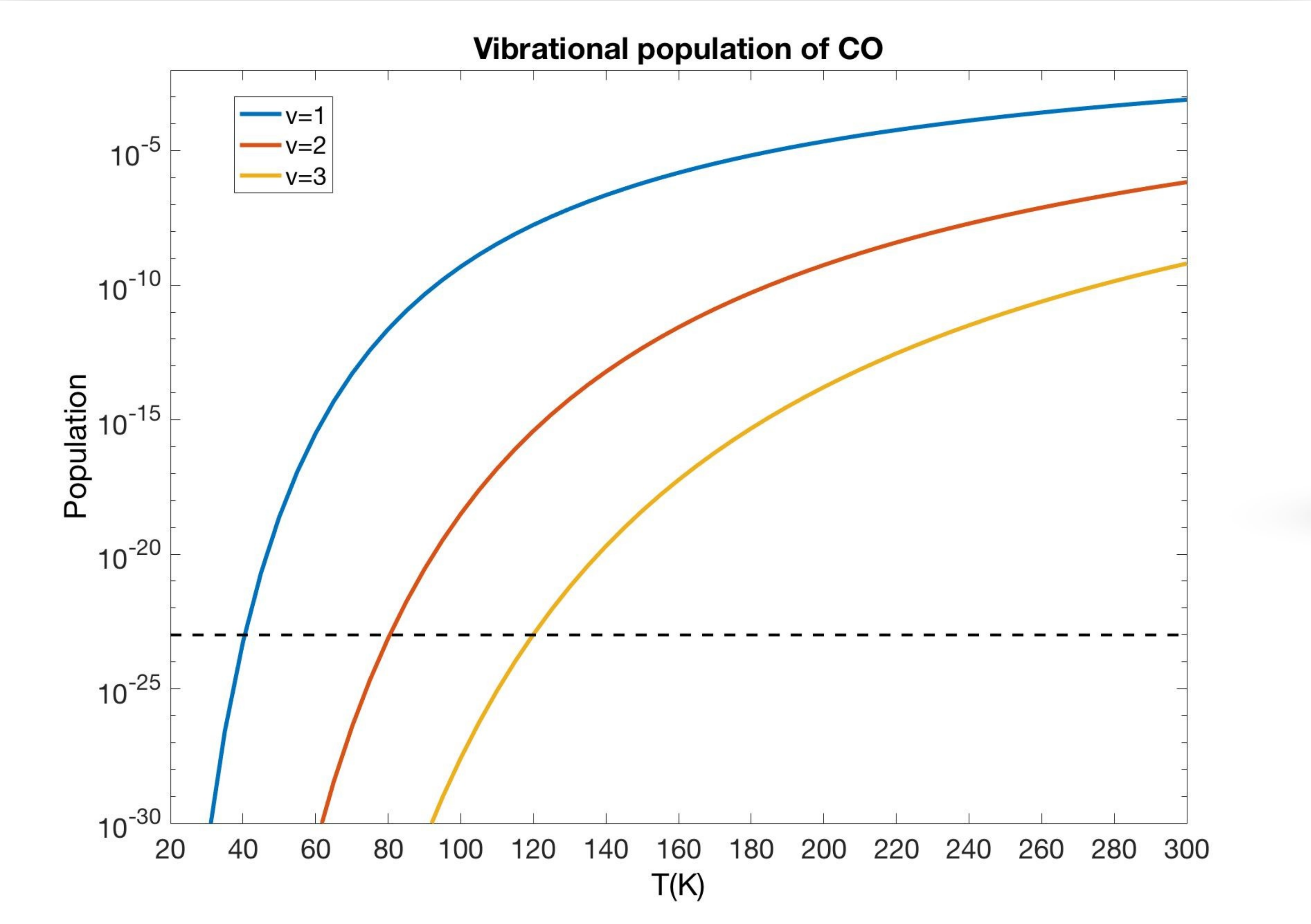
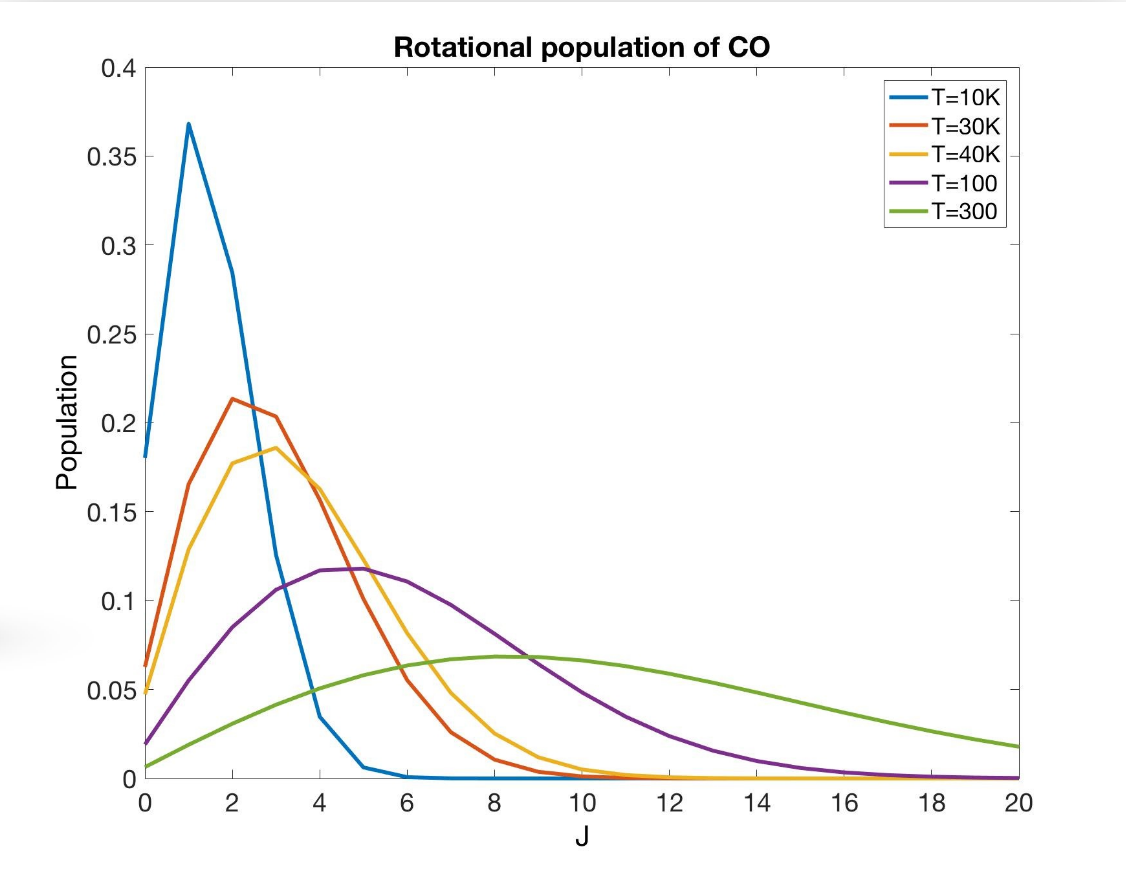



**For CO @ 40 K the <u>pressure must be ≲ 0.1 mbar</u> to have all the molecules in gas phase**

**The rotational level distribution is accounted for in the rate calculation**



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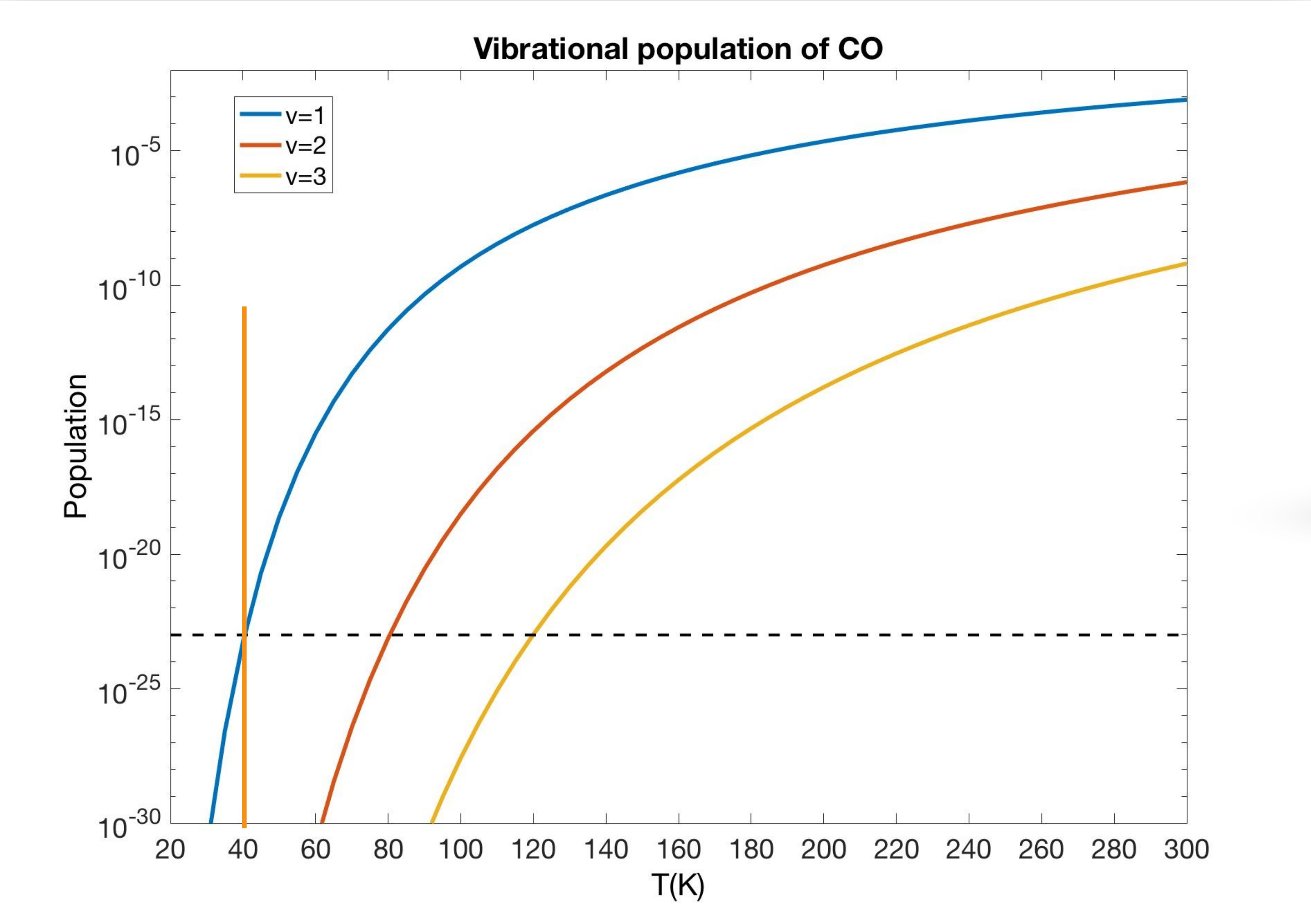


