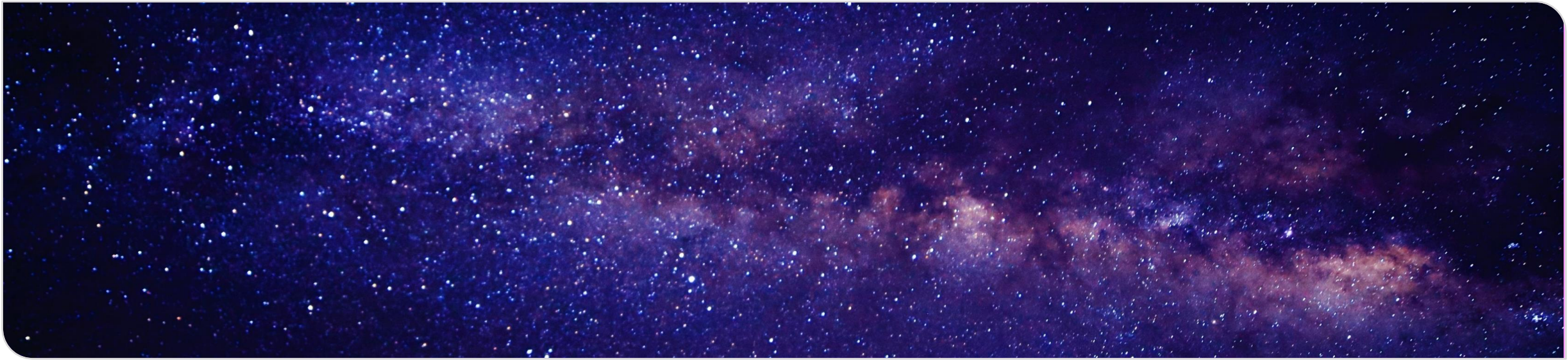
Signal partitioning in superfluid ^{4}He: A Monte Carlo approach

