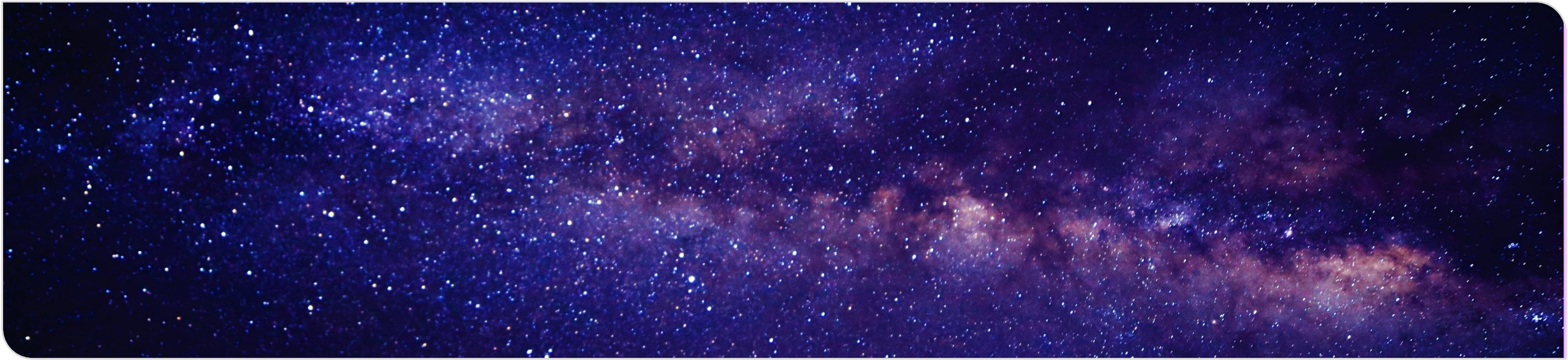
# Signal partitioning in superfluid $^4$He: A Monte Carlo approach

*Francesco Toschi* *on behalf of the DELight collaboration*

*DPG Spring Meeting, Göttingen*

*31.03.2025*

Phys. Rev. D **111**, 032013



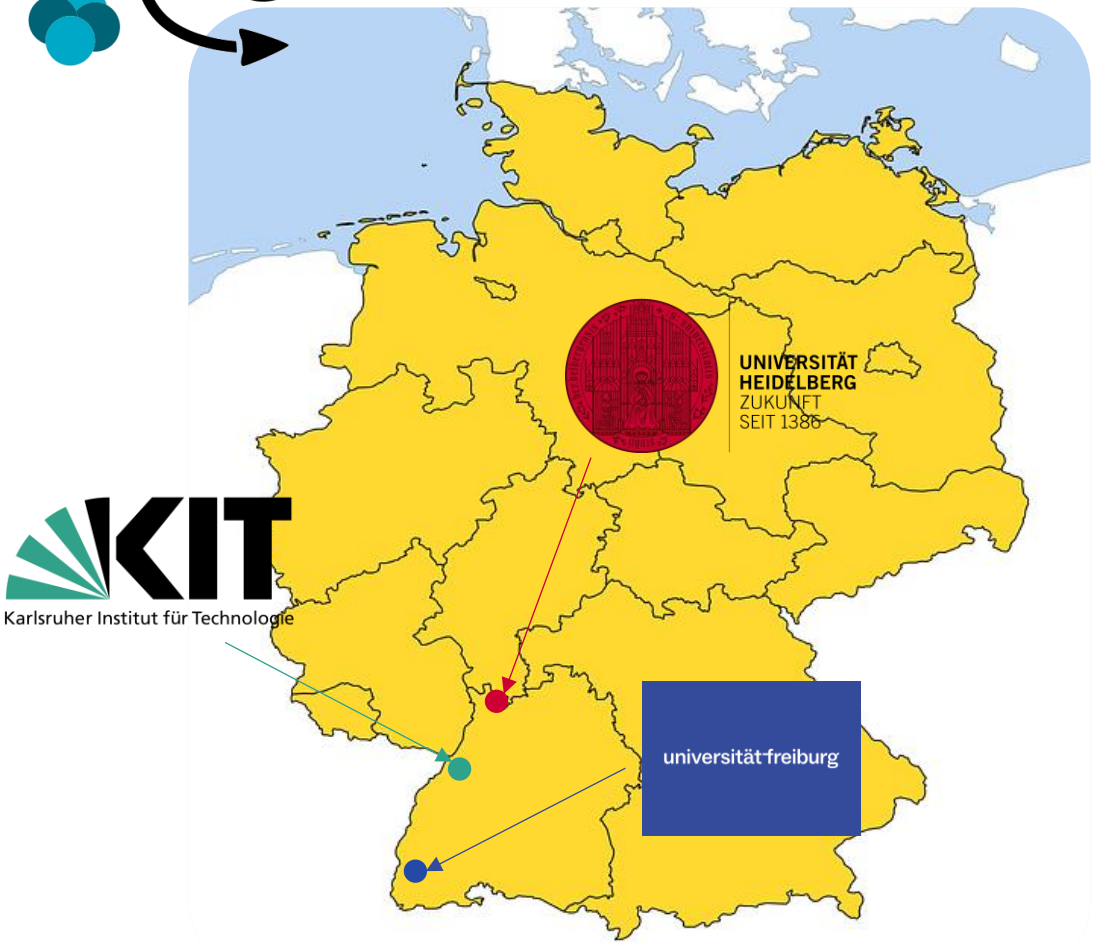
# The DELight collaboration

DELight

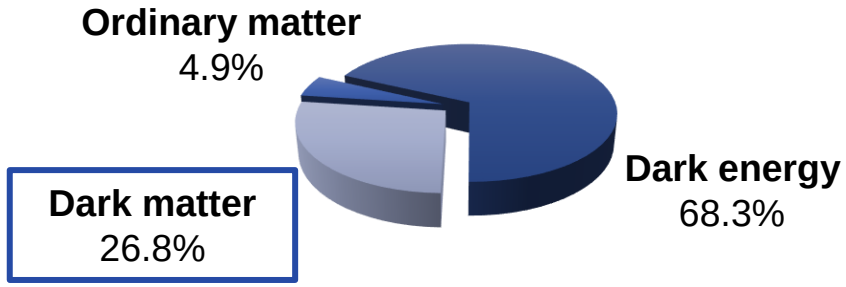
Karlsruhe Institute of Technology

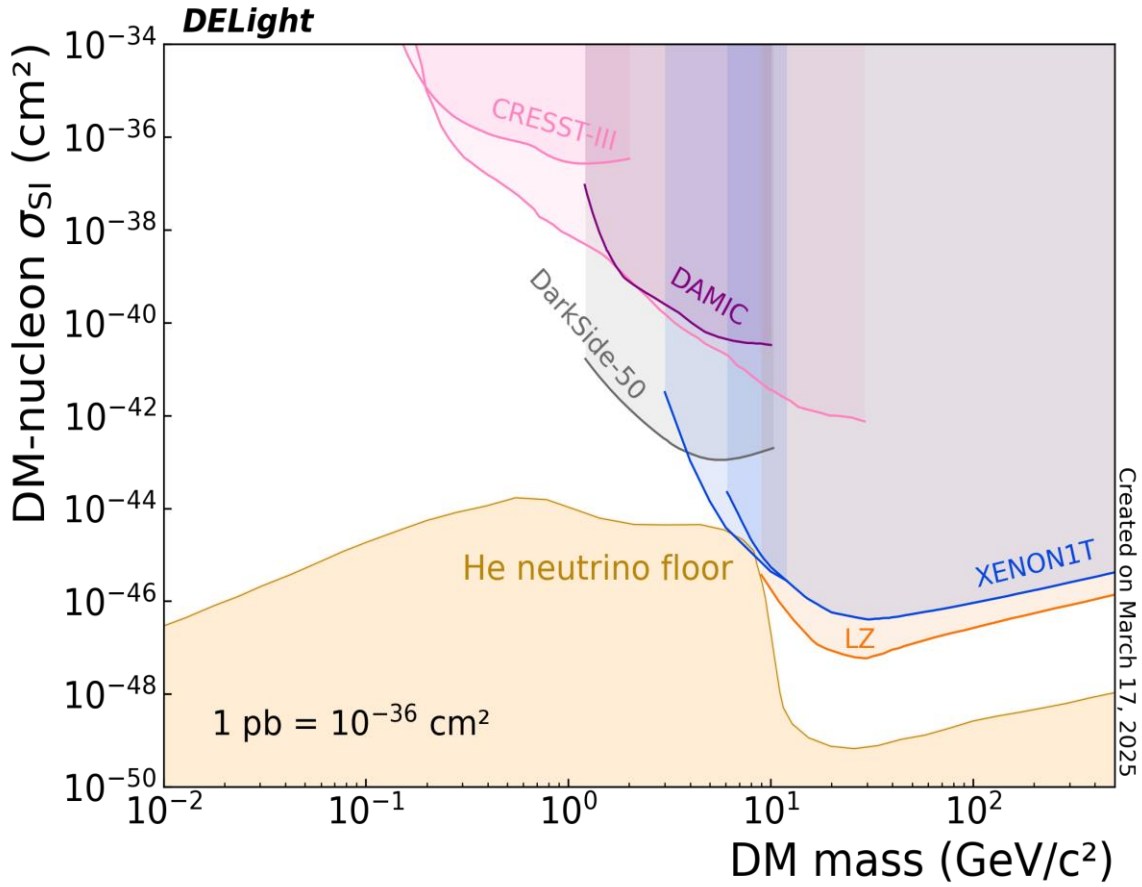
3 institutes from Baden-Württemberg

~20 scientists



# The hunt for Dark Matter



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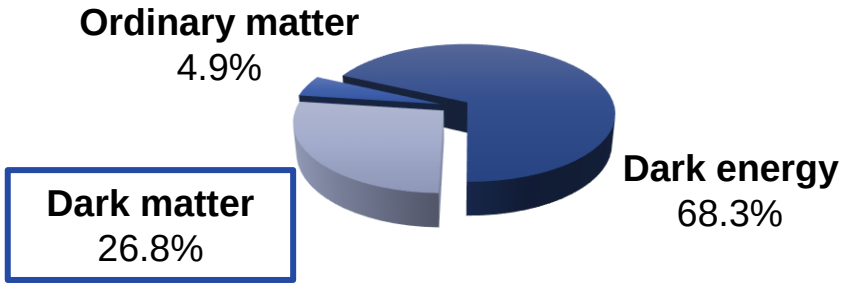
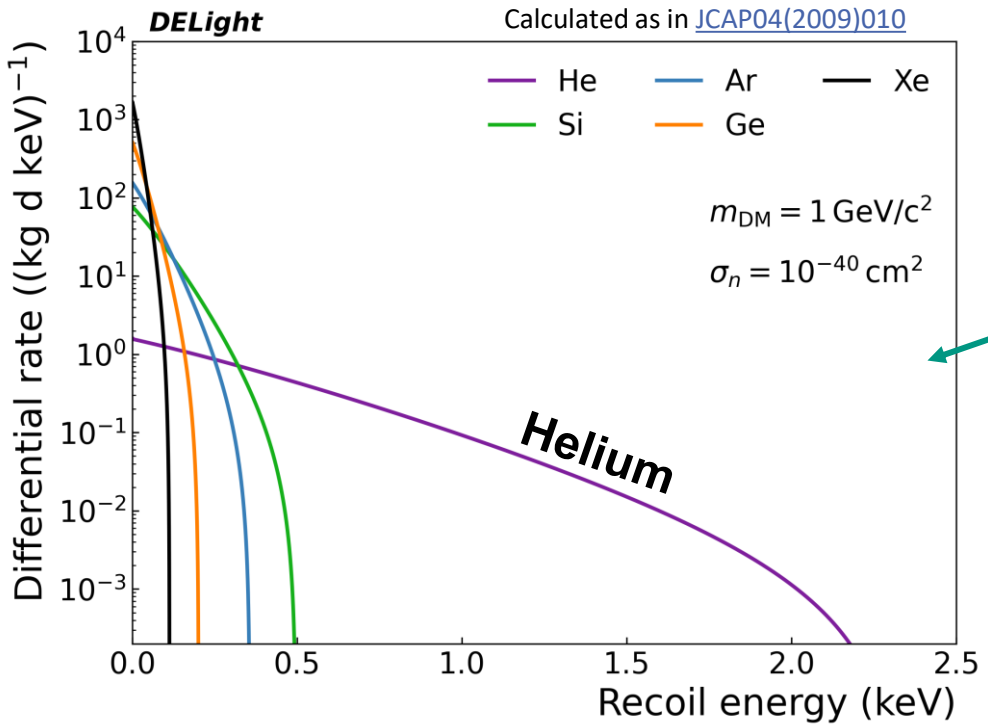
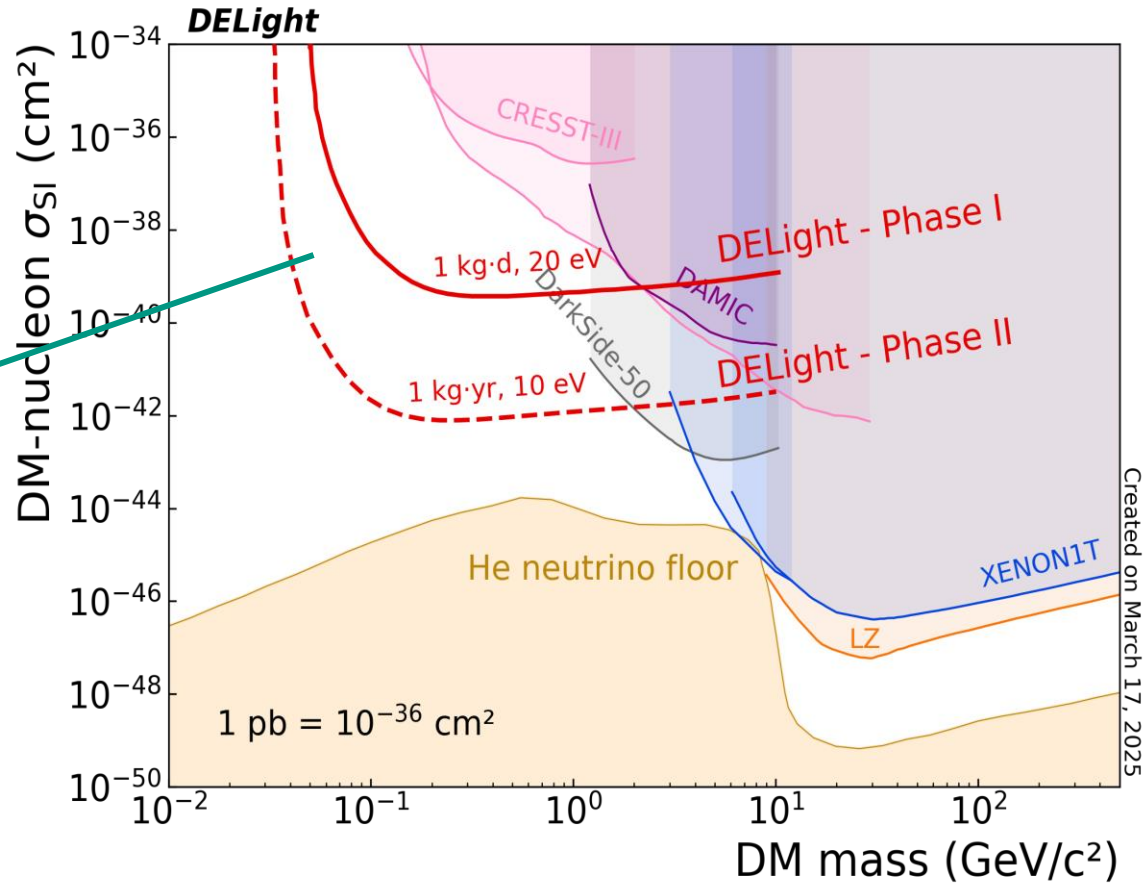
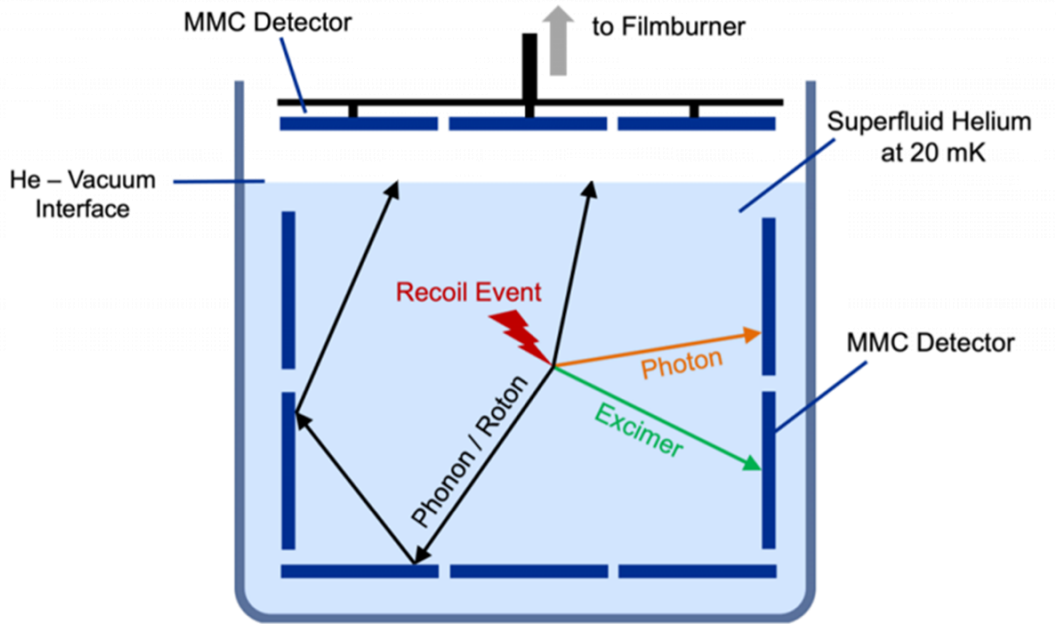