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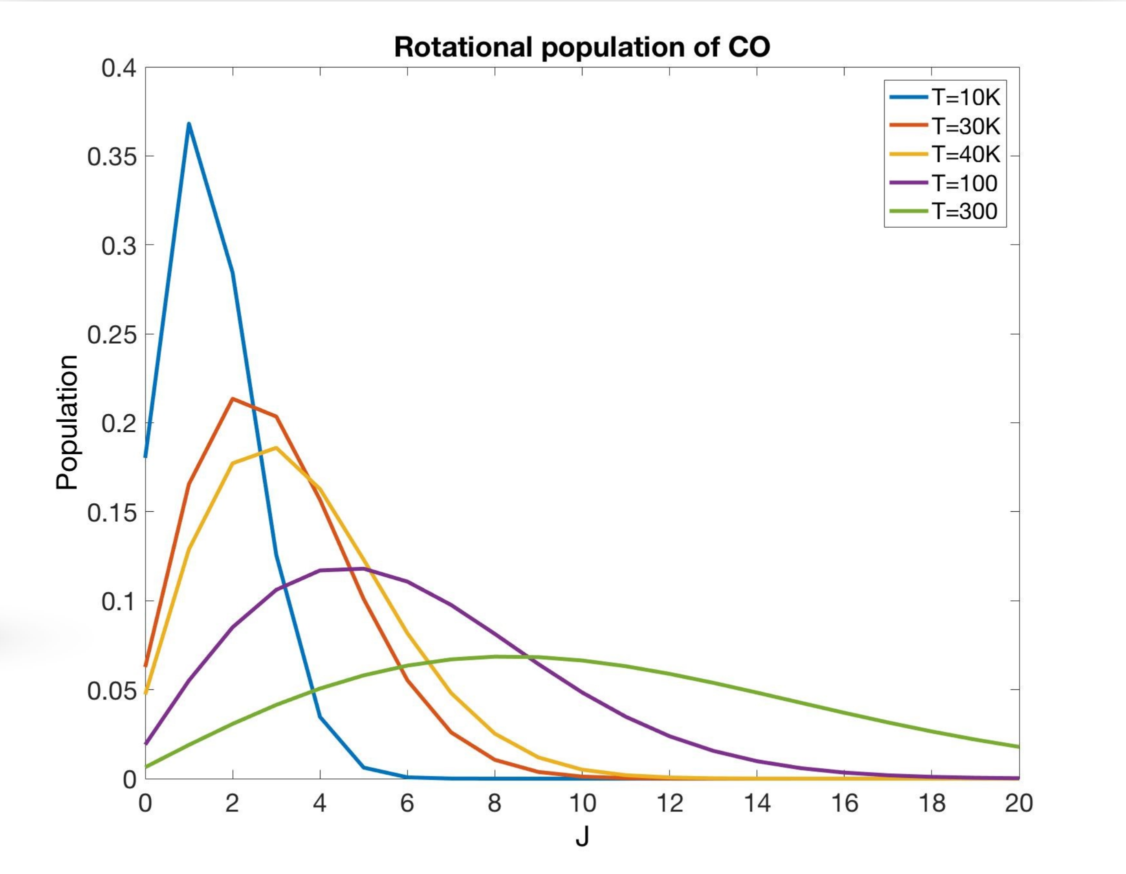


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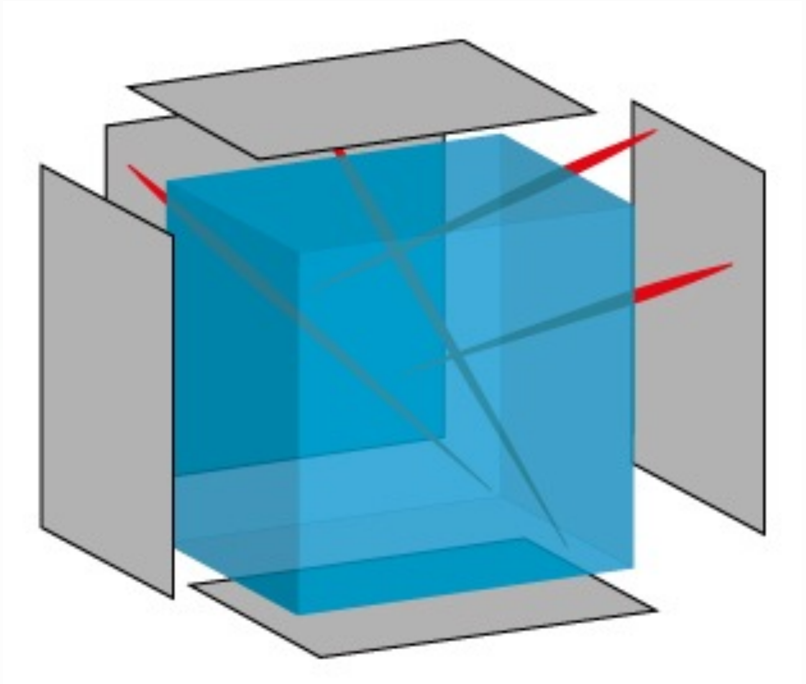
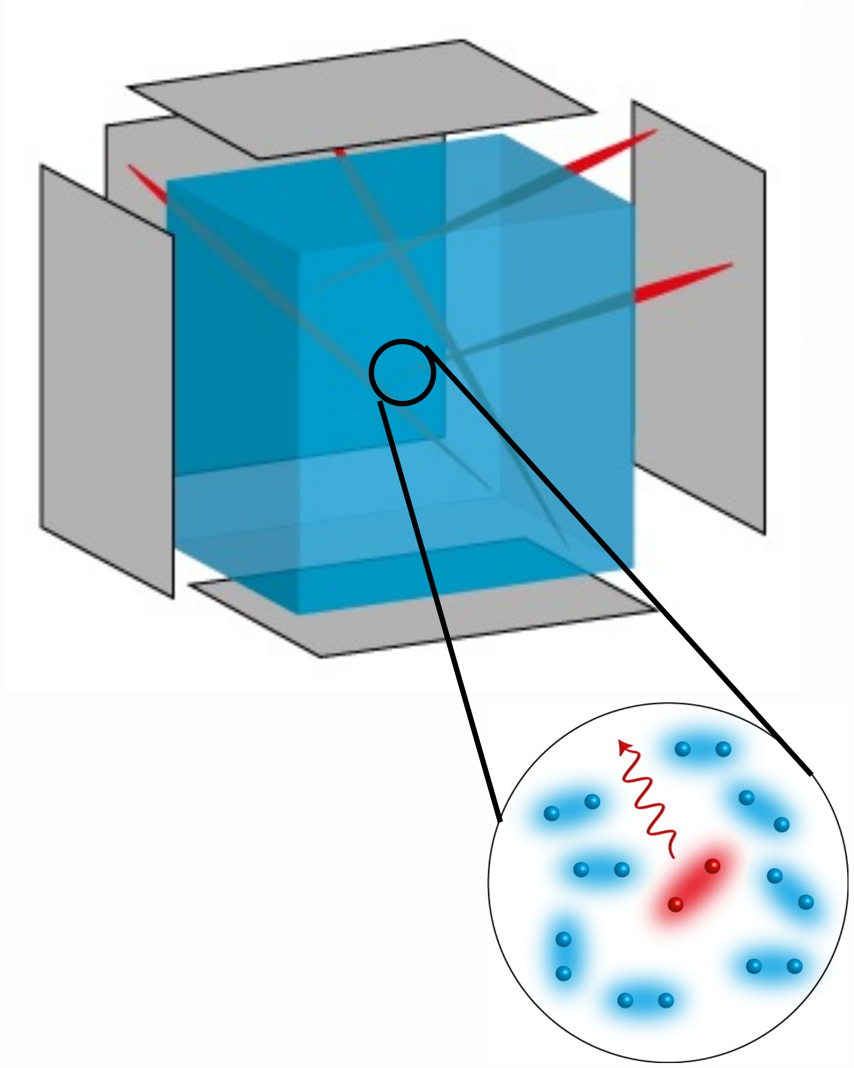


# CO in detail

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



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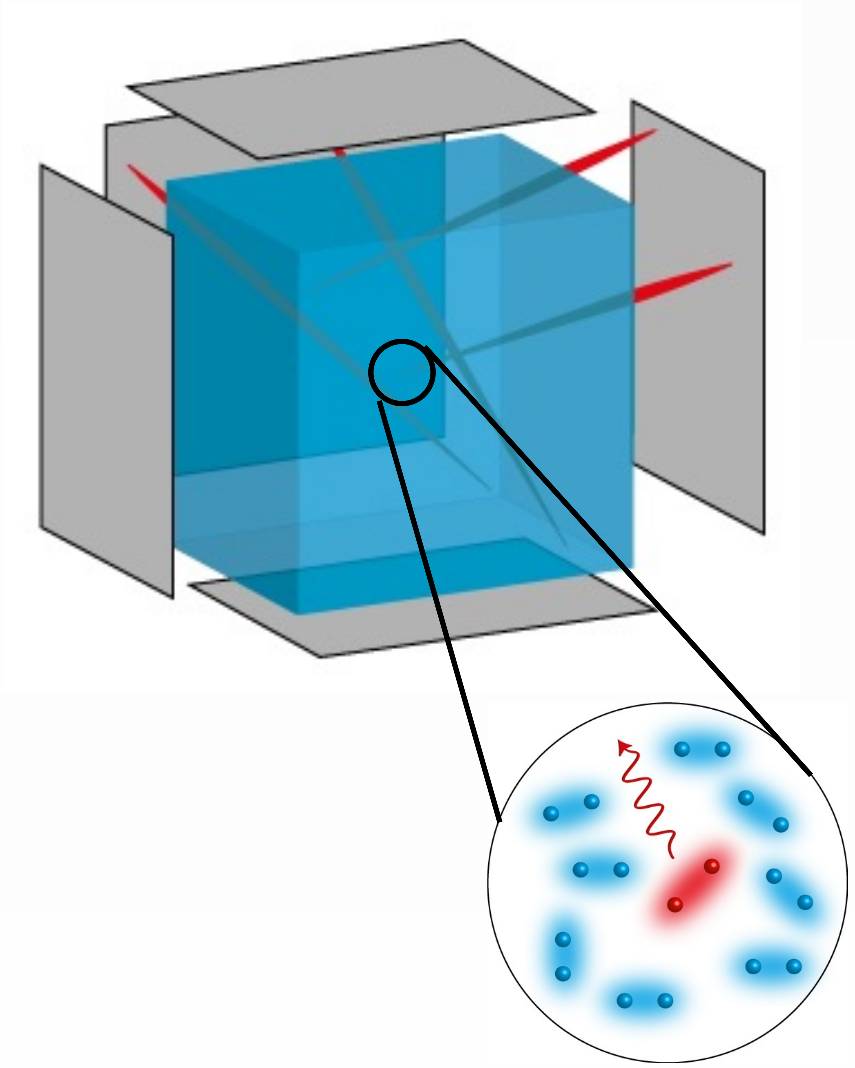