Francesco Toschi *on behalf of the DELight collaboration*

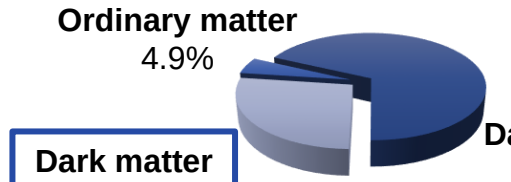
DPG Spring Meeting, Göttingen

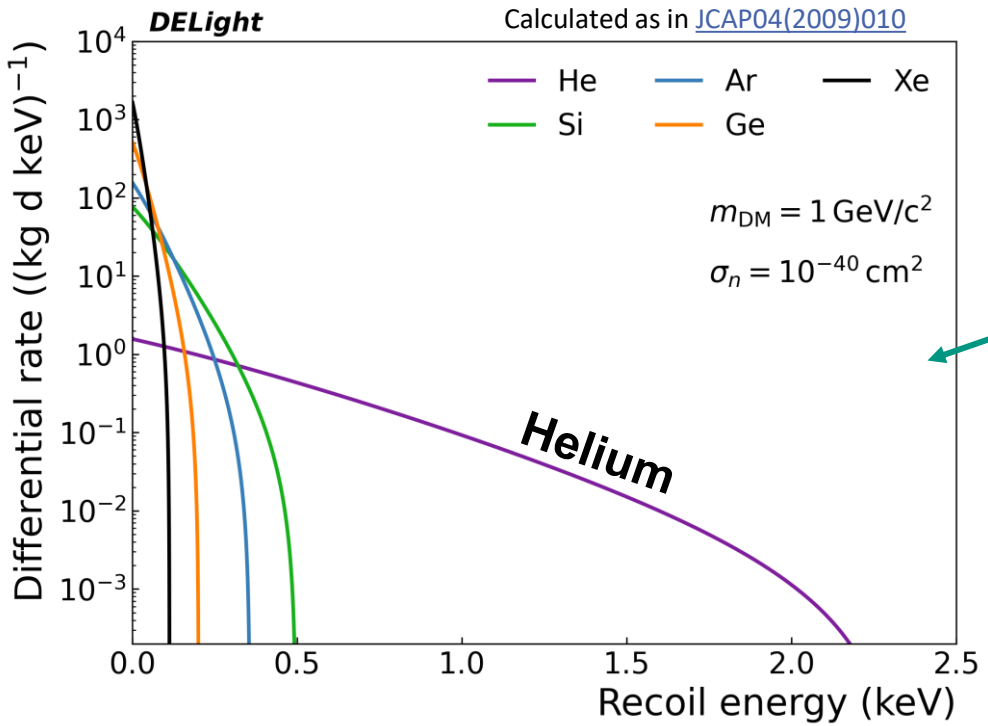
31.03.2025

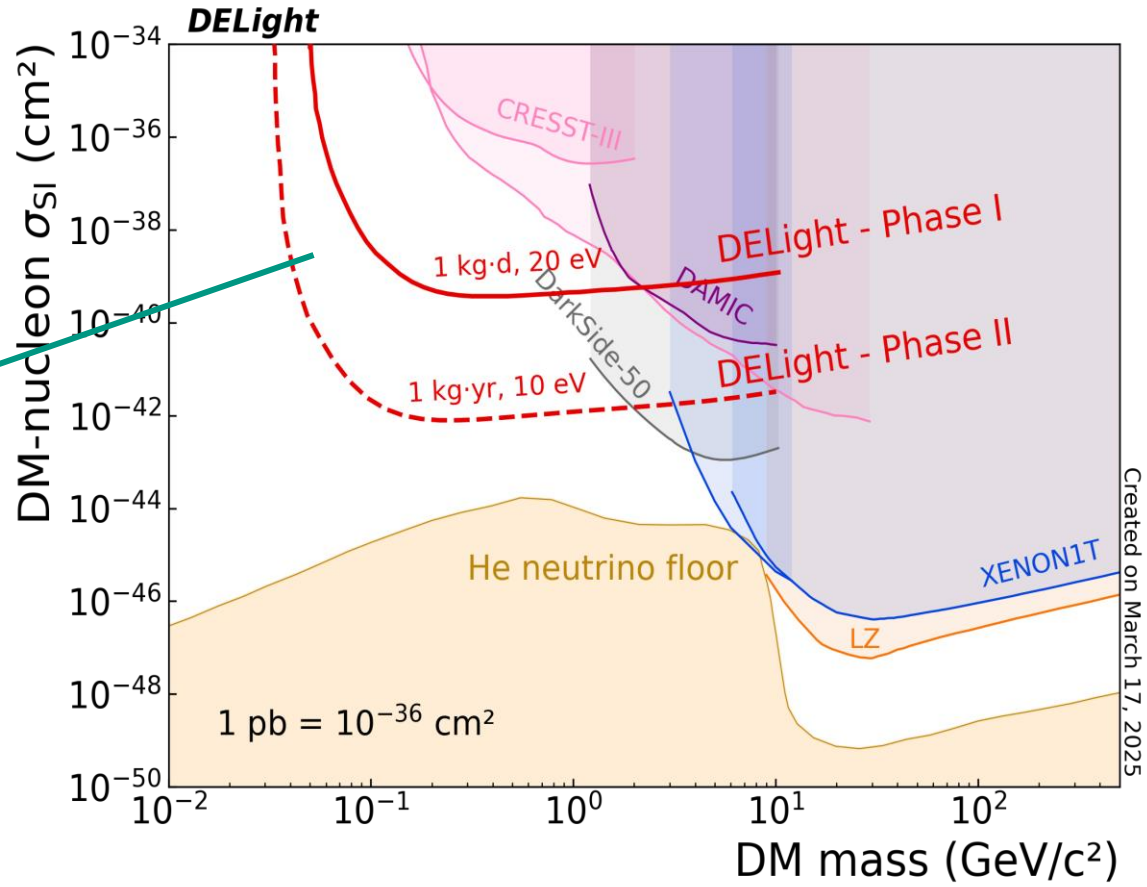
Phys. Rev. D **111**, 032013



Hunting Dark Matter with DELight

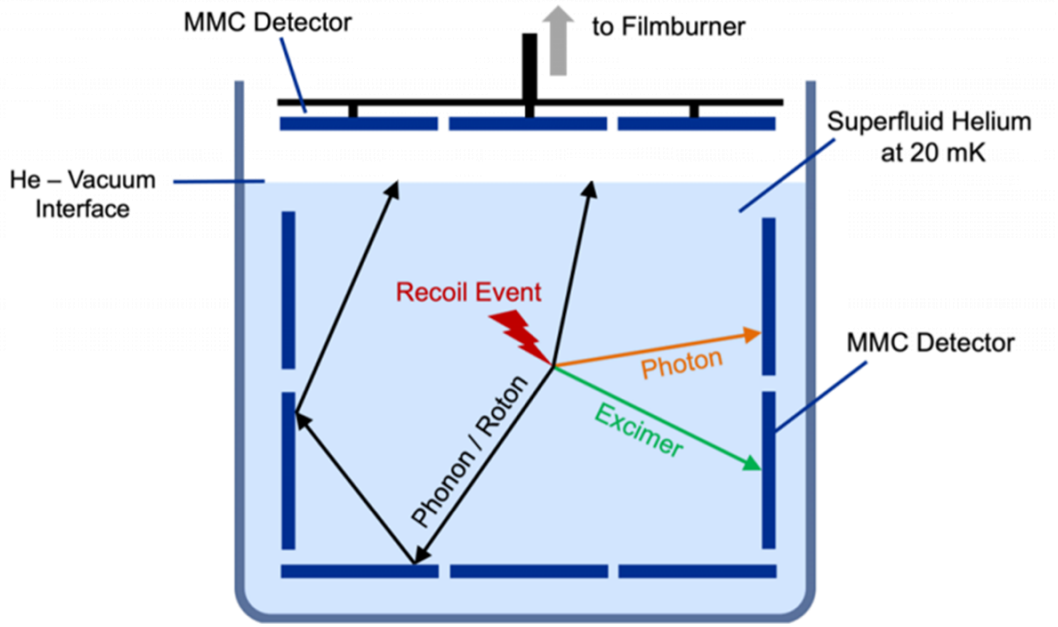


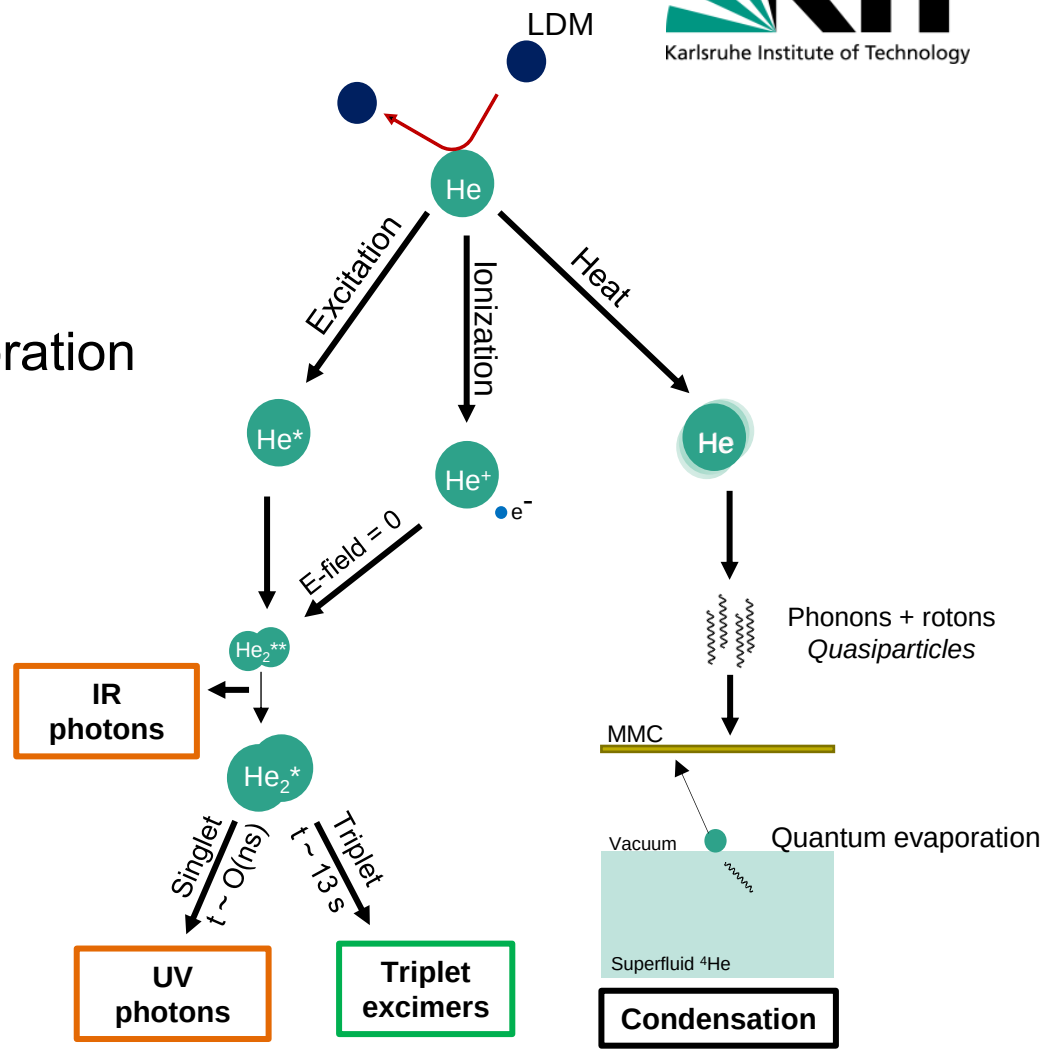




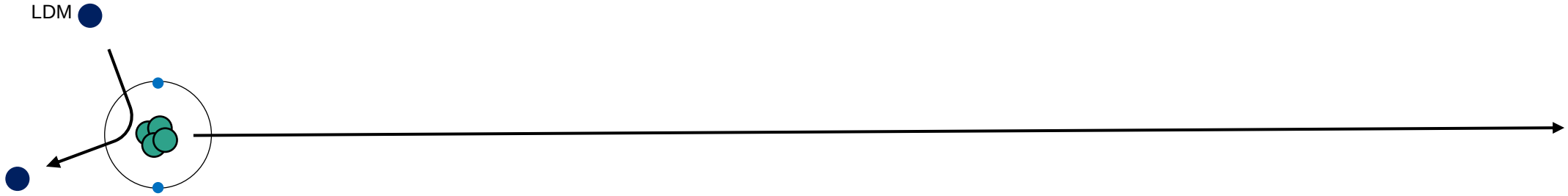
