UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Towards light dark matter with superfluid helium: The DELight experiment

Gentner-Kolloquium, MPIK, 18.10.2023

Belina VON KROSIGK (bkrosigk@kip.uni-heidelberg.de)

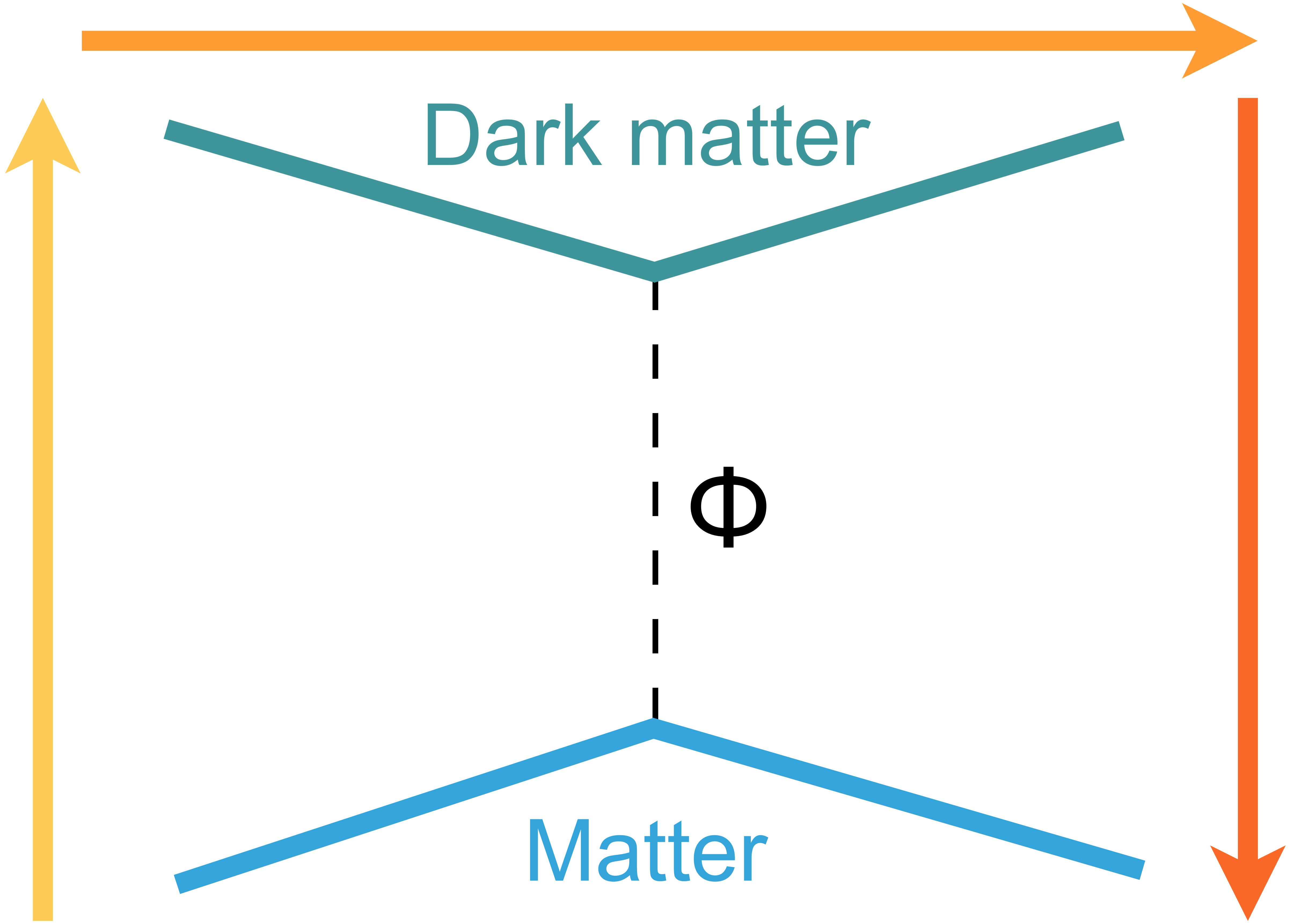
Credit: Swinburne Astronomy Productions - J. Josephides

5 / 6

Ways to detect dark matter particles

direct searches

Shake it



Make it

accelerator searches

(collider, fixed target)

Brake it

indirect searches

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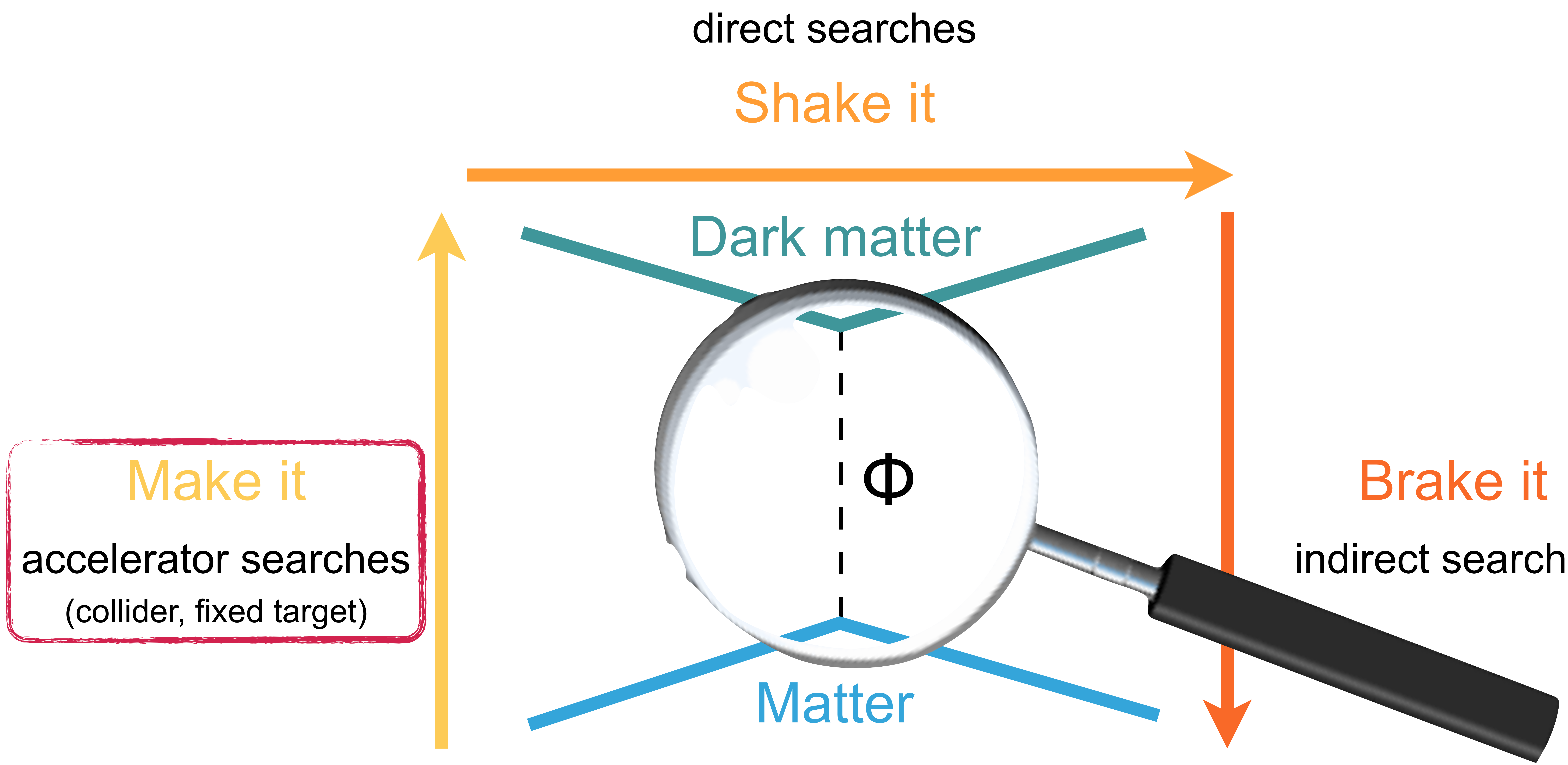
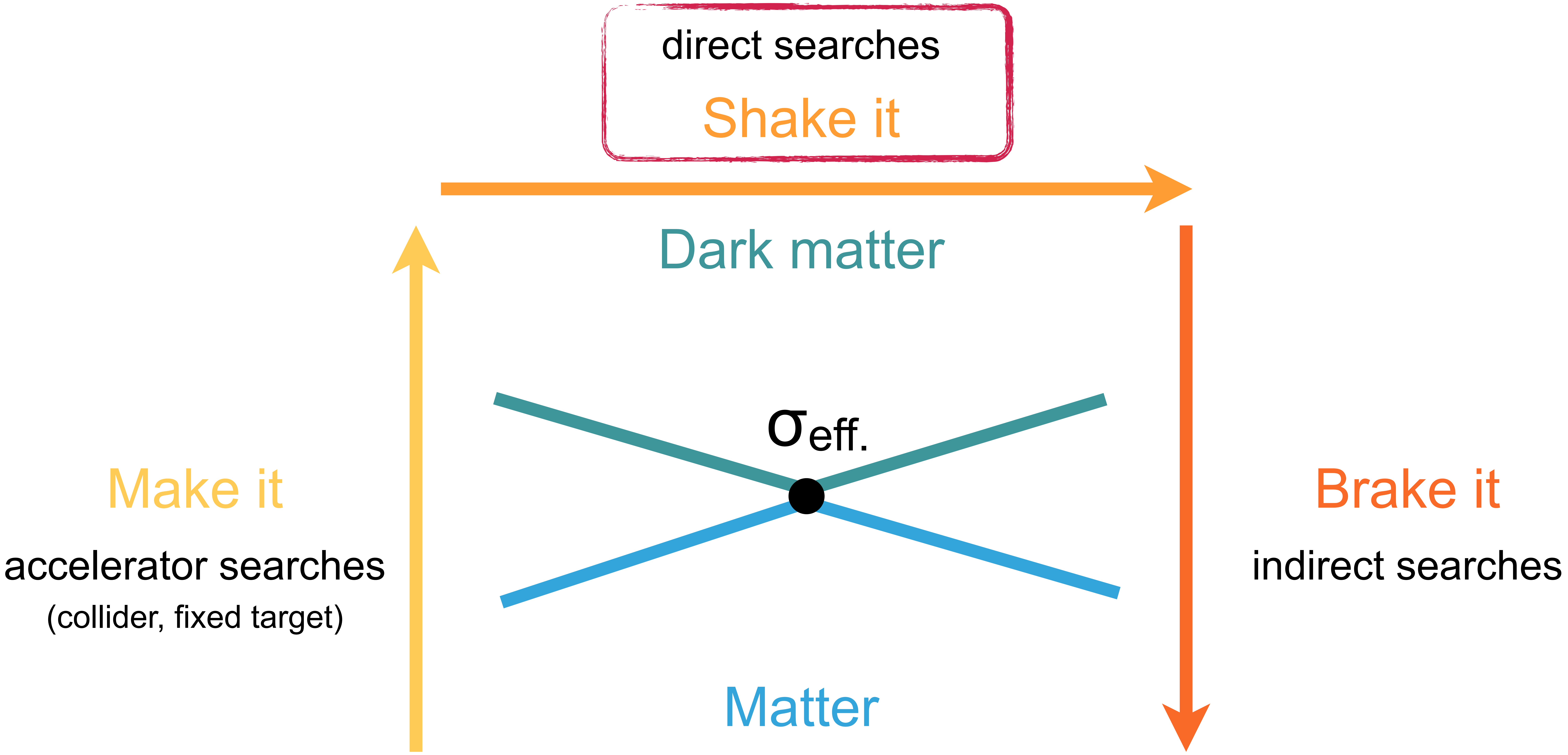
Ways to detect dark matter particles



Ways to detect dark matter particles

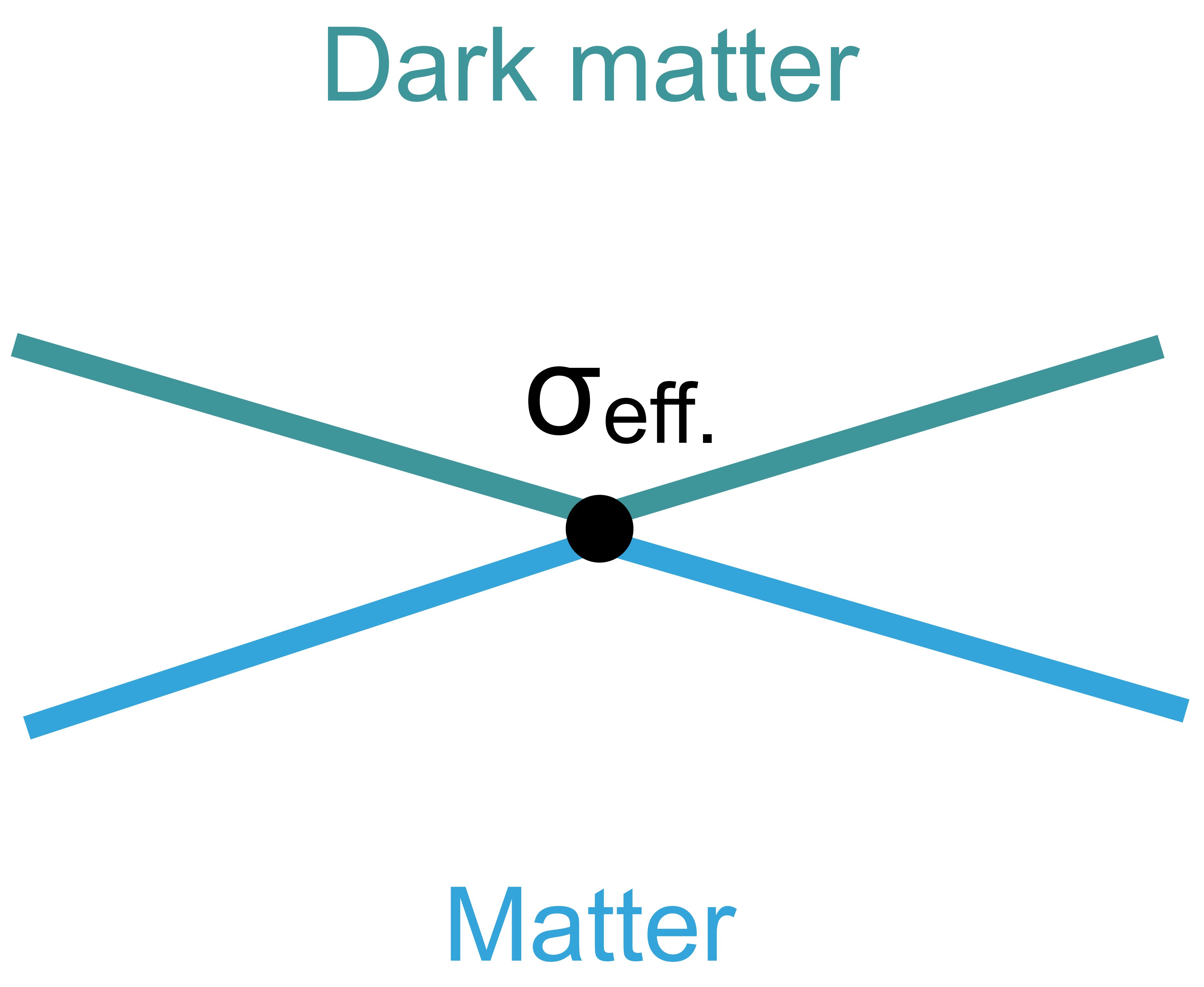


Ways to detect dark matter particles

Although direct detection experiments don’t probe the fundamental couplings directly, the effective scattering cross sections depend on them and can vary.

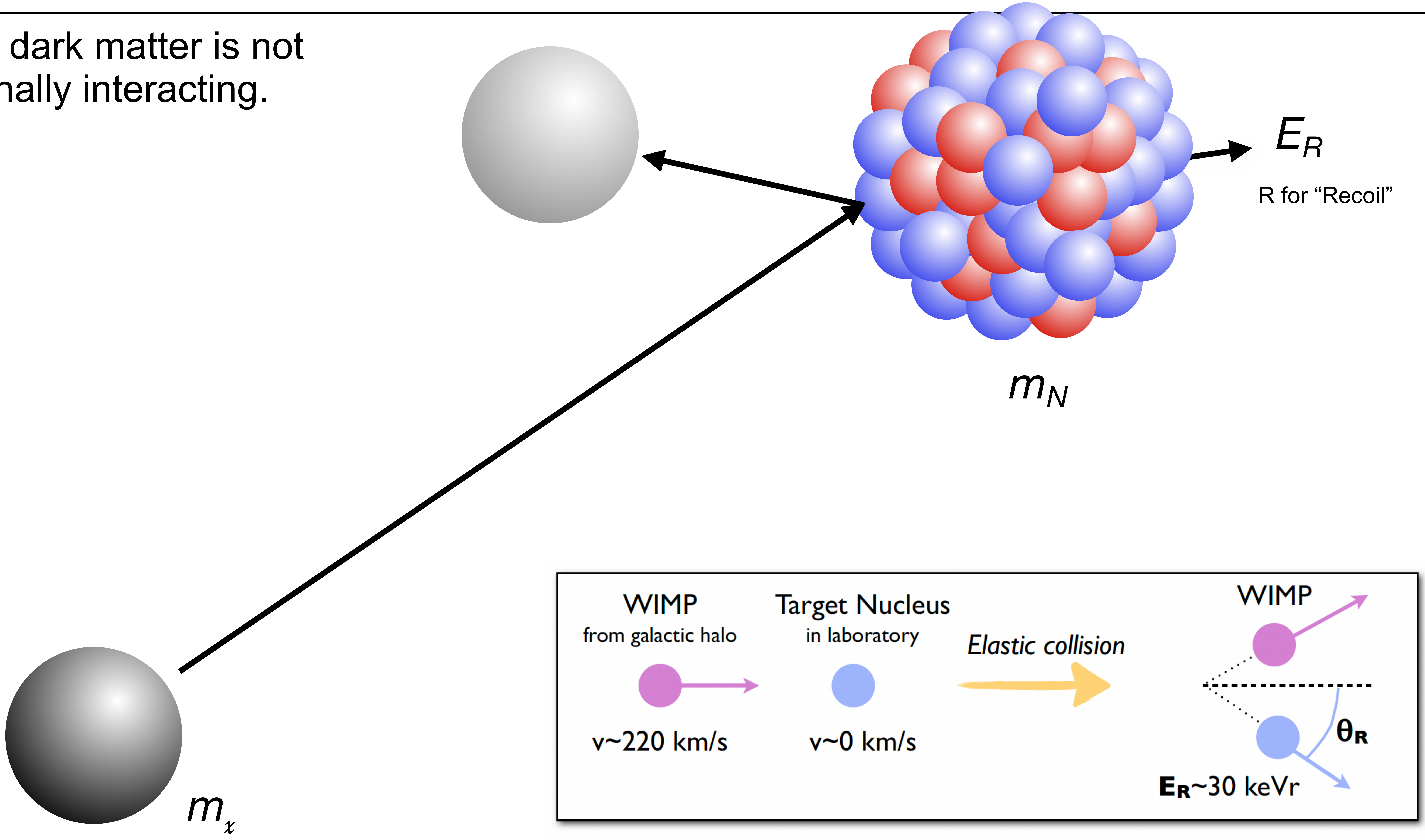
direct searches

Shake it



Basic idea of direct detection

Assume that the dark matter is not only gravitationally interacting.



Dark matter - nucleon scattering

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{\mathrm{min.}}}^{\infty} v f\left(\vec{v}\right) \frac{d\sigma}{dE_R} d\vec{v}$$

Dark matter - nucleon scattering

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The DM-nucleon cross section can be separated:

$$\frac{d\sigma}{dE_R} = \left[\left(\frac{d\sigma}{dE_R}\right)_{\text{SI}} + \left(\frac{d\sigma}{dE_R}\right)_{\text{SD}}\right]$$

arises from scalar or vector couplings to quarks

Spin Independent

Spin Dependent

arises from axial-vector coupling to quarks

$$= \frac{m_N}{2\mu^2 v^2} \left[\sigma_0^{\text{SI}} F_{\text{SI}}^2(E_R) + \sigma_0^{\text{SD}} F_{\text{SD}}^2(E_R)\right]$$

F: nuclear form-factor

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Dark matter - nucleon scattering

particle theory

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\boxed{\sigma_0^{\mathrm{SI}}} F_{\mathrm{SI}}^2(E_R) + \boxed{\sigma_0^{\mathrm{SD}}} F_{\mathrm{SD}}^2(E_R)\right]$$

nuclear form factors:
quantum mechanics of interaction with nucleus

Dark matter - nucleon scattering

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nuclear form factors:
quantum mechanics of interaction with nucleus

Spin-Independent

$$\sigma_0^{\mathrm{SI}} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$

scalar couplings to protons and neutrons

Spin-Dependent

Fermi constant

expectation value of proton/neutron spin within nucleus

$$\sigma_0^{\mathrm{SD}} = \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

nuclear angular momentum

effective couplings to protons and neutrons

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In most models $f_p \sim f_n$.

⇒ scattering adds coherently with A^2 enhancement.

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nuclear angular momentum

effective couplings to protons and neutrons

Nuclei with non-zero angular momentum required.

No coherent effect!