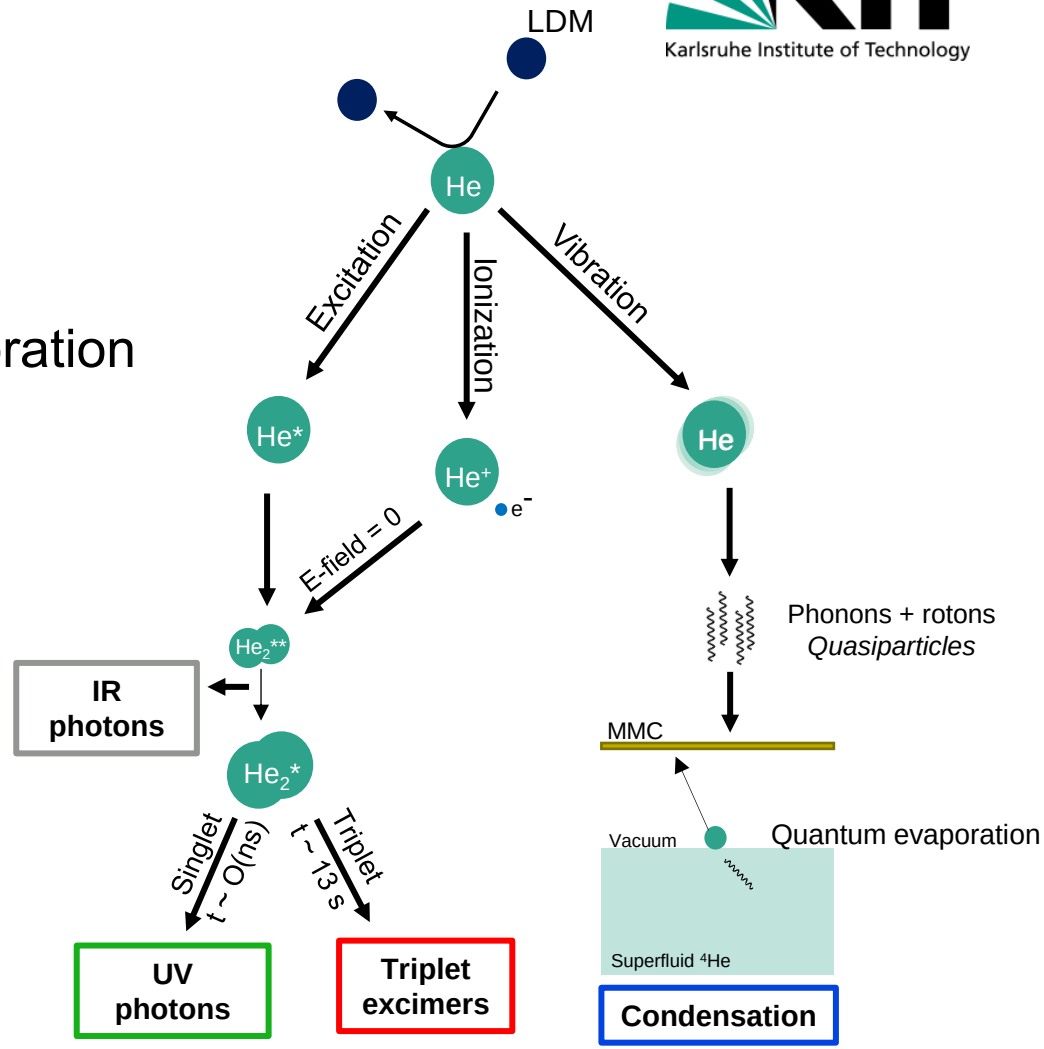



# DELight detection principle

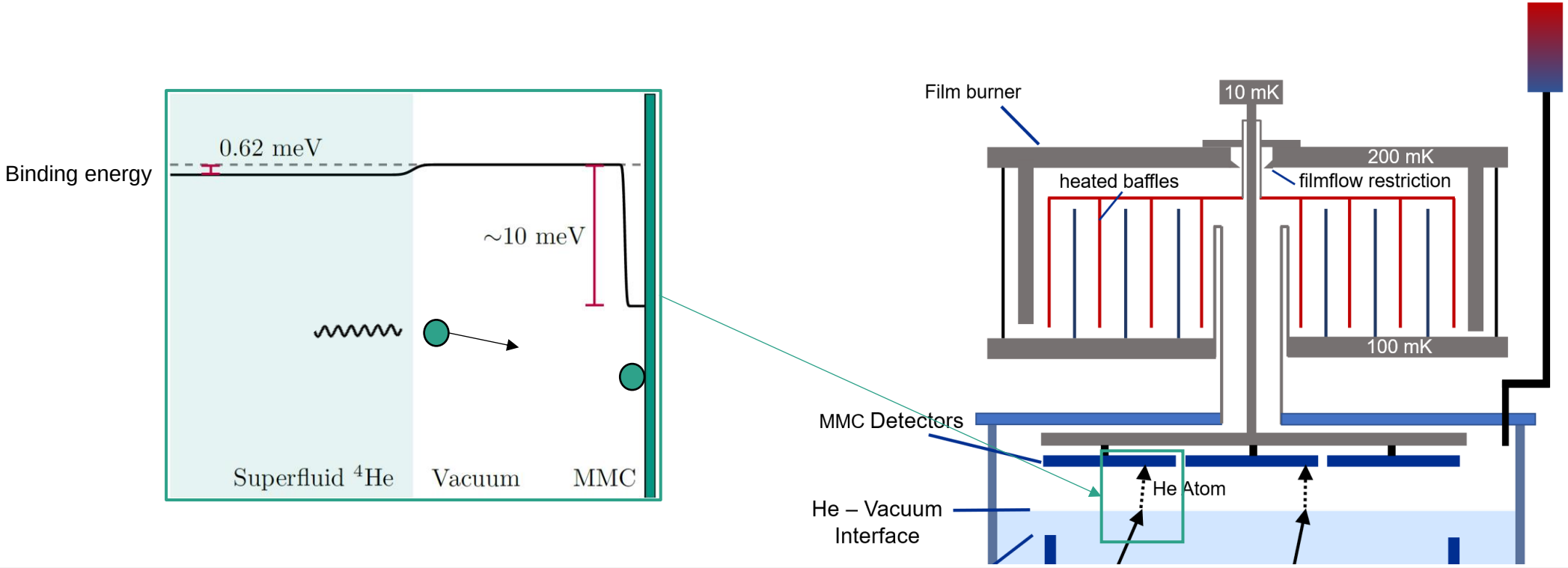
- Prompt detection of UV and IR photons
- Ballistic triplet excimer → decay at surface
- Quasiparticles propagate ballistically → quantum evaporation



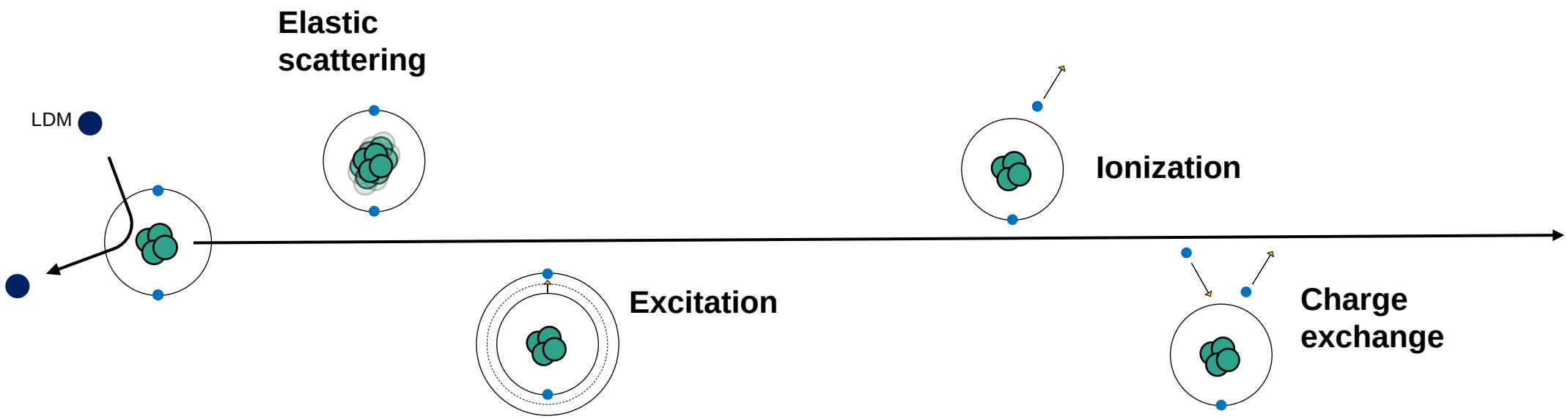



# DELight quasiparticle detection principle

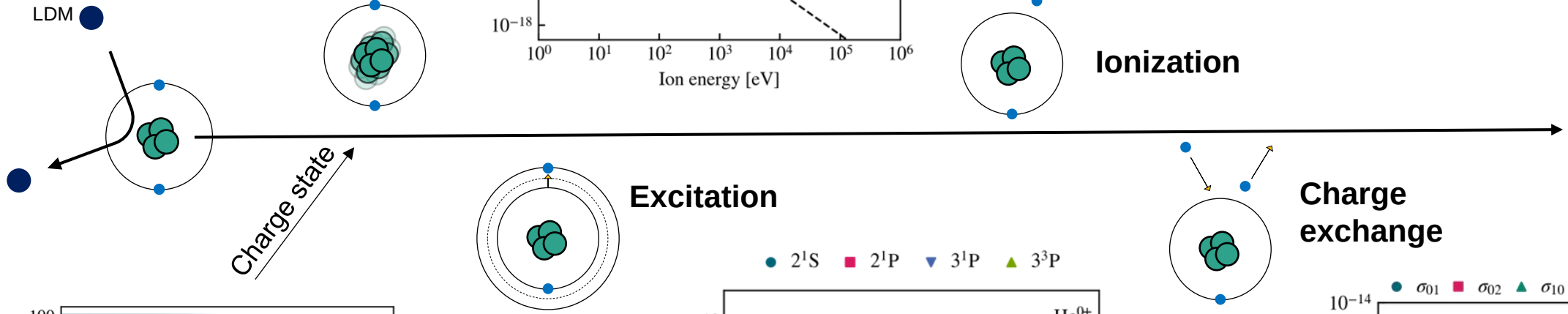
- Noise-free gain $\gtrsim$10 in the MMC as binding energy He-He is smaller than He-absorber
- MMCs in vacuum need to be $^4$He film-free → film burner