DELight detection principle

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



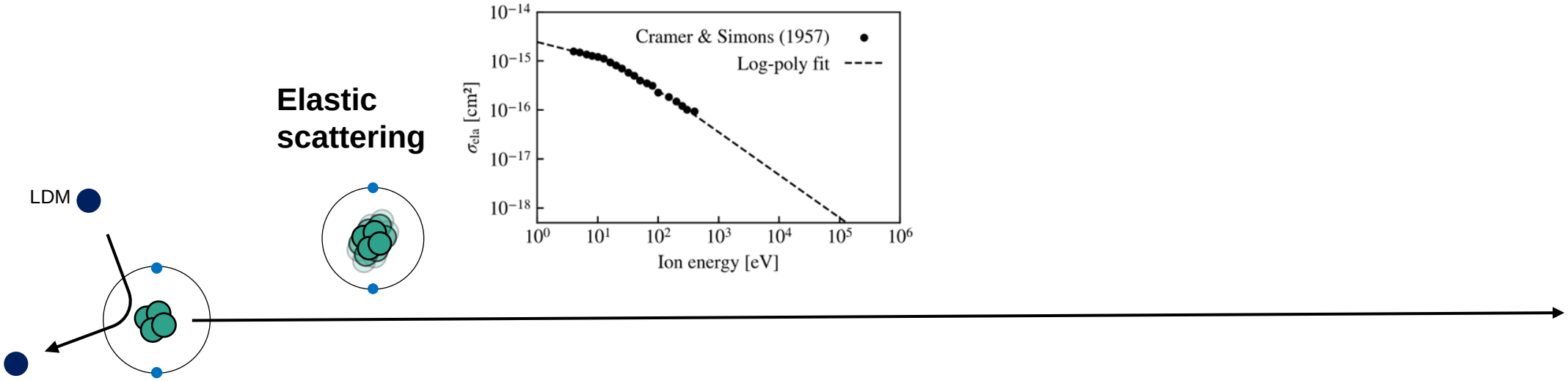


The journey of a helium ion



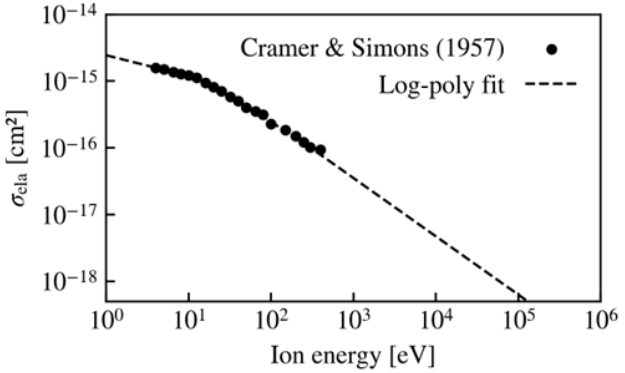
The journey of a helium ion

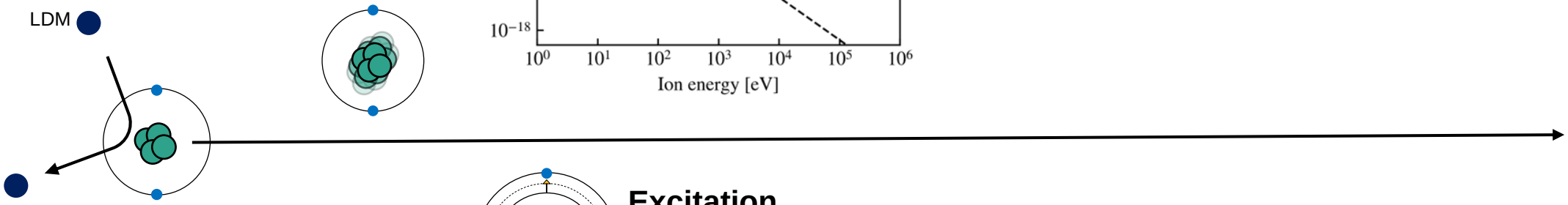
Elastic scattering



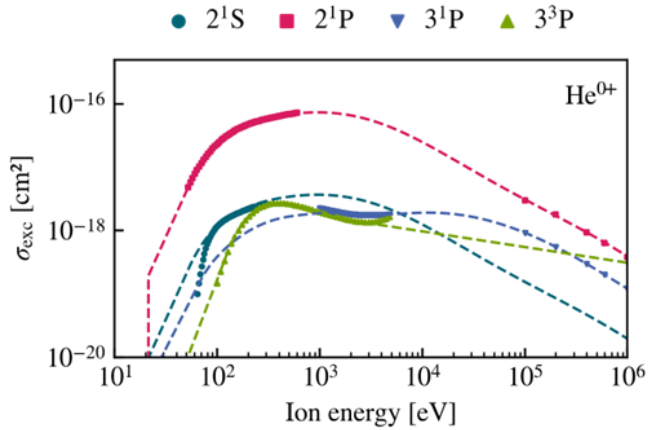
The journey of a helium ion

Elastic scattering