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Dark matter - nucleon scattering

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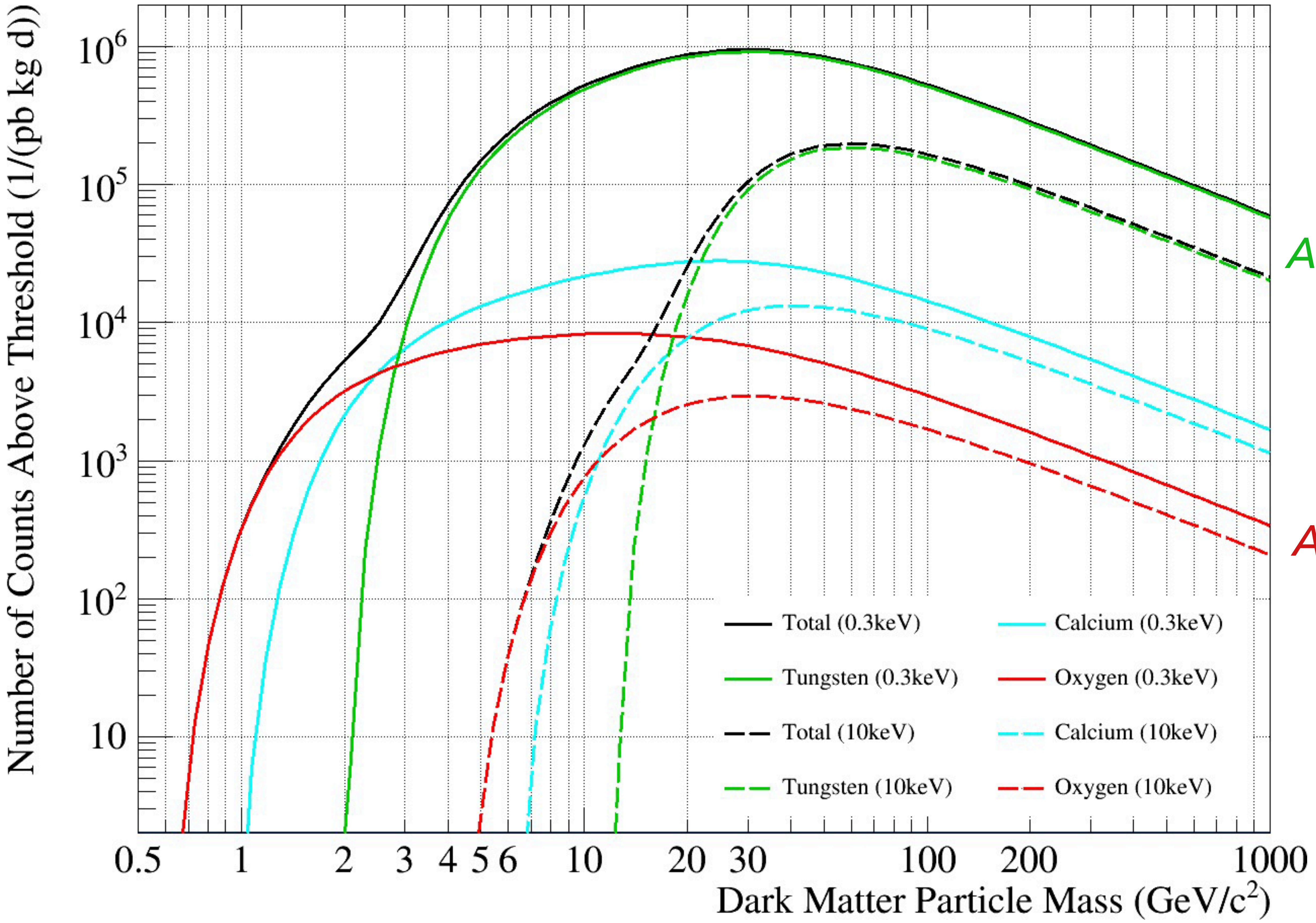
Dark matter - nucleon scattering



A(Tungsten) = 184

A^2 boost

A(Oxygen) = 16

Dark matter - nucleon scattering

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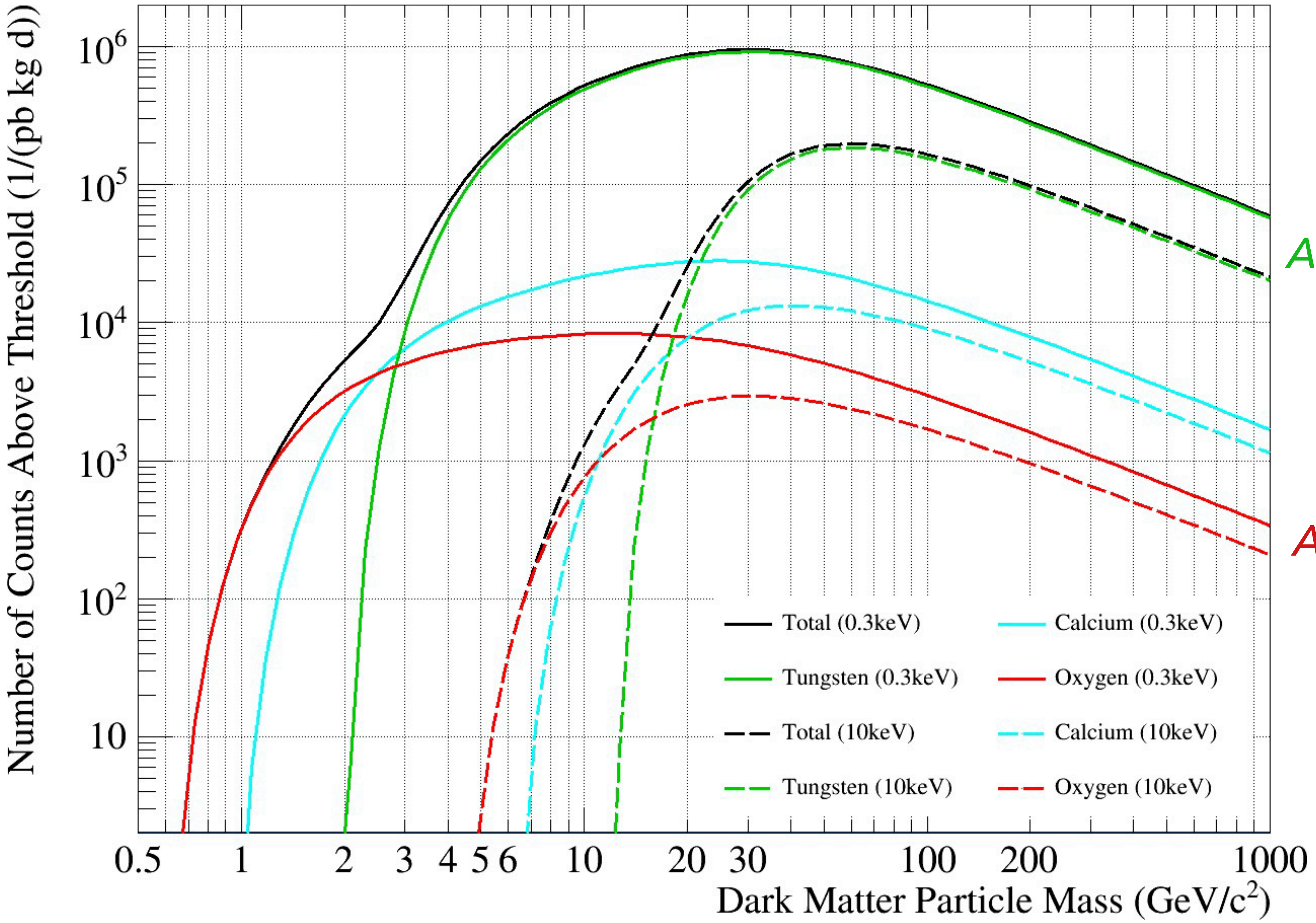

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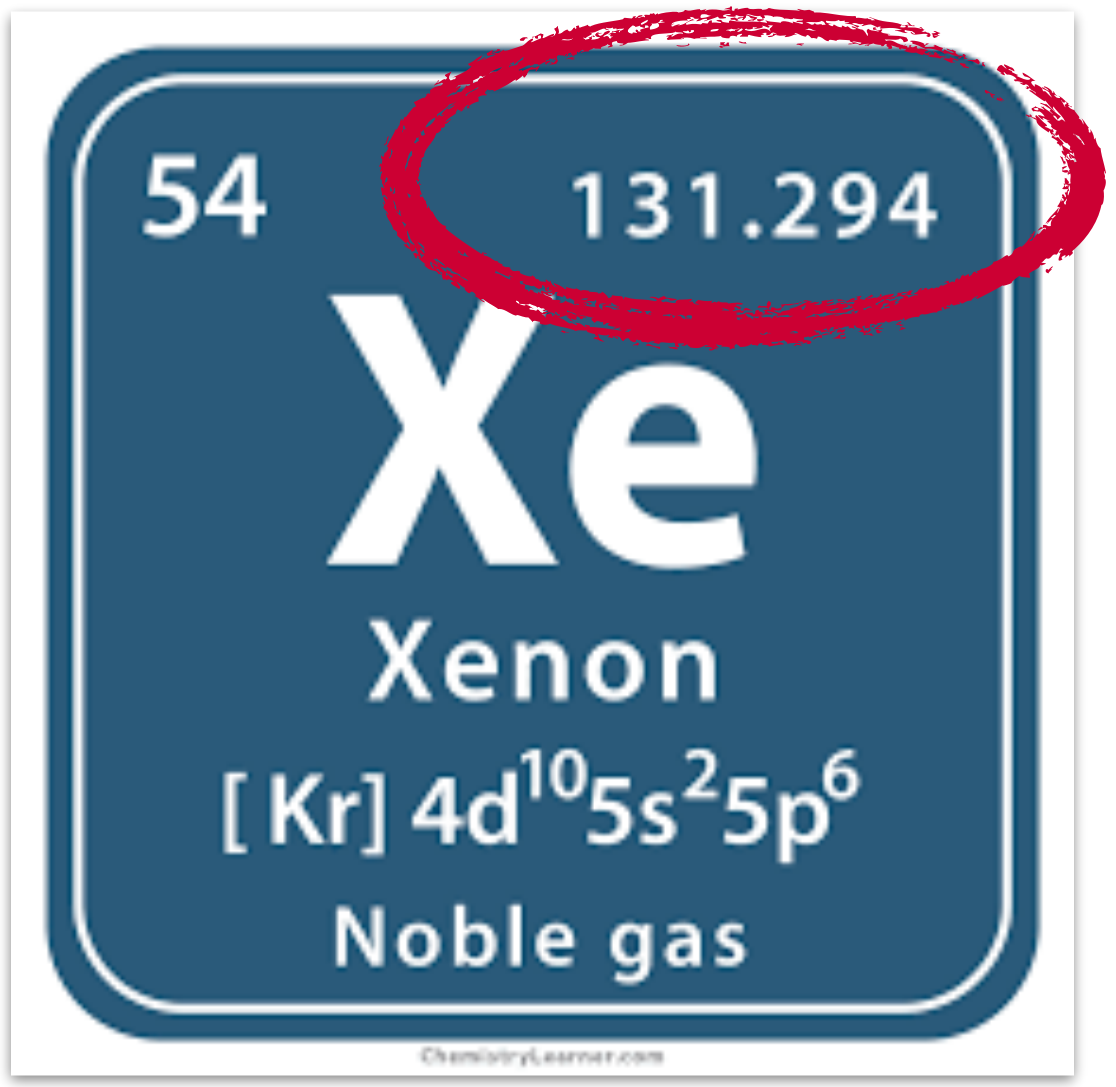
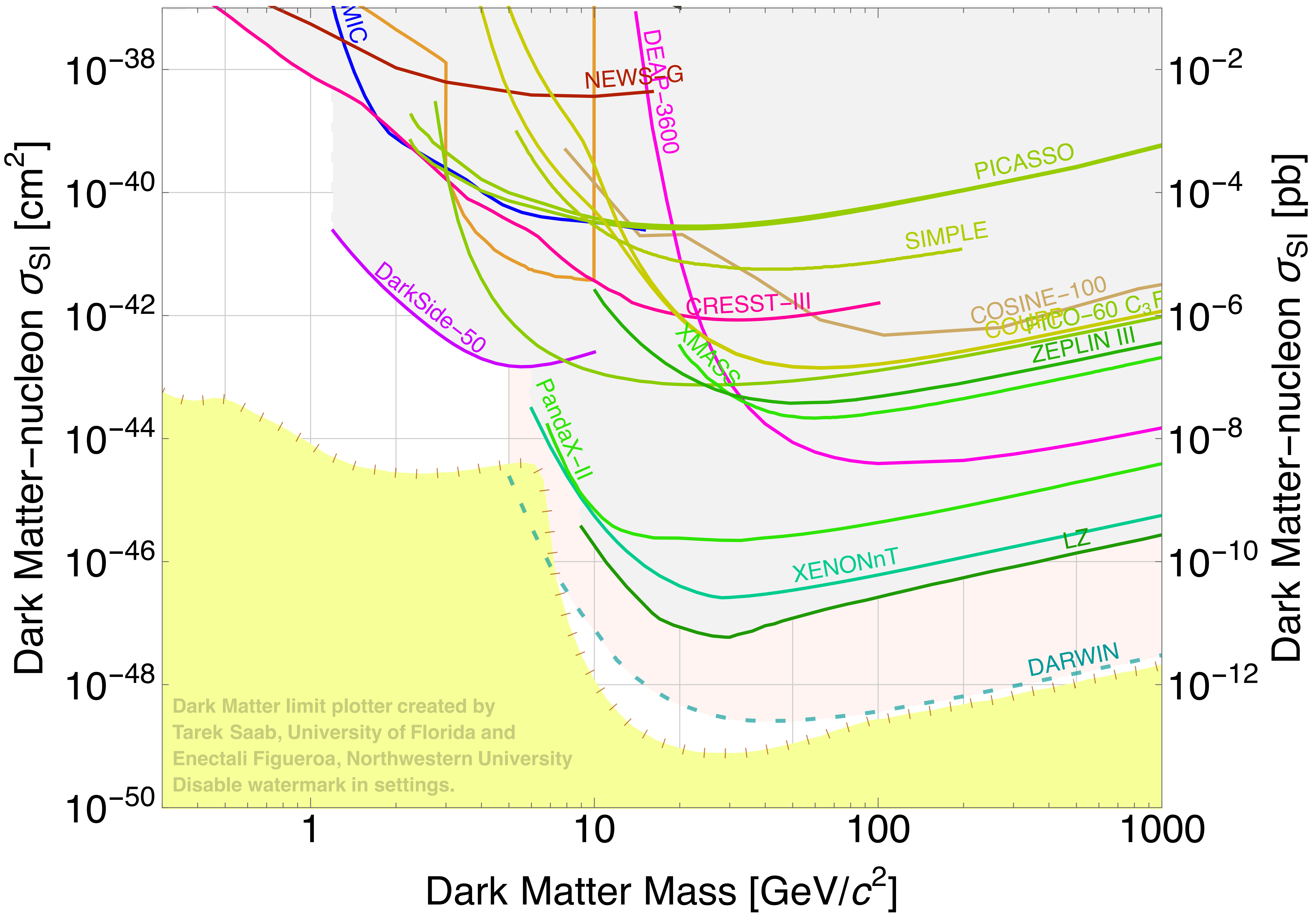
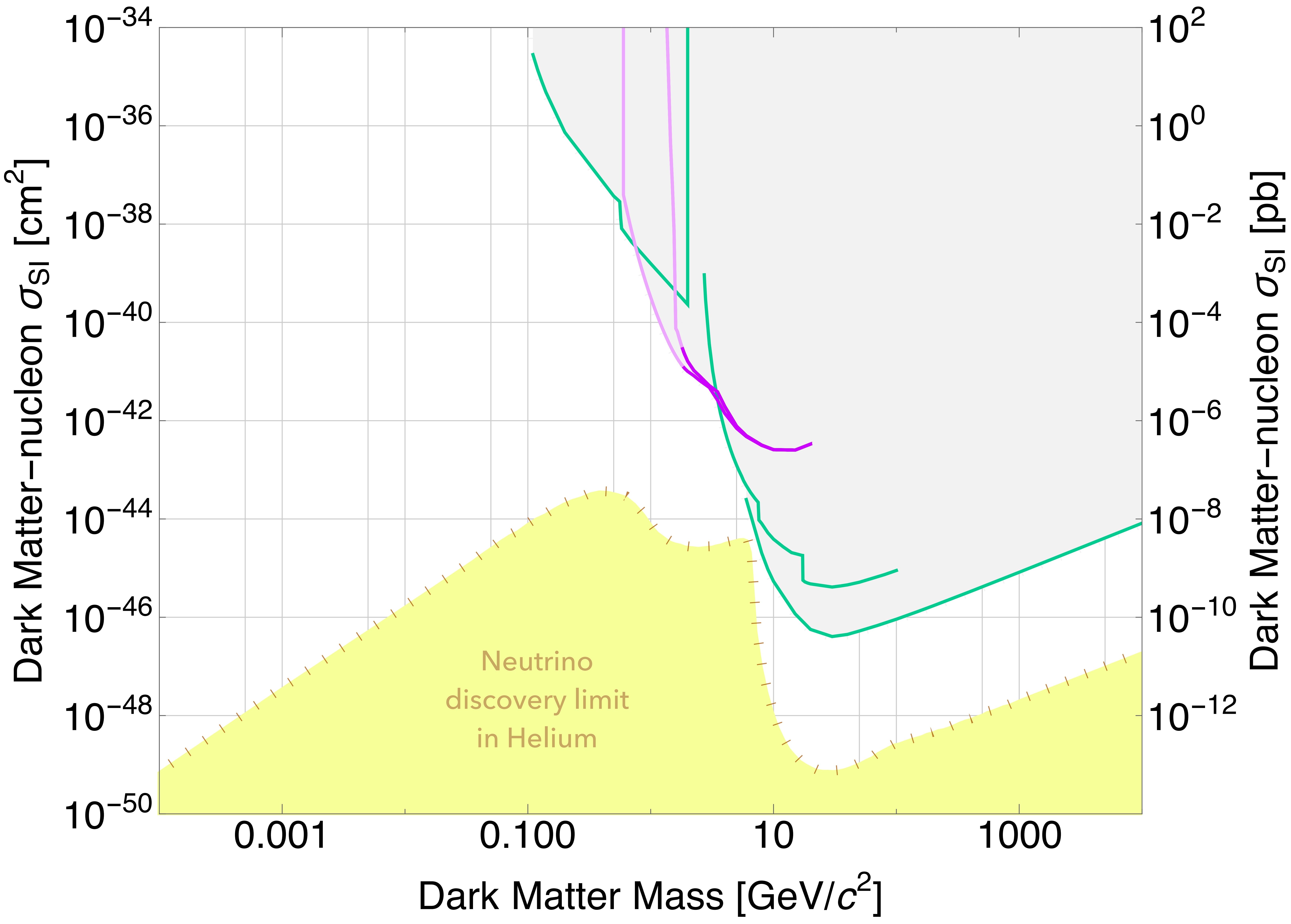


The power of LXe TPC experiments



What’s the motivation then for helium?