## Photon mean free path l=$\alpha^{-1}$

$$\alpha = \frac{\lambda^2 A_{10}}{8\pi^3 \sigma_{\mathrm{elastic}} \langle v \rangle}$$

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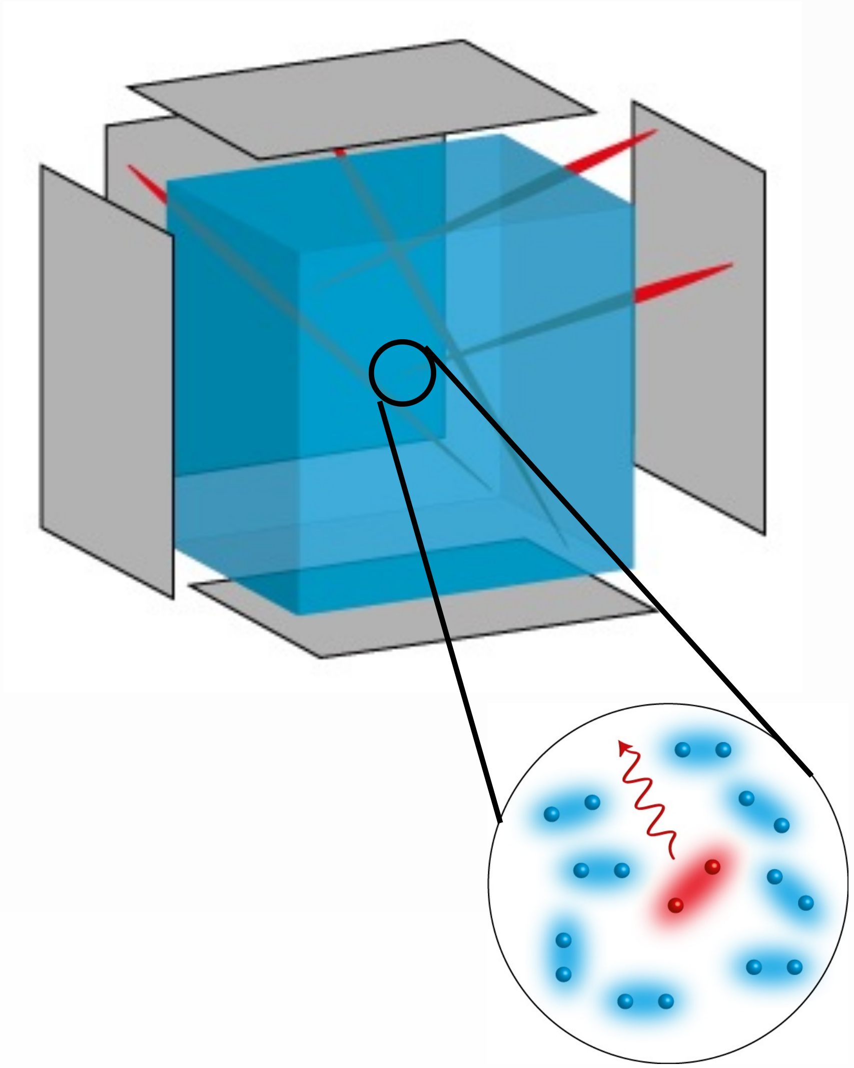

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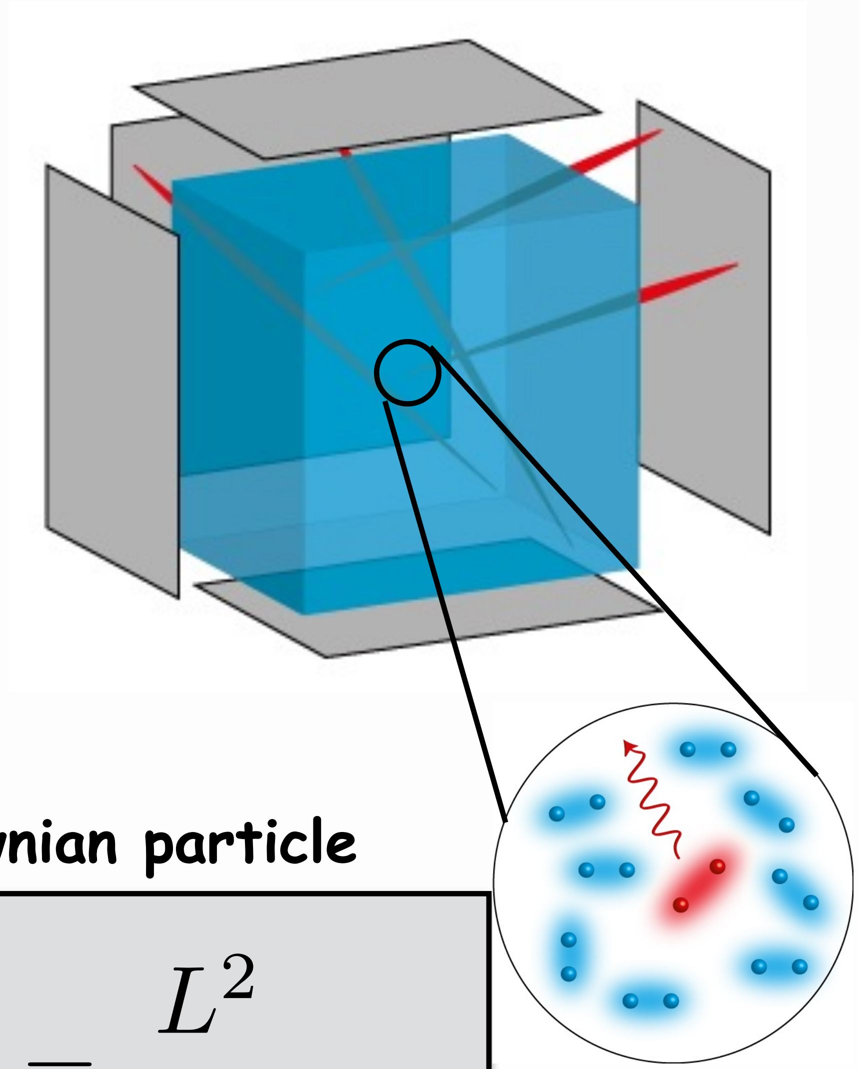

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**3D Brownian particle**

$$\langle n_{\text{abs}} \rangle = \frac{L^2}{6\lambda^2}$$

$$\gamma_{\text{vib}} << \frac{L^2}{6\lambda^2} A_{10}$$

# CO in detail

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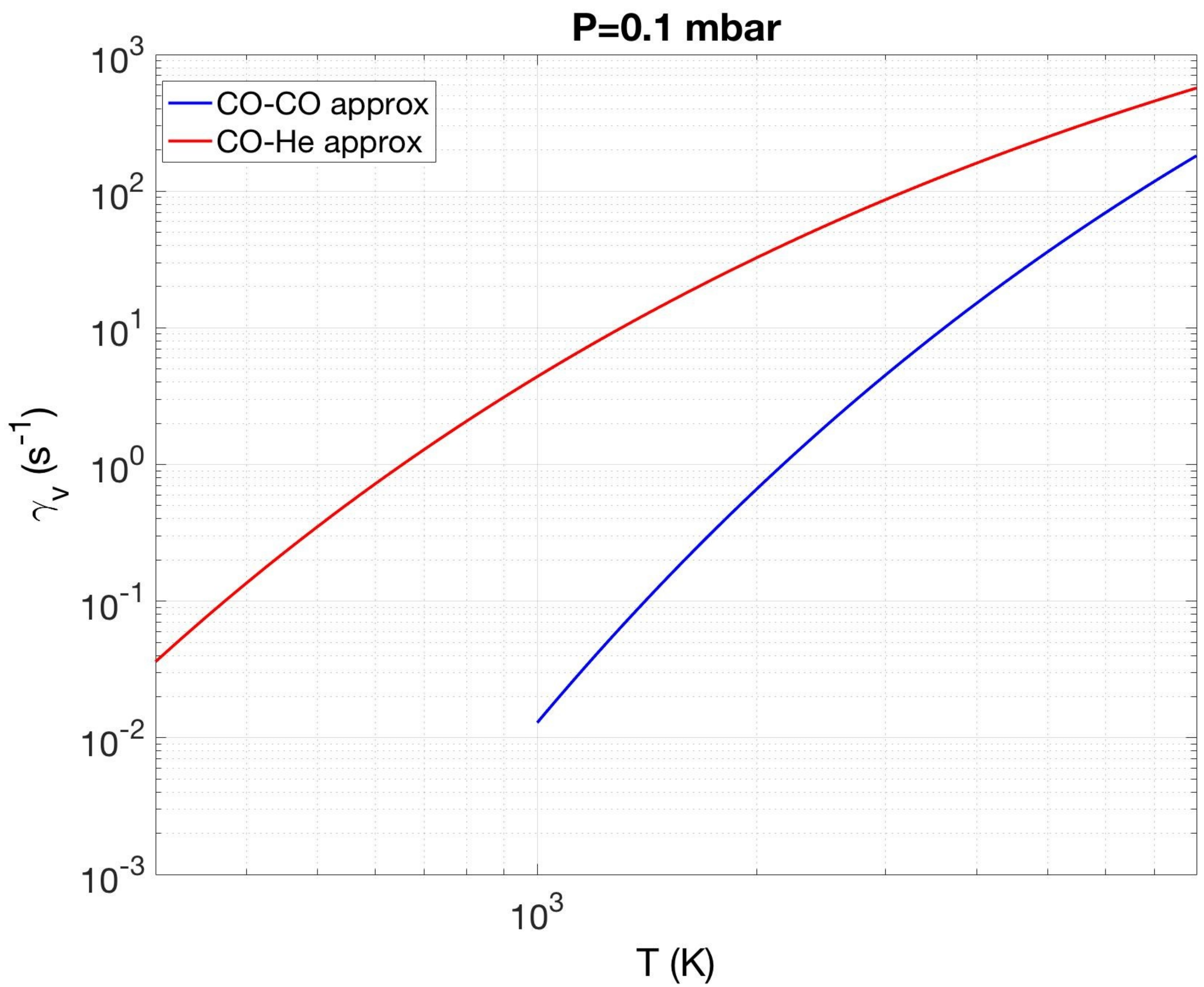