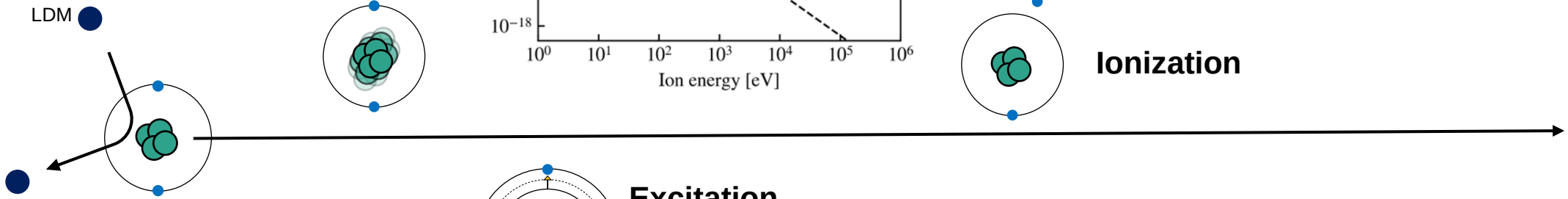




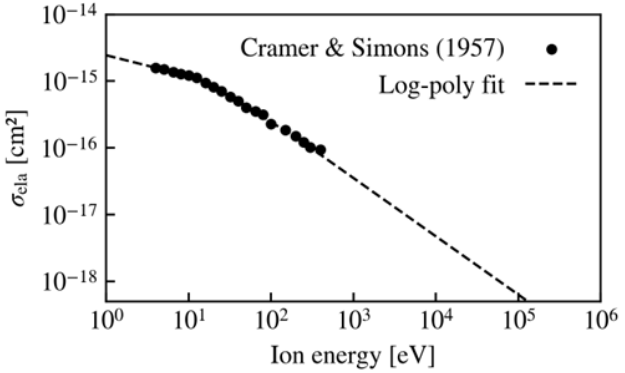
Excitation

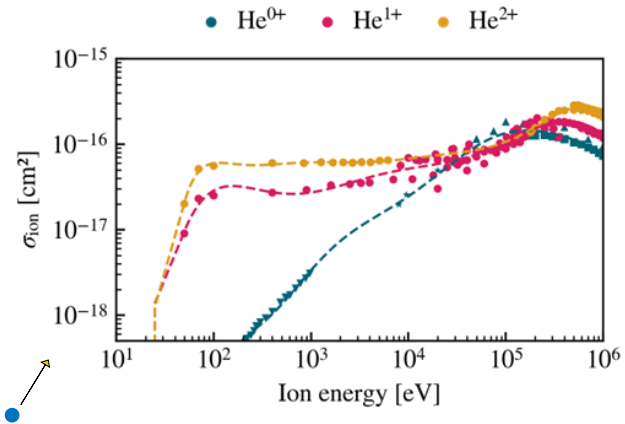


The journey of a helium ion



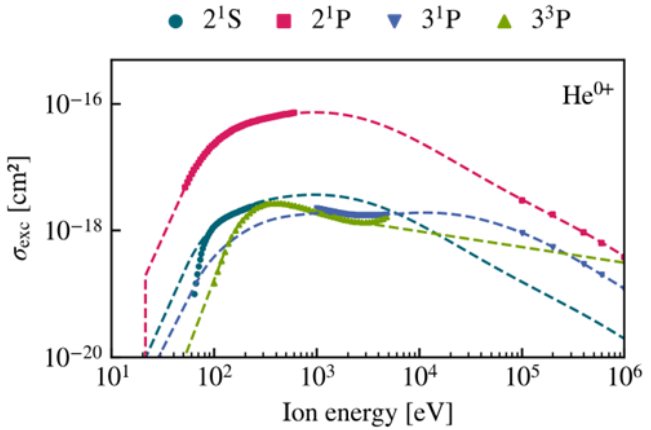
Elastic scattering



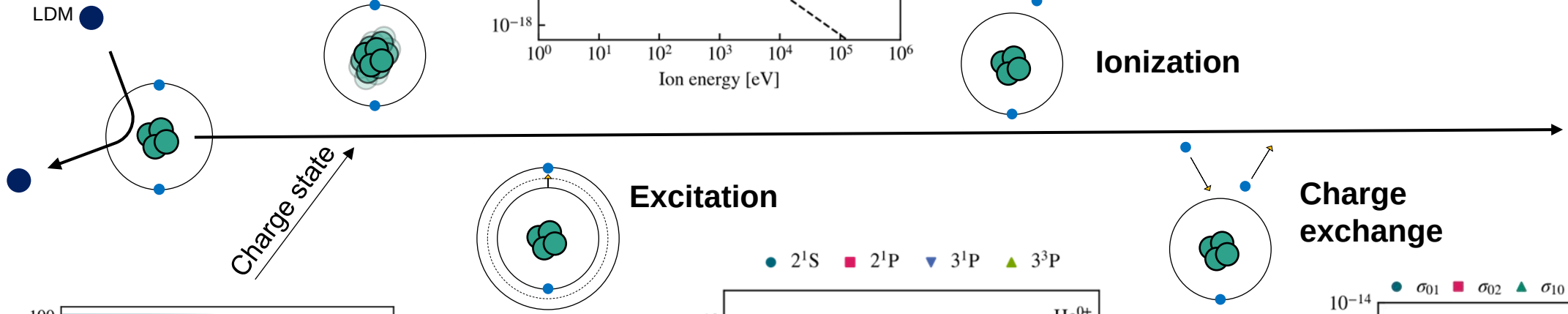


Ionization

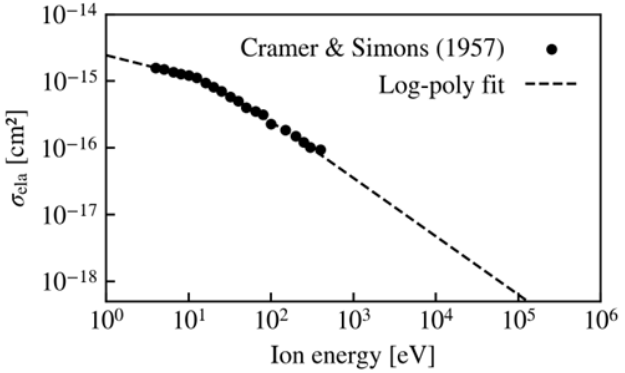
Excitation



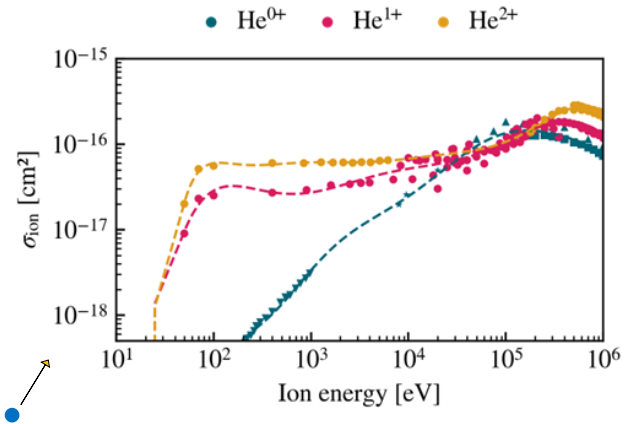
The journey of a helium ion