Towards light dark matter with superfluid ^{4}He



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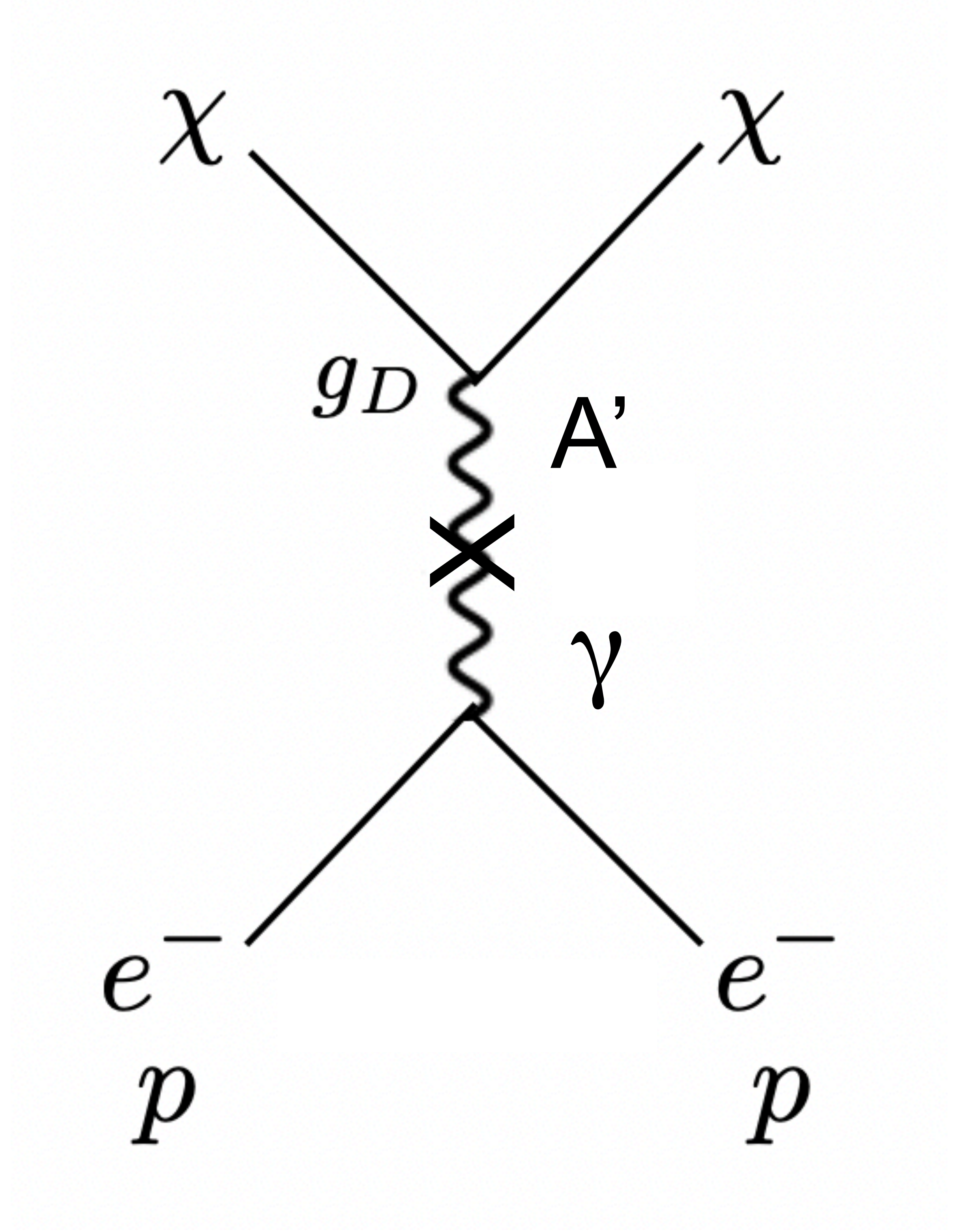
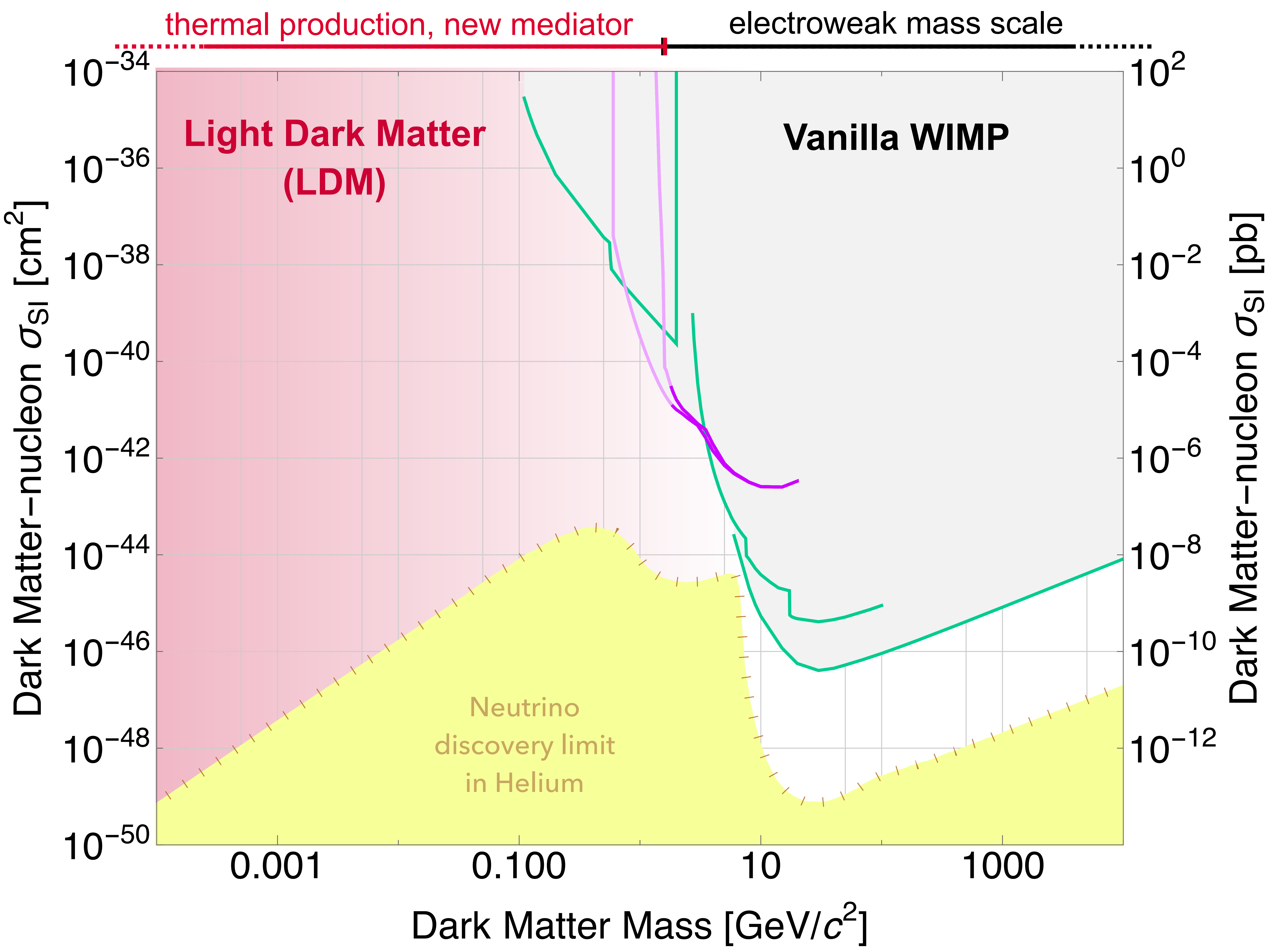
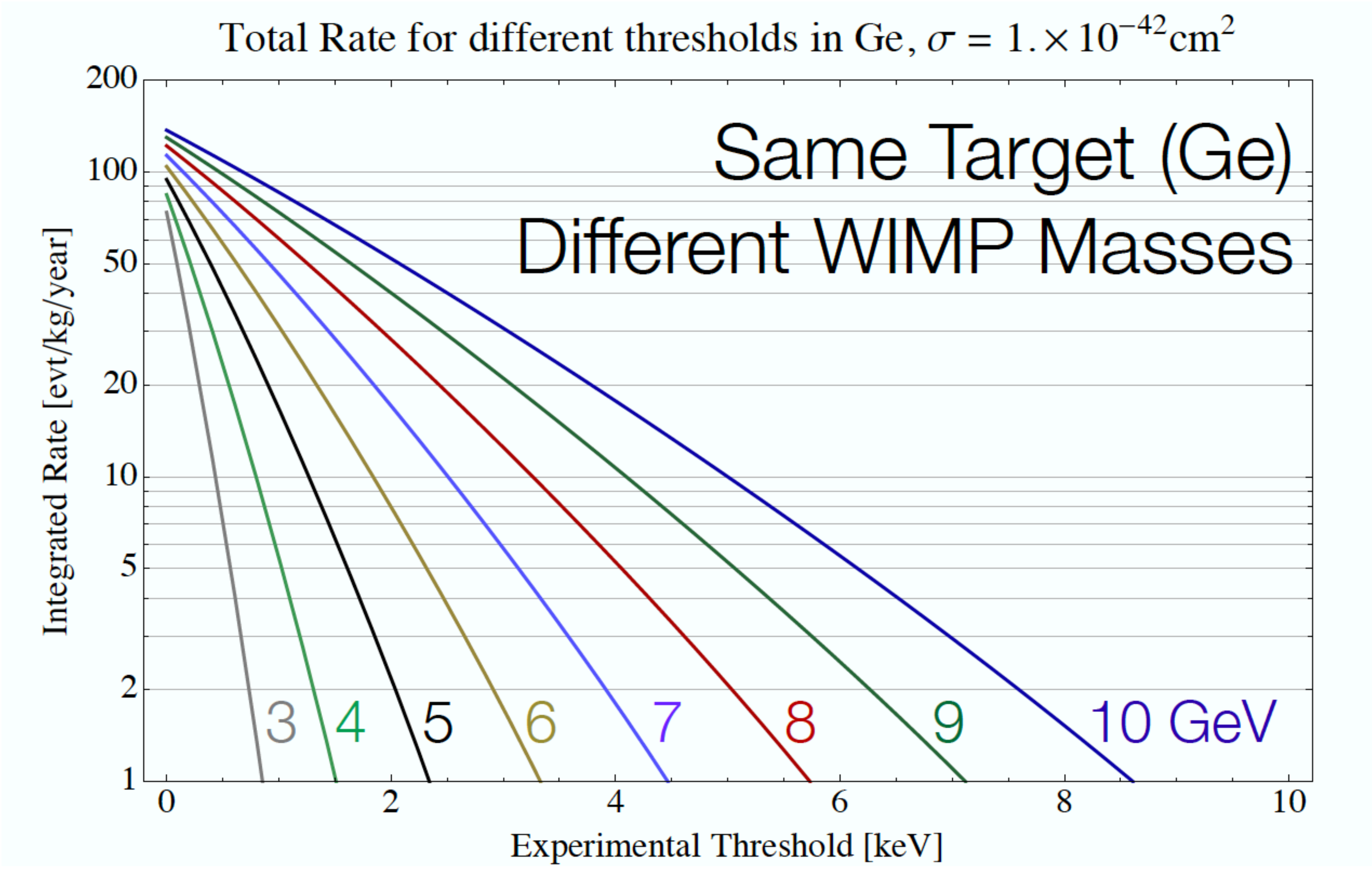
Towards light dark matter with superfluid ^{4}He

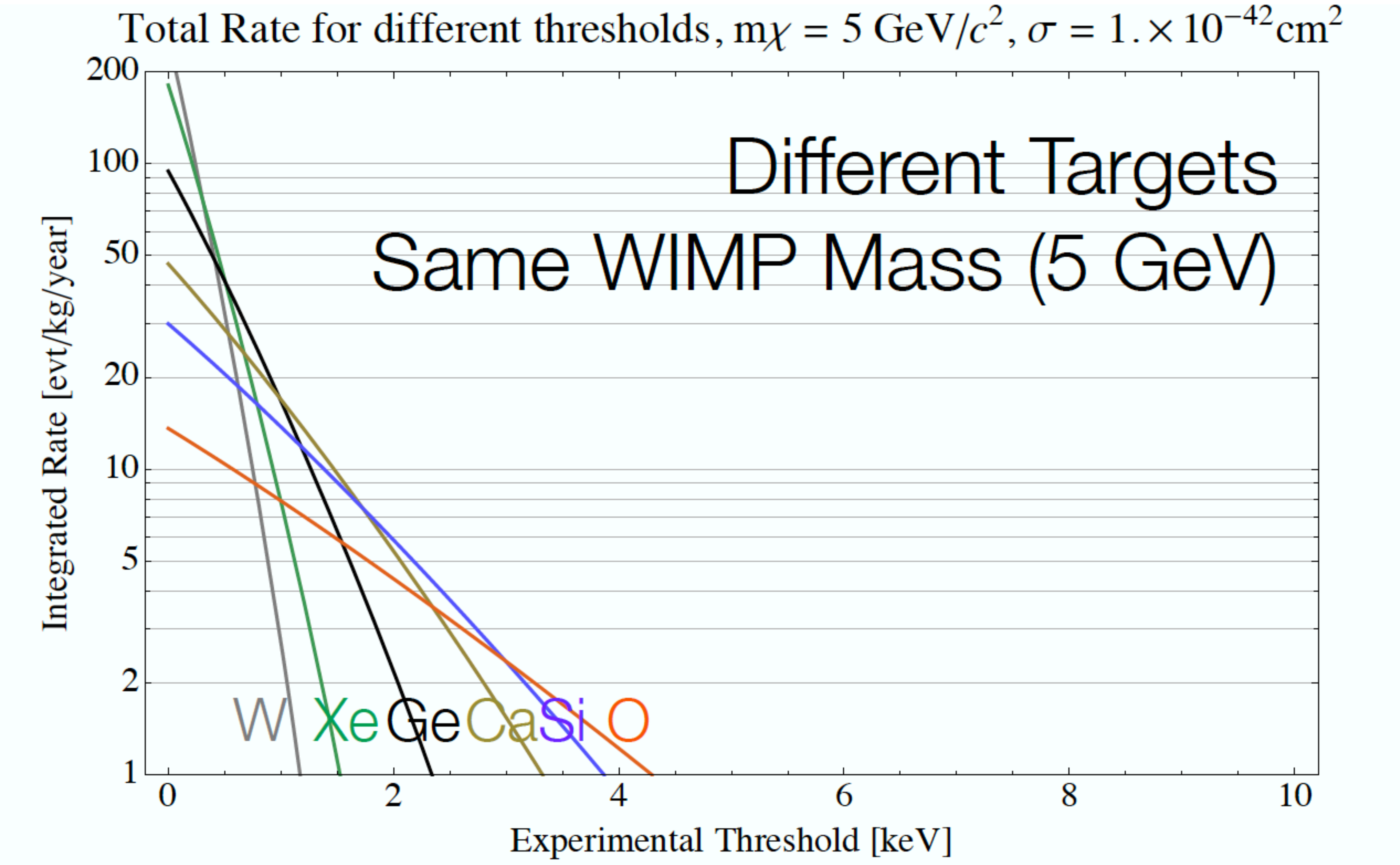


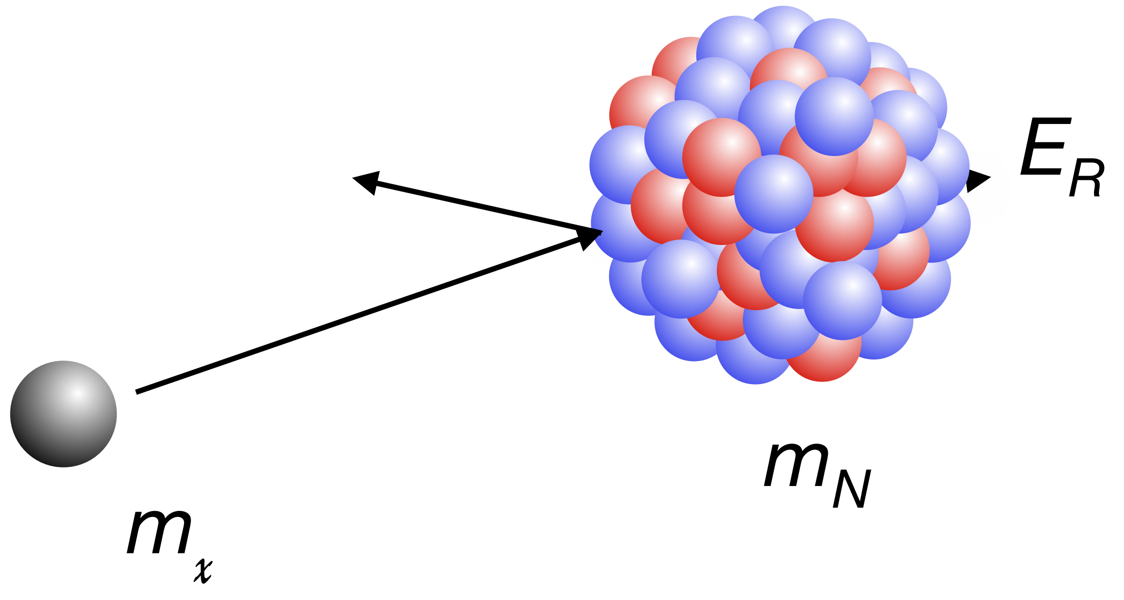
- New mediator, e.g. dark photon A'.
- Coupling to electrons and nuclei via kinetic mixing with SM photon.