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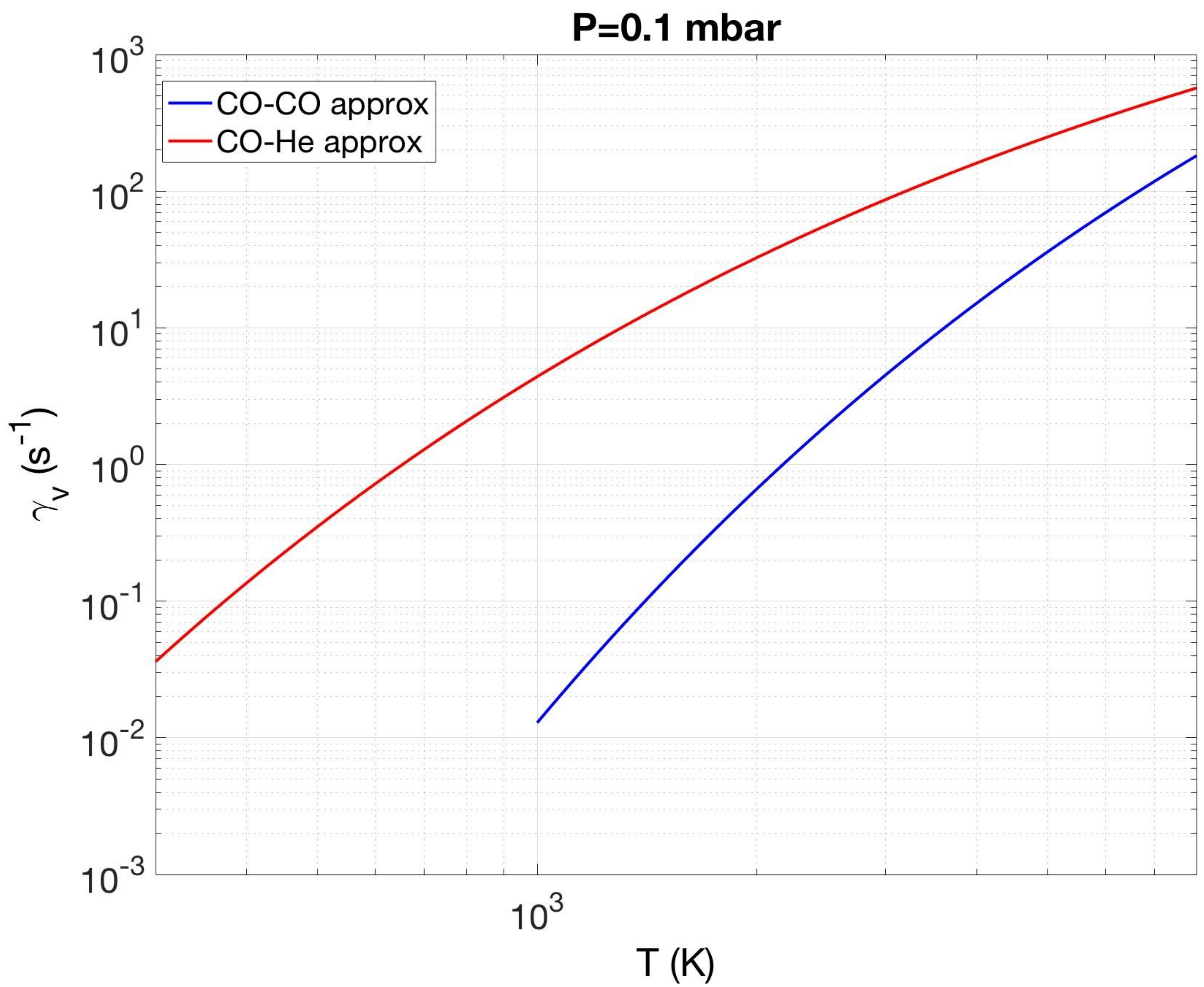

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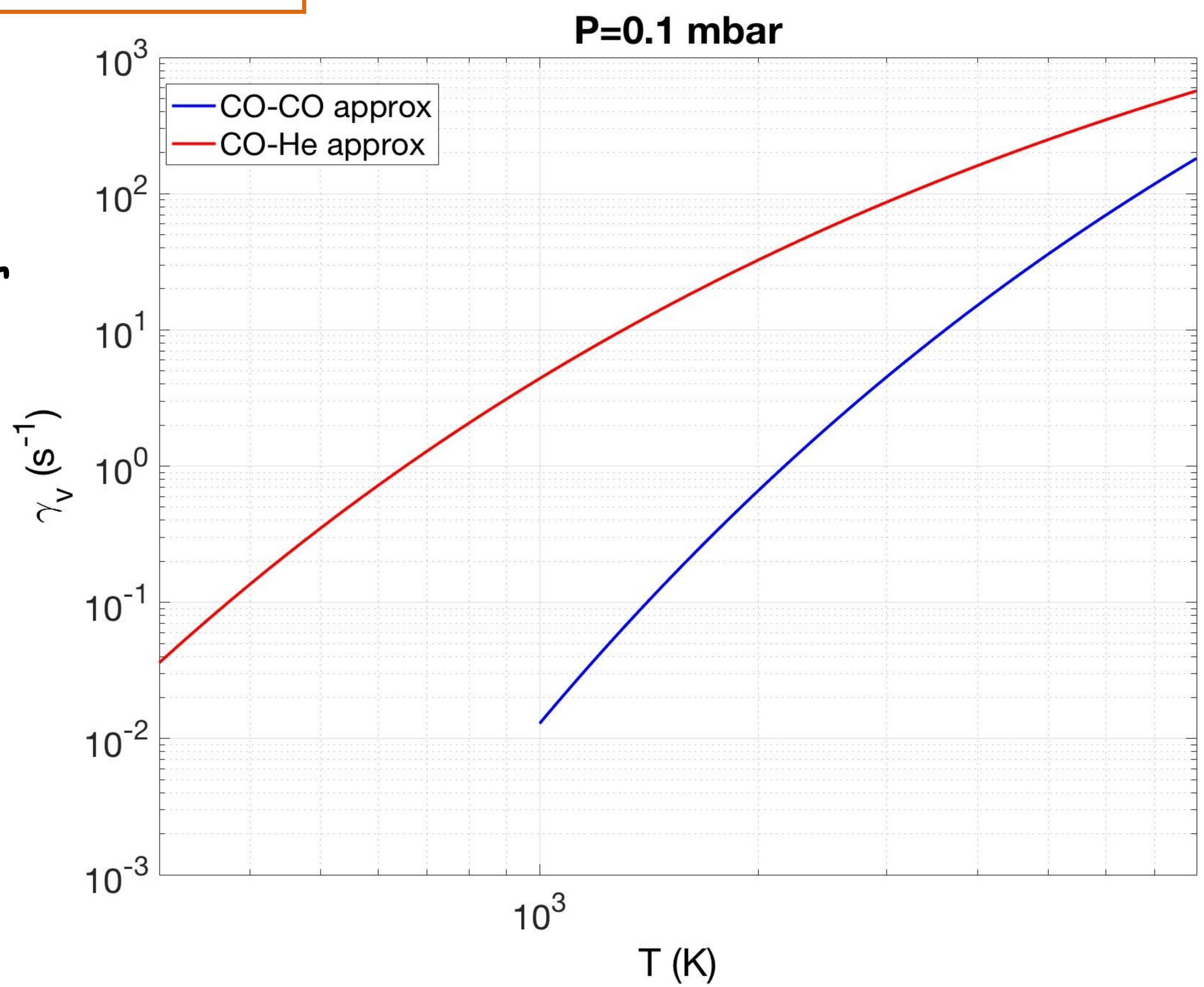