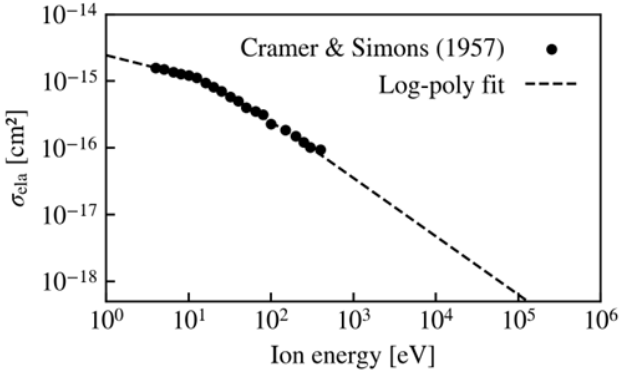
# The journey of a helium ion



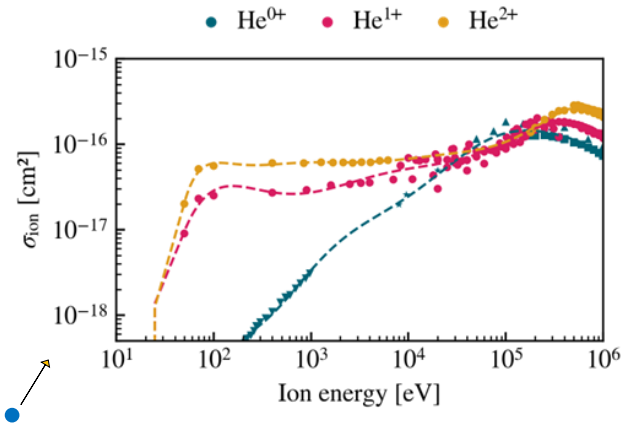
# The journey of a helium ion



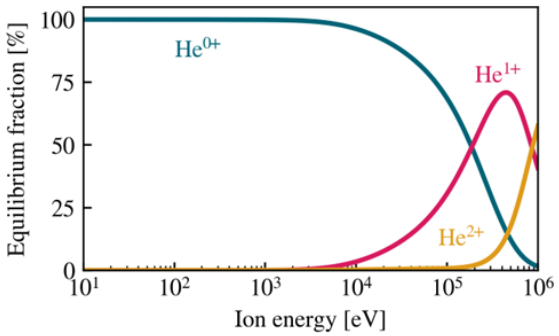

**Elastic scattering**

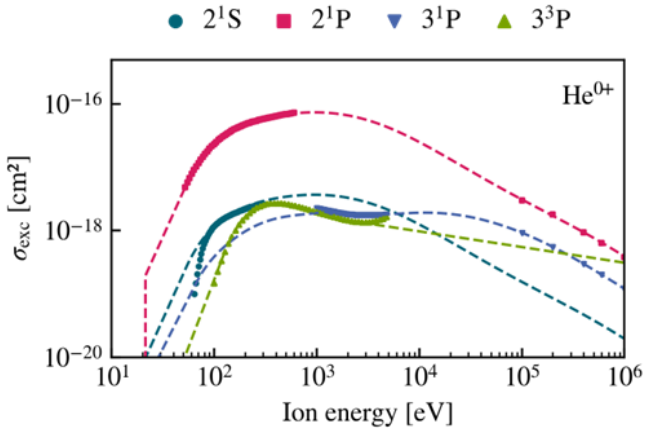



**Ionization**

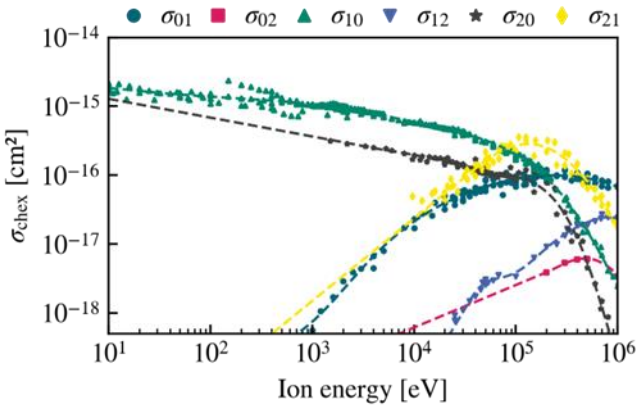



**Excitation**

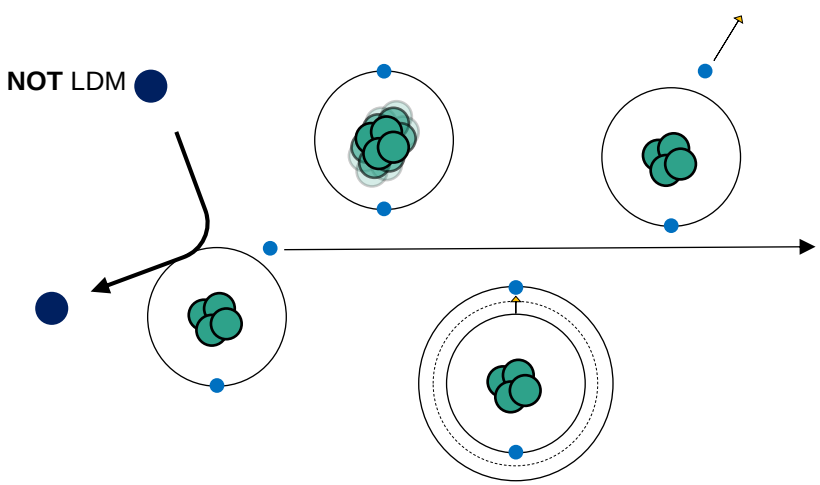


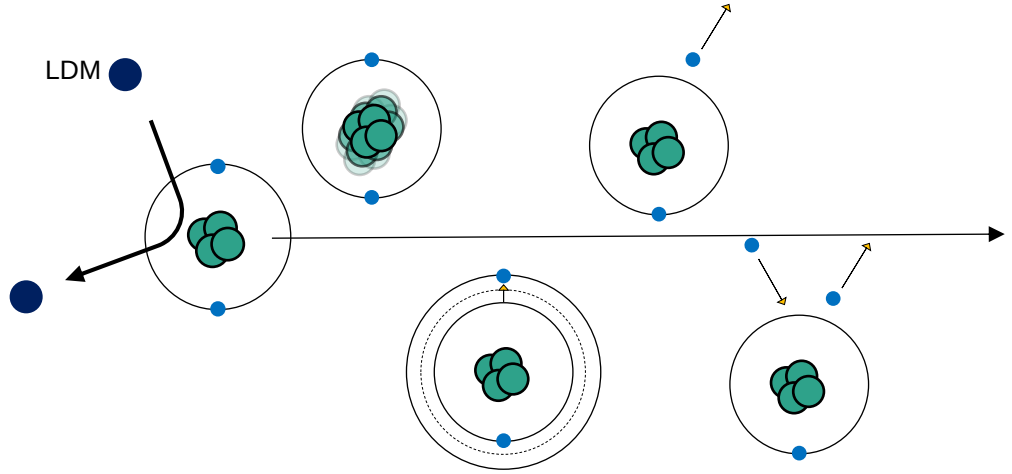



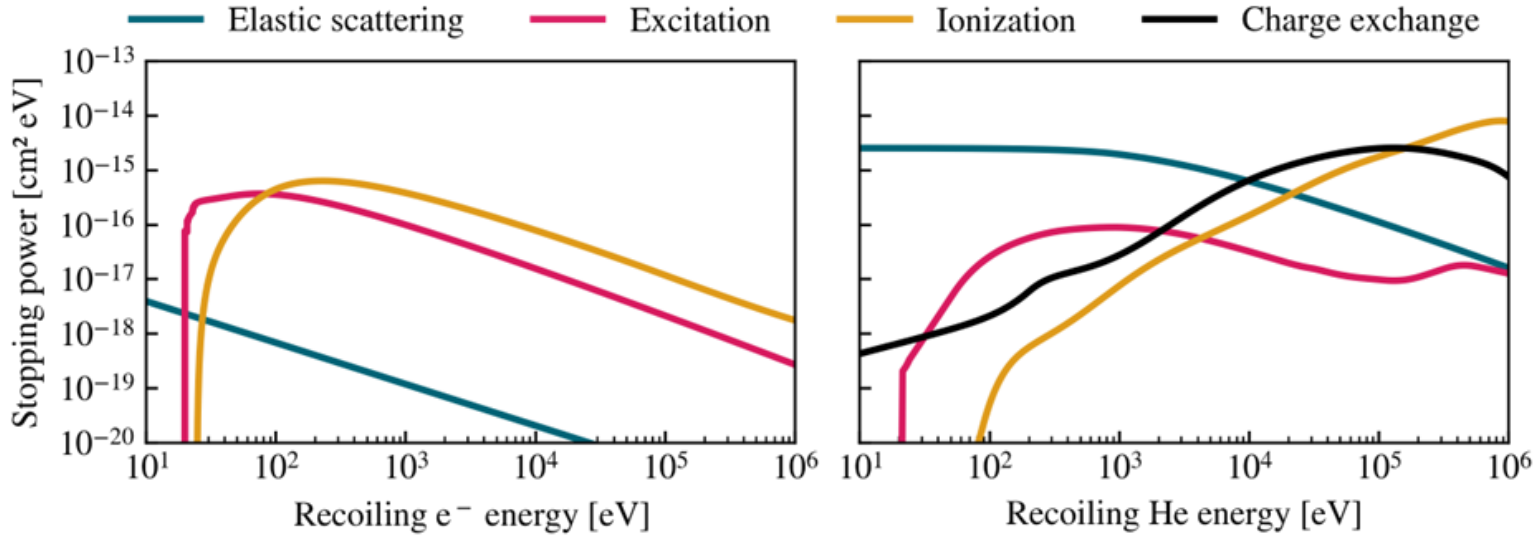

**Charge exchange**



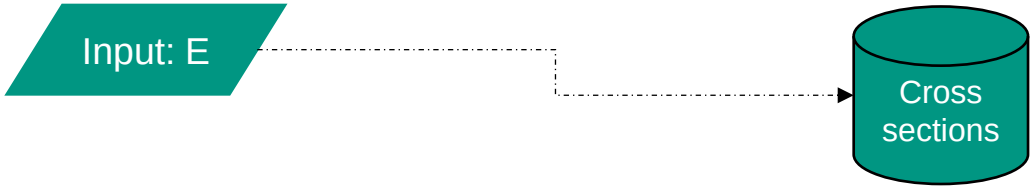
# Recoil of electrons (ER) vs. helium ions (NR)



# From interactions to signal quanta (ER)



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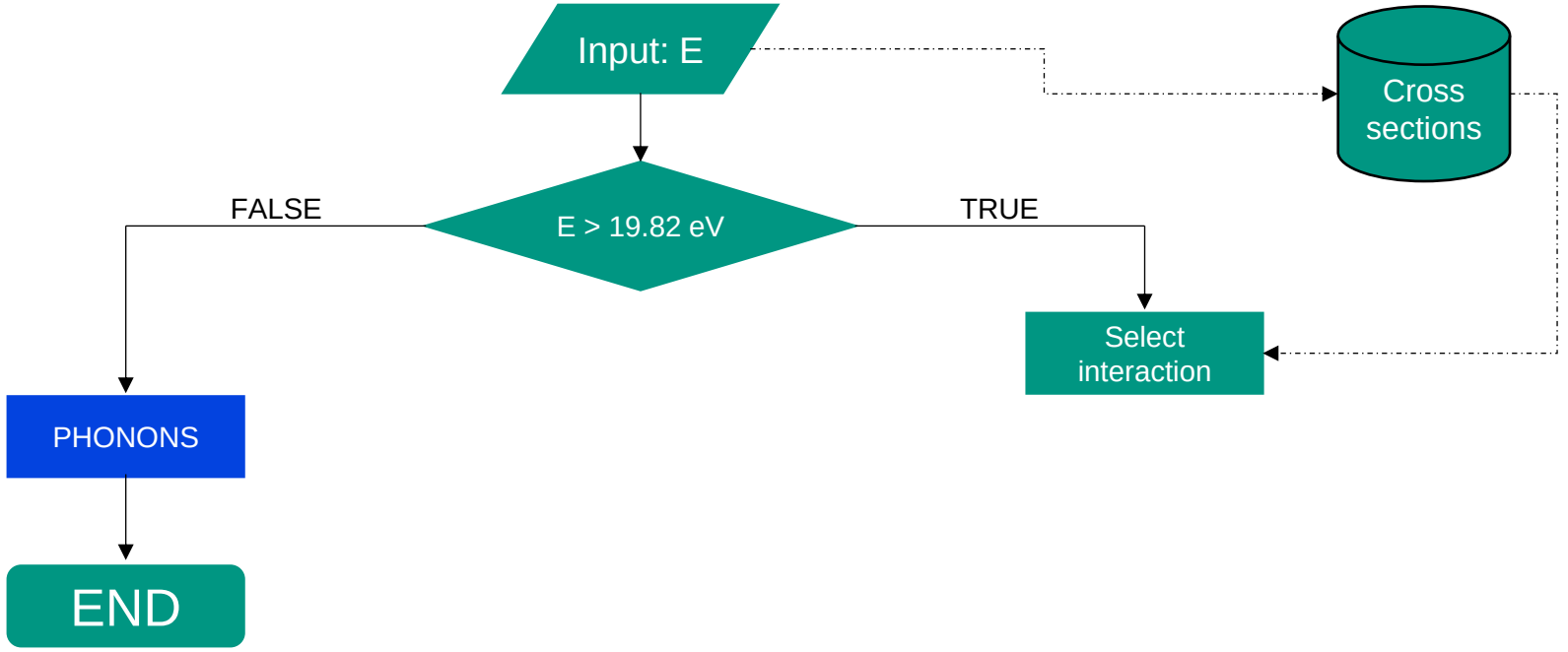

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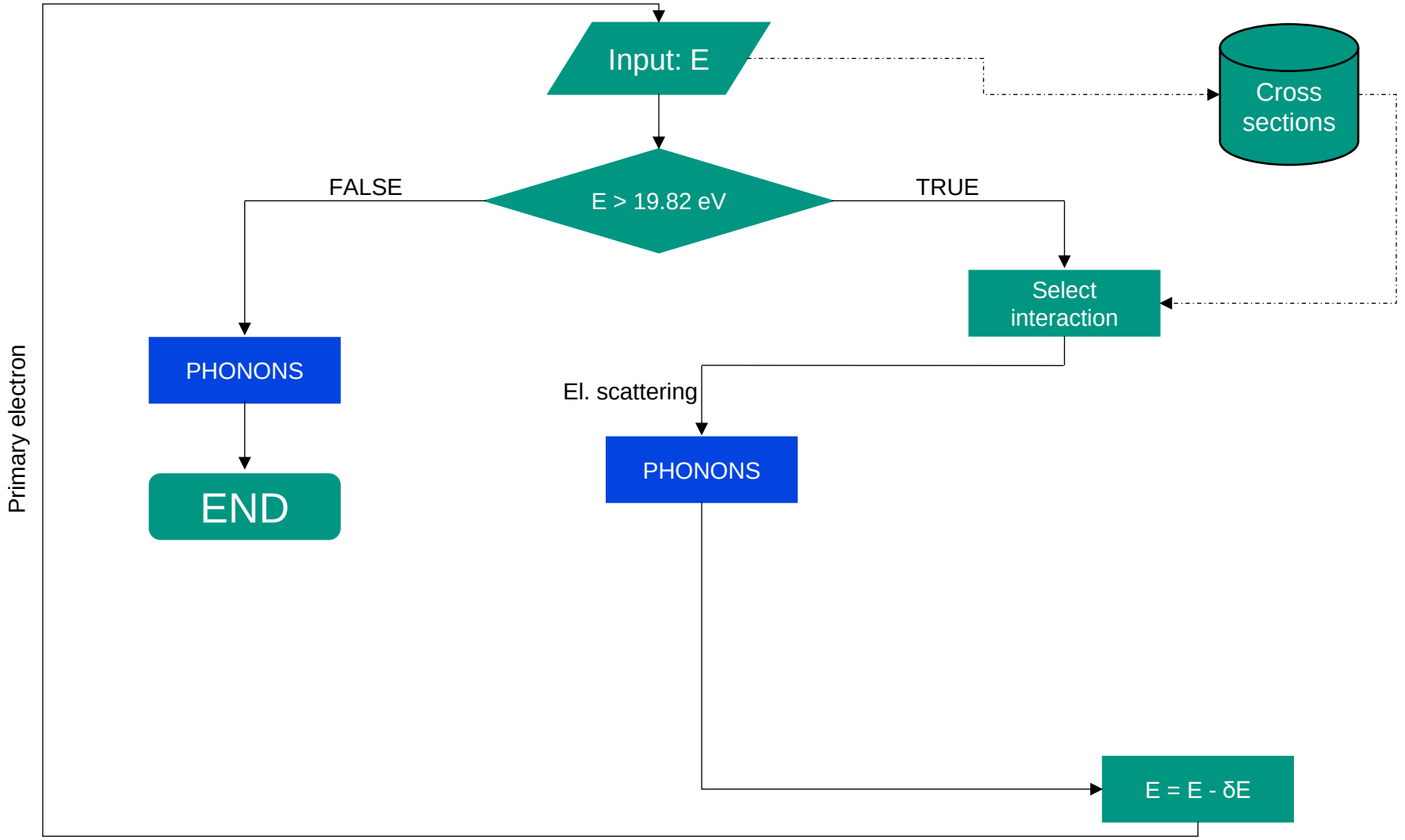