Dark matter - nucleon scattering

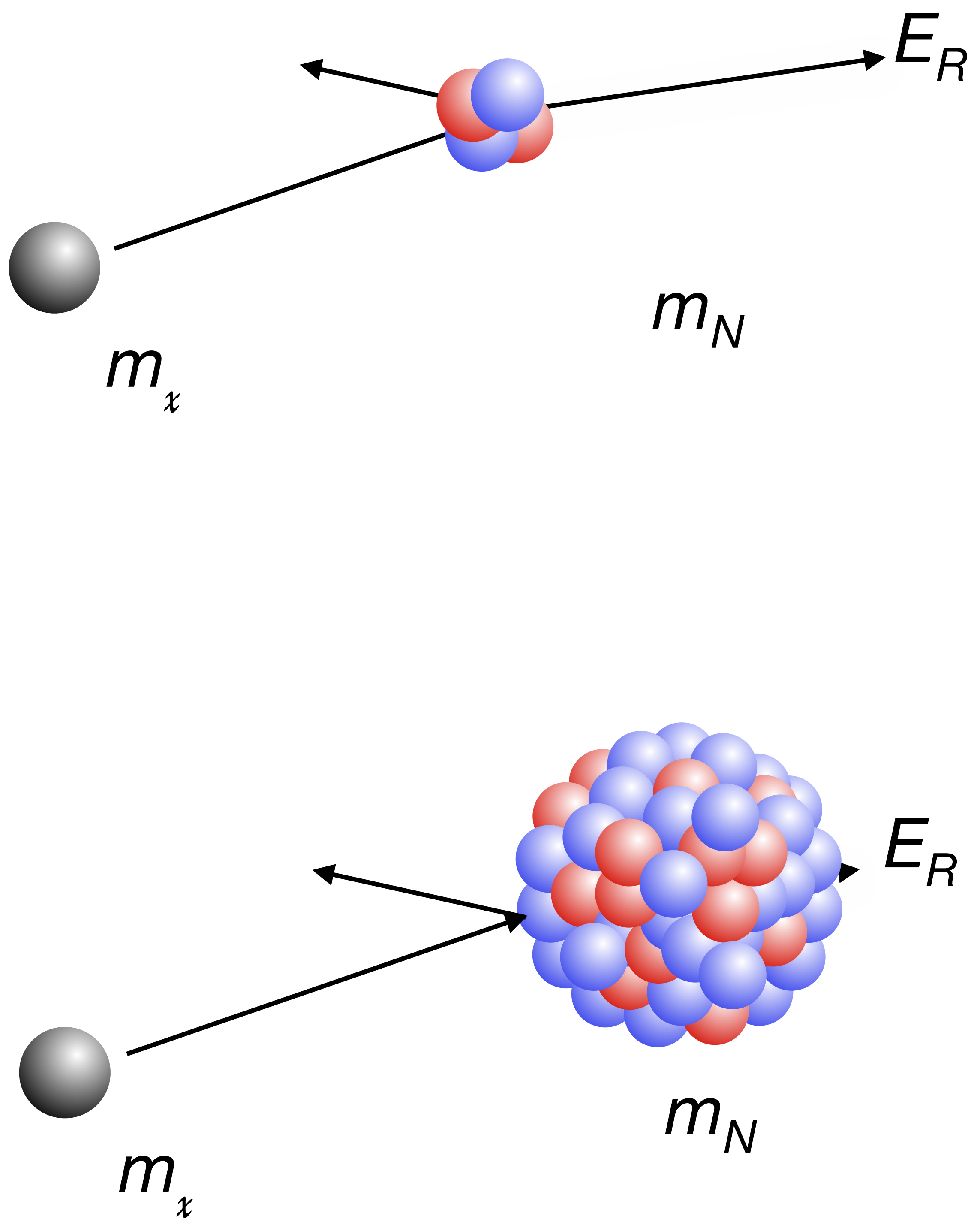


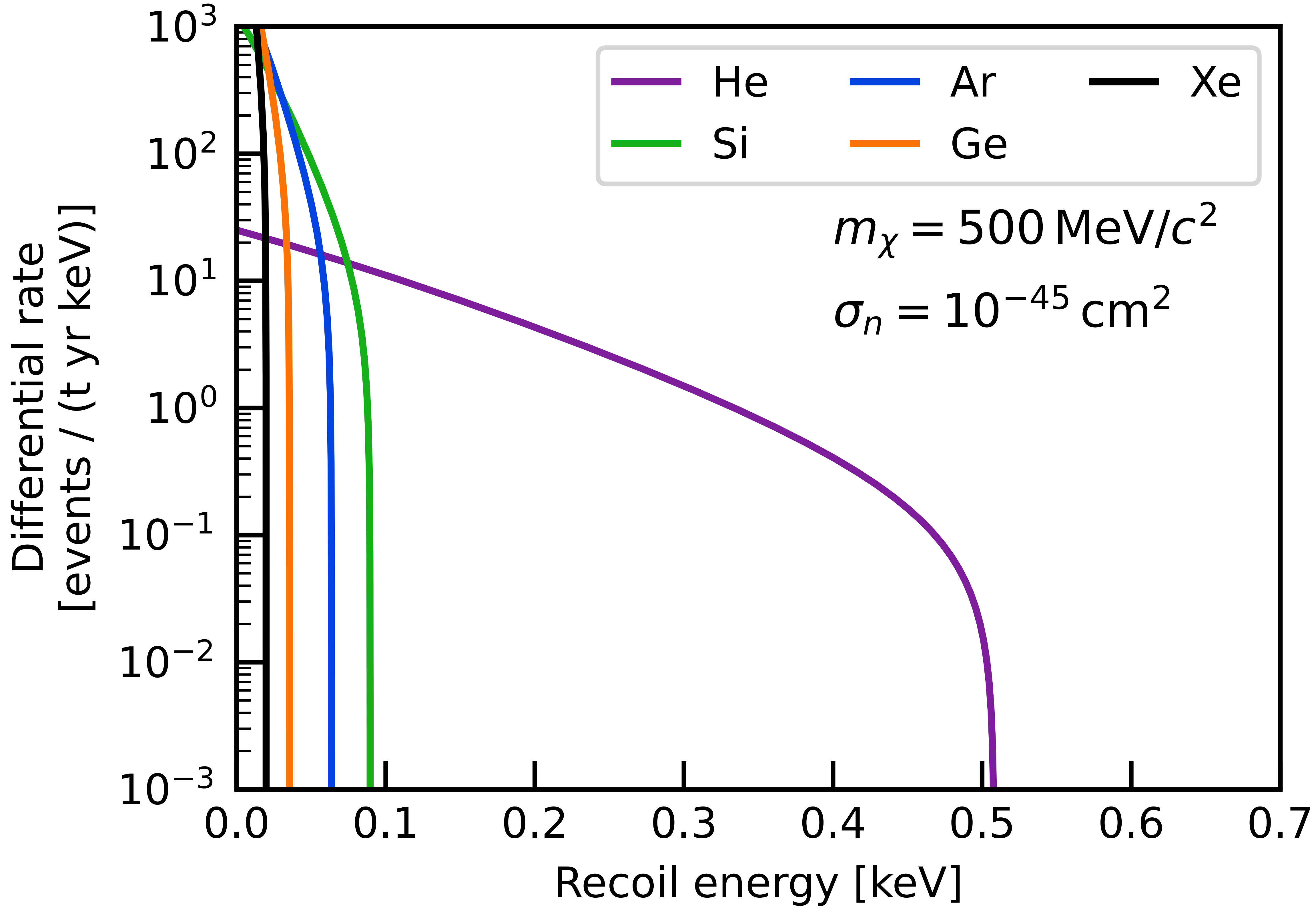




$$E_R = \frac{1}{2}\frac{q^2}{m_N} \lesssim \frac{2\,m_\chi^2 v^2}{m_N}$$

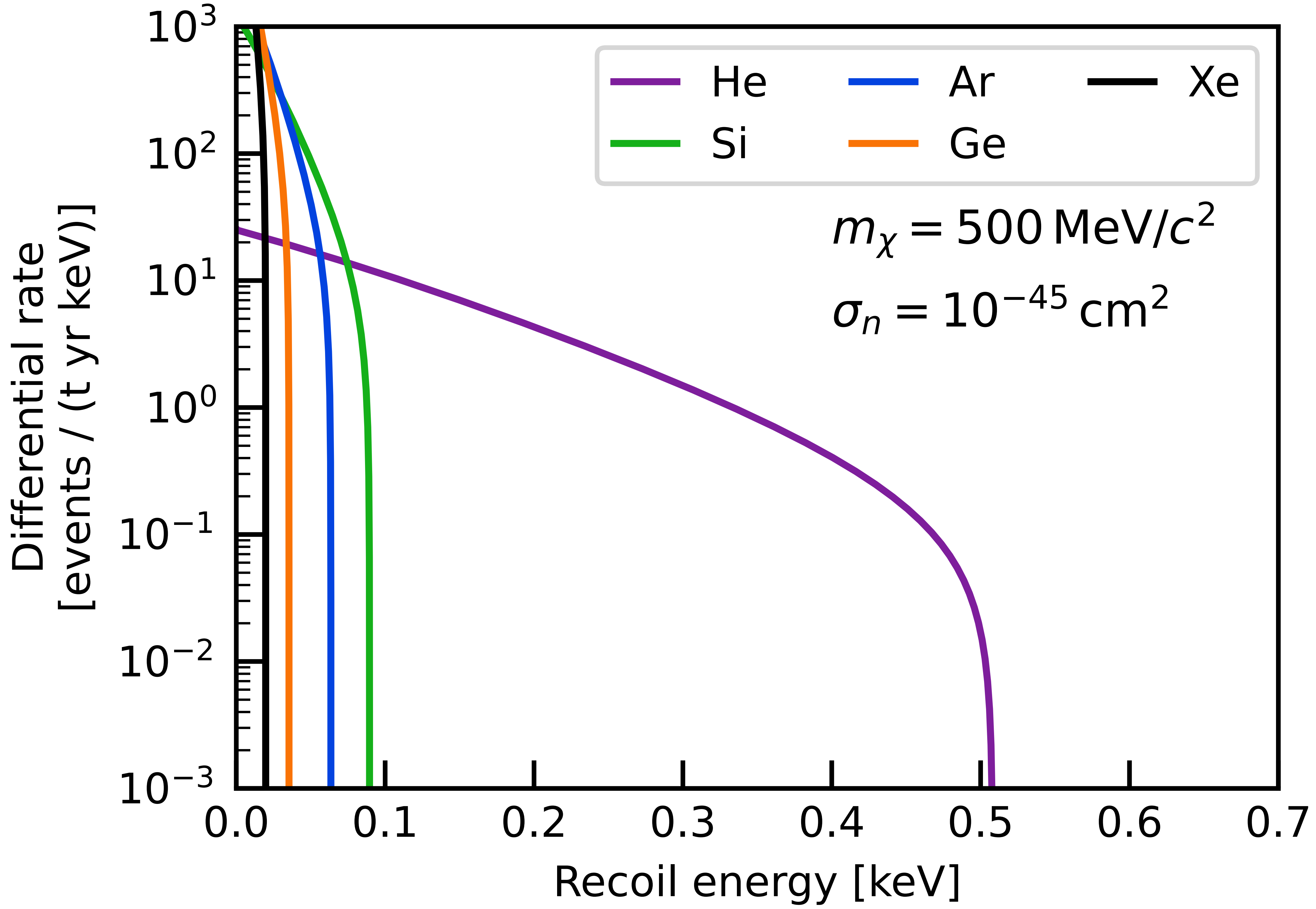
Dark matter - nucleon scattering





Advantages of helium

- Very light
- Cheap
- Ultra-pure (no internal background)
- Multiple signals (phonon & rotons, photons, excimers)
  - NR / ER discrimination
- Fiducialization possible
- Scalable
- Overall concept demonstrated
  - S. Bandler et al. PRL 78, 2429 (1992)
    C. Enss et al. Physica B 194-196, 515 (1994)
    S. Bandler et al. PRL 74, 3169 (1995)
    D.N. McKinsey et al. PRA 59, 200 (1999)
    W. Guo et al. PRL 102, 235301 (2009)
    F.W. Carter et al. JLTP 186, 183 (2017)

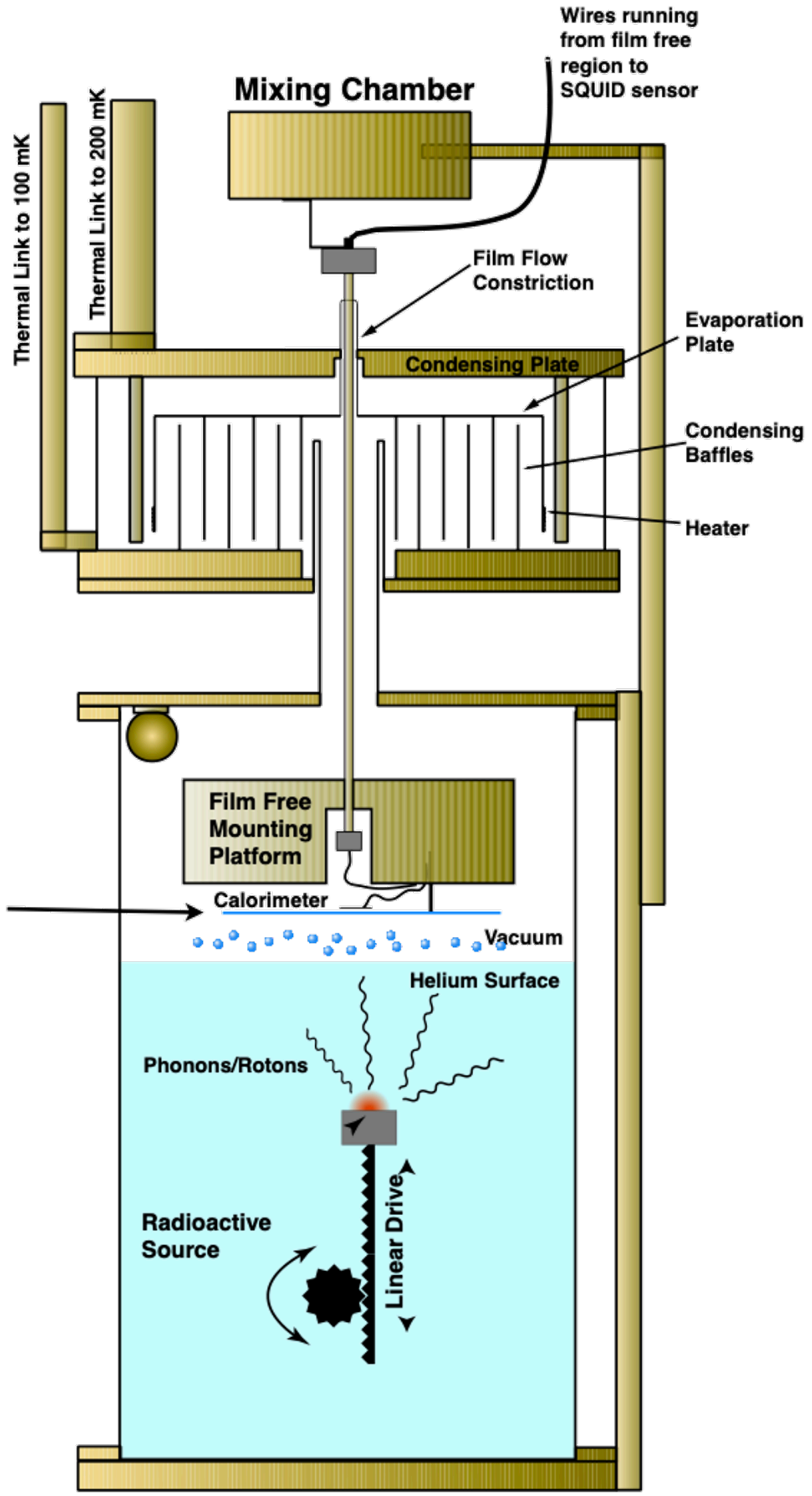


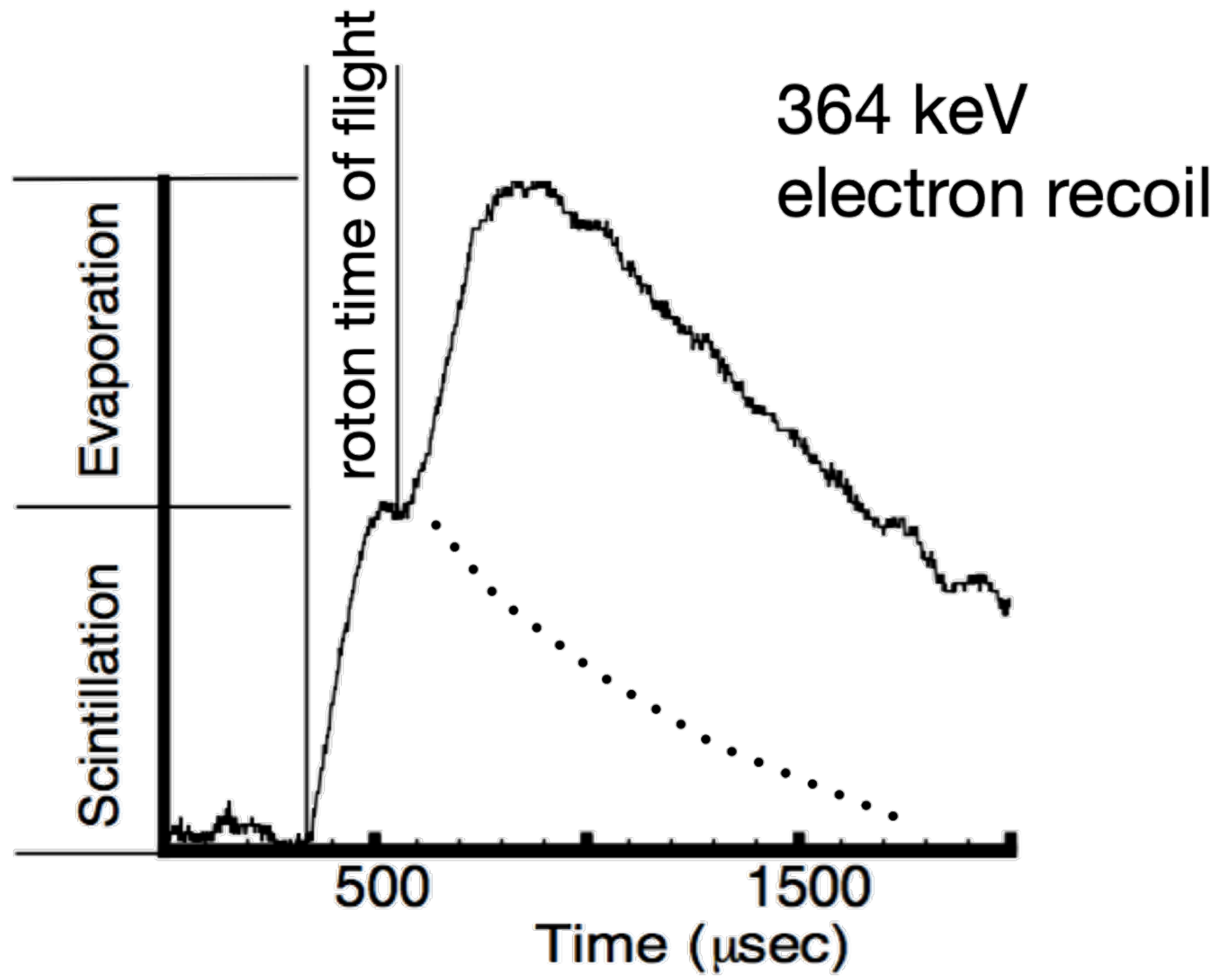
HERON: HElium-ROton detection of Neutrinos

He film burner

wafer calorimeter

kg-scale
LHe mass





C. Enss et al., Physica B 194-196, 515 (1994)
S. Bandler et al., PRL 74, 3169 (1995)
J. S. Adams et al. Phys. Let. B 341, 431-434 (1995)

The DELight Collaboration

DELight

SciPost Phys. Proc. 12, 016 (2023)

DELight: a Direct search Experiment for Light dark matter with superfluid helium

B. von Krosigk[1*], K. Eitel[1], C. Enss[2,3], T. Ferber[4], L. Gastaldo[2], F. Kahlhoefer[5], S. Kempf[6,3], M. Klute[4], S. Lindemann[7], M. Schumann[7], F. Toschi[1,7] and K. Valerius[1]

+ K. Gerbig, G.S. Heine, B. Maier, M. Mikaya and A. Reiser

Karlsruhe Institute of Technology

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universität freiburg

Credit: Freepik Company

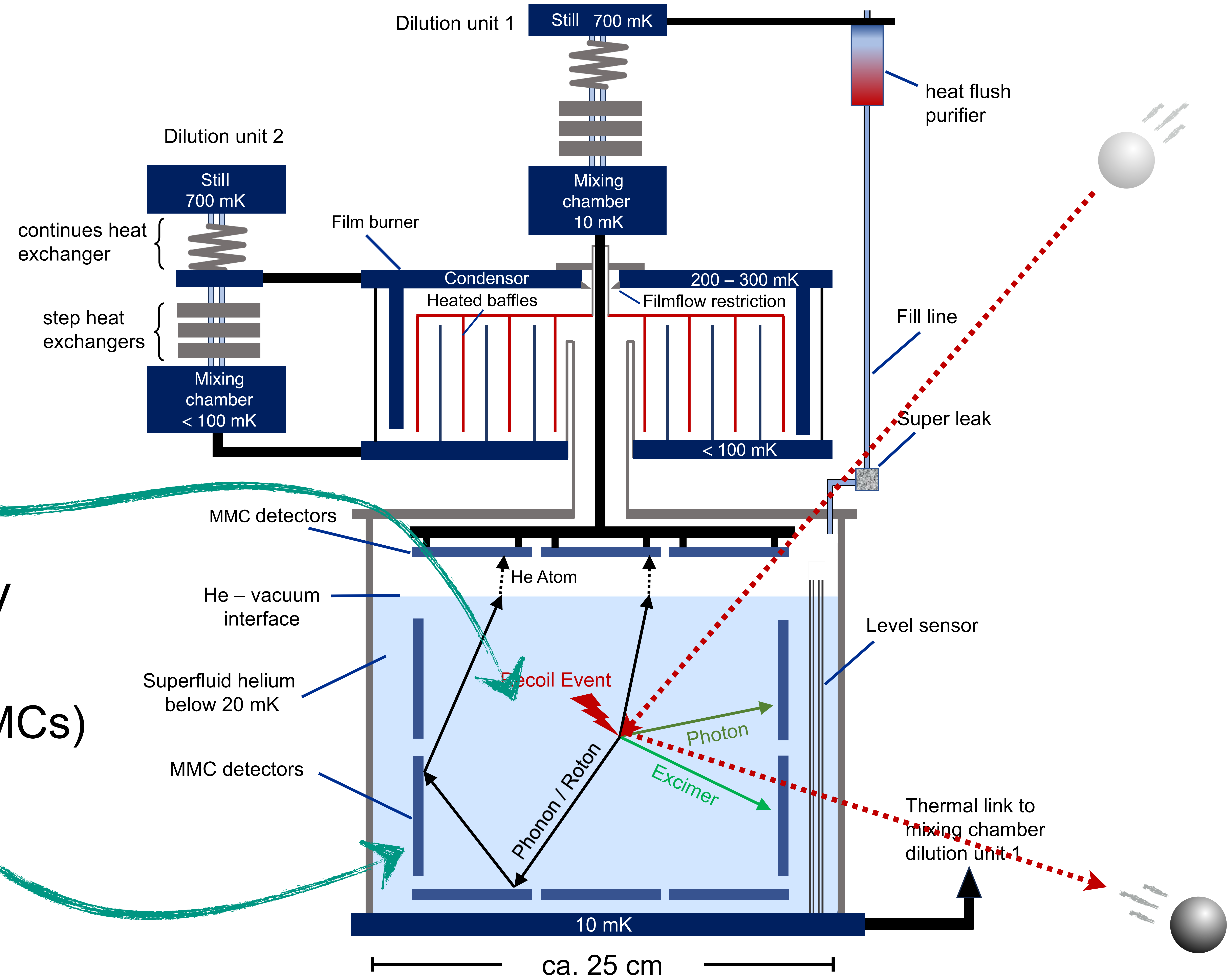
DELight: Direct search Experiment for Light dark matter

Superfluid ^{4}He

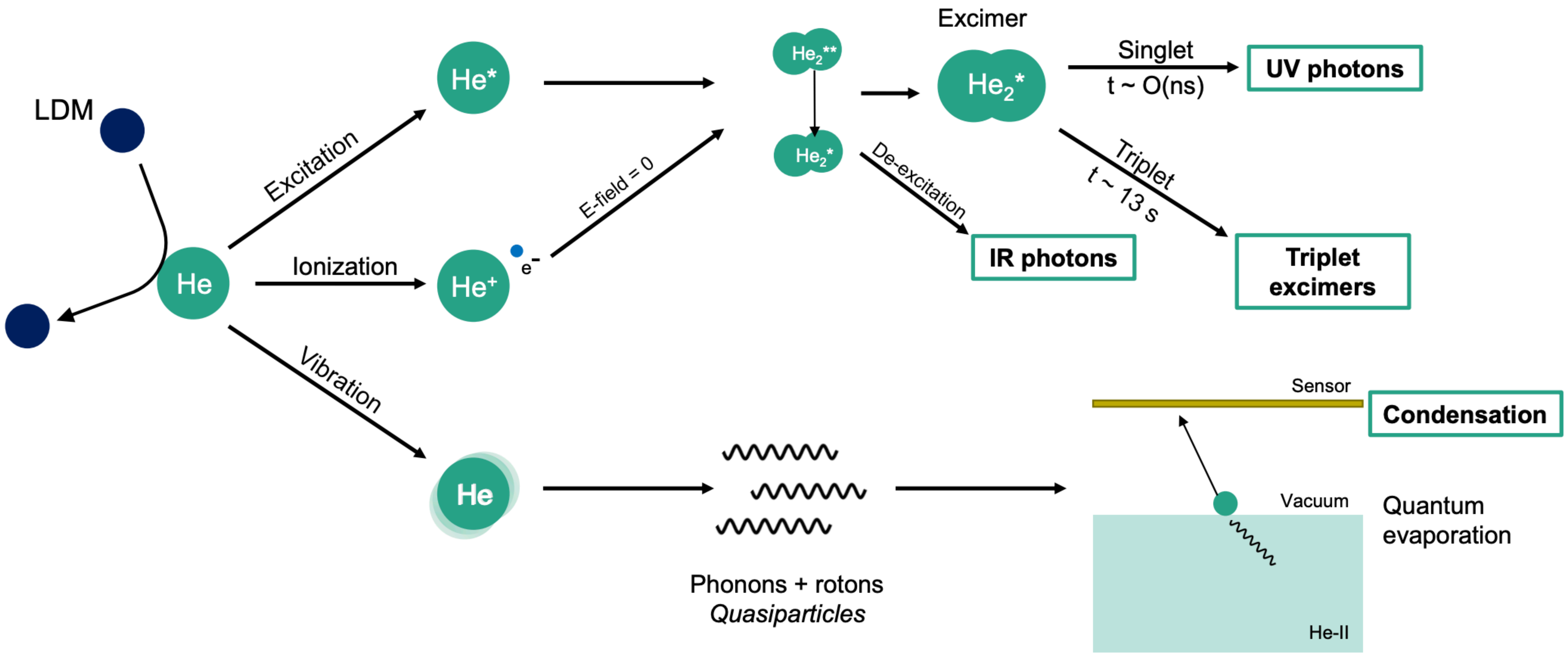
(~ 10 liters in phase-I)

Ultra-sensitive heat/energy sensors

(Magnetic Micro-Calorimeters: MMCs)