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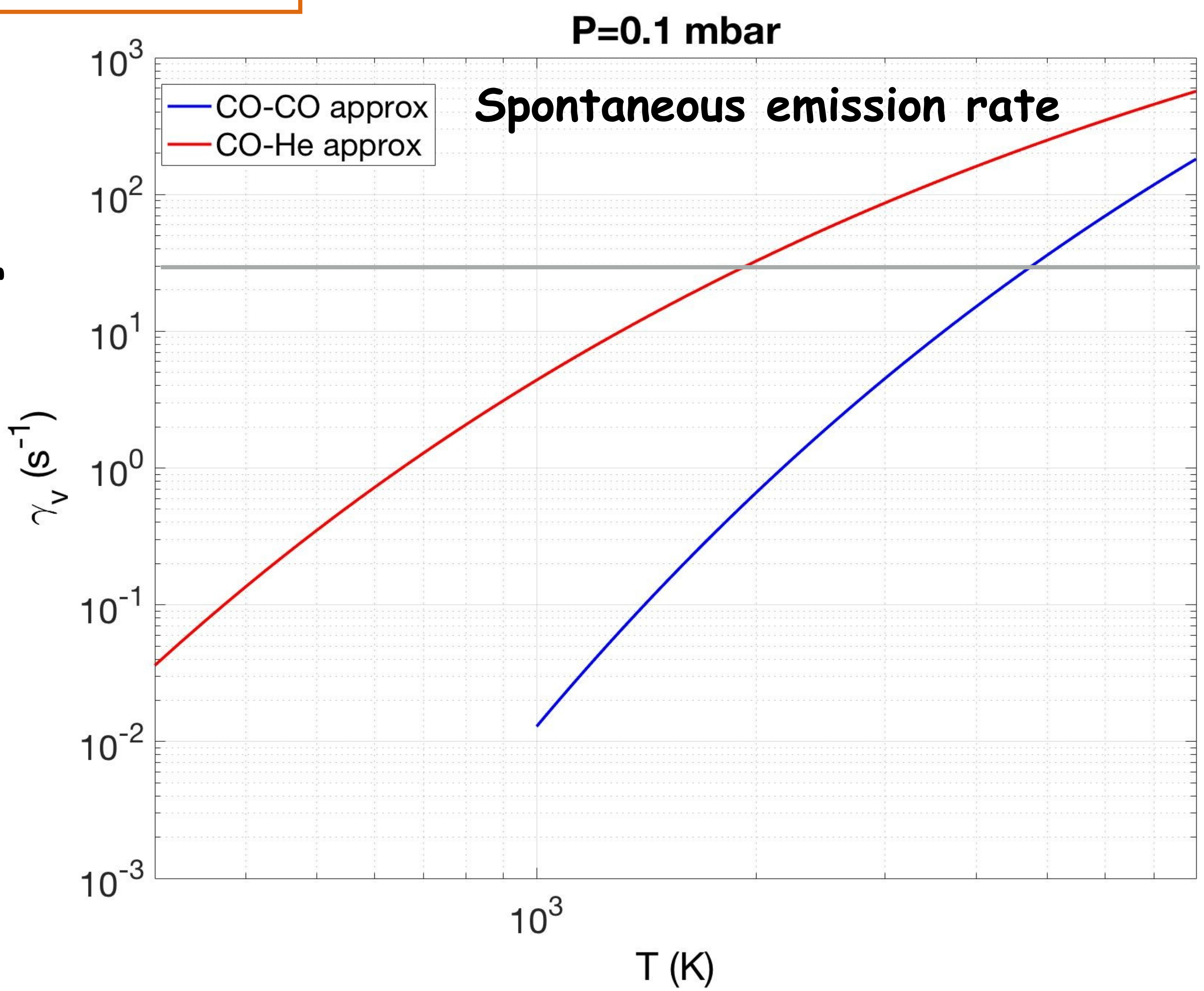

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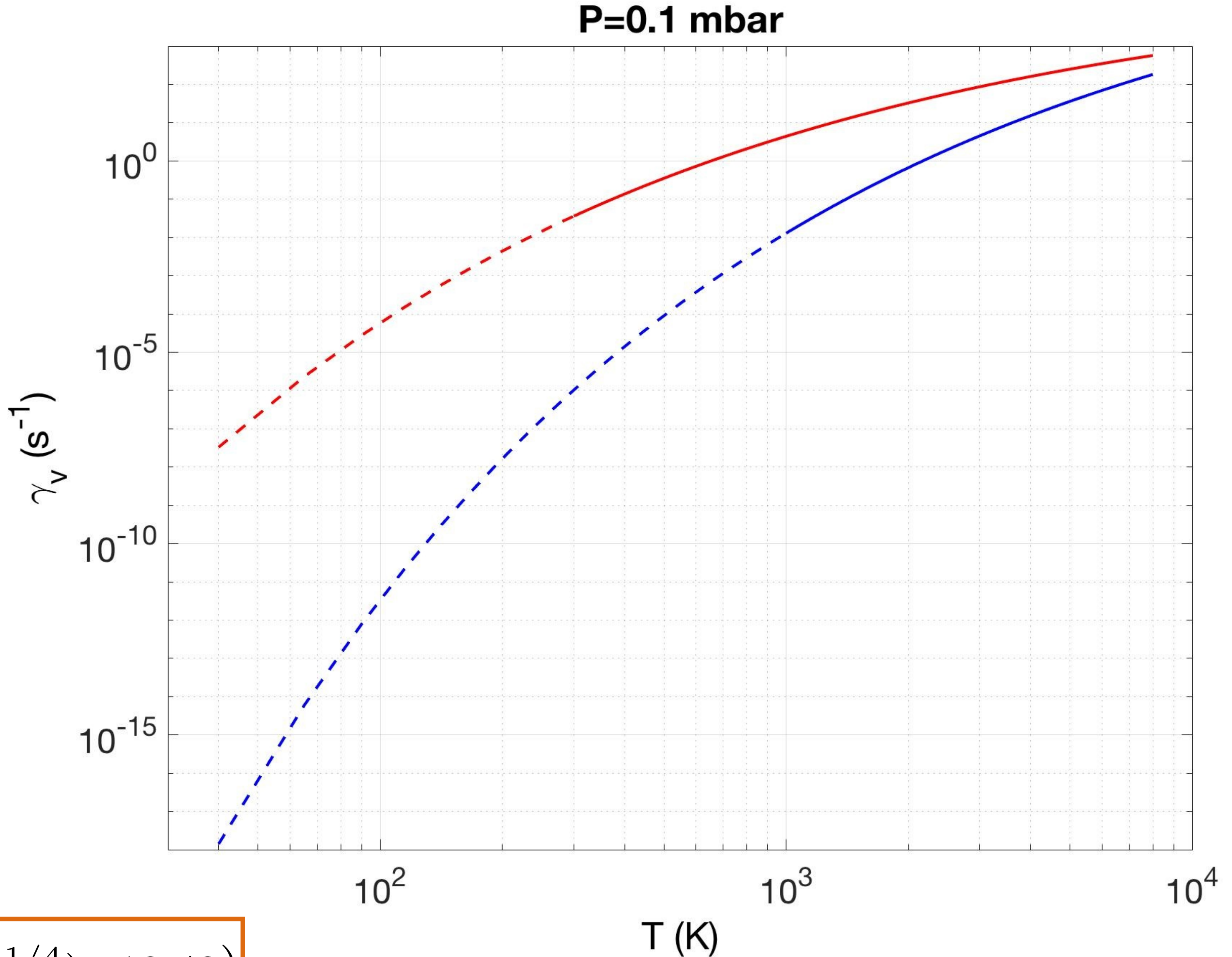


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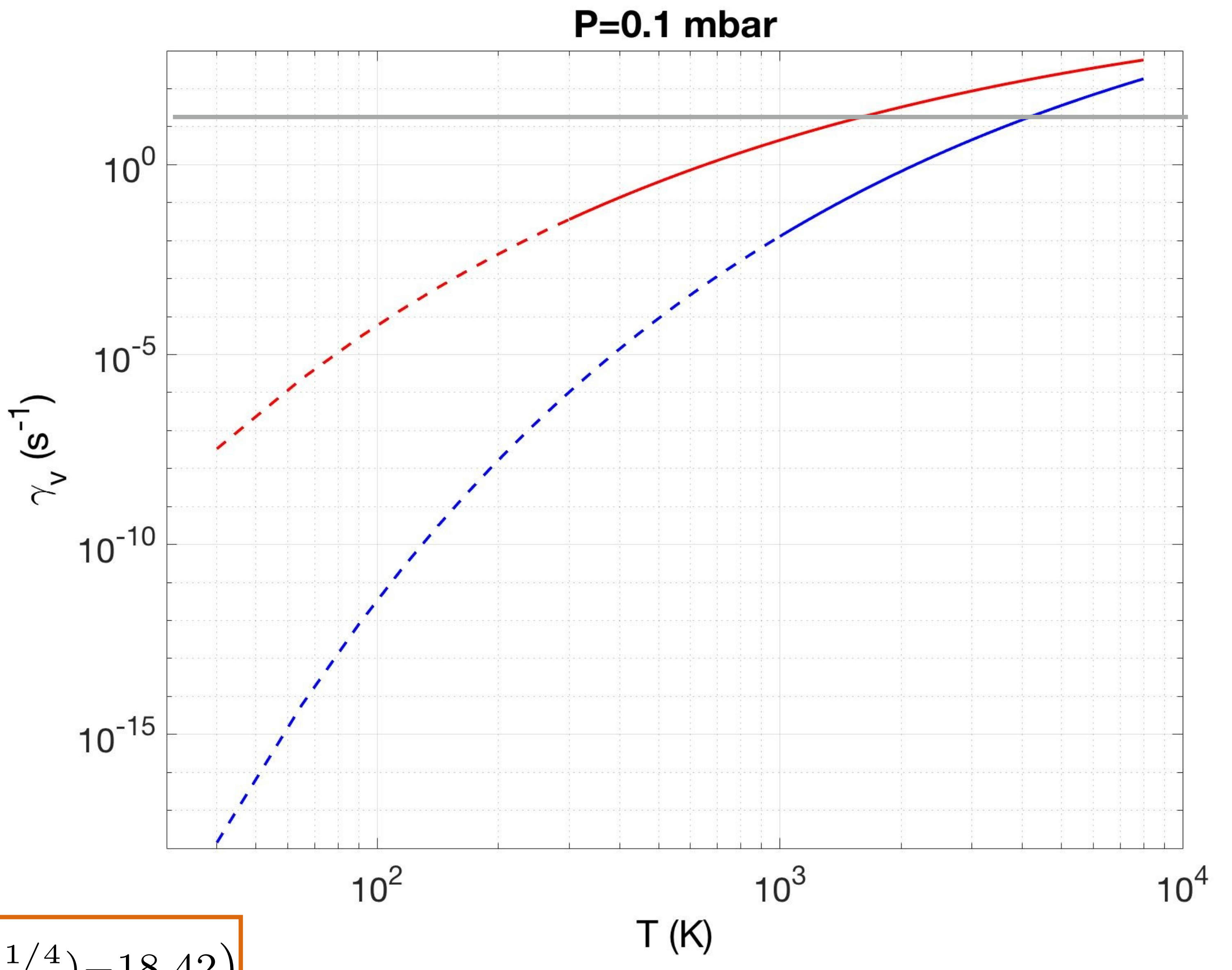