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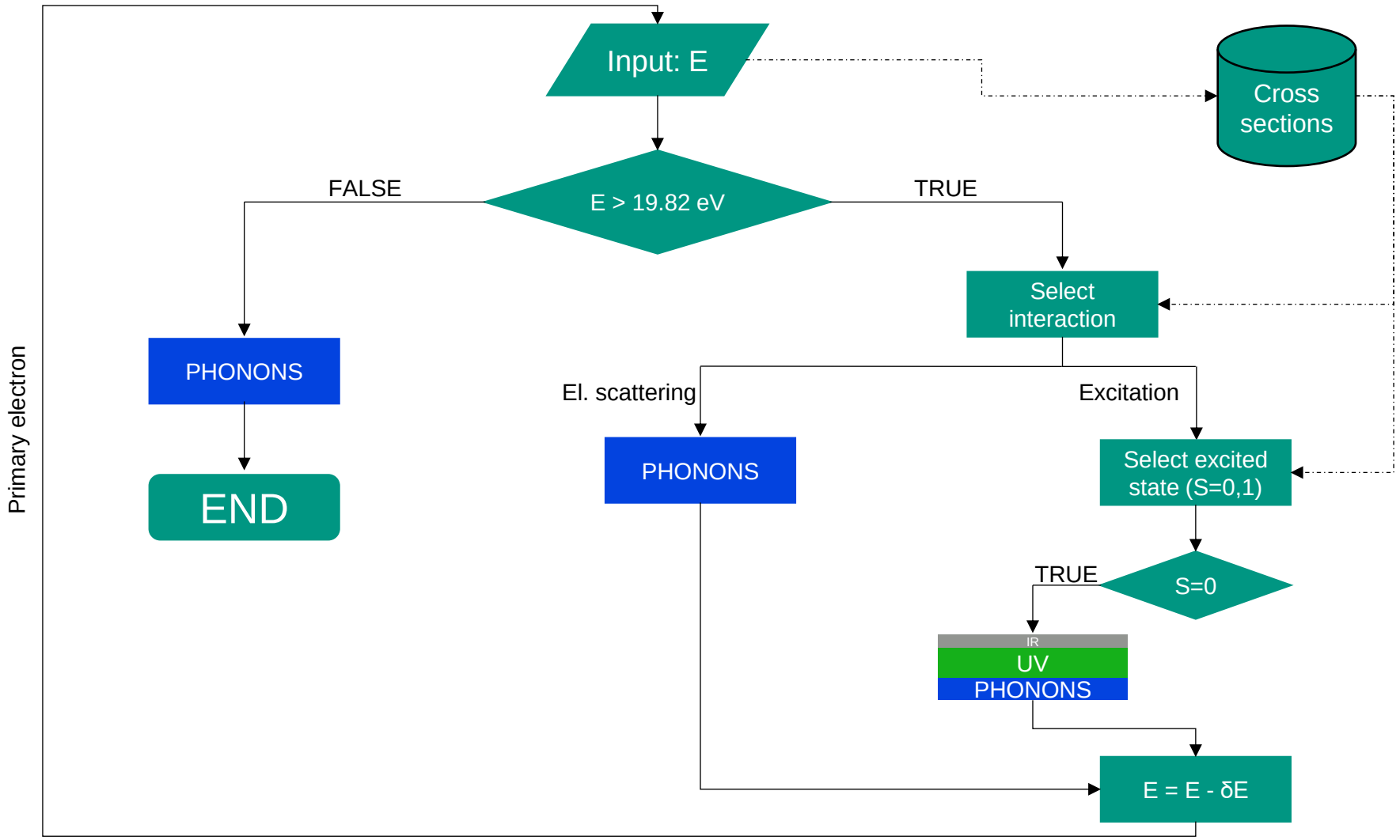


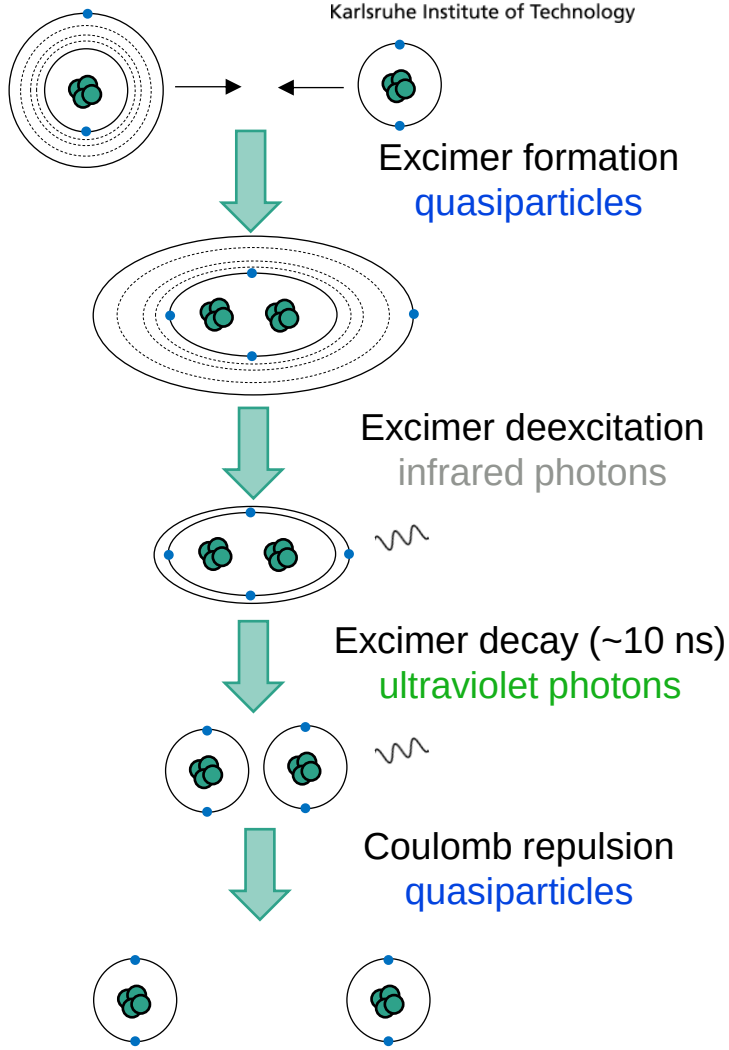

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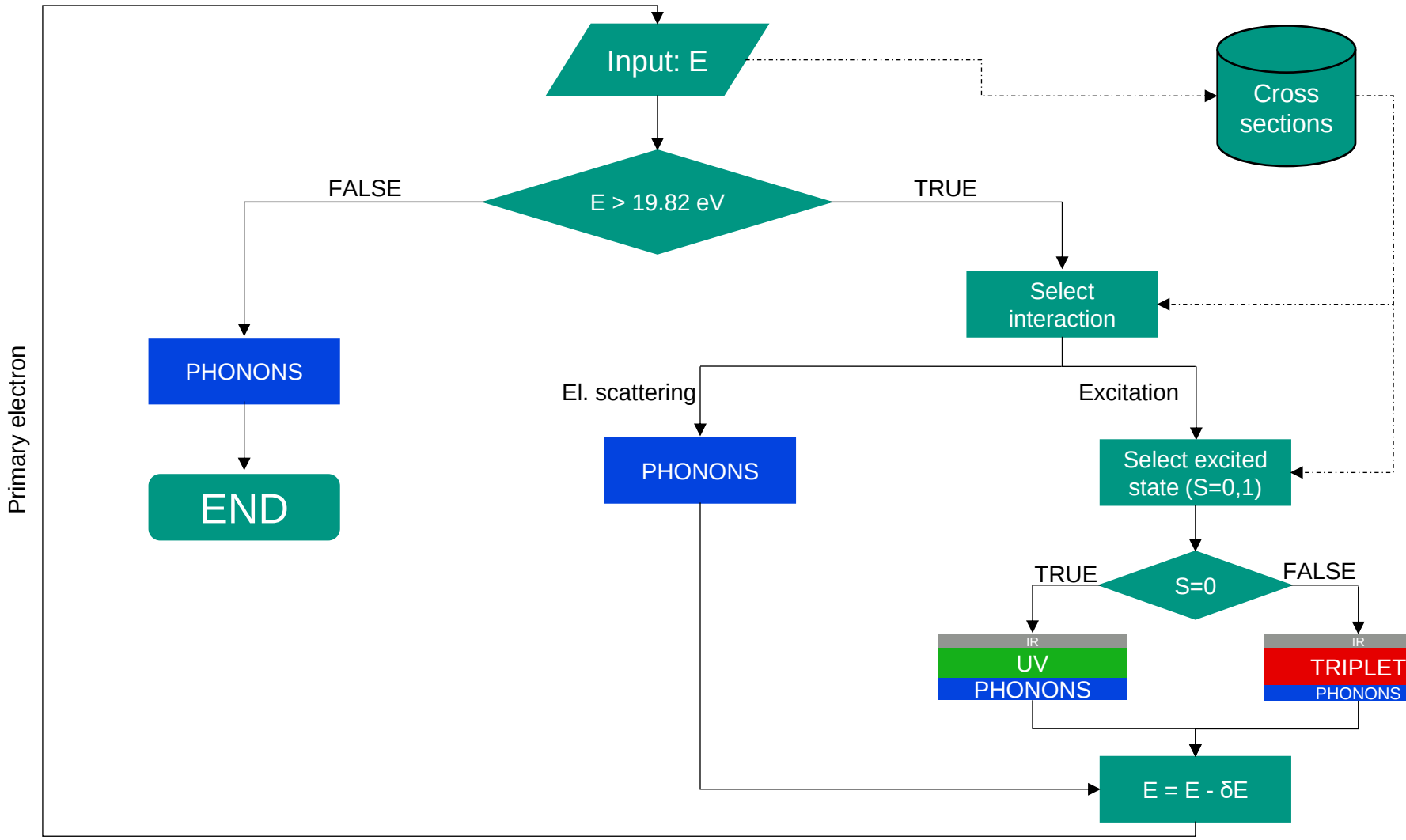