Multiple signals in superfluid ^{4}He



Credit: F. Toschi

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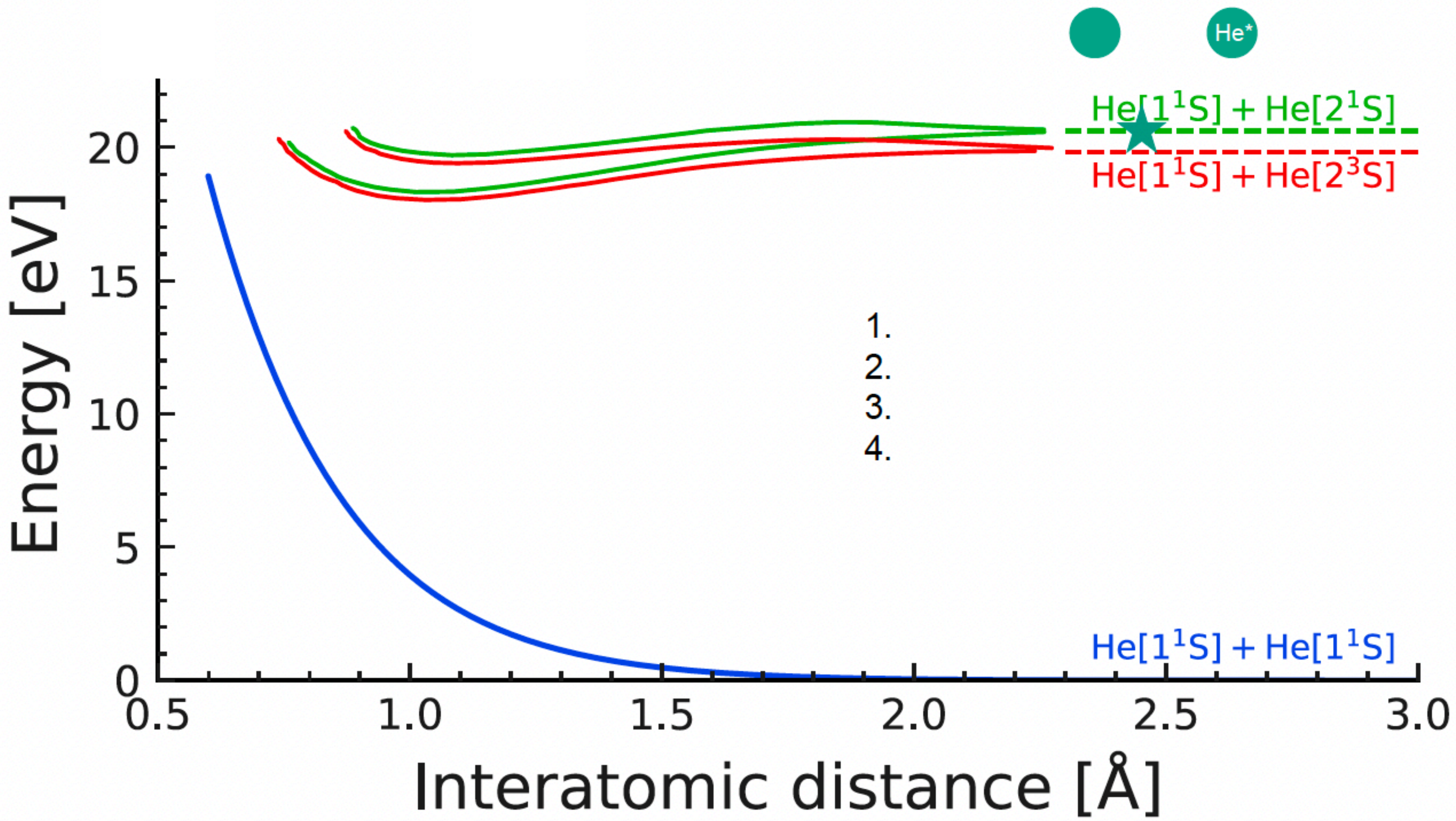
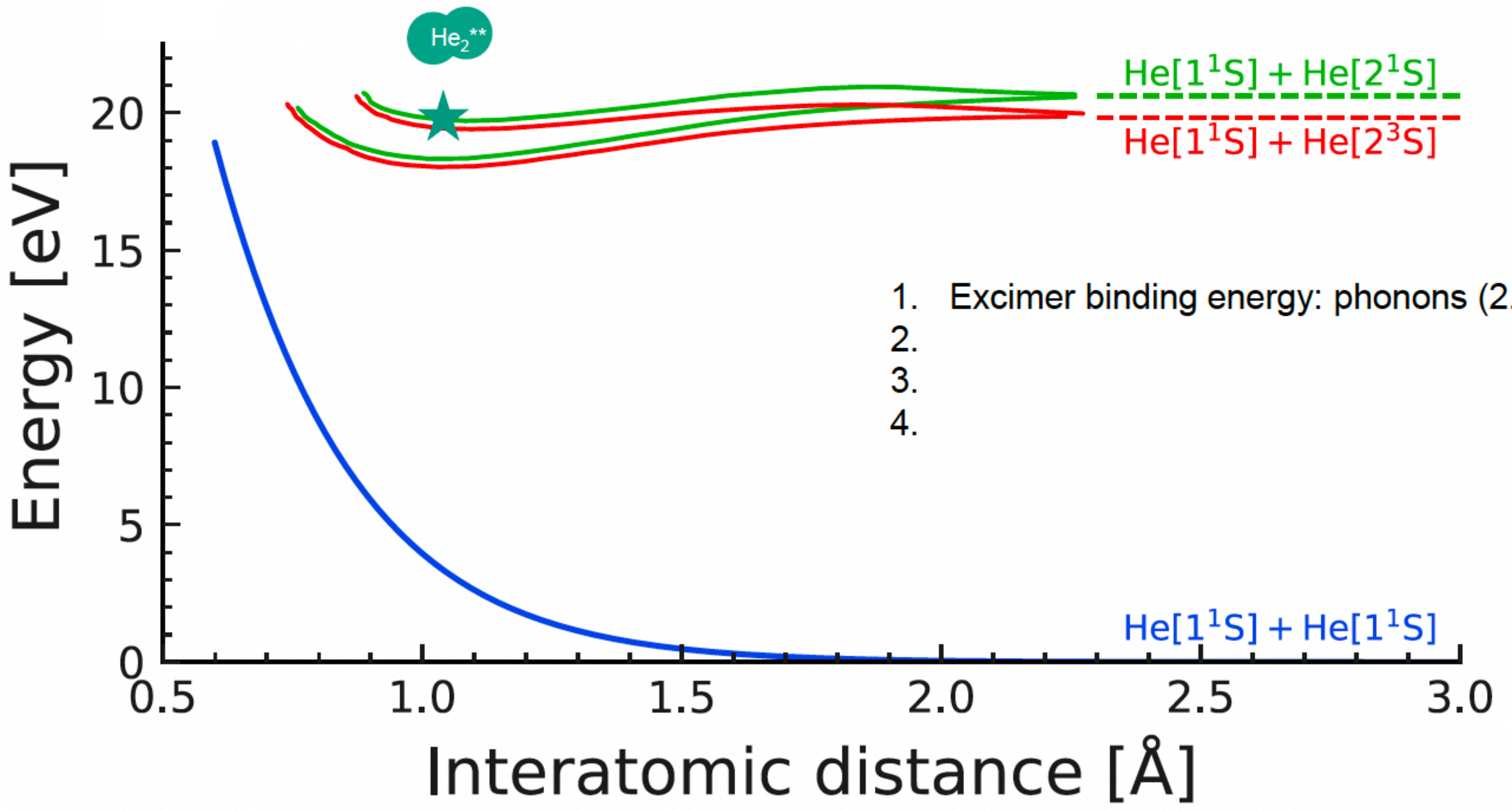
Atomic excitation: singlet



1.
2.
3.
4.

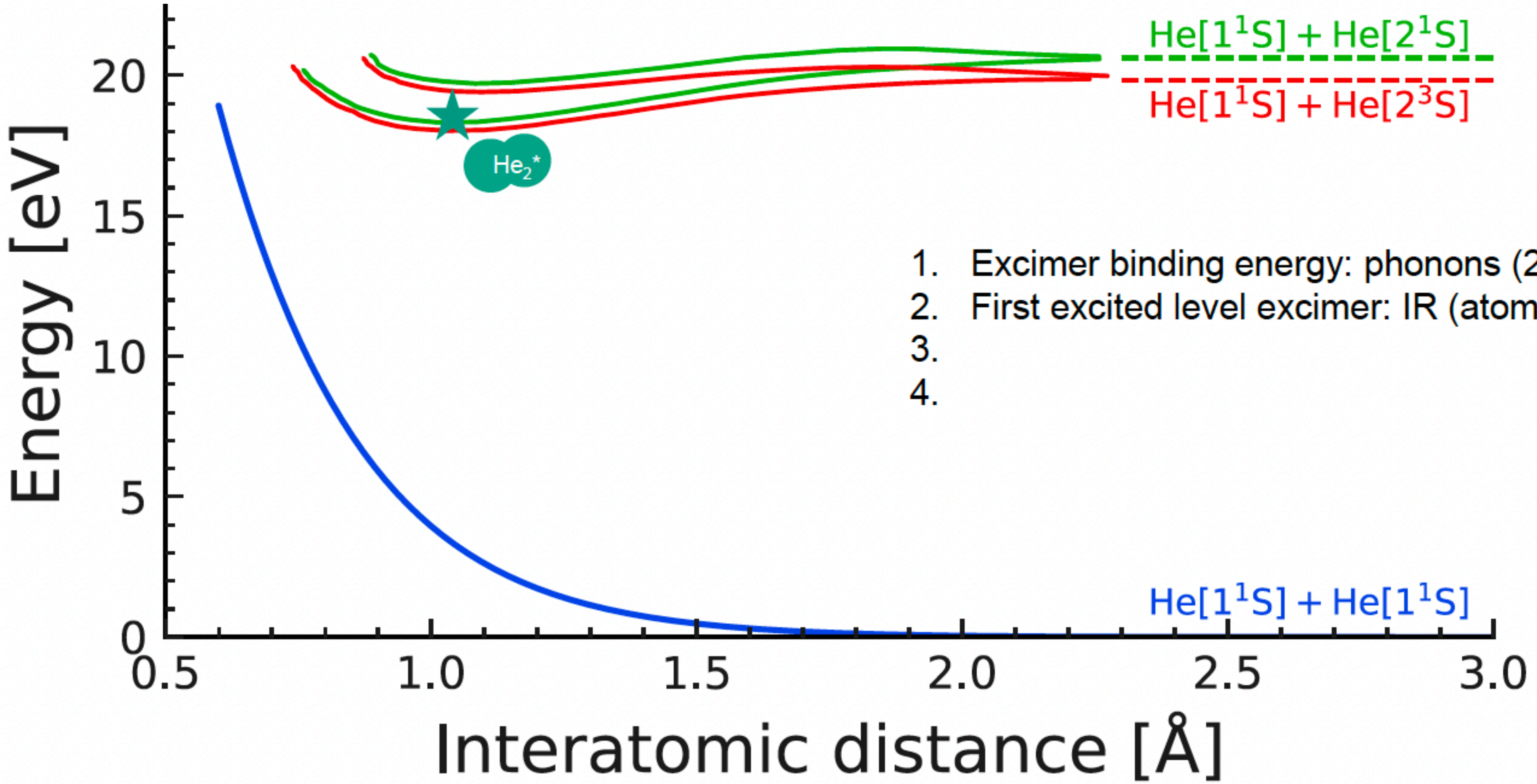
Credit: G. Seidel, F. Toschi

Atomic excitation: singlet



1. Excimer binding energy: phonons (2.4 eV)
2.
3.
4.

Atomic excitation: singlet



1. Excimer binding energy: phonons (2.4 eV)
2. First excited level excimer: IR (atomic de-exc. ΔE_f)
3.
4.

Credit: G. Seidel, F. Toschi

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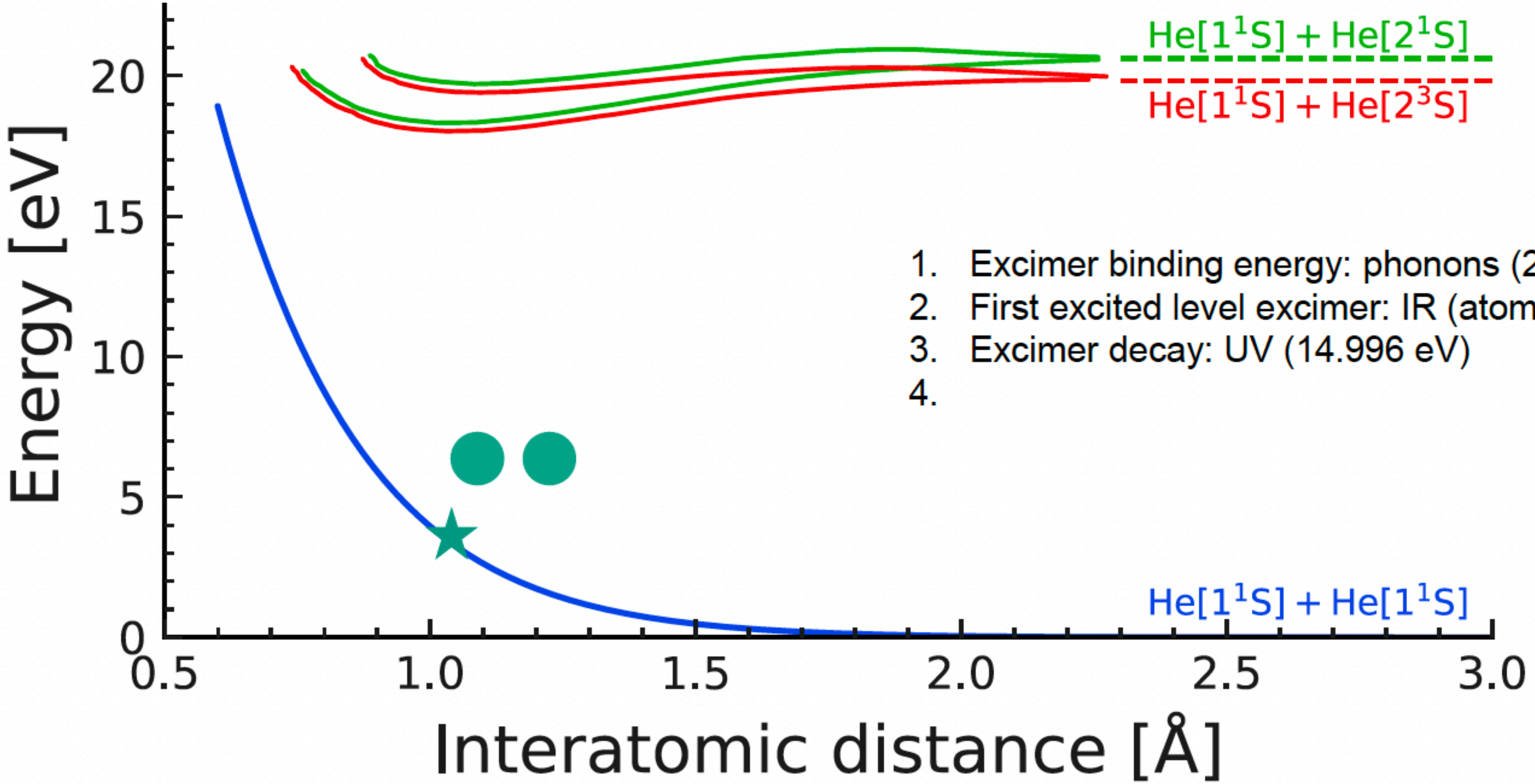
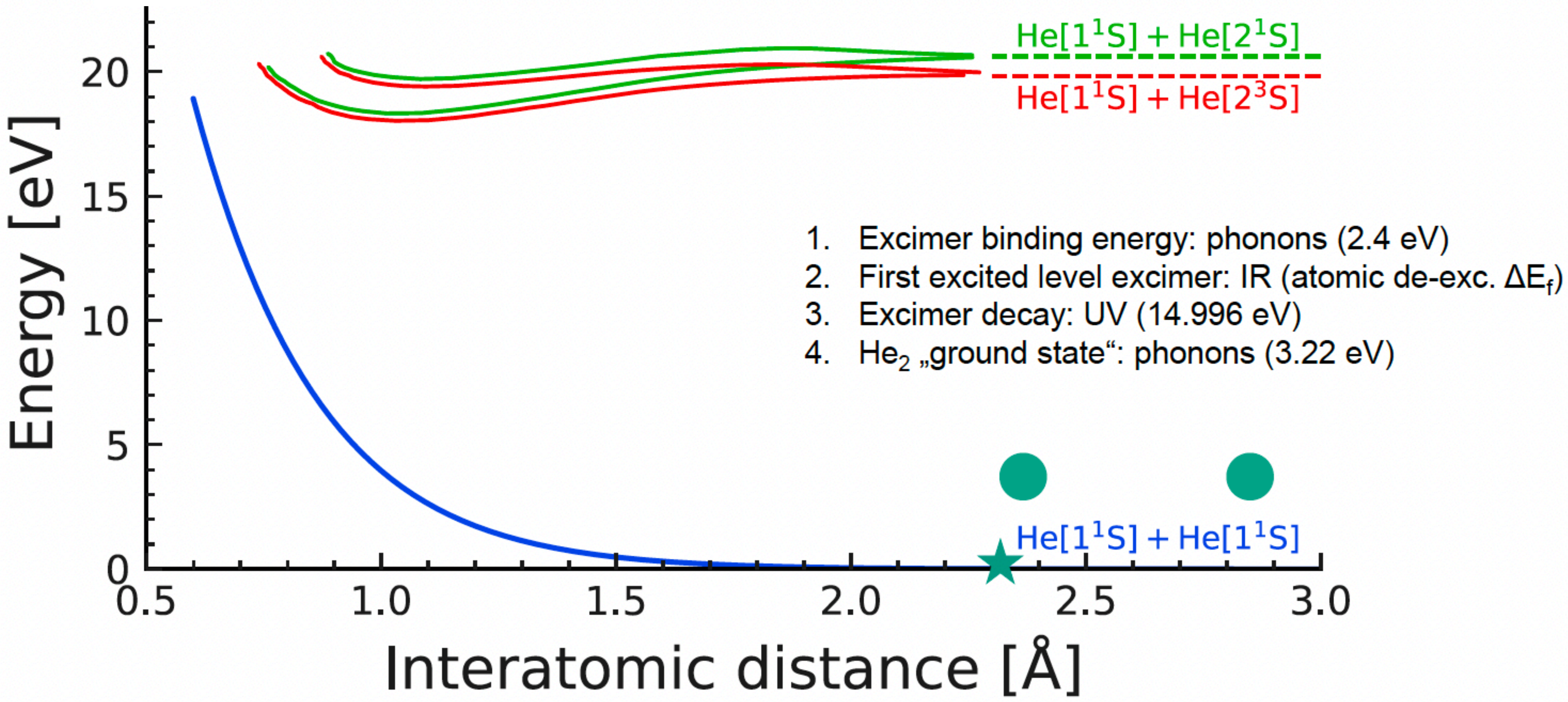
Atomic excitation: singlet



1. Excimer binding energy: phonons (2.4 eV)
2. First excited level excimer: IR (atomic de-exc. ΔE_f)
3. Excimer decay: UV (14.996 eV)
4.

Atomic excitation: singlet



Credit: G. Seidel, F. Toschi

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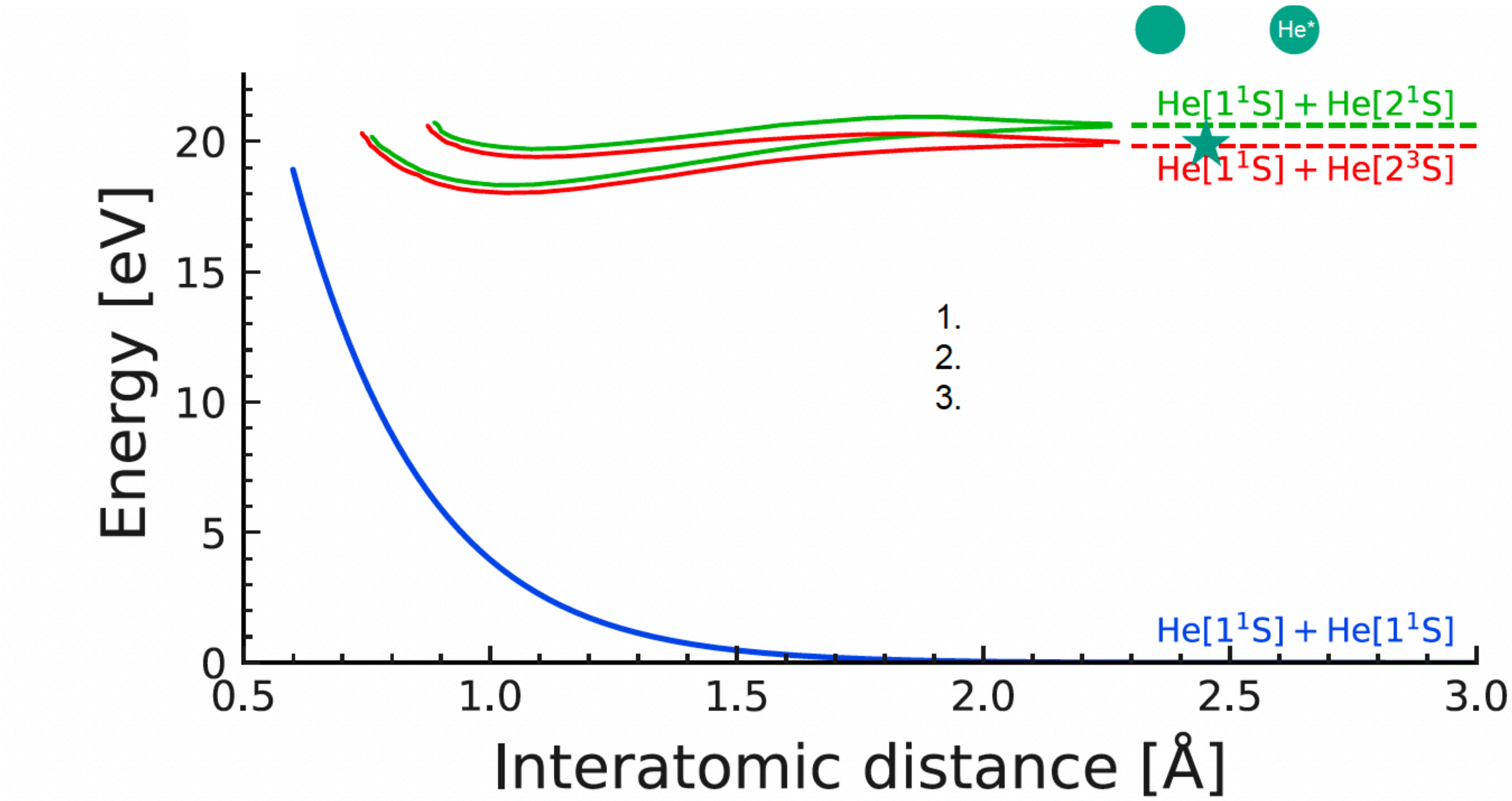
Atomic excitation: triplet