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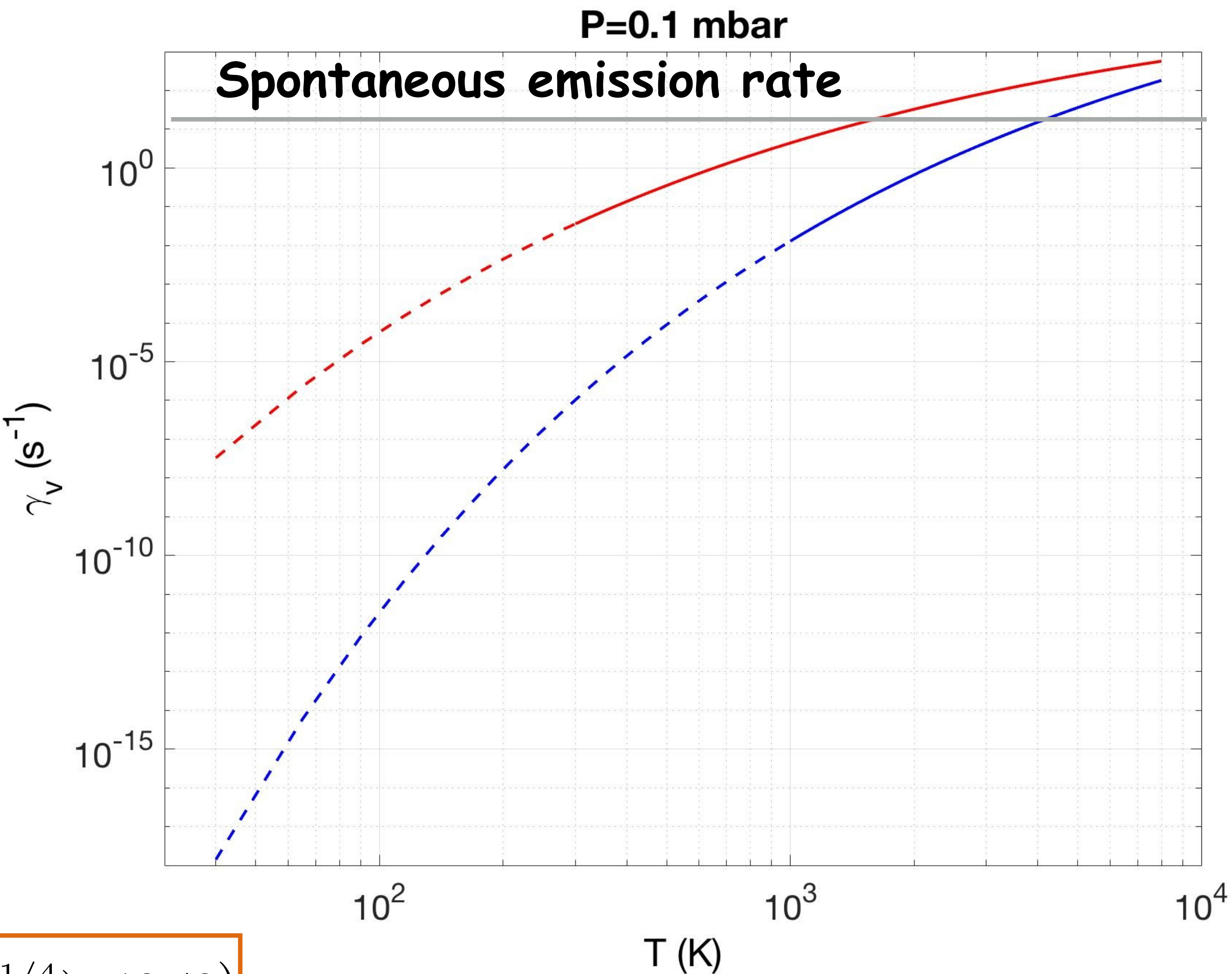


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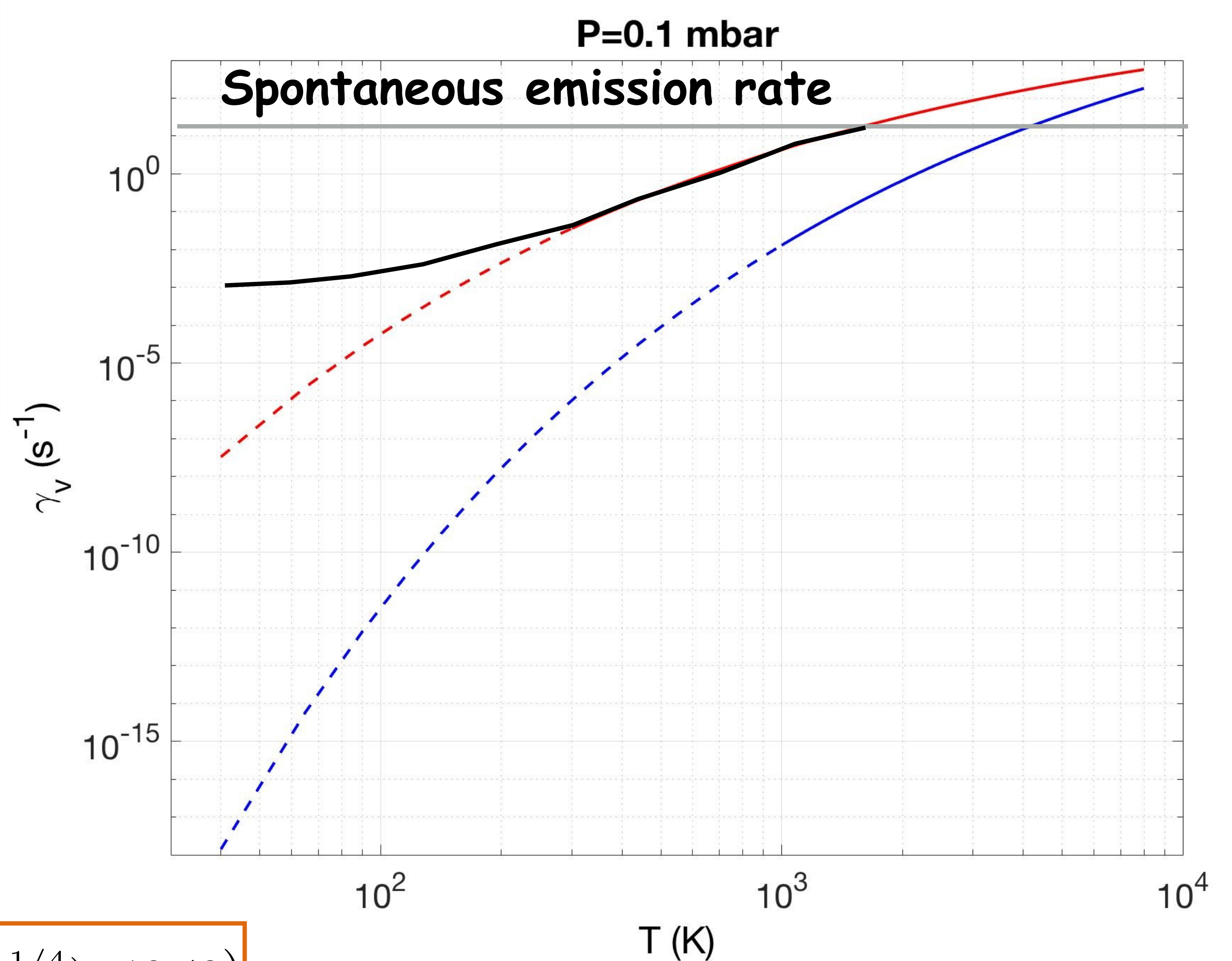
# CO in detail

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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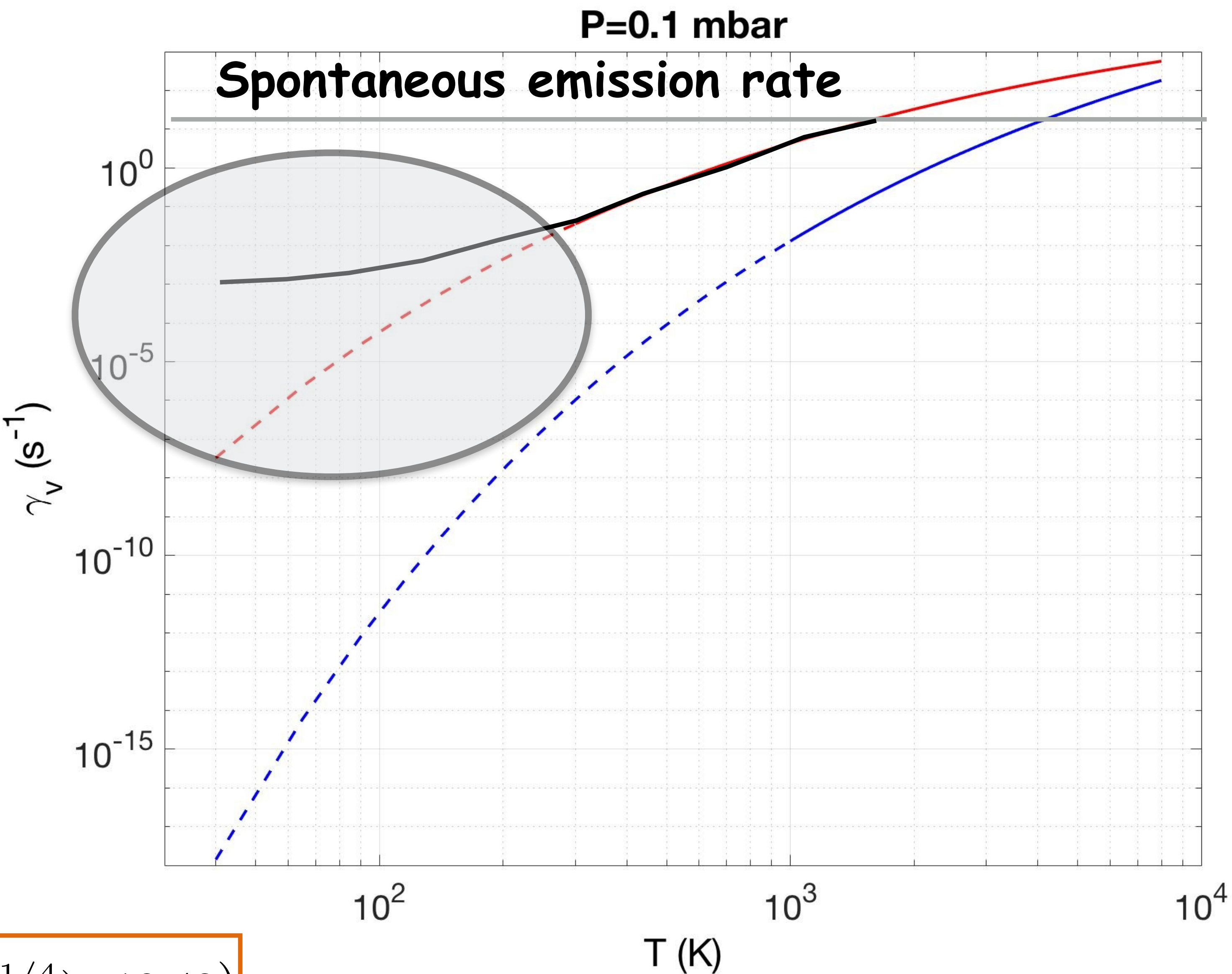