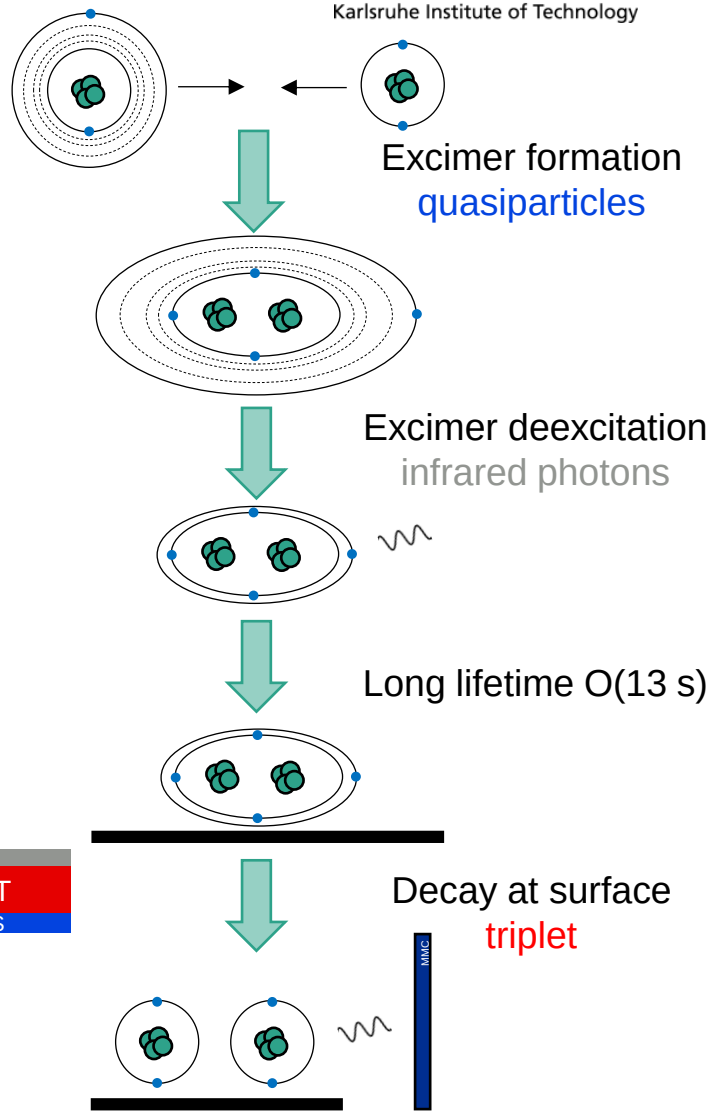

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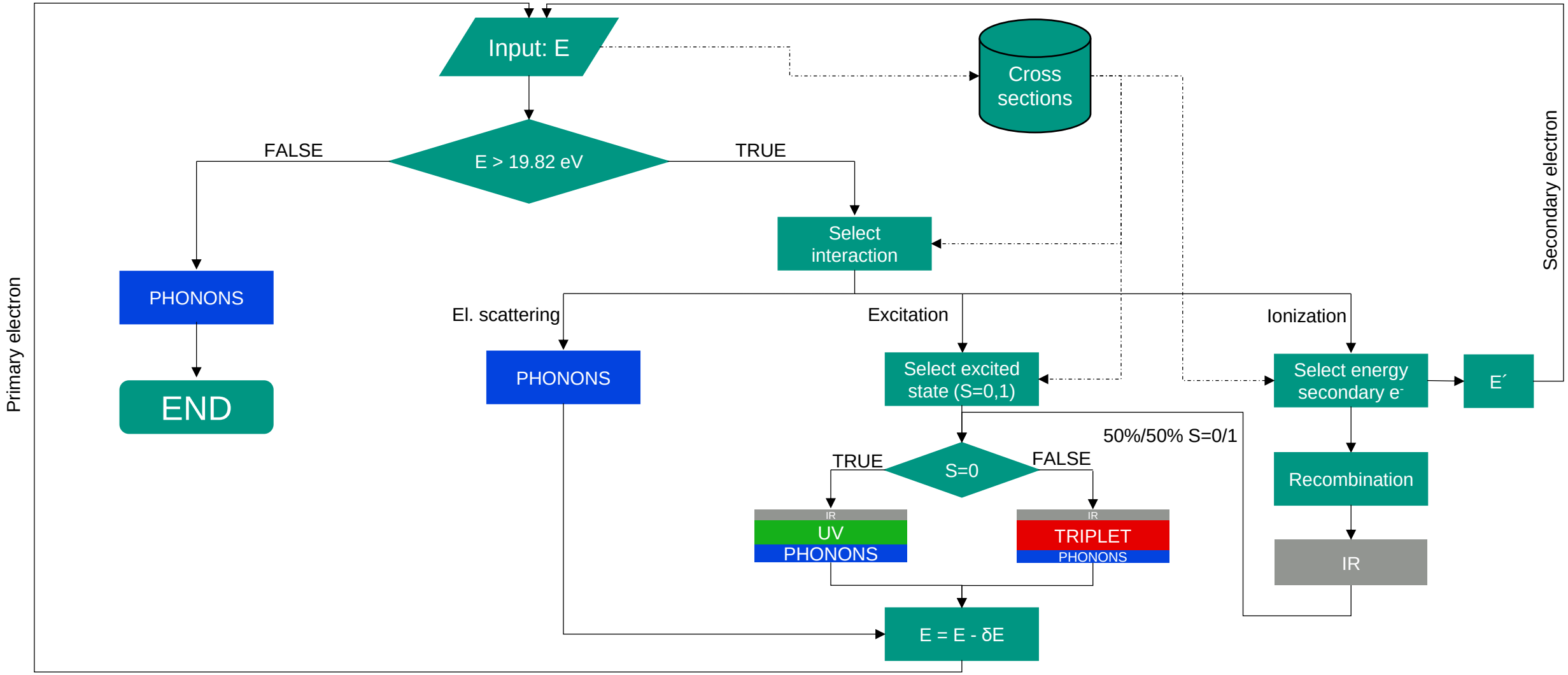
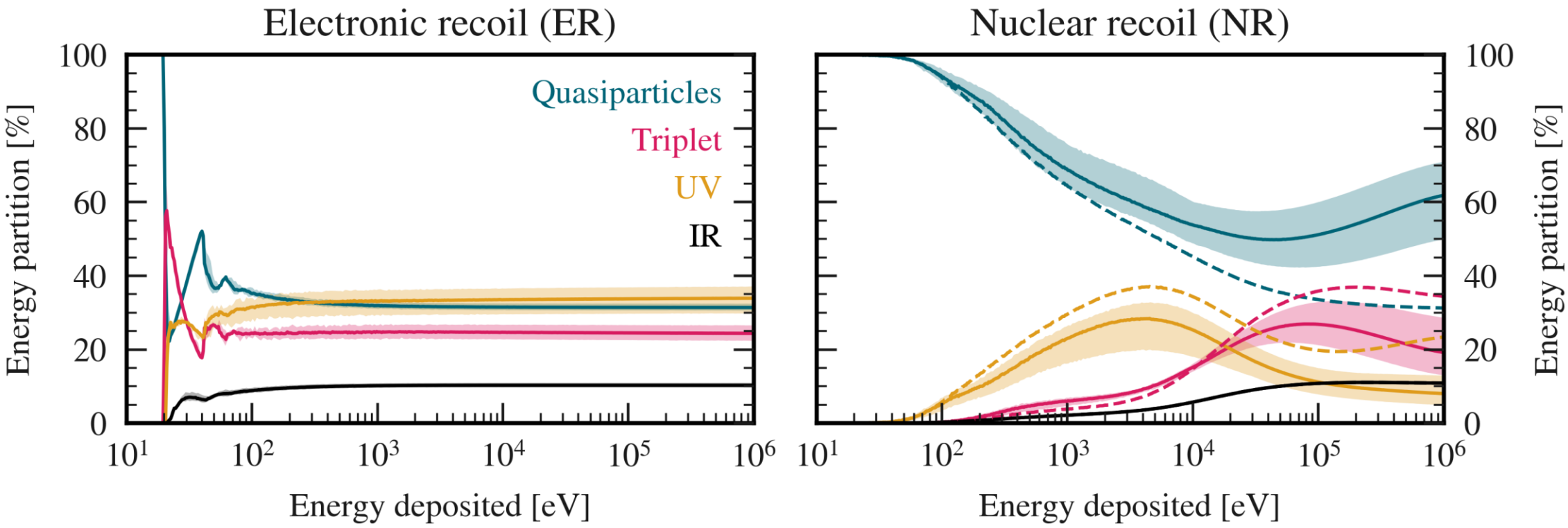


# Signal partitioning in superfluid $^4$He



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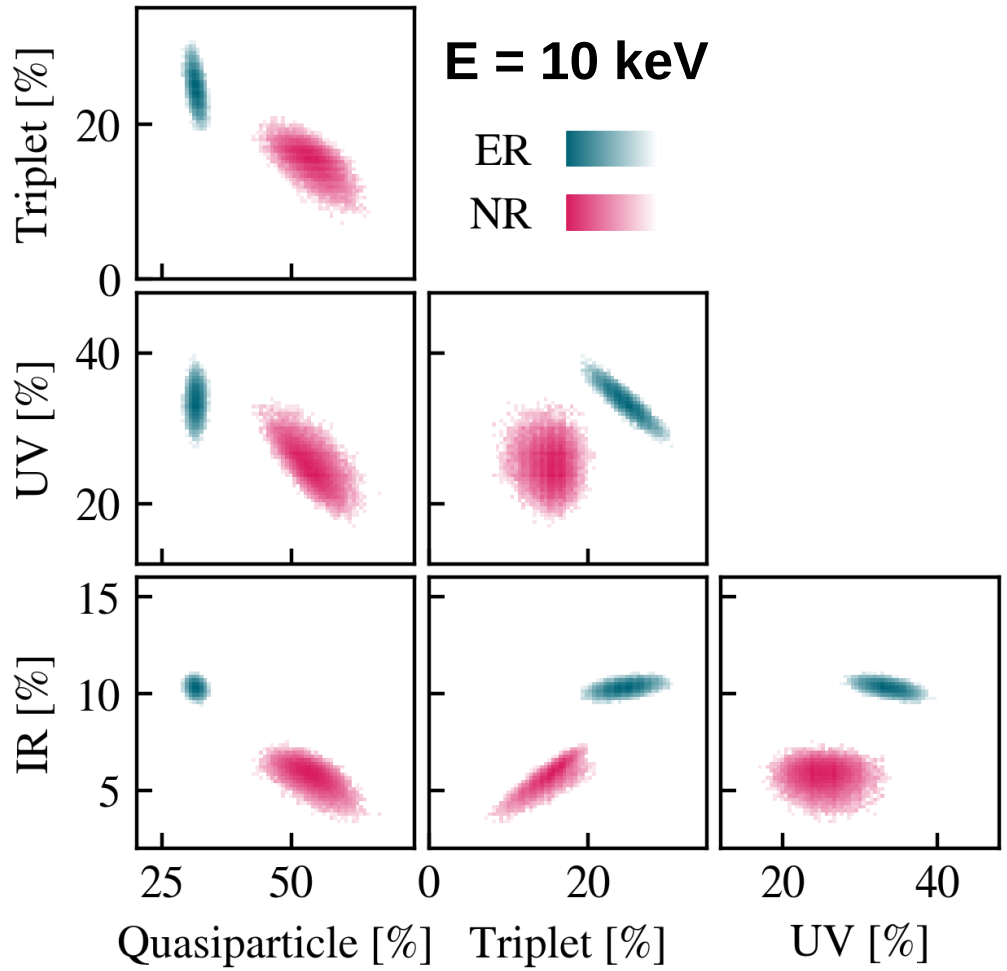

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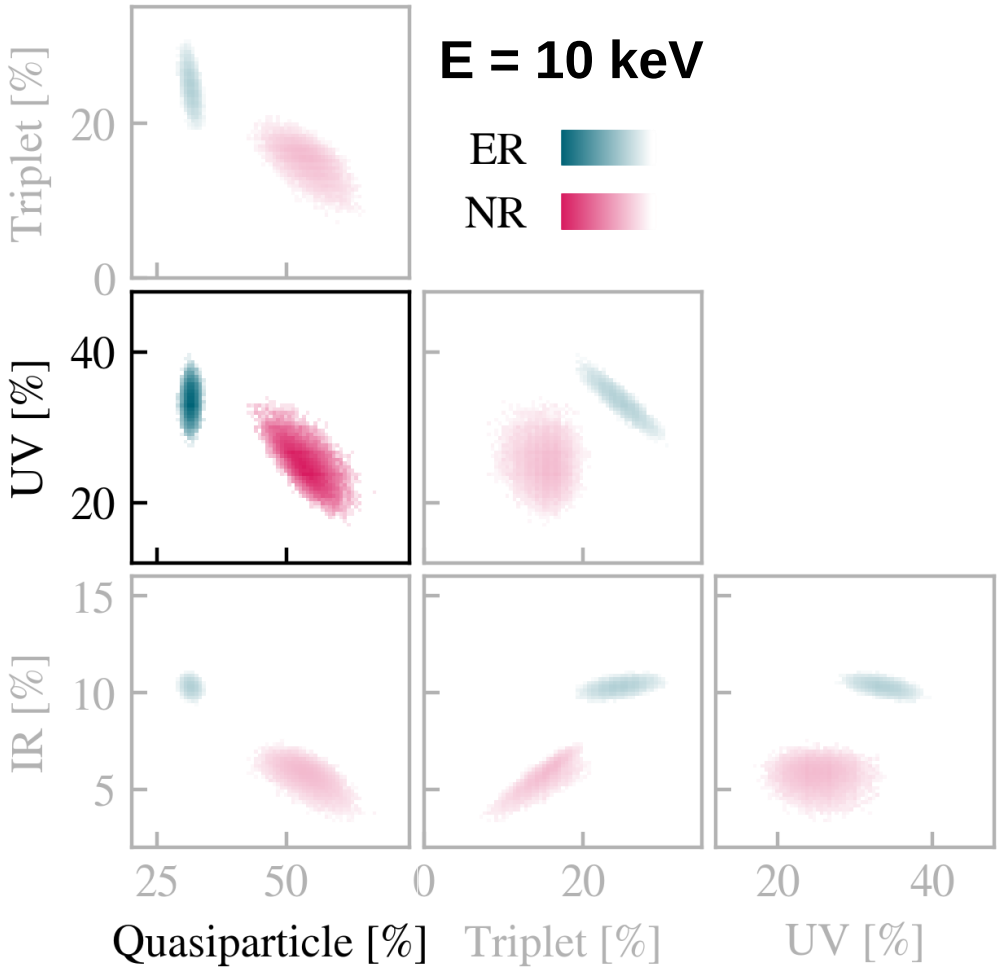
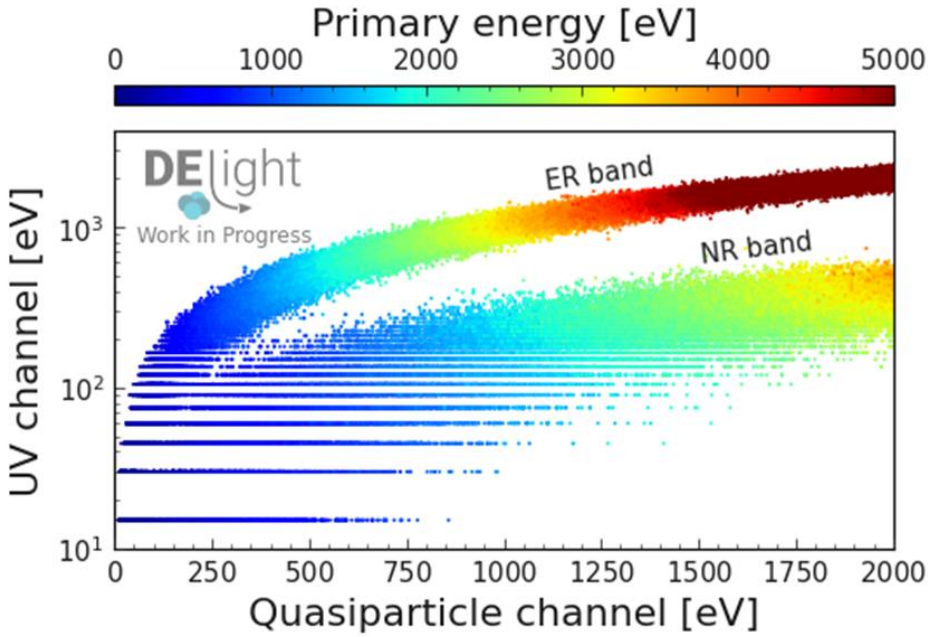
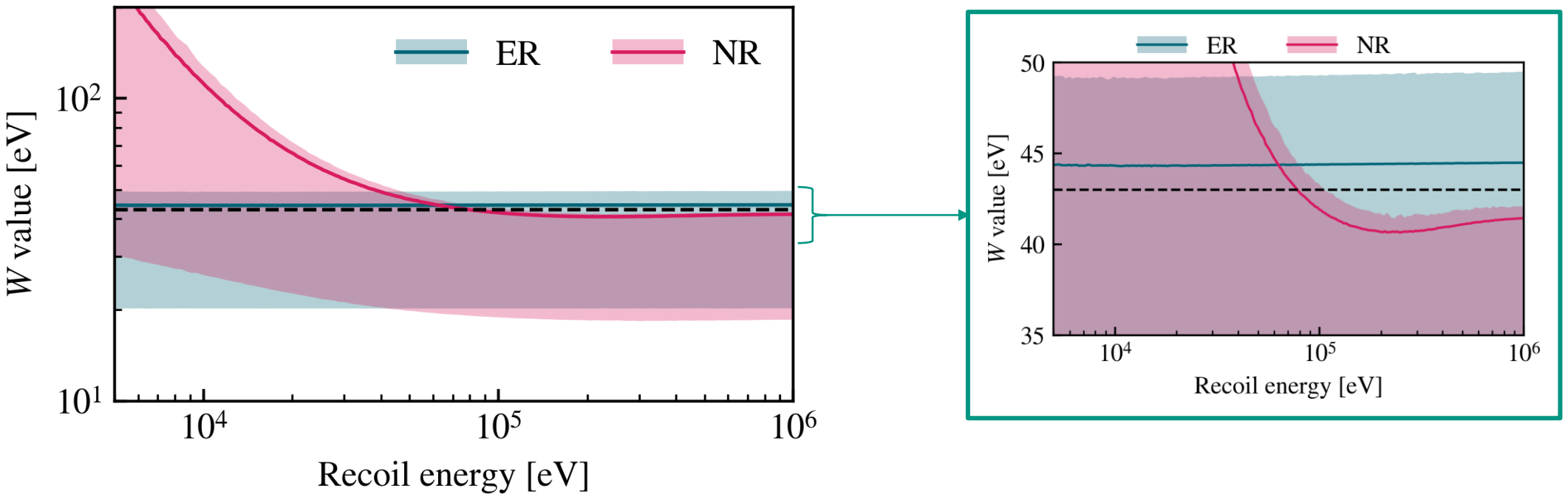


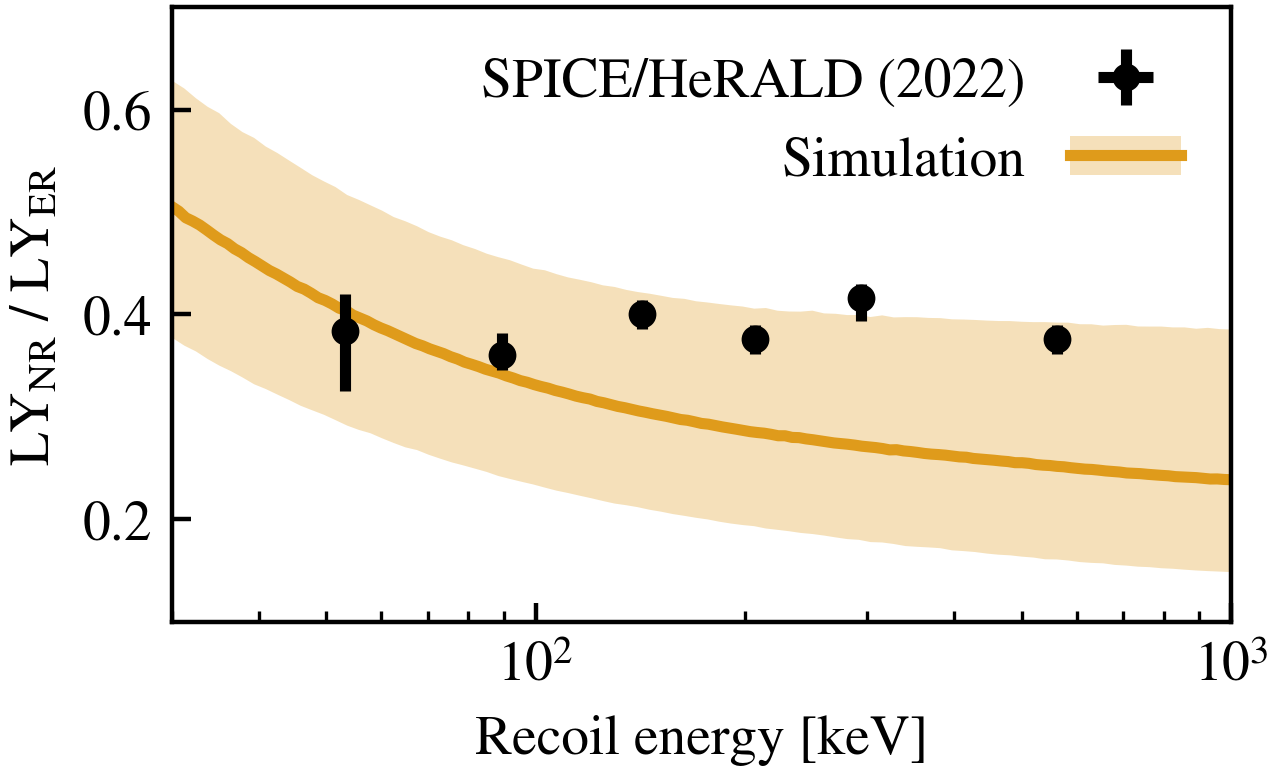
# Comparison with available measurements