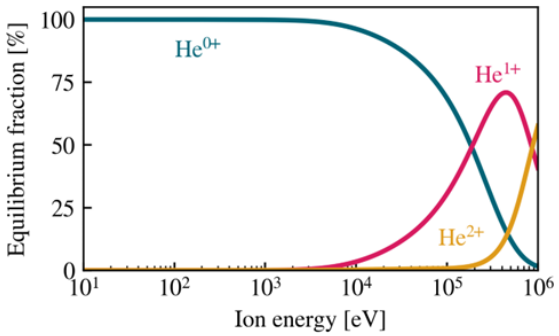
Elastic scattering

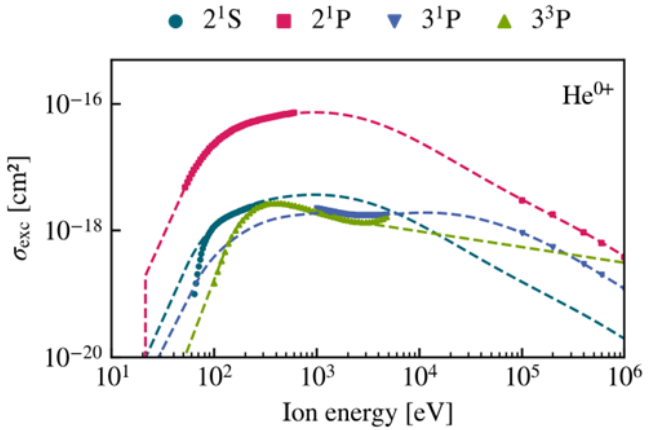


Ionization

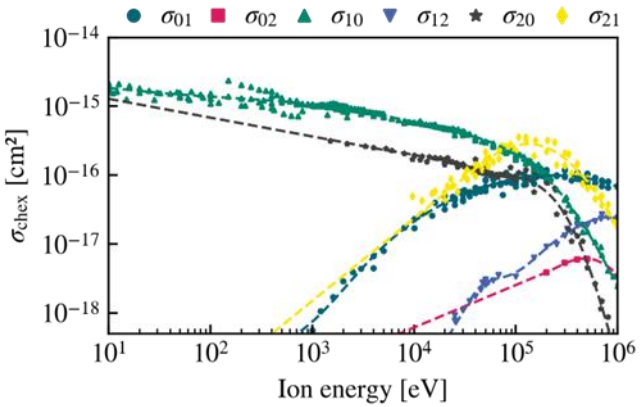


Excitation

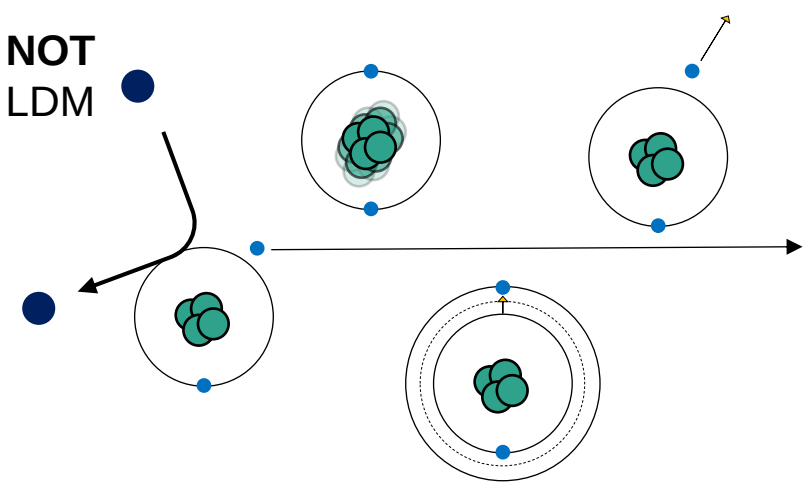


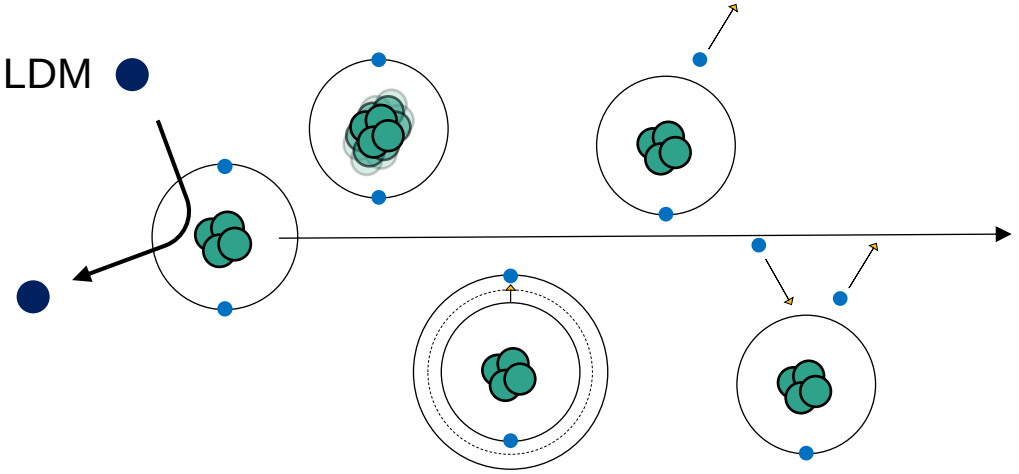


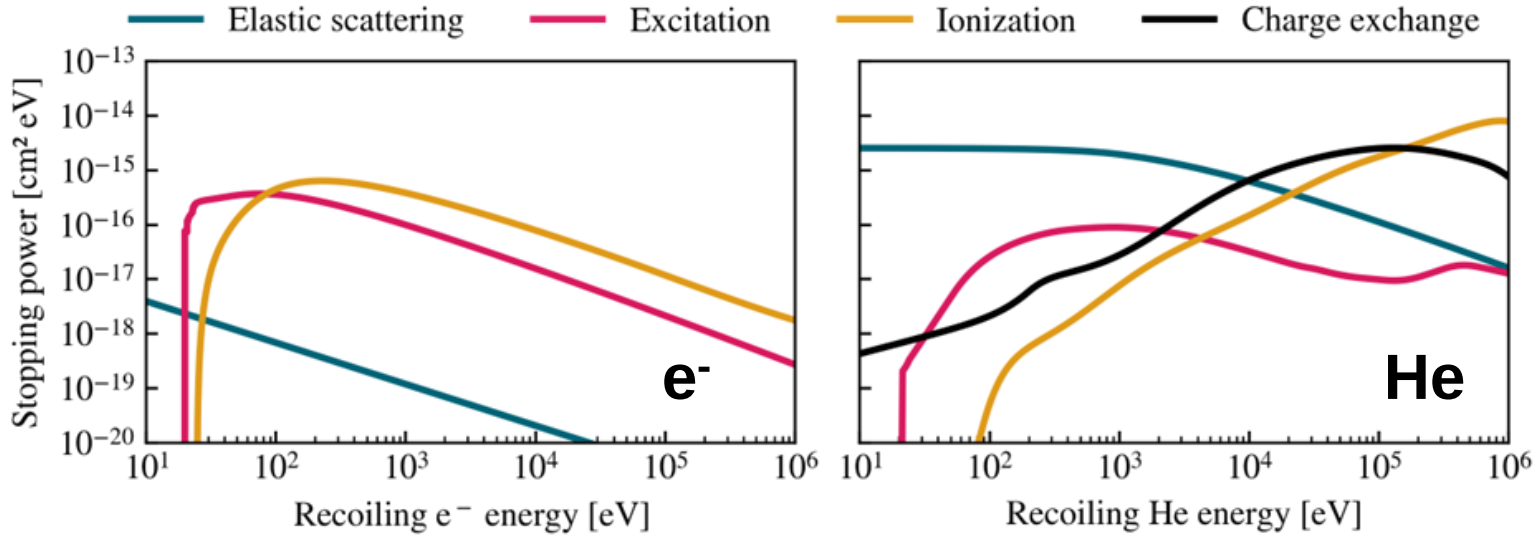
Charge exchange



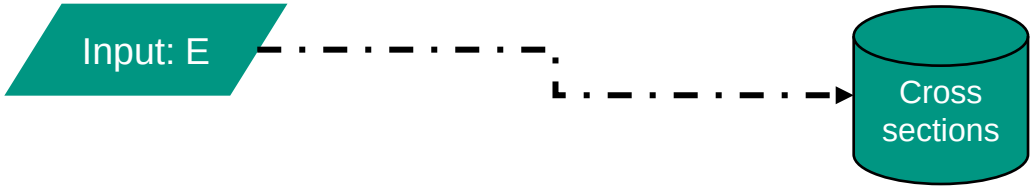
Recoil of electrons (ER) vs. helium ions (NR)