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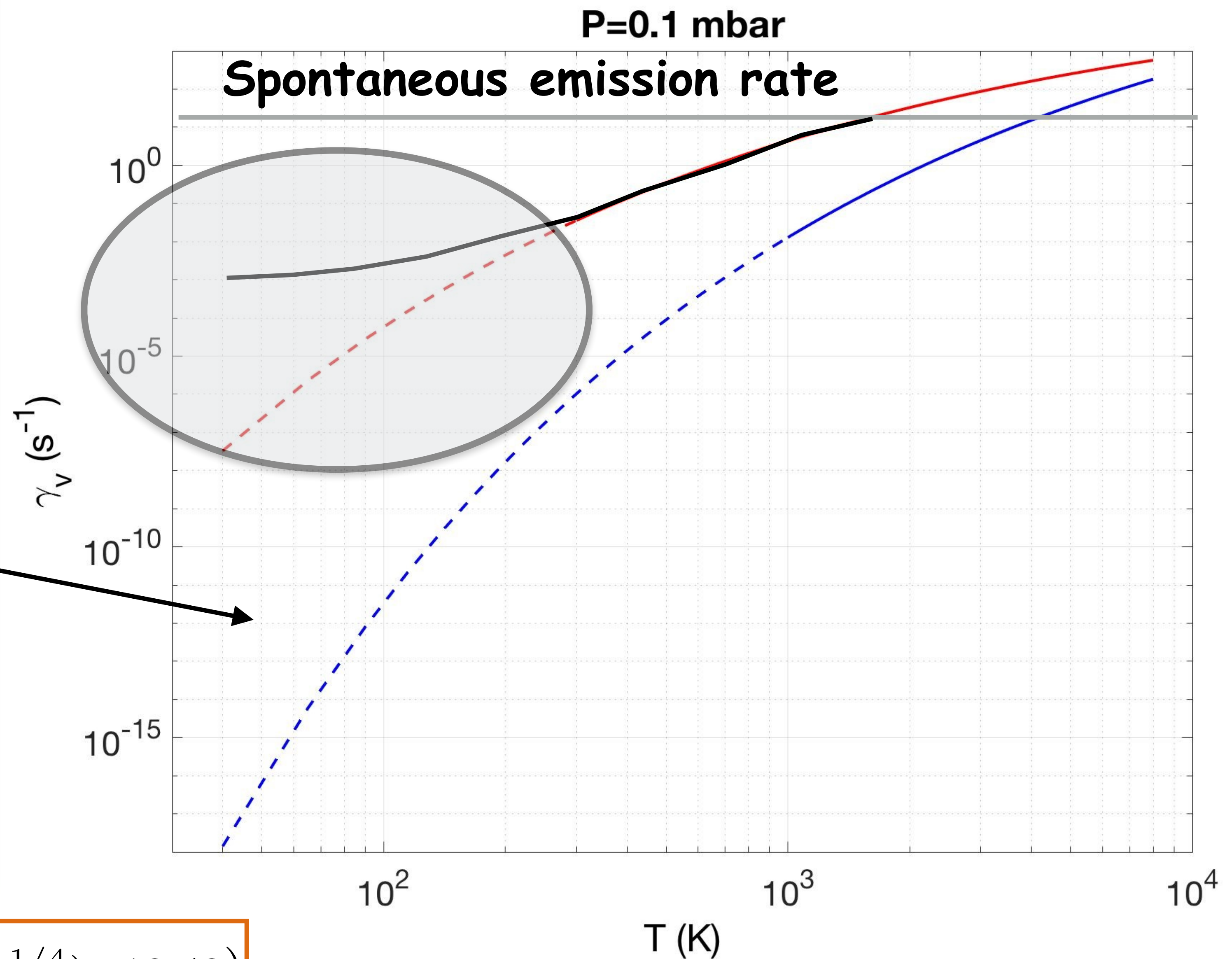
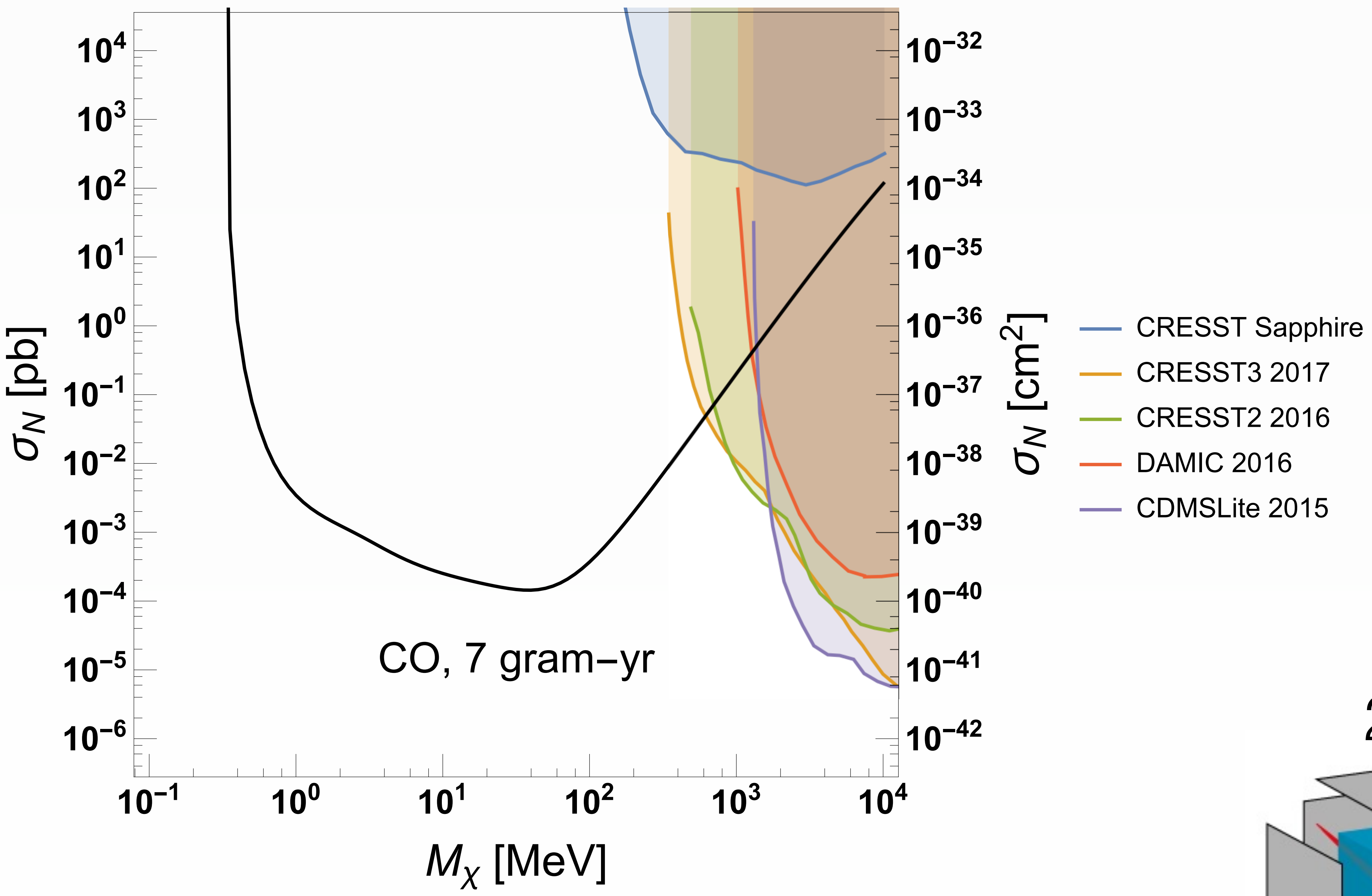
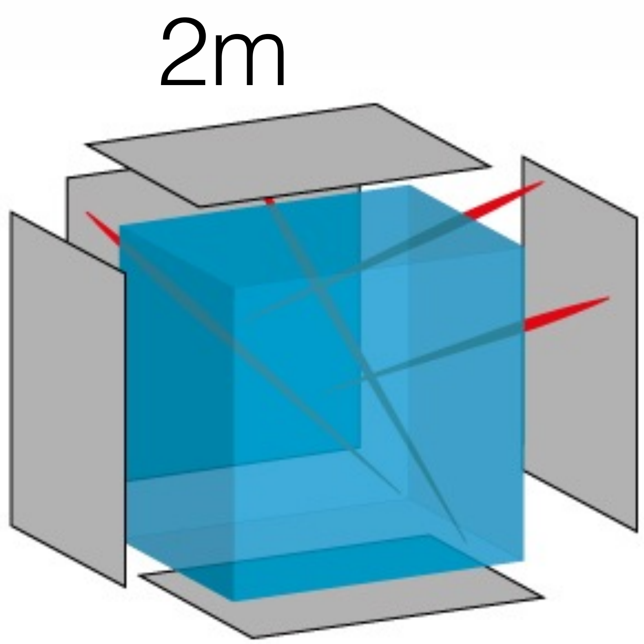