- W is the average energy needed to produce an electron-ion pair in superfluid $^4$He



# Comparison with available measurements

- Difference with measured UV light yield ratio NR/ER might come from **Penning quenching** model
  - Penning affects NR LY, but not W value

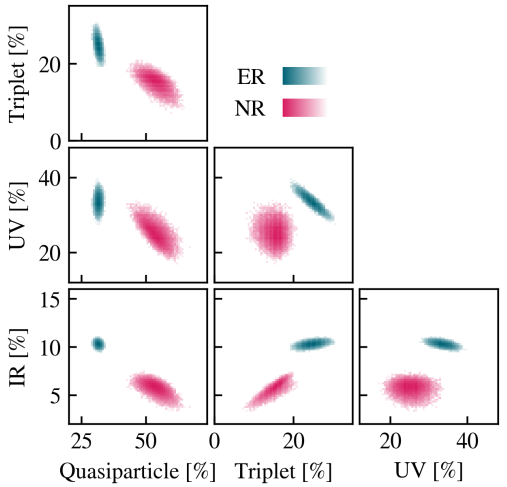


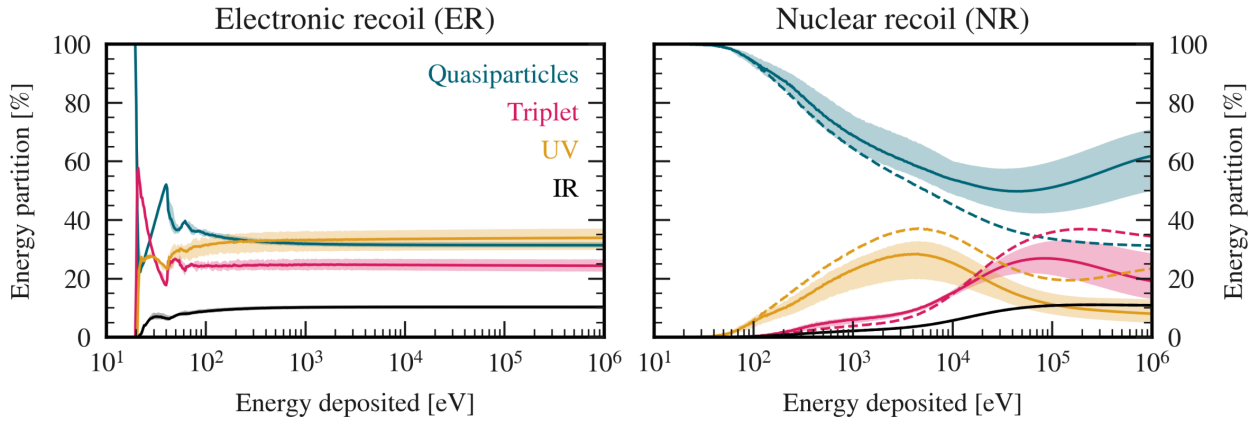

Penning quenching

$$He_2^* + He_2^* \rightarrow 2He + He_2^+ + e^-,$$
$$\rightarrow 3He + He^+ + e^-.$$

# Conclusion & outlook

- DELight is a proposed direct detection experiment using superfluid $^4$He
- Multichannel signal nature allows for ER/NR discrimination
- Signal partitioning from measured/calculated cross sections
- Implemented in our simulation framework
- Limited results for comparison
  - └ we need measurements!

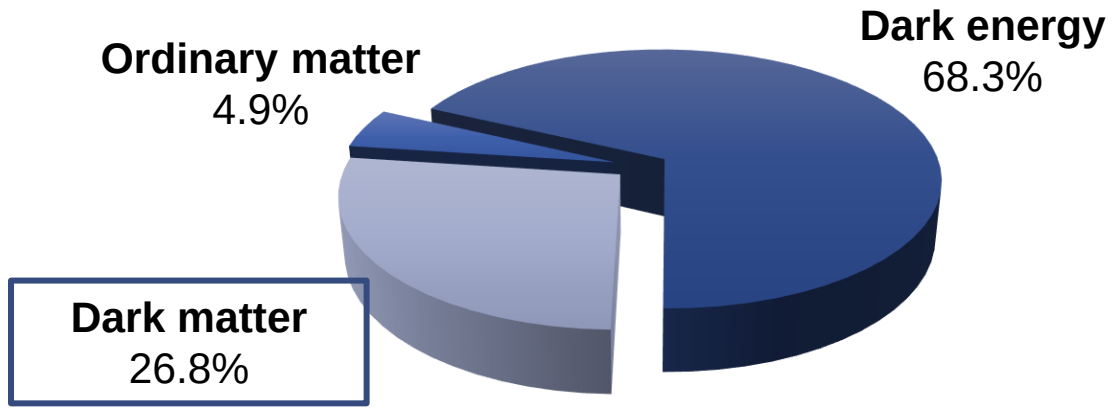


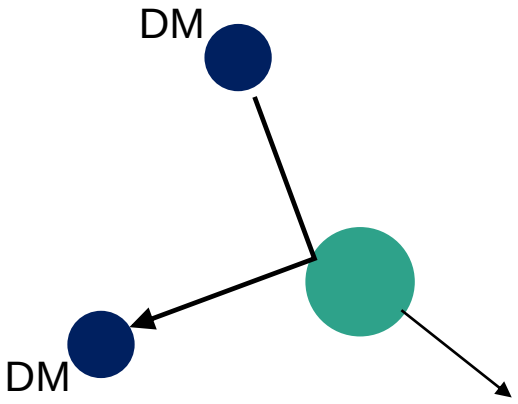



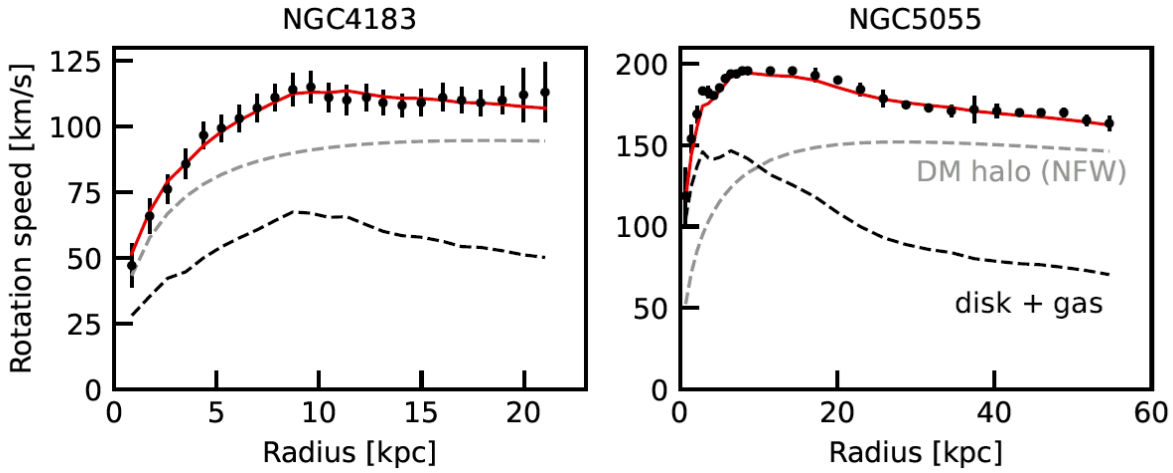
# Back-up slides

# Dark Matter

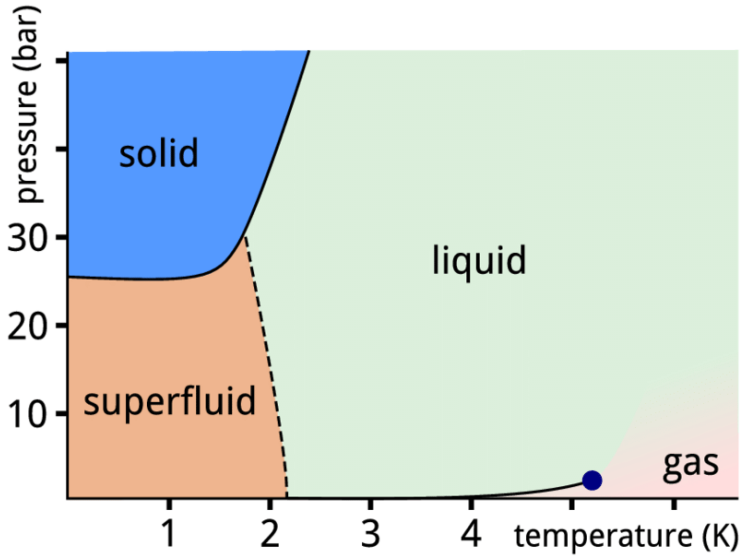
- No electromagnetic interaction → **dark**;
- Evidences of gravitational nature → **massive**;
- No particle candidate in SM → **BSM physics**;
- Direct searches for DM-nucleus scattering.

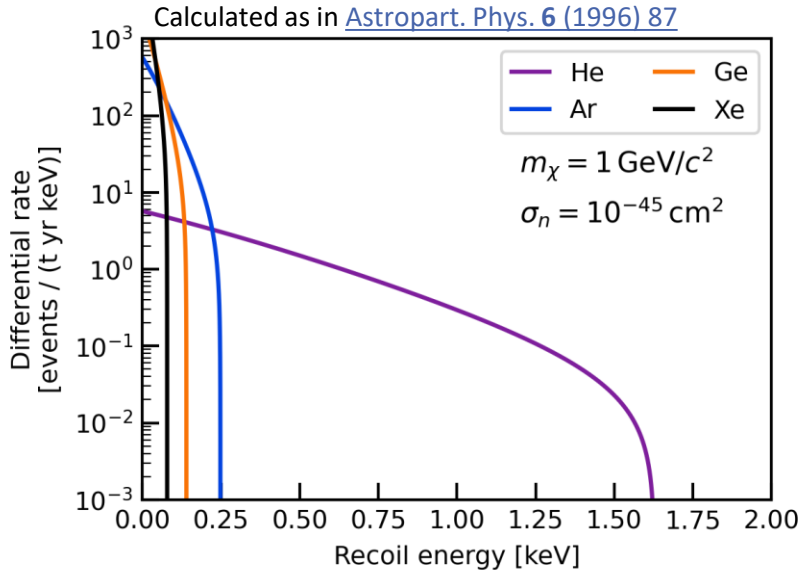


# Superfluid $^4$He as target

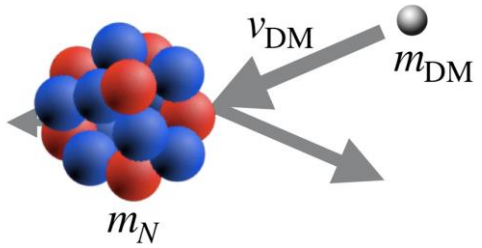



- Impurities freezing out (~20 mK)
- Multiple signals
- Unexpensive material and scalable technology

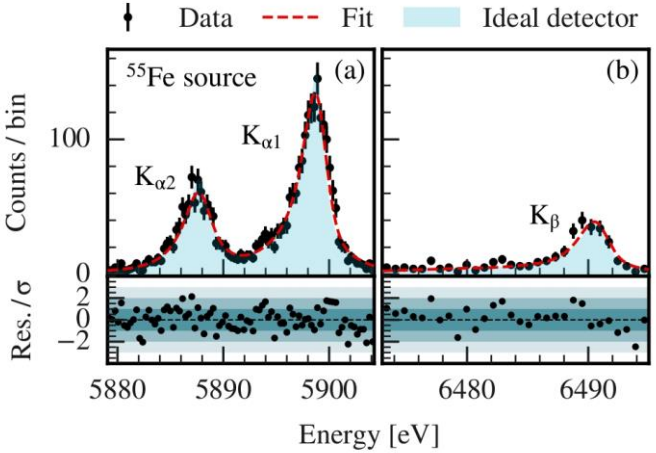
- Light nuclei maximize recoil energy for LDM

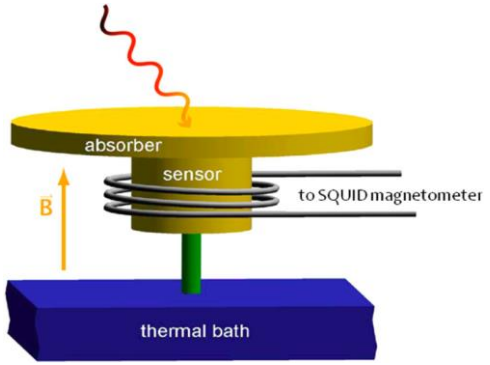
vs.