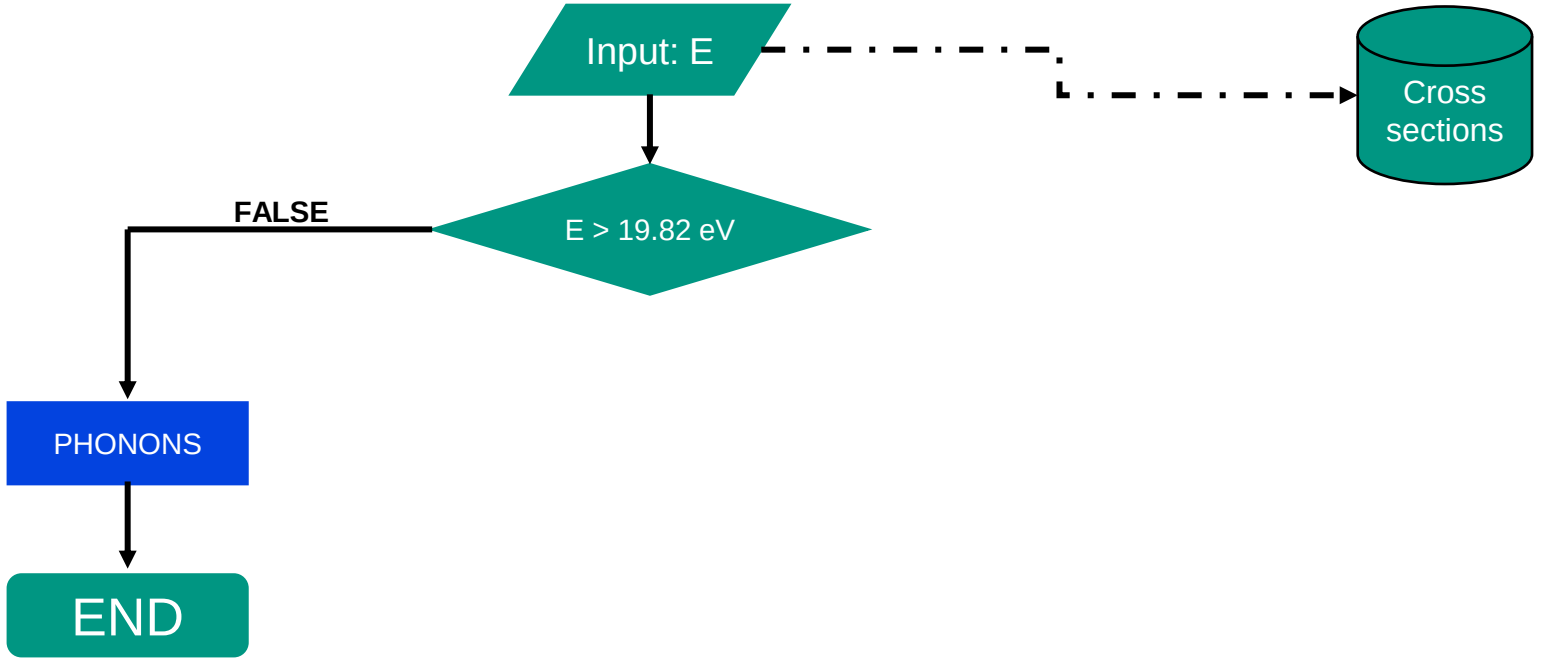




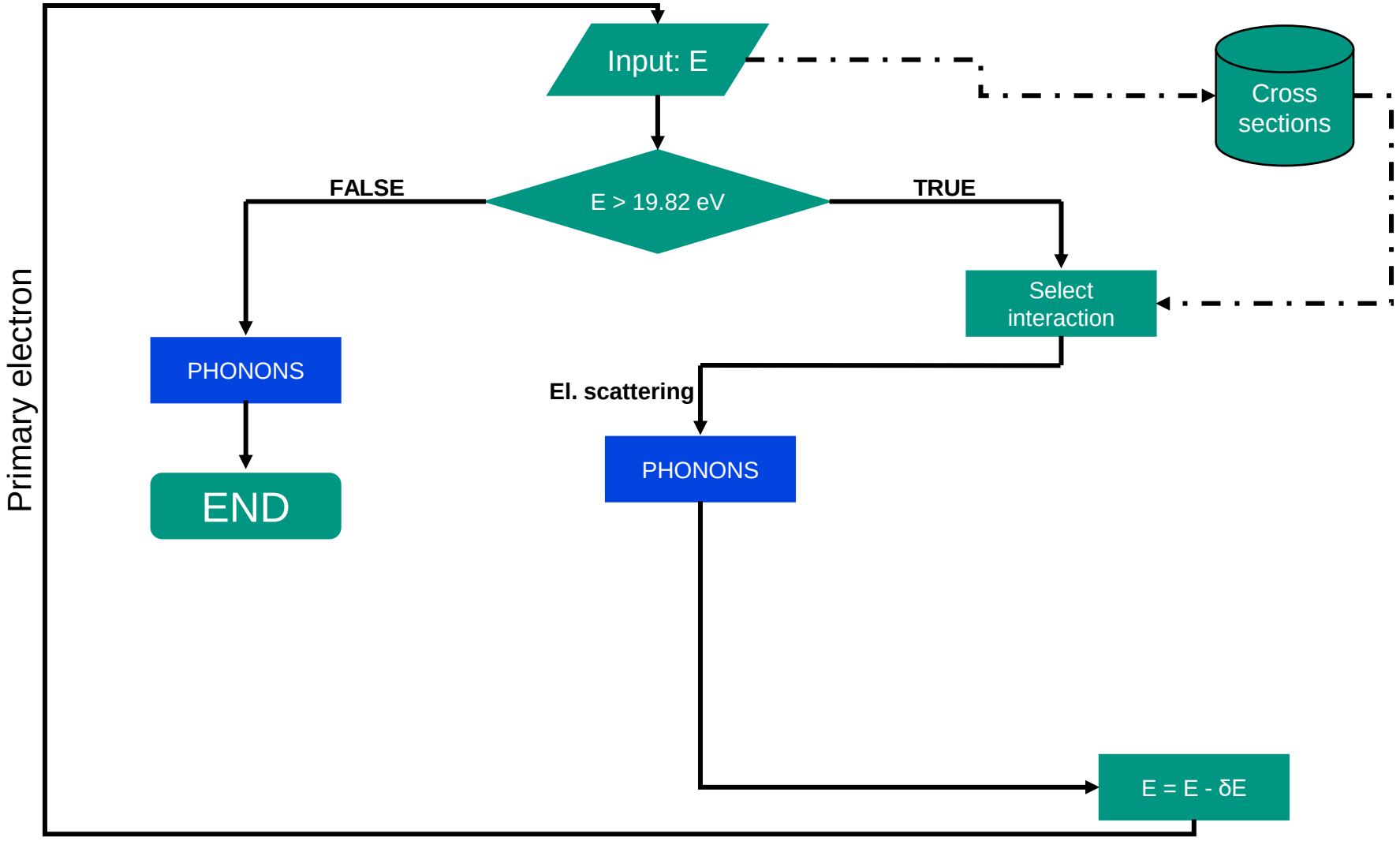
From interactions to signal quanta (ER)