**It will work for us**

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

# CO in detail

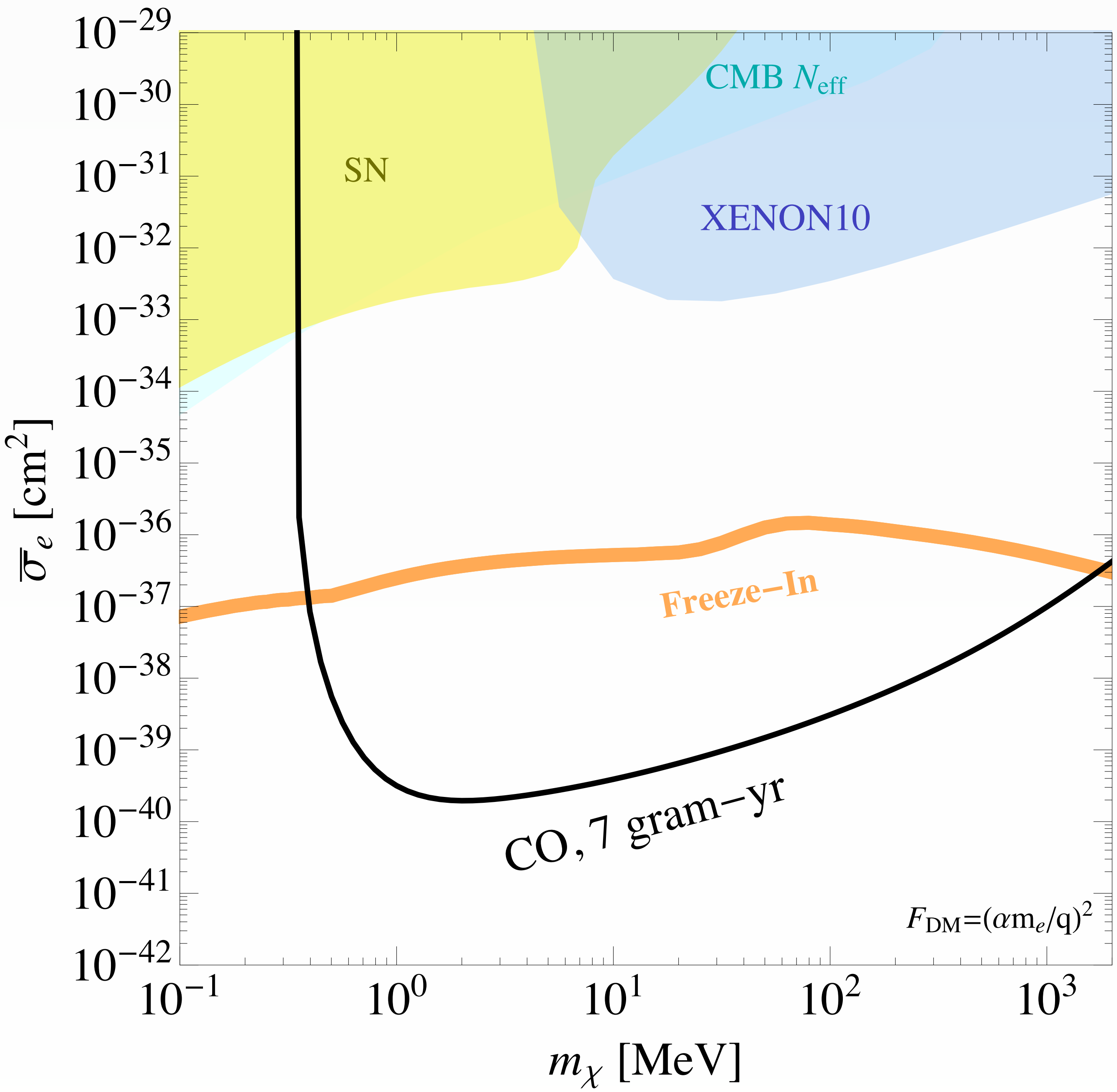


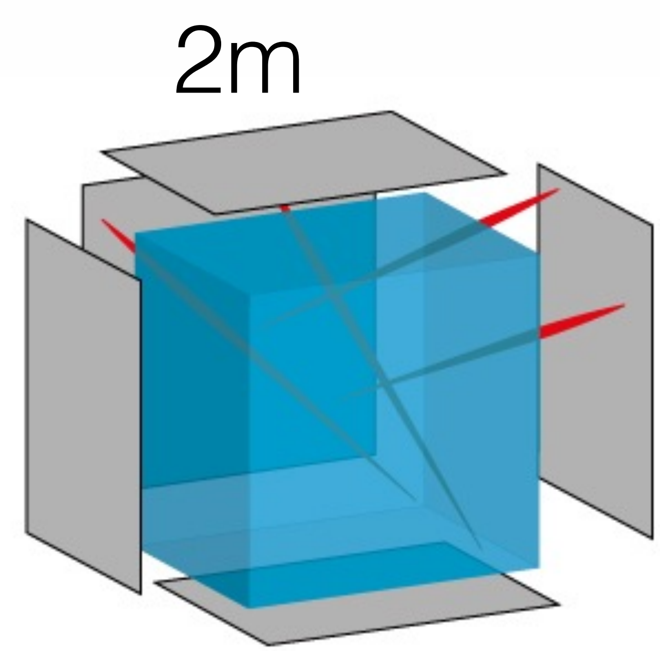




**We will be able to explore DM particles in a mass range of almost 4 orders of magnitude, from 100 keV to 1GeV.**

# CO in detail

## Assuming an ultra-light mediator

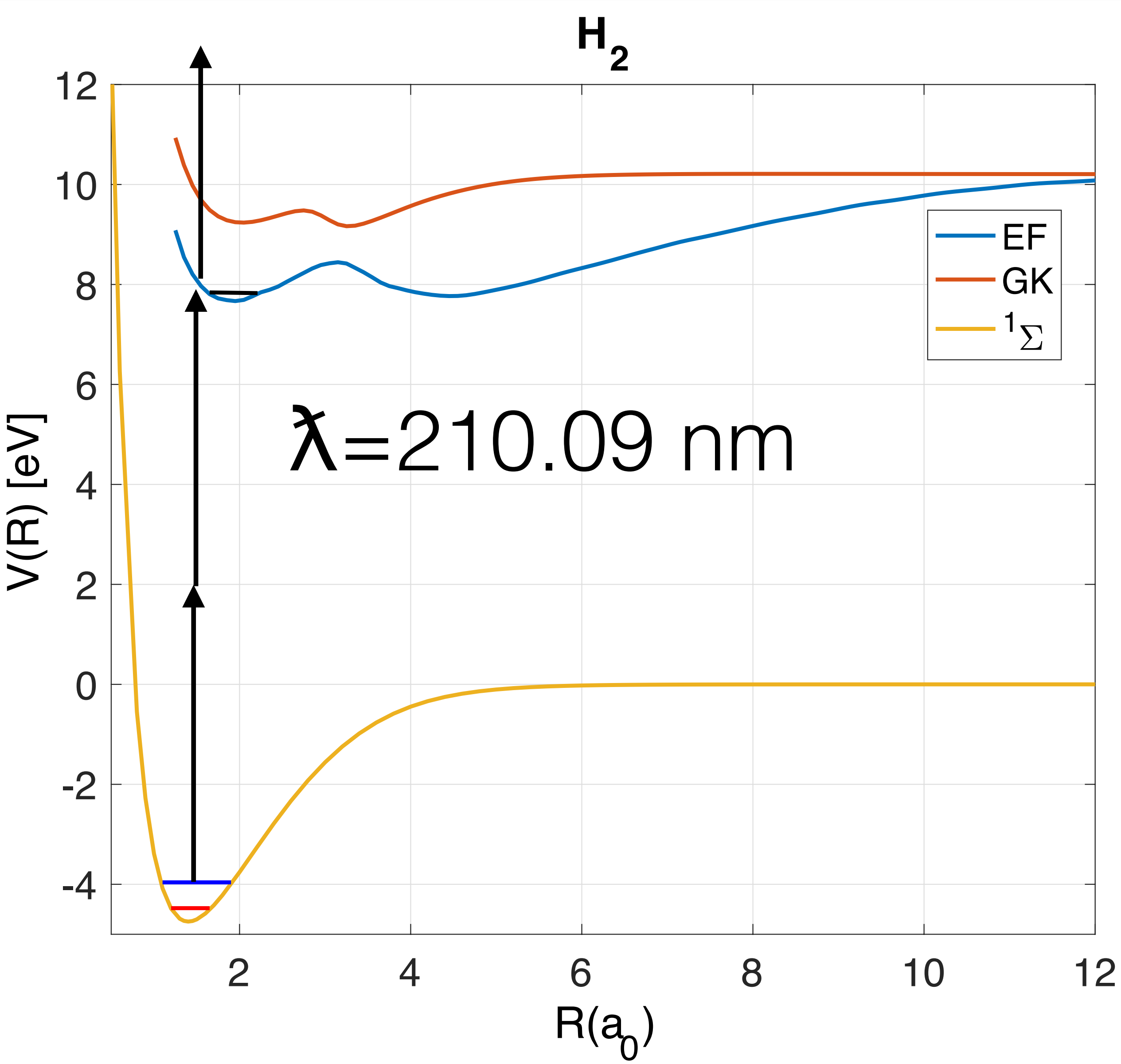


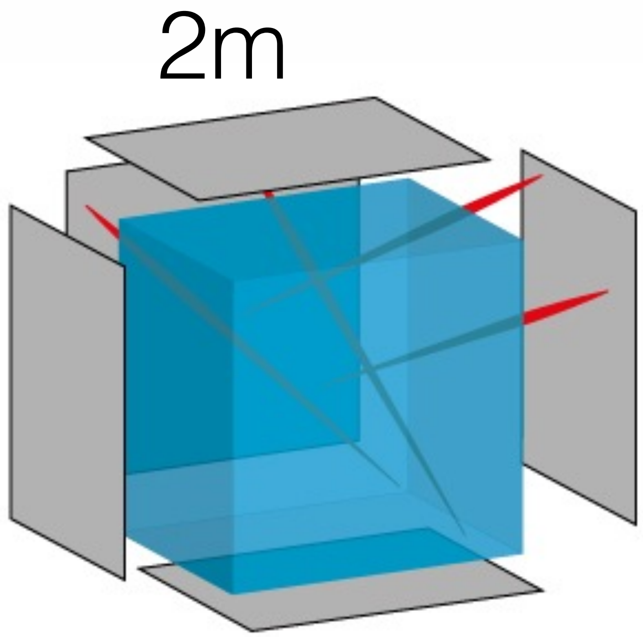



# Some future work

CO-CO accurate scattering properties

REMPI detection through a dark state



# That´s all folks

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