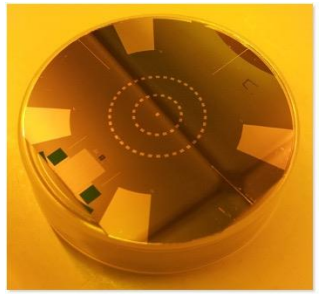


# Magnetic Micro-Calorimeters (MMCs)

- Energy deposit in an *absorber* leads to a temperature increase δT changing the magnetization of the *paramagnetic* sensor δM ∝ δT
- Change in magnetization measured by a coupled SQUID as change in current δI ∝ δT
- Measured best resolution of **1.25 eV** (@ 5.9 keV)



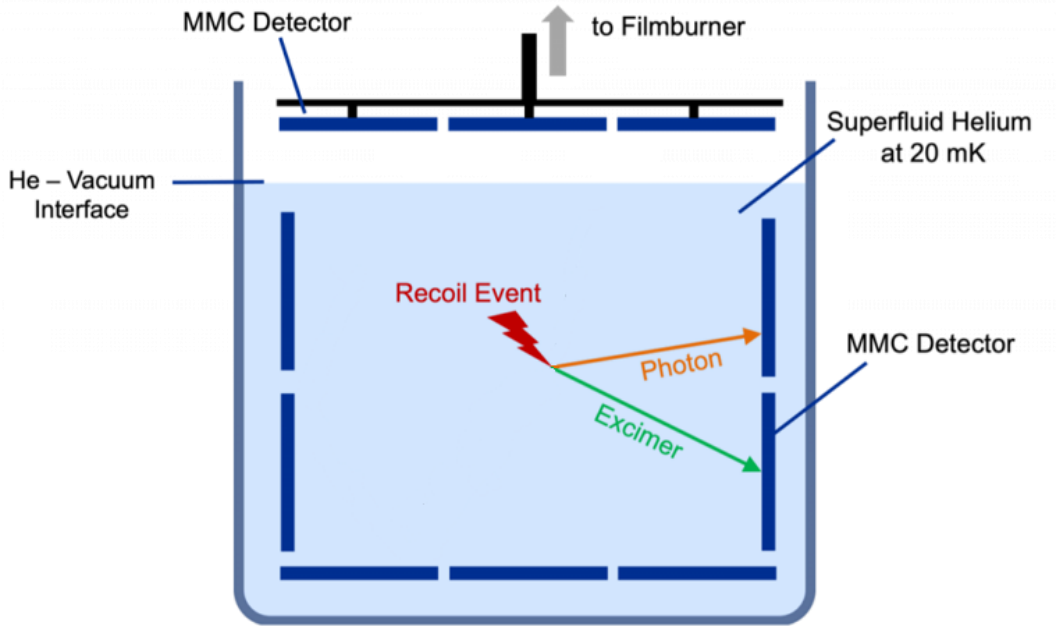



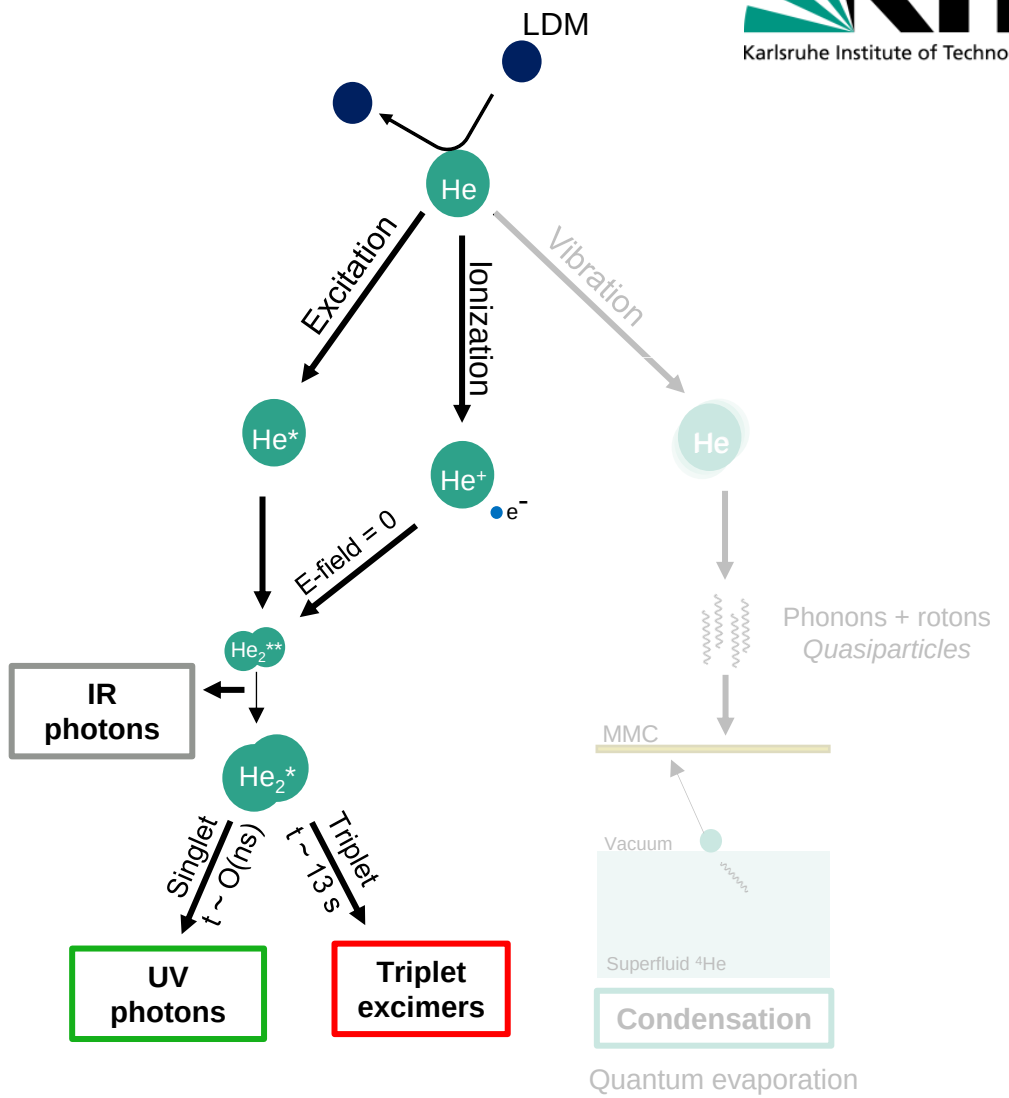



J. Low Temp. Phys. 193, 365-379 (2018)

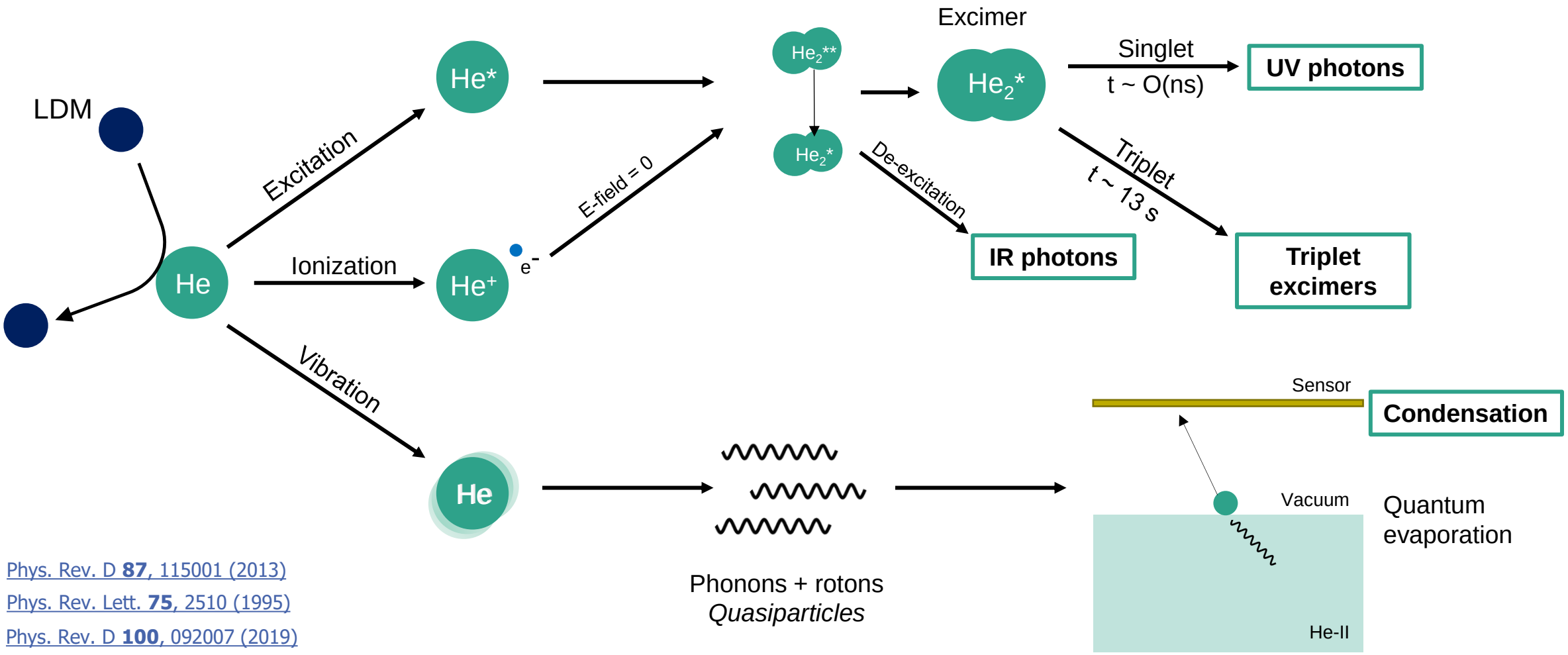
# DELight detection principle

- Prompt detection of UV and IR photons
- Ballistic triplet excimer (13 s lifetime, O(m/s) speed)
  - Detected when in contact with MMC sensor



# Superfluid $^4$He as target

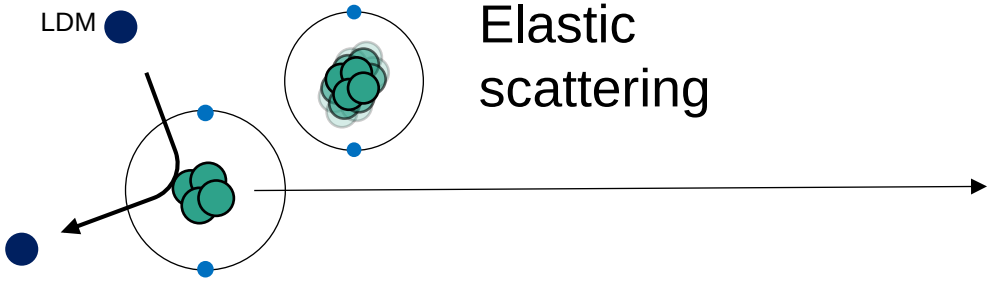



Phys. Rev. D **87**, 115001 (2013)

Phys. Rev. Lett. **75**, 2510 (1995)

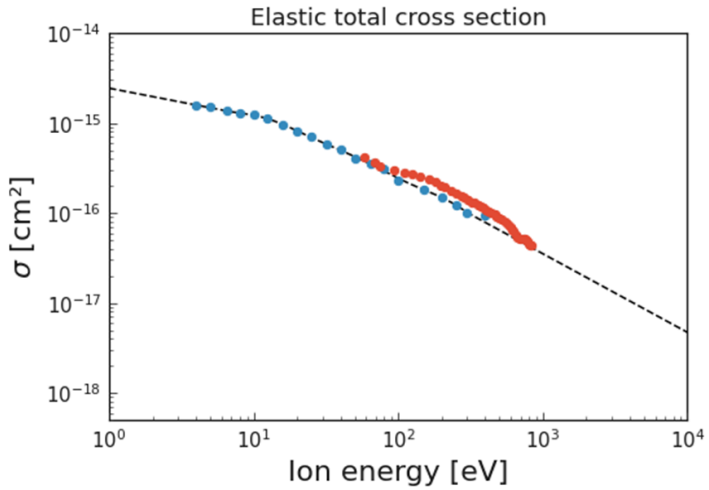
Phys. Rev. D **100**, 092007 (2019)

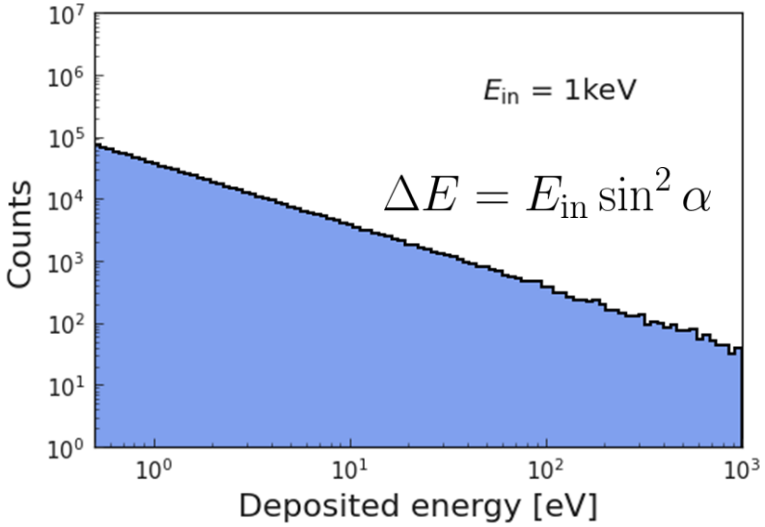
# The journey of an helium ion




Elastic scattering

- Total cross section measurements from $He^+$;
- energy loss from non-relativistic collision;
- Rutherford-like angular distribution;
- large energy deposition possible (target = projectile).




J. Chem. Phys. 26, 1272–1275 (1957)

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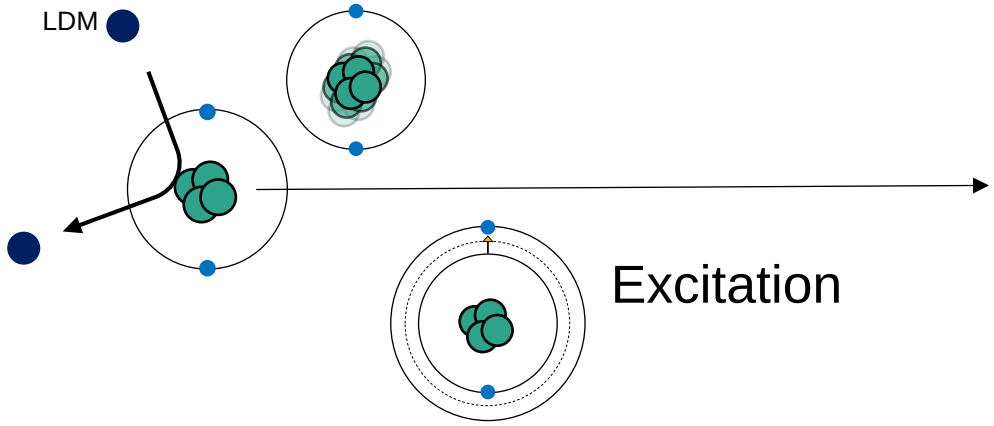
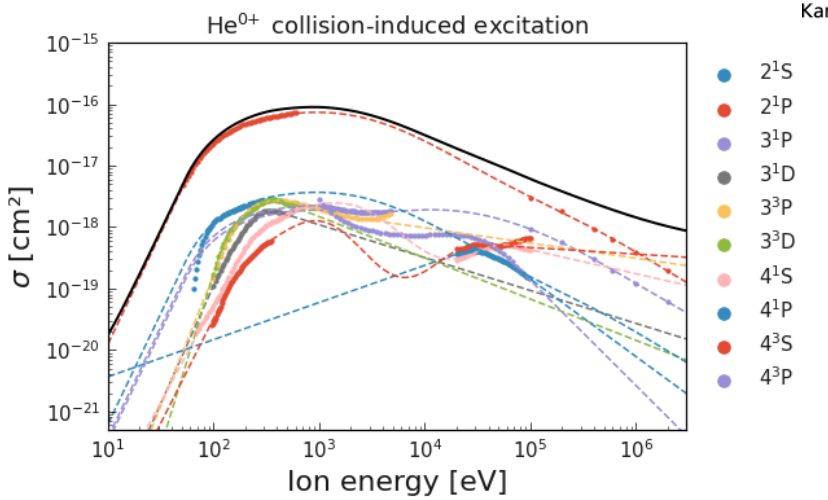
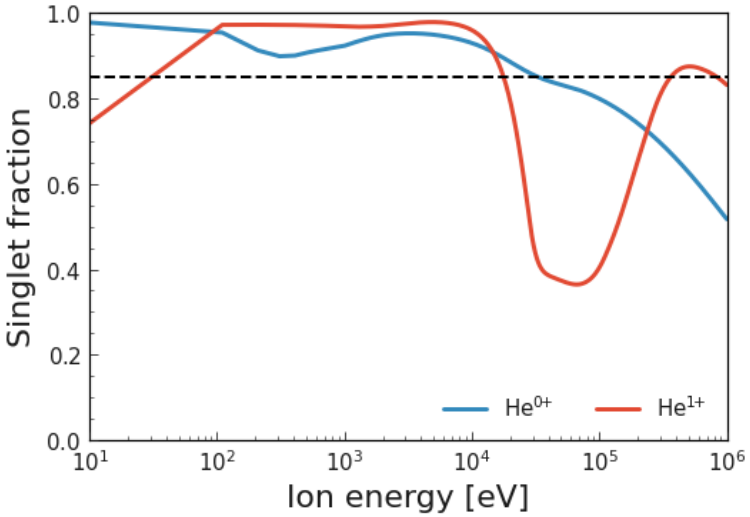



- Excitation of target neutral He;
- first accessible state is $2^3S$ (*1s2s*) at 19.82 eV*;*
- cross sections form database ALADDIN;
- singlet/triplet ratio from cross sections.