Credit: G. Seidel, F. Toschi

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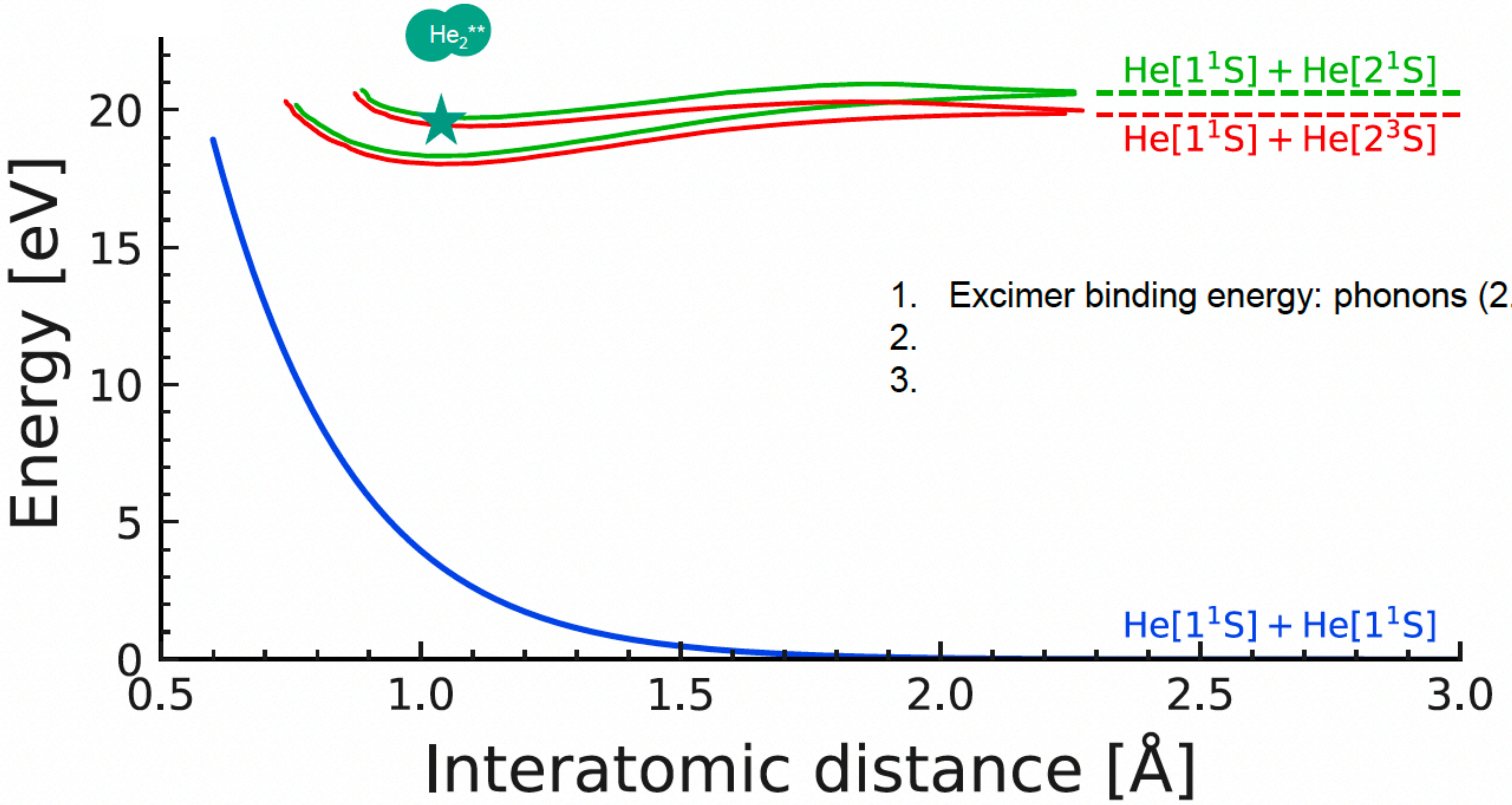

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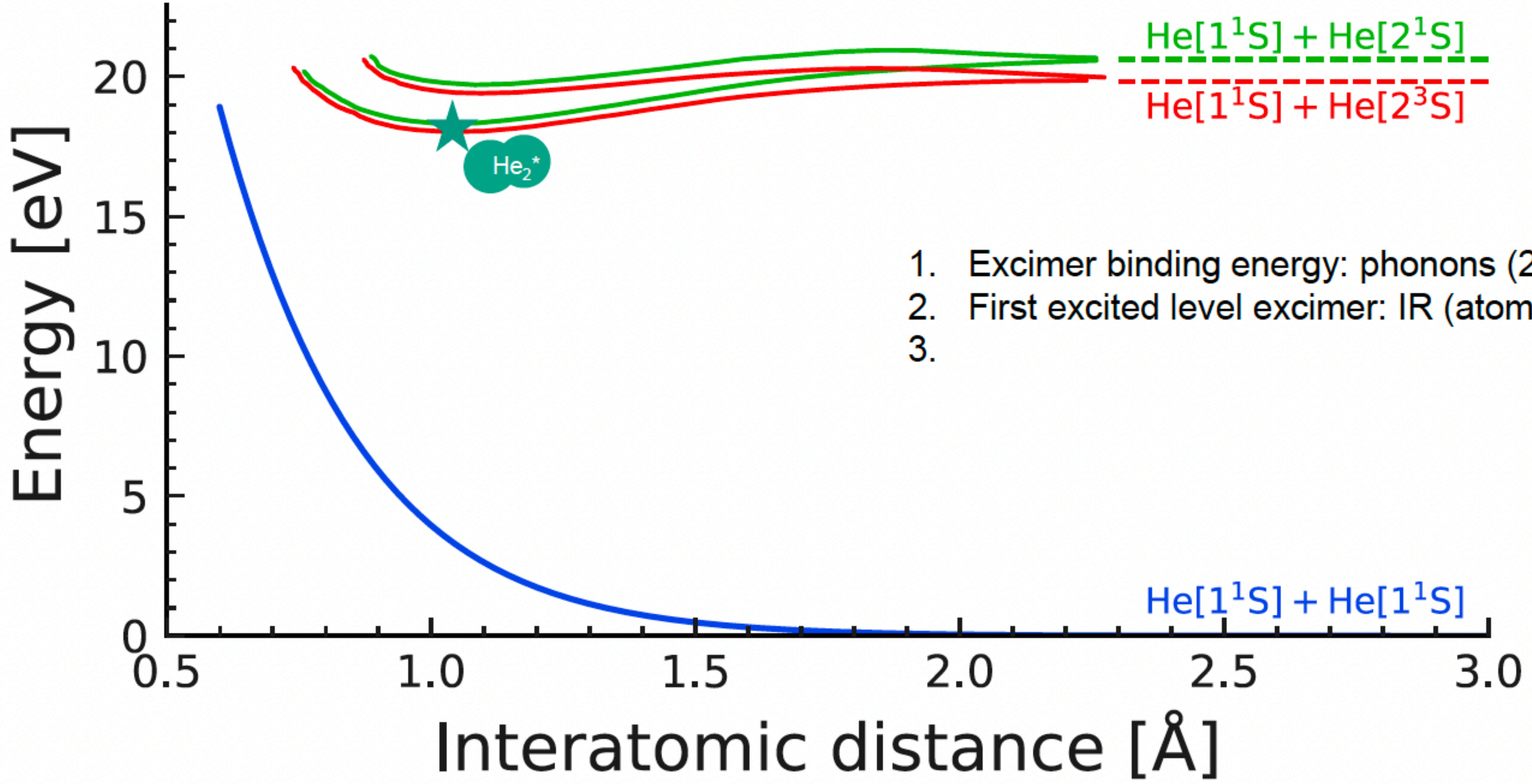

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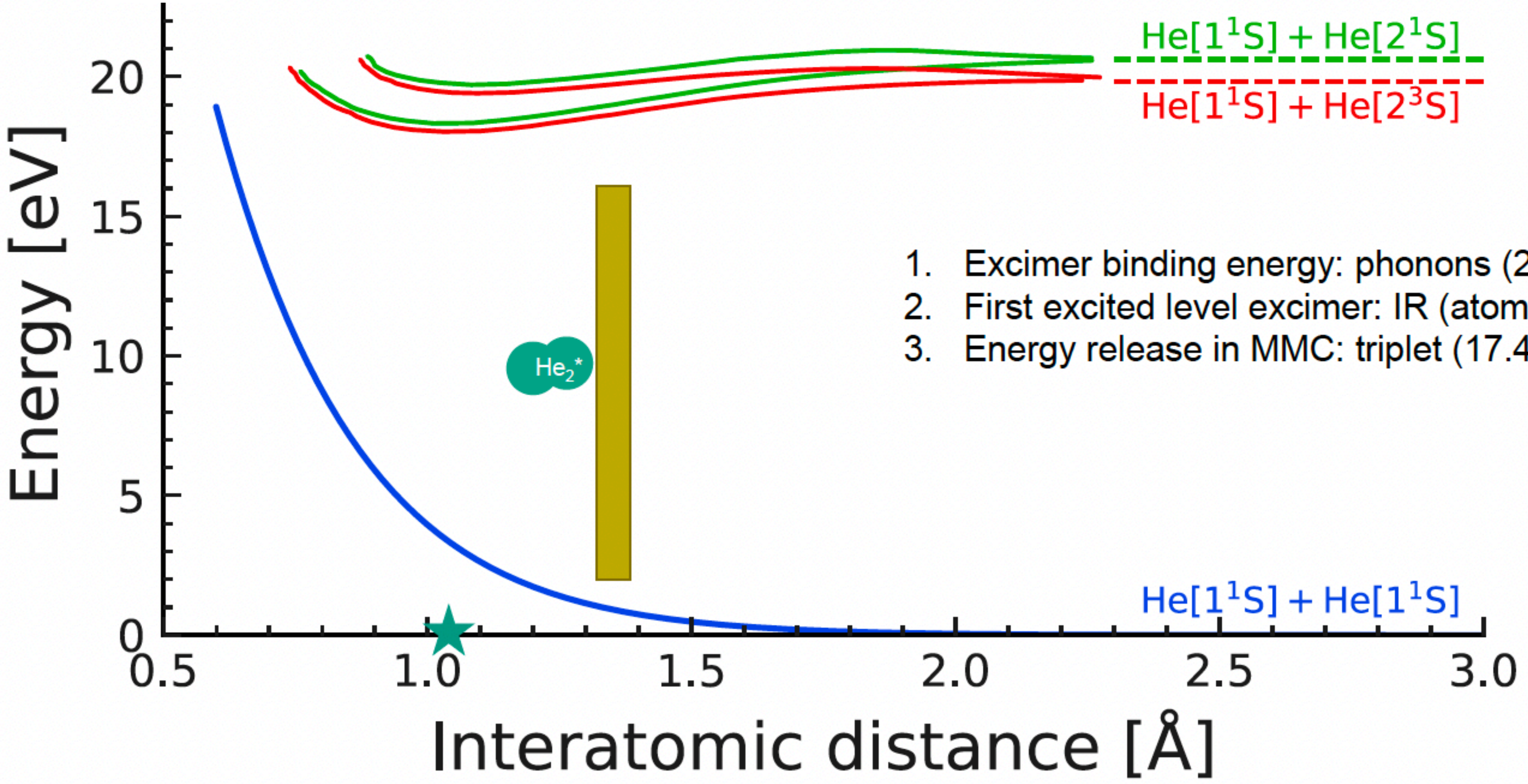
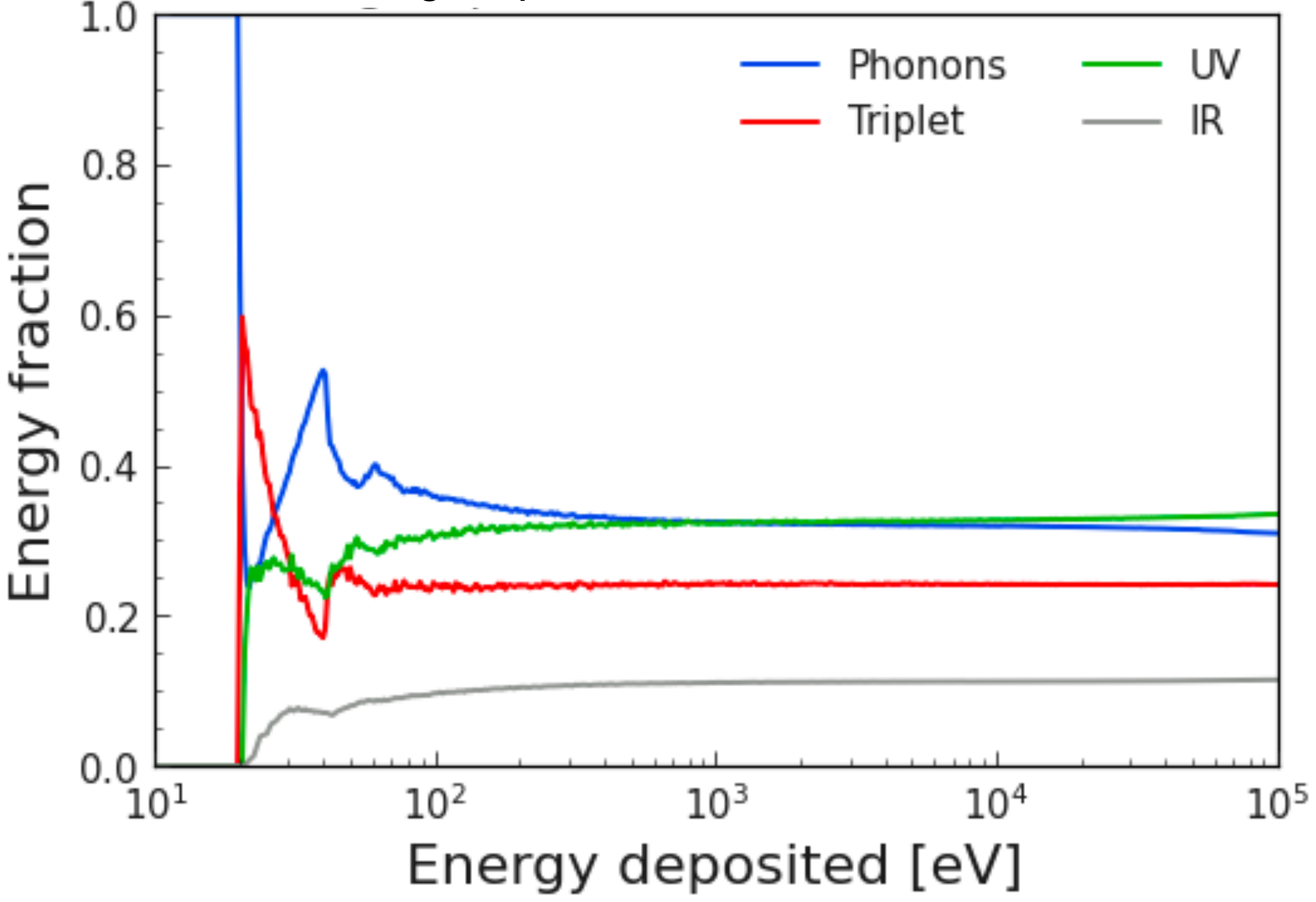


1. Excimer binding energy: phonons (2.4 eV)
2. First excited level excimer: IR (atomic de-exc. ΔE_f)
3. Energy release in MMC: triplet (17.42 eV)

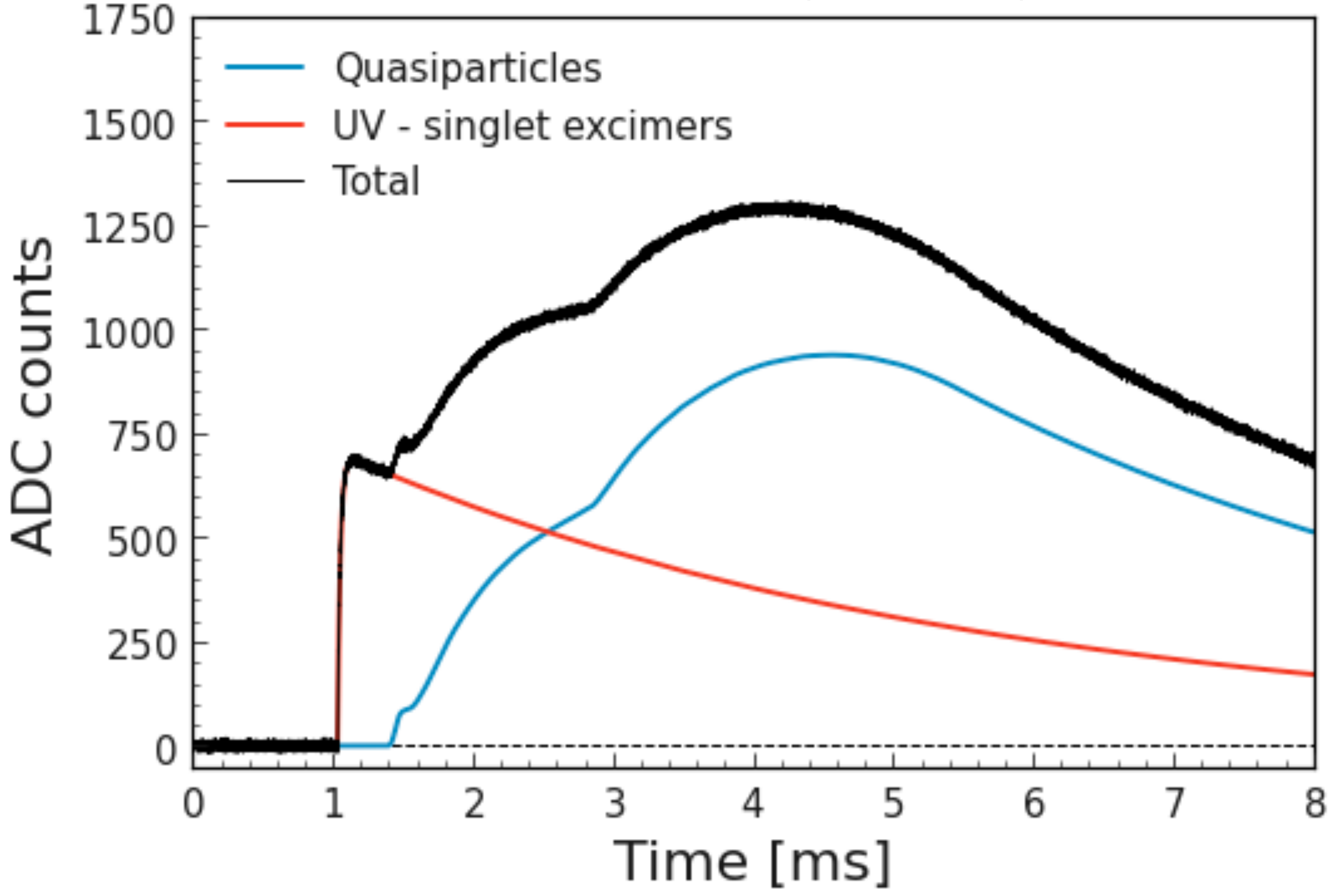
Credit: G. Seidel, F. Toschi

Energy partitioning and pulse-shape discrimination

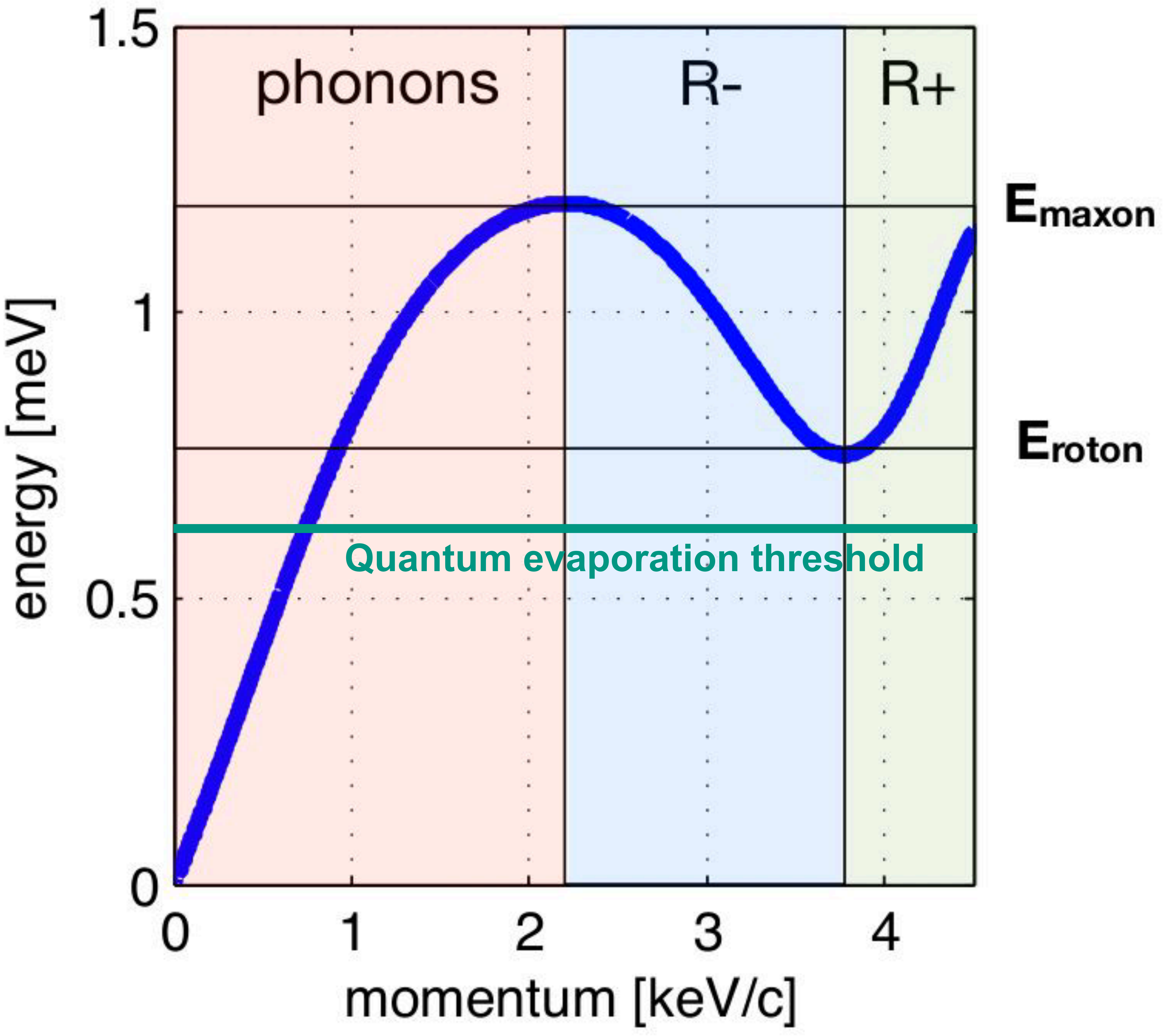
Signal partition for electron recoils



1 keV electron recoil (simulation)