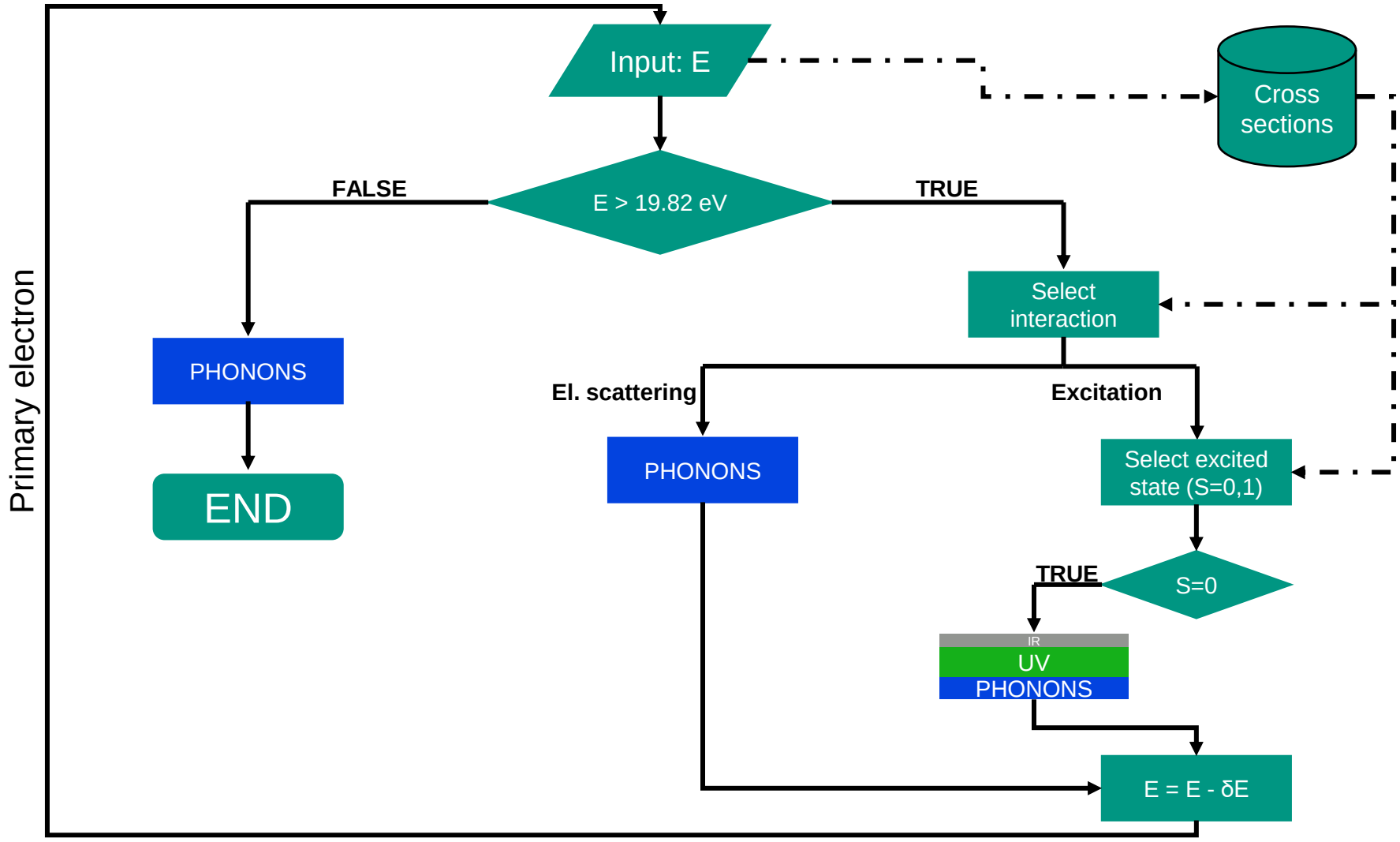
From interactions to signal quanta (ER)

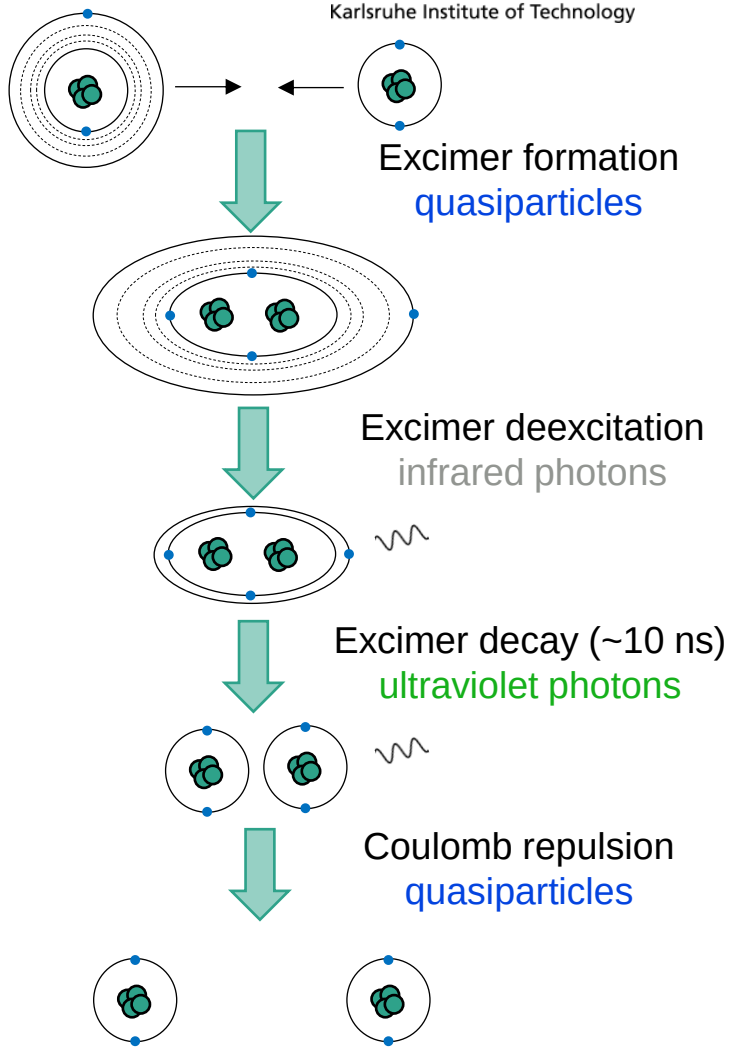


From interactions to signal quanta (ER)