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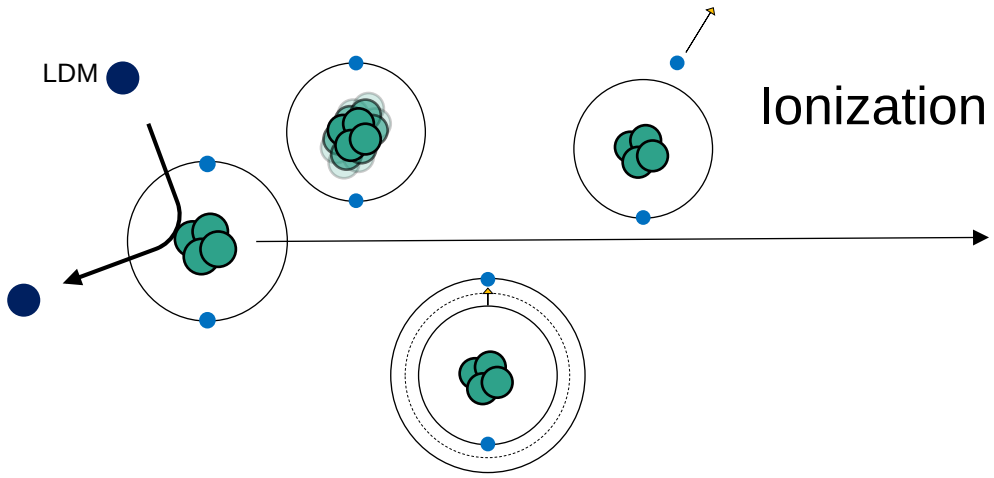
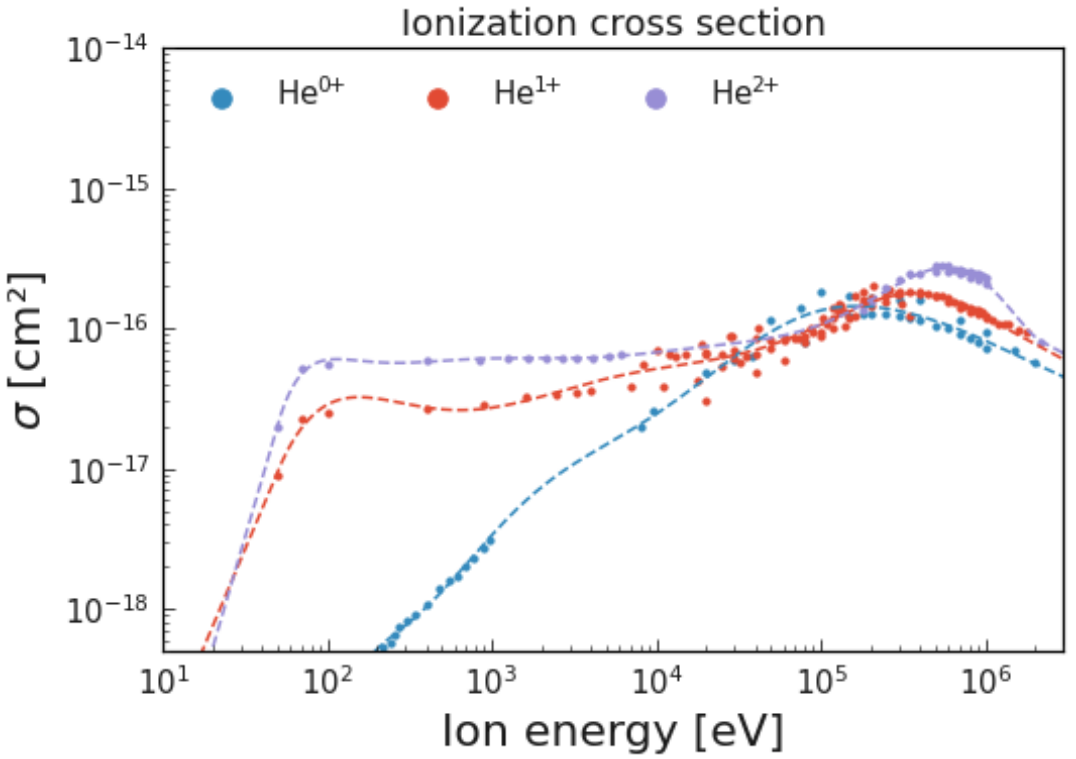
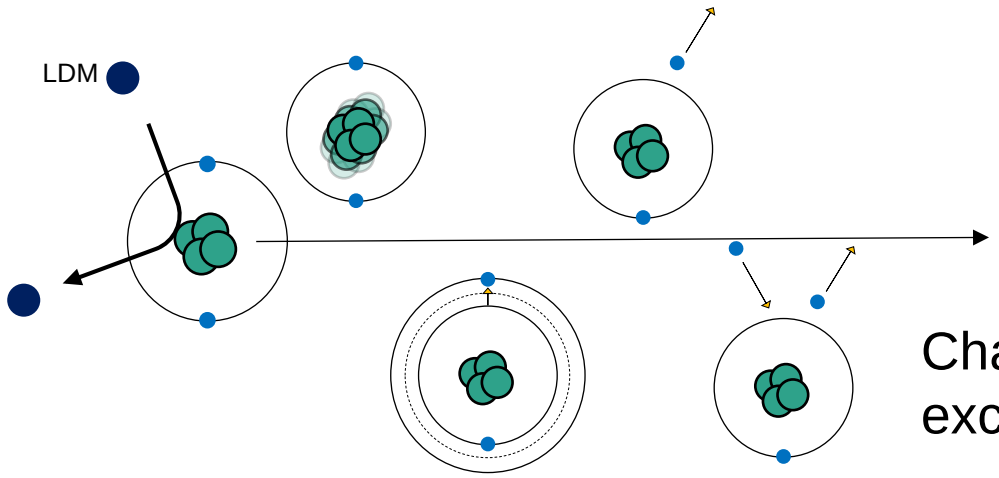


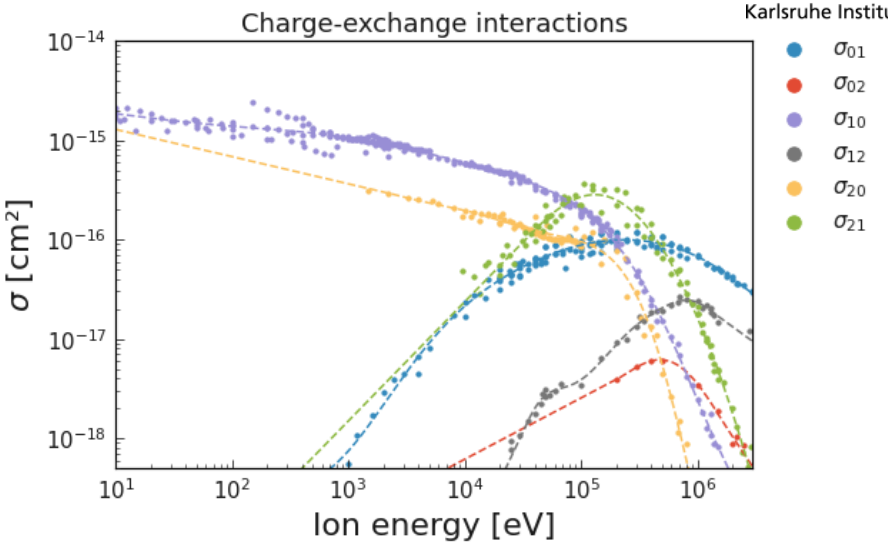

- Ionization of the target ground He;
- fit to measured cross section;
- measurements for different projectile charge states;
- negligible double-ionization.

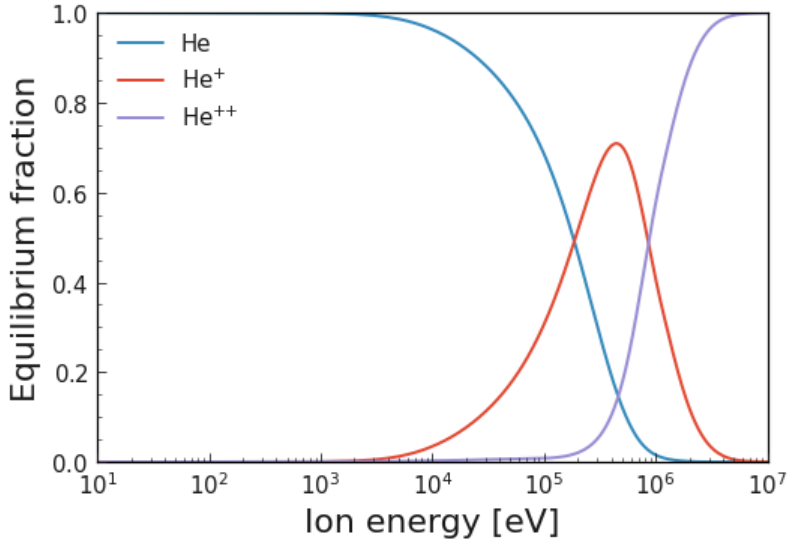



JAERI-M 9310 (1981)

# The journey of an helium ion

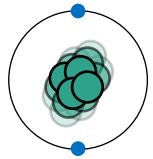


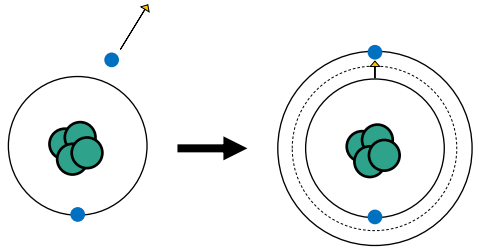




- Target and projectile He ions exchange electrons;
- projectile He changes charge state as it propagates;
- at low energy, projectile He is neutral.

# From interactions to signal quanta



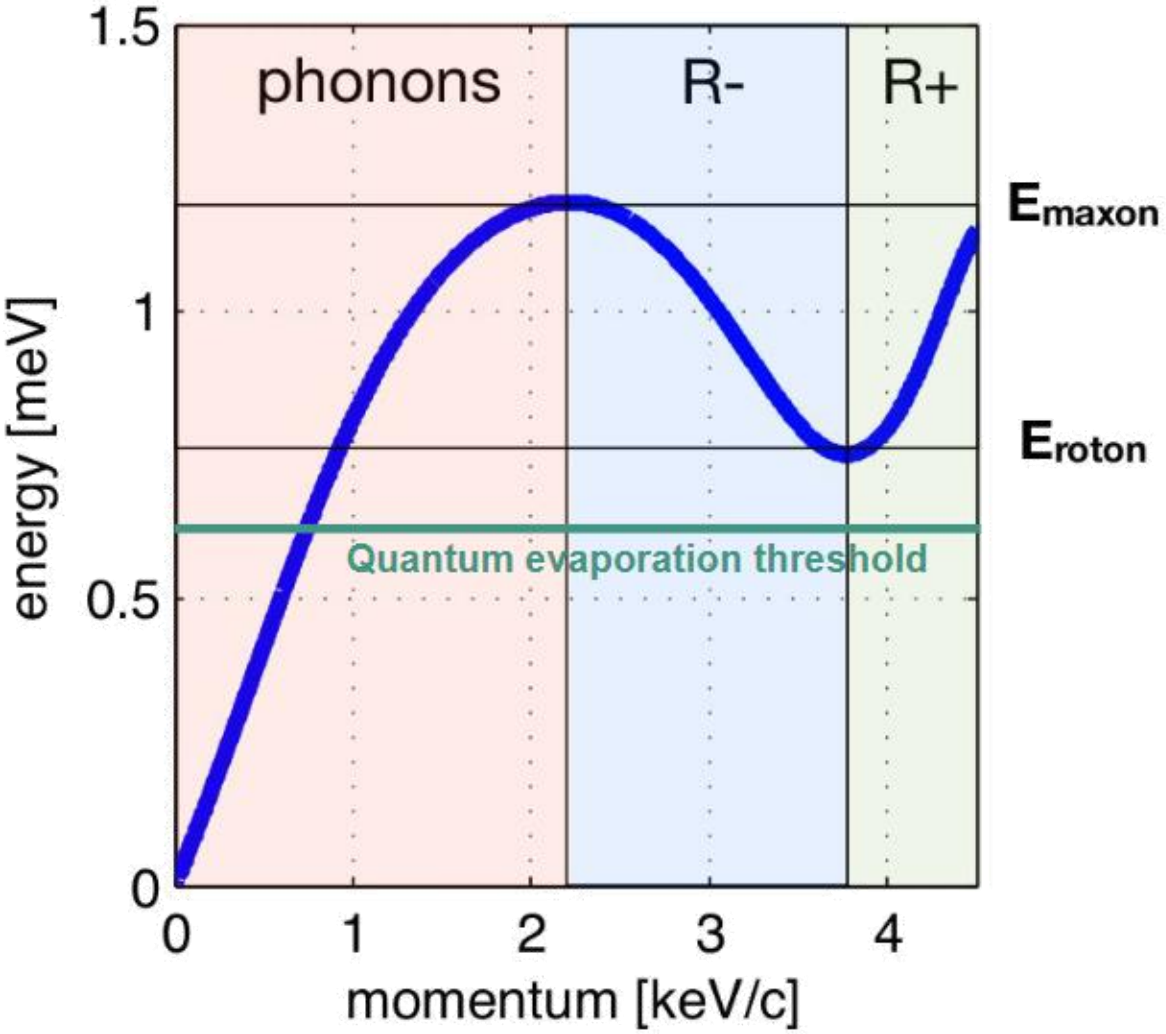
- Elastic scattering goes into quasiparticles (phonons and rotons)



- No E-field, hence the ion-$e^-$ pair recombines into an excited state
- Charge exchange can lead to electron emission (~ER signal) or ionization
- Penning recombination significantly reduces excitation contribution for NR

$$\mathrm{He}^* + \mathrm{He}^* \rightarrow \mathrm{He} + \mathrm{He}^+ + \underbrace{e^-}_{\text{subexcitational}}$$

# Phonon in superfluid Helium



# HERON

He film burner

wafer calorimeter

kg-scale
LHe mass