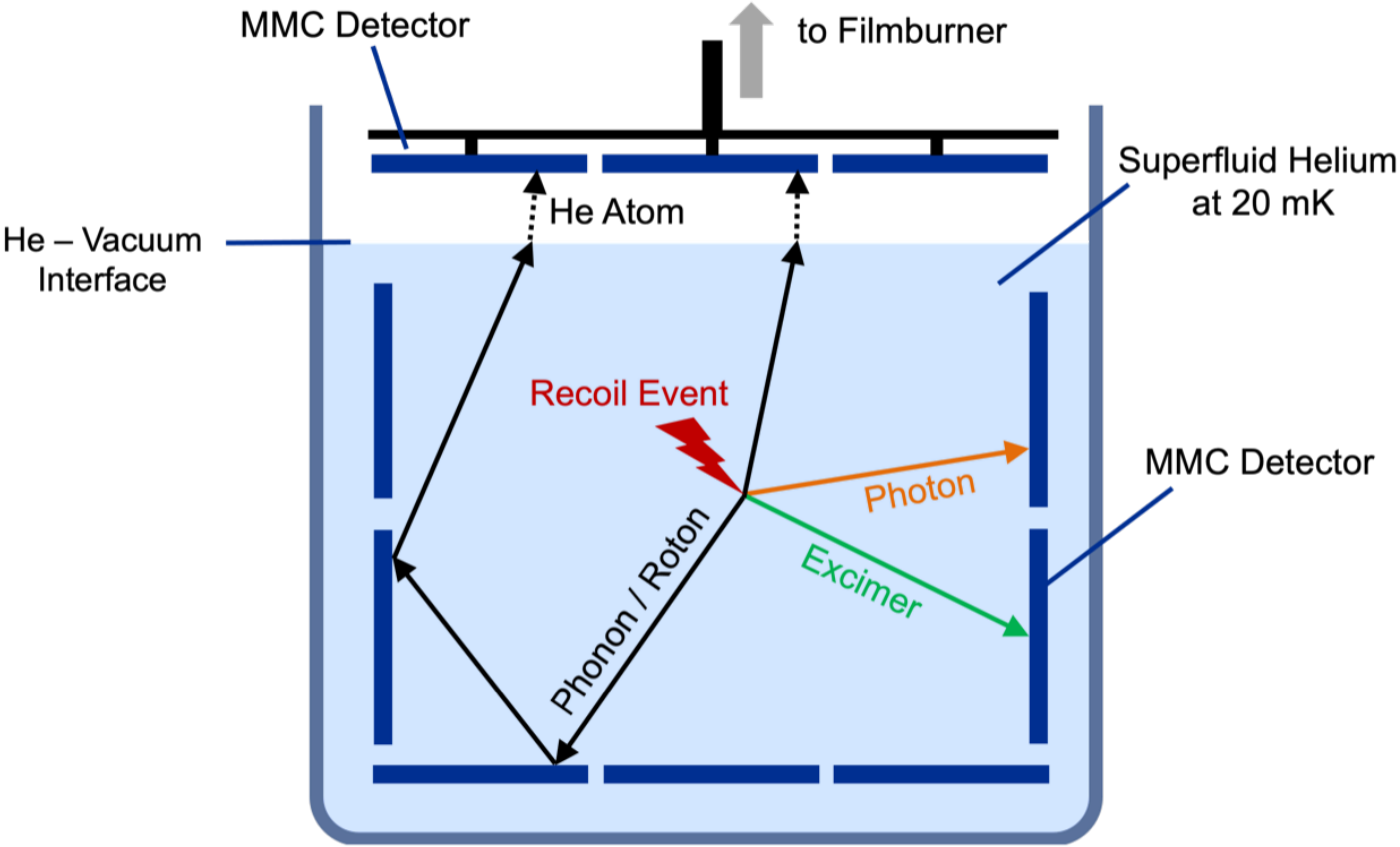


Vibrations: phonons and rotons



- Collective long-lived excitations in superfluid He
- Classified based on momentum
  - Phonons, R- rotons, R+ rotons
  - Roton ≈ high-momentum phonon

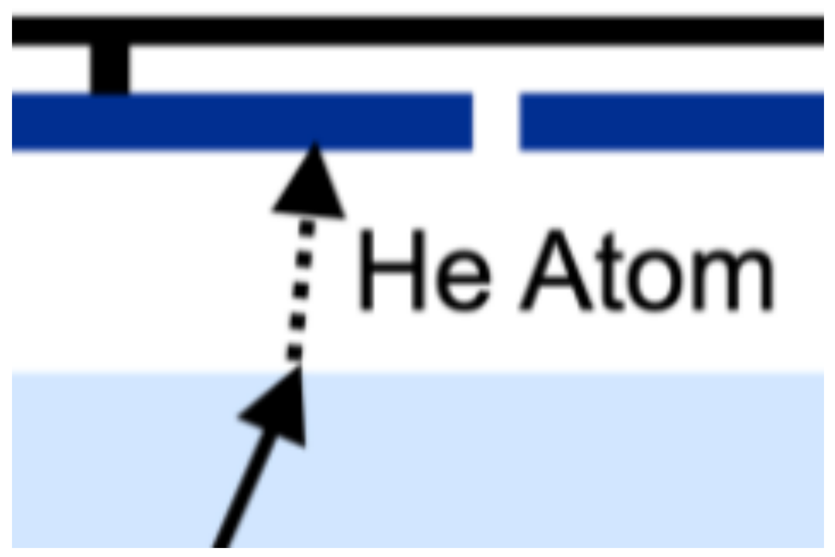
Vibrations: phonons and rotons

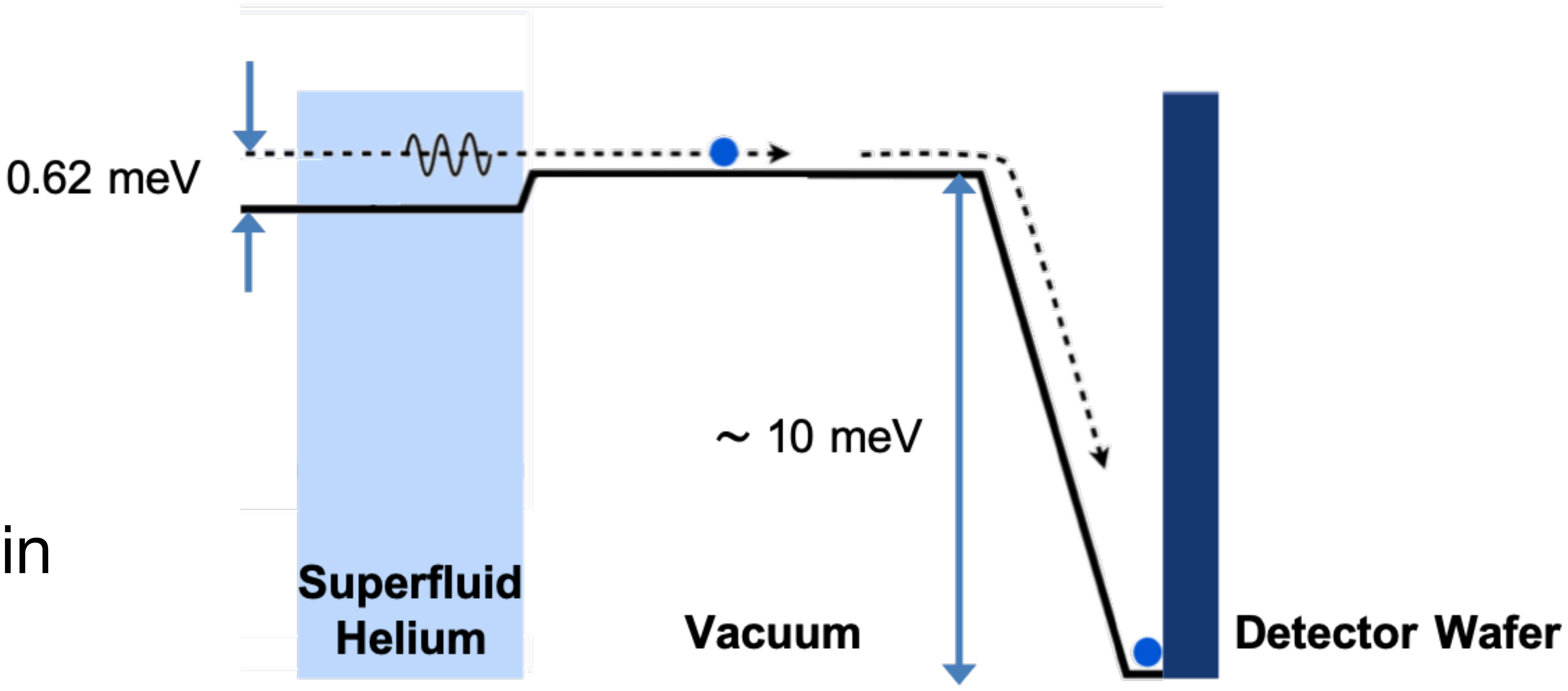


Vibrations: phonons and rotons

Phonon / Roton → Free He atom → He atom on solid

Quantum evaporation Condensation

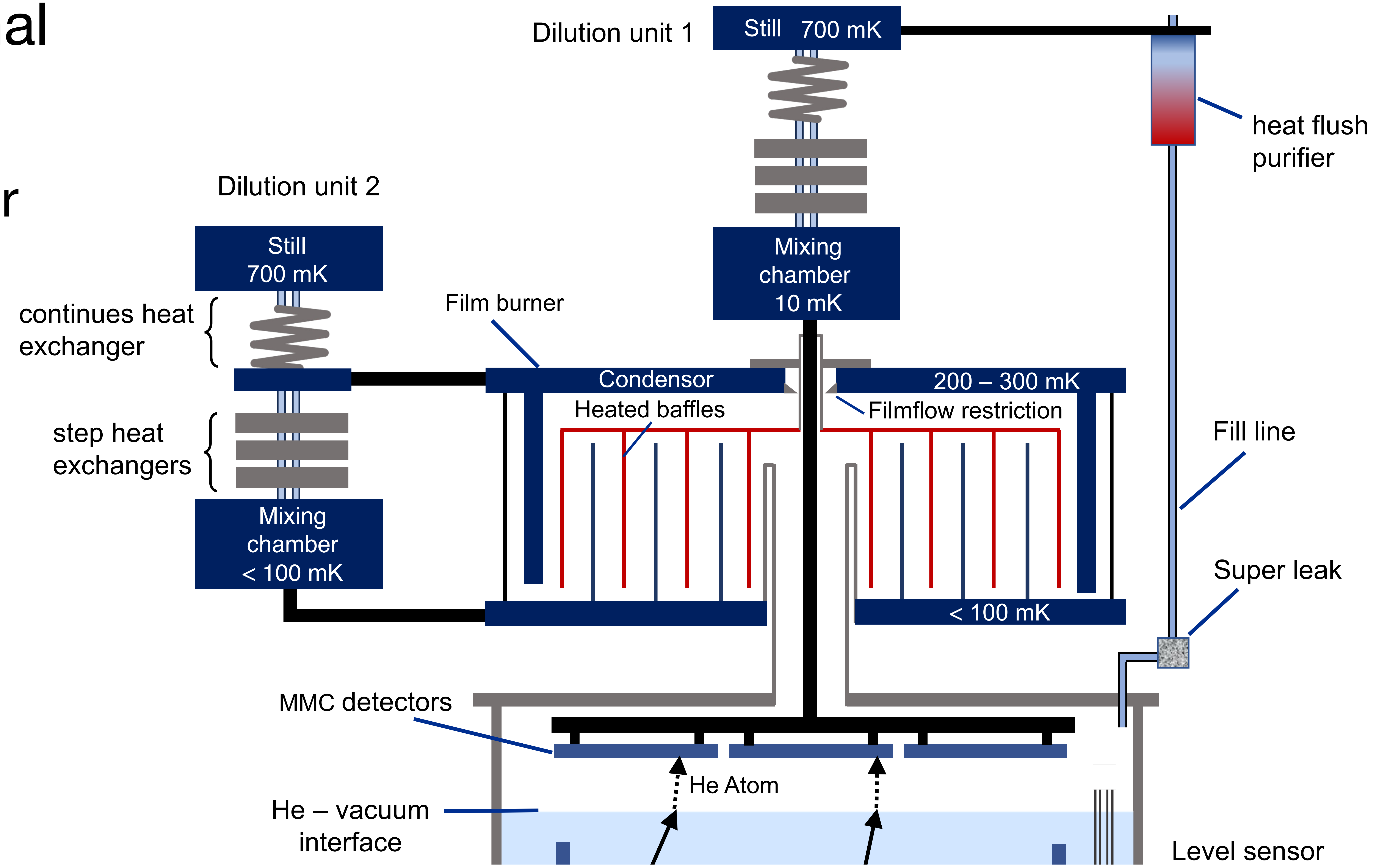




- Noise-free signal gain by a factor 10 to 40

The DELight concept

- Film burner to keep external MMC wafers He free
  - Maintain amplification factor



The DELight concept

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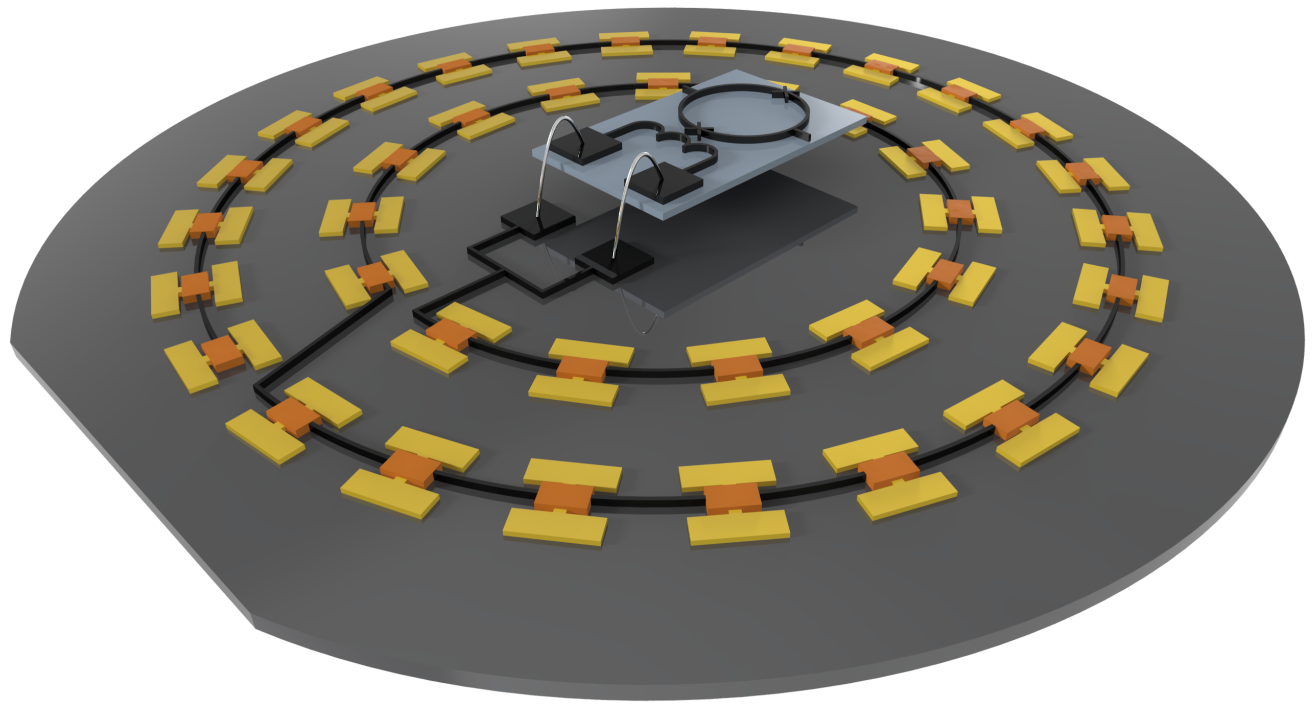
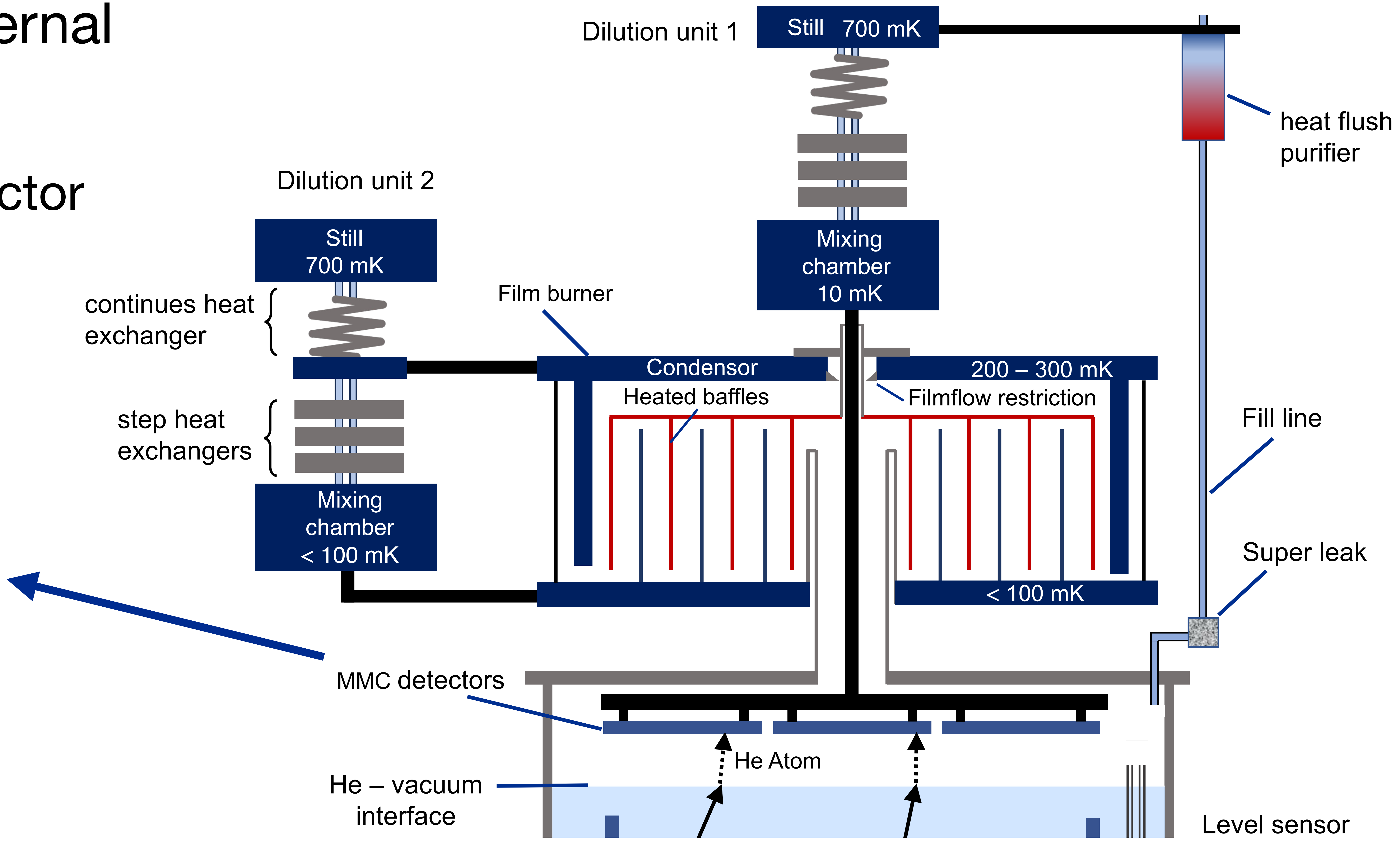
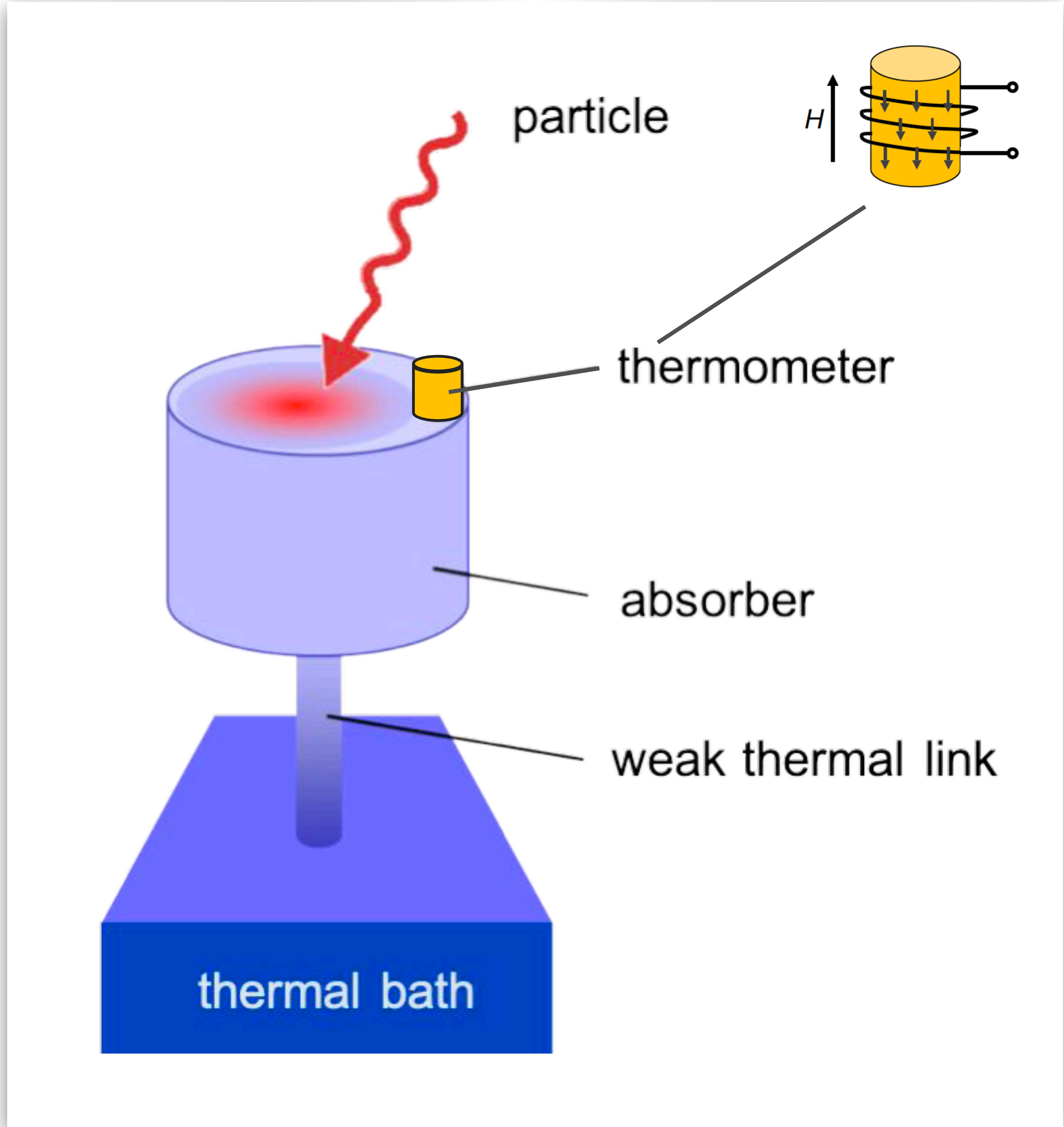
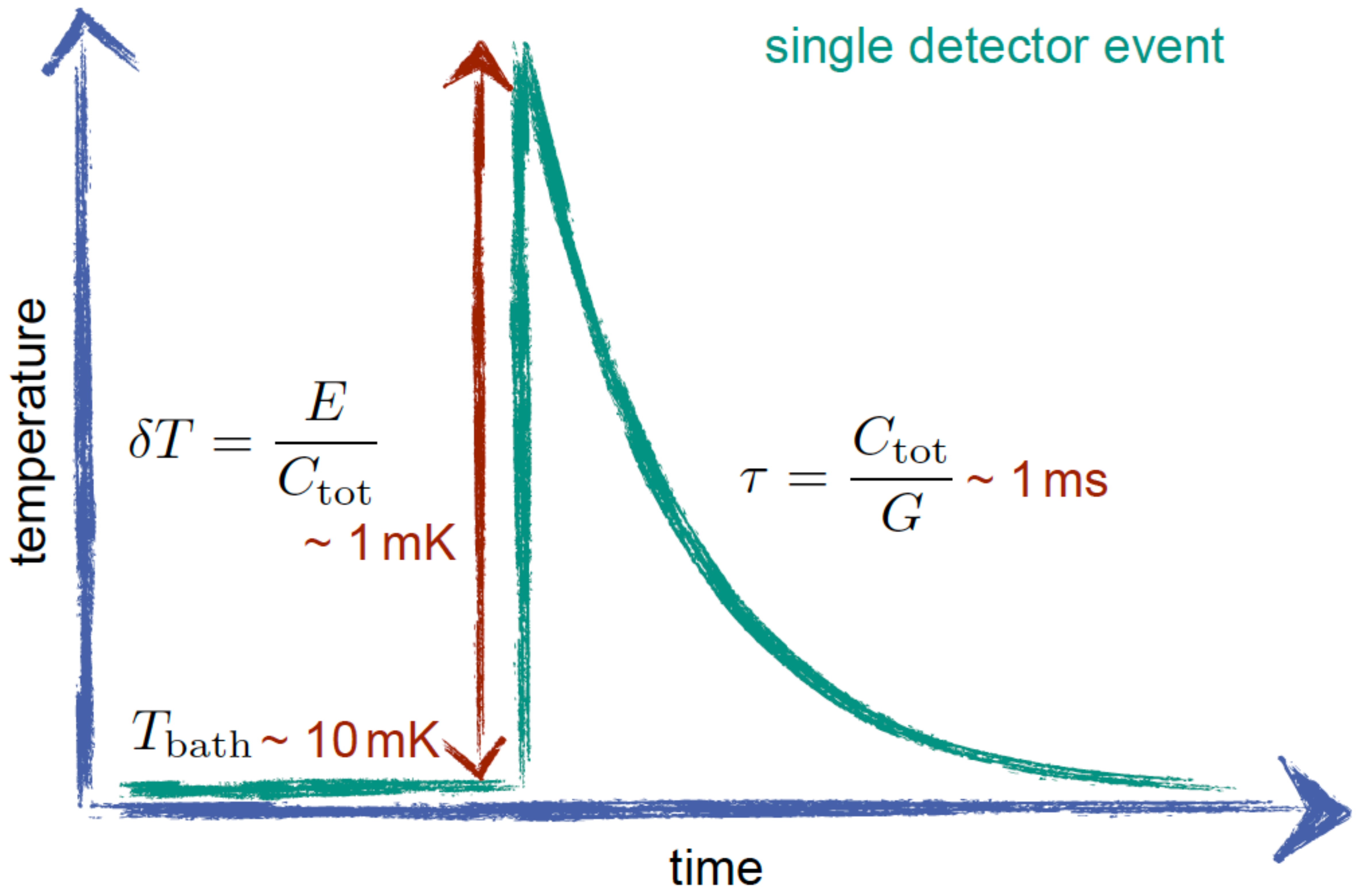