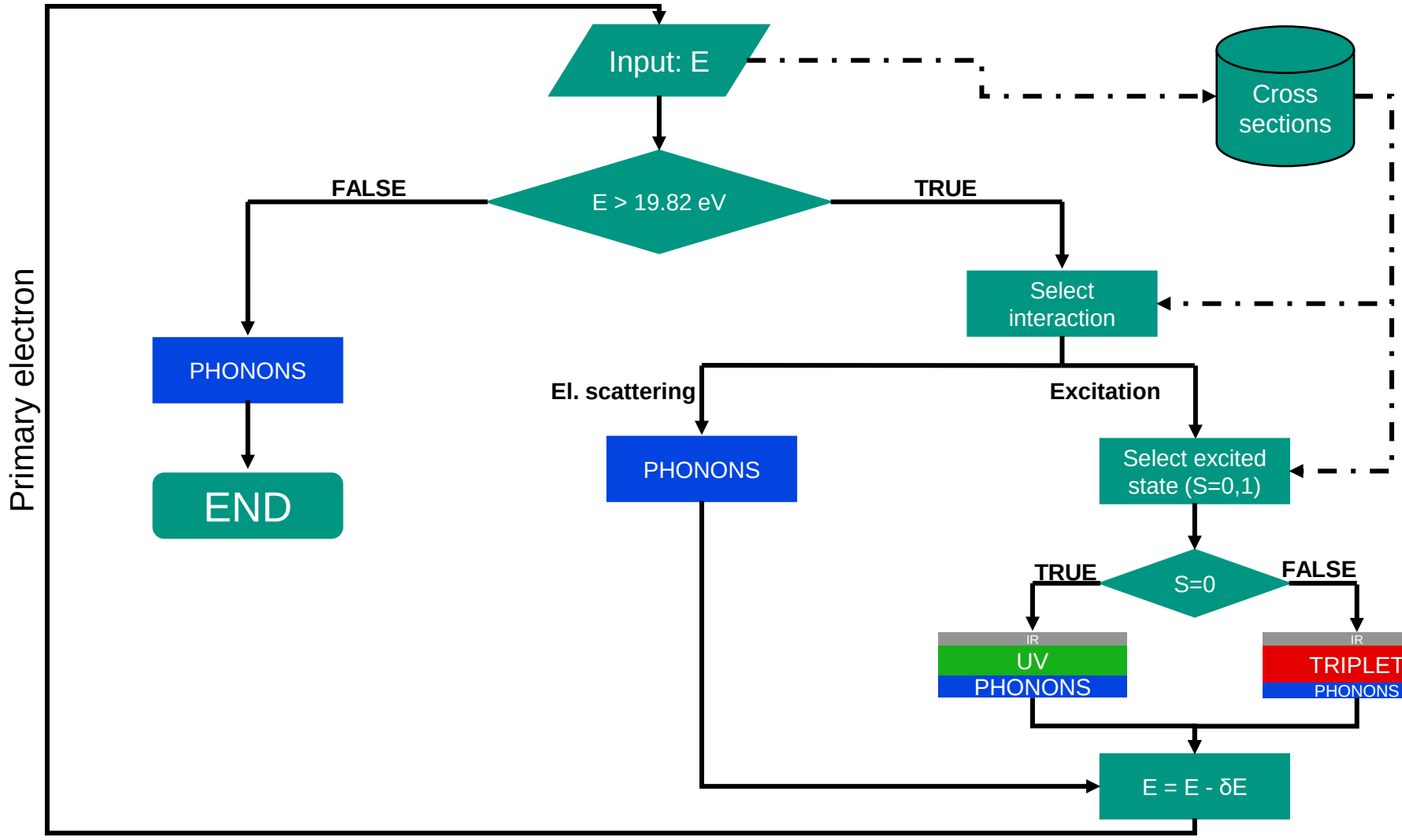


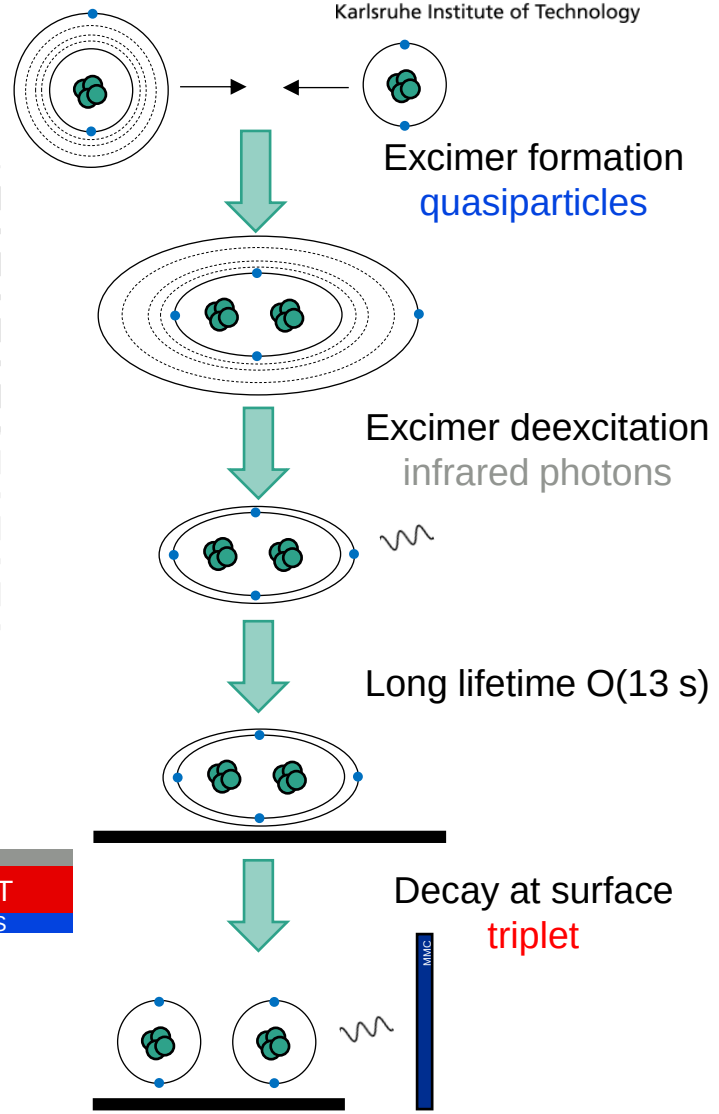
From interactions to signal quanta (ER)