- 3-inch Si wafers of 300 µm thickness

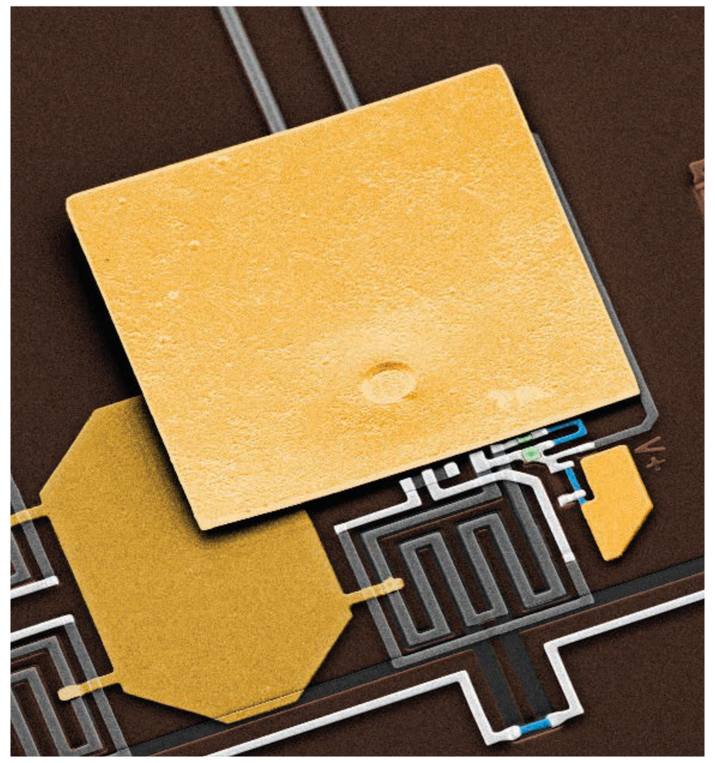


MMC: Magnetic MicroCalorimeter





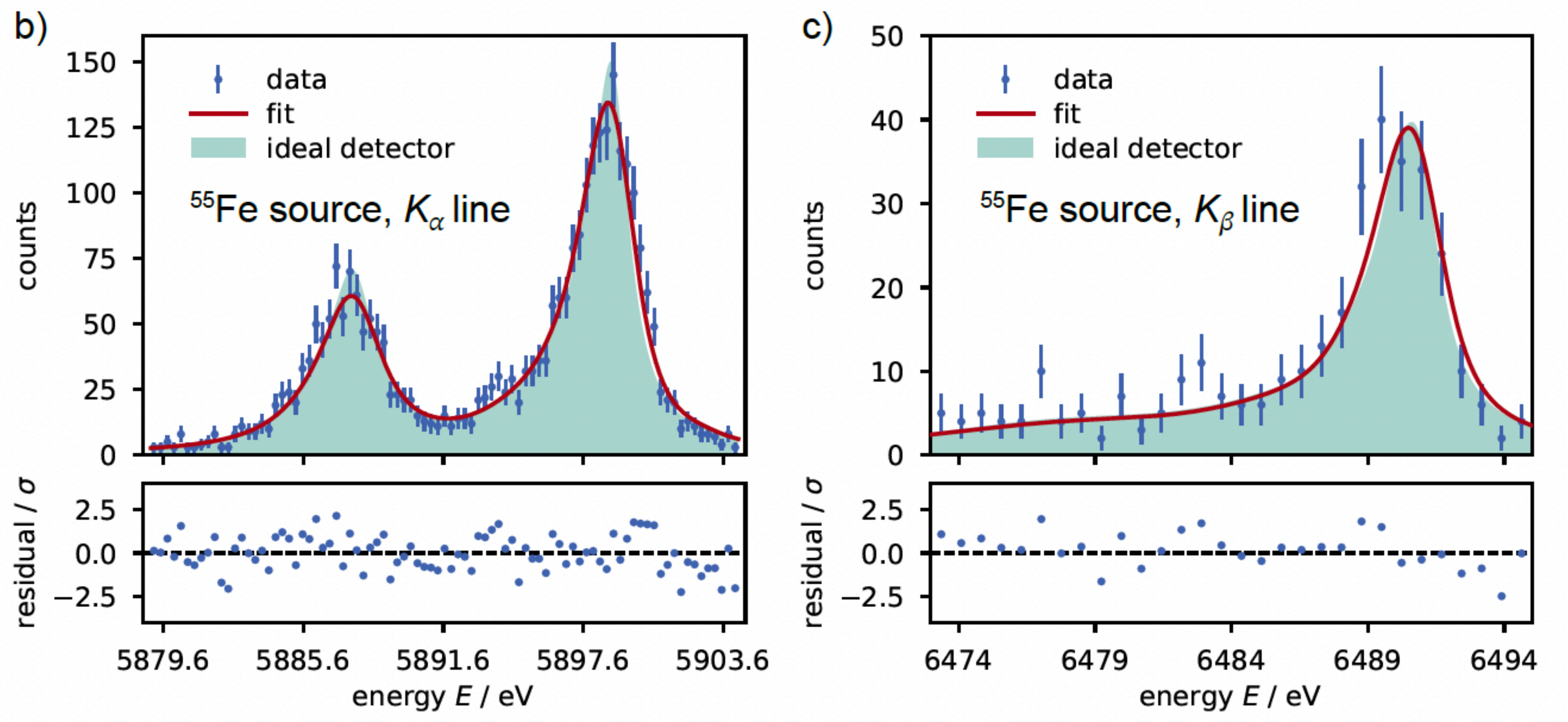
Current R&D activities: DELight

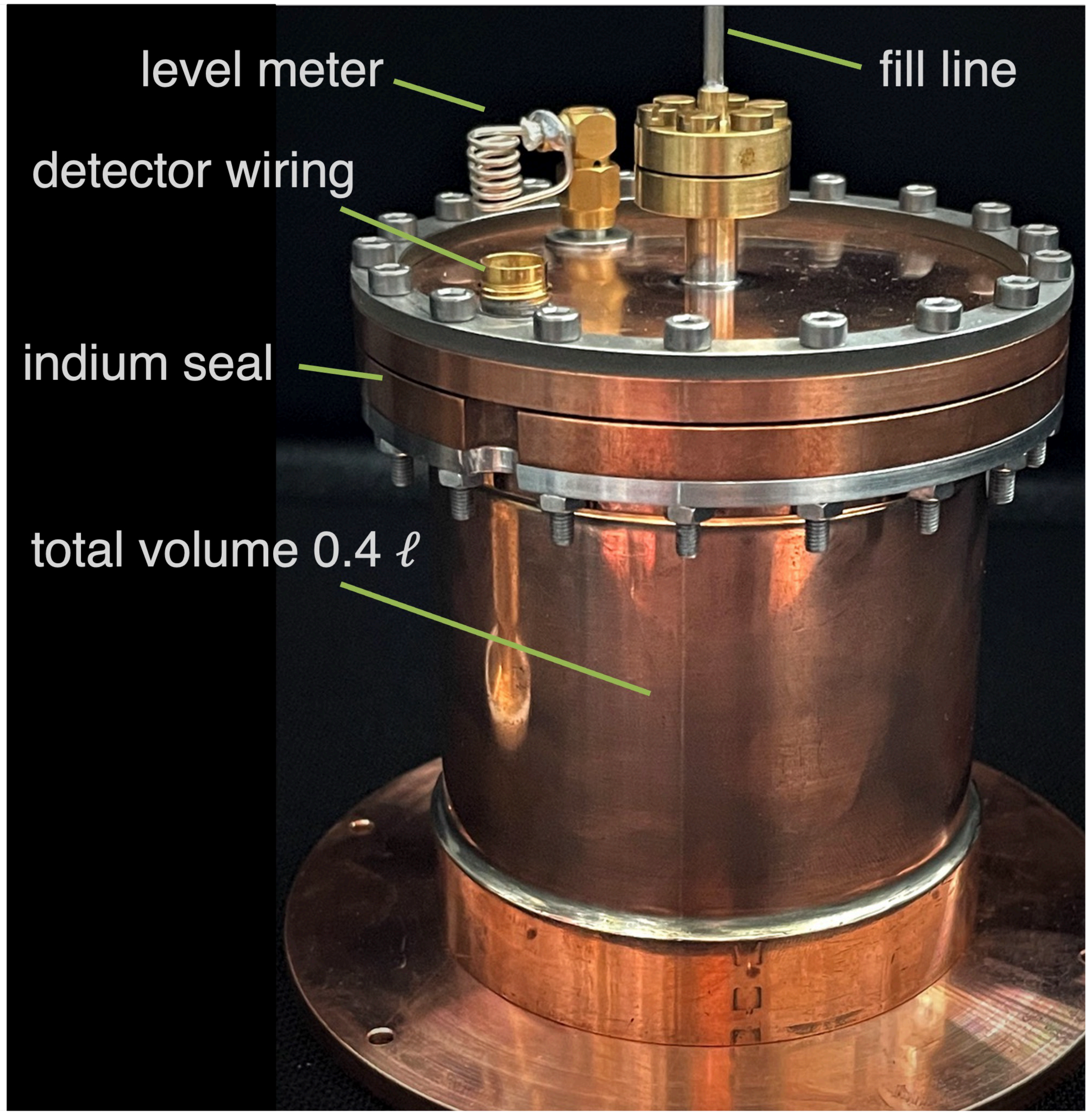


- R&D program started
  - DELight v0 cell built
    - first run expected this/next month
  - existing MMCs as test-bed

[arXiv:2310.08698](https://arxiv.org/abs/2310.08698)

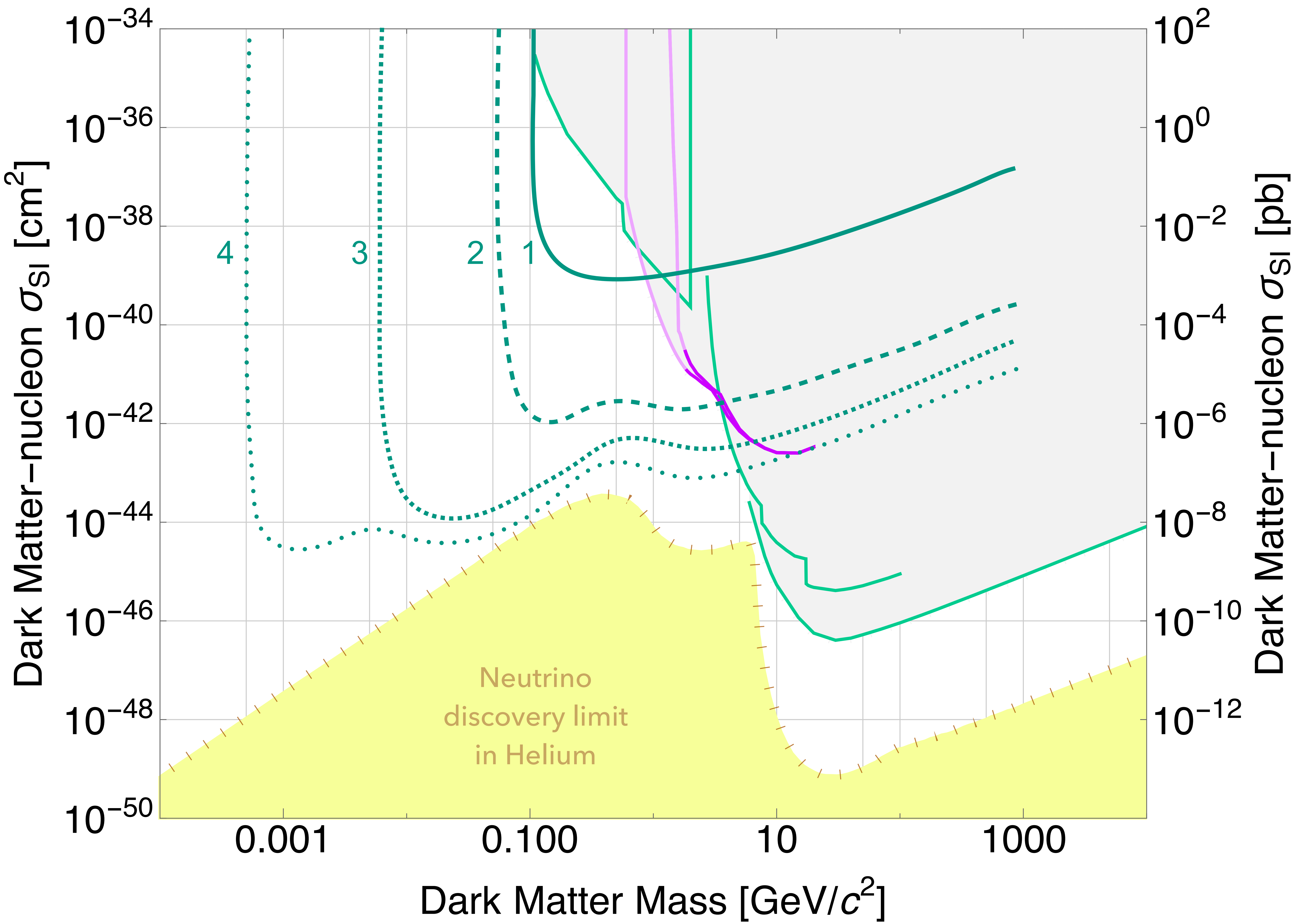
[arXiv:2310.08512](https://arxiv.org/abs/2310.08512)





$$\Delta E_{\mathrm{FWHM}} = \left(1.25 \pm 0.17(\mathrm{stat})^{+0.05}_{-0.07}(\mathrm{syst})\right)\ \mathrm{eV}$$

Towards light dark matter with superfluid ^{4}He



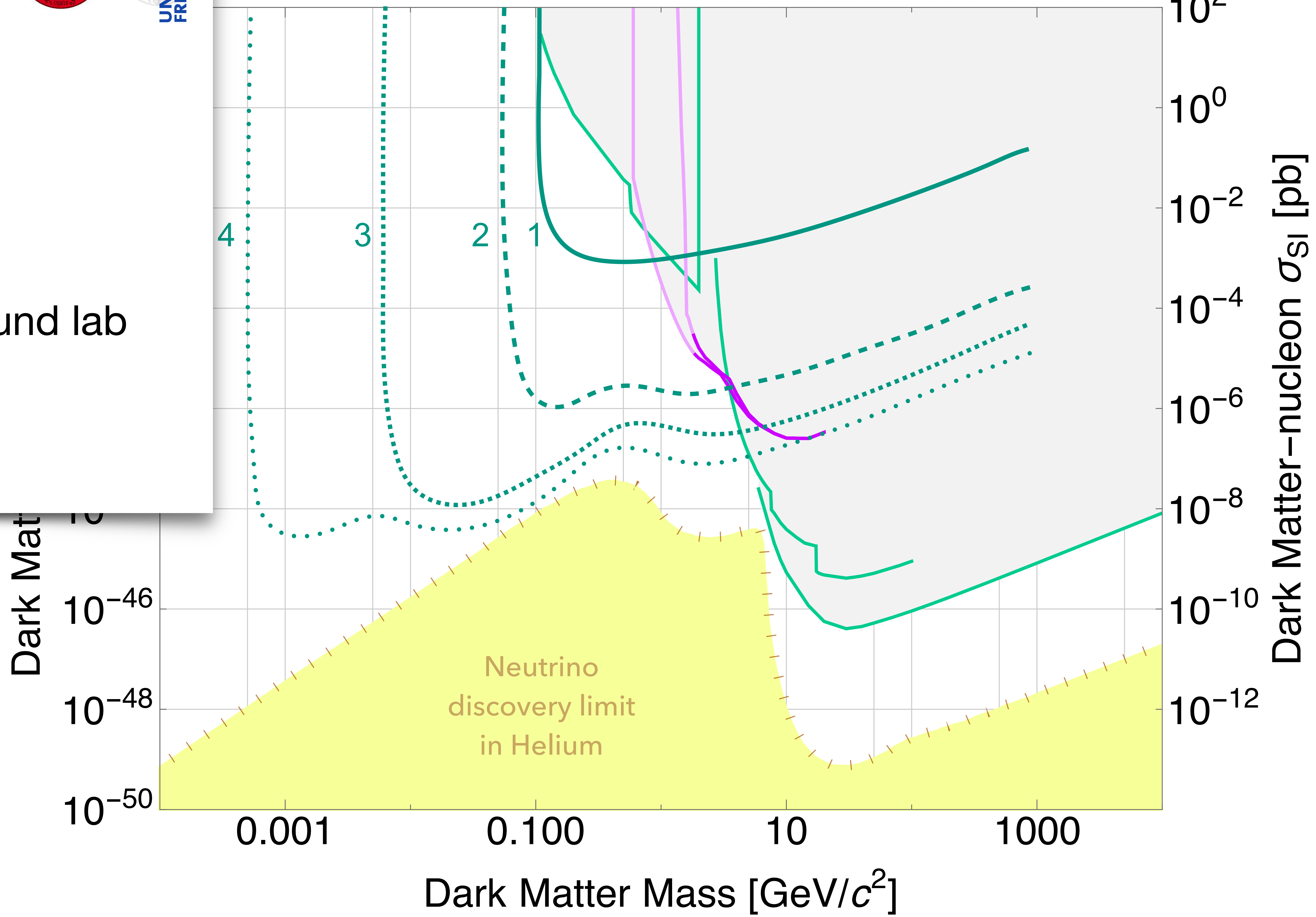
HeRALD

S. A. Hertel et al.
Phys. Rev. D 100, 092007 (2019)

- He projections:
  - 1: 1 kg•d, 40 eV
  - 2: 1 kg•yr, 10 eV
  - 3: 10 kg•yr, 0.1 eV
  - 4: 100 kg•ry, 1 meV

Towards light dark matter with superfluid 4He

- **<u>DELight</u>** <u>Phase 1:</u>
  - 10 L cell in shallow lab
  - 1 kg•d exposure
  - 20-30 eV threshold
- Long range plan:
  - Up to 200 L cell in underground lab
  - O(kg•yr) exposure
  - <10 eV threshold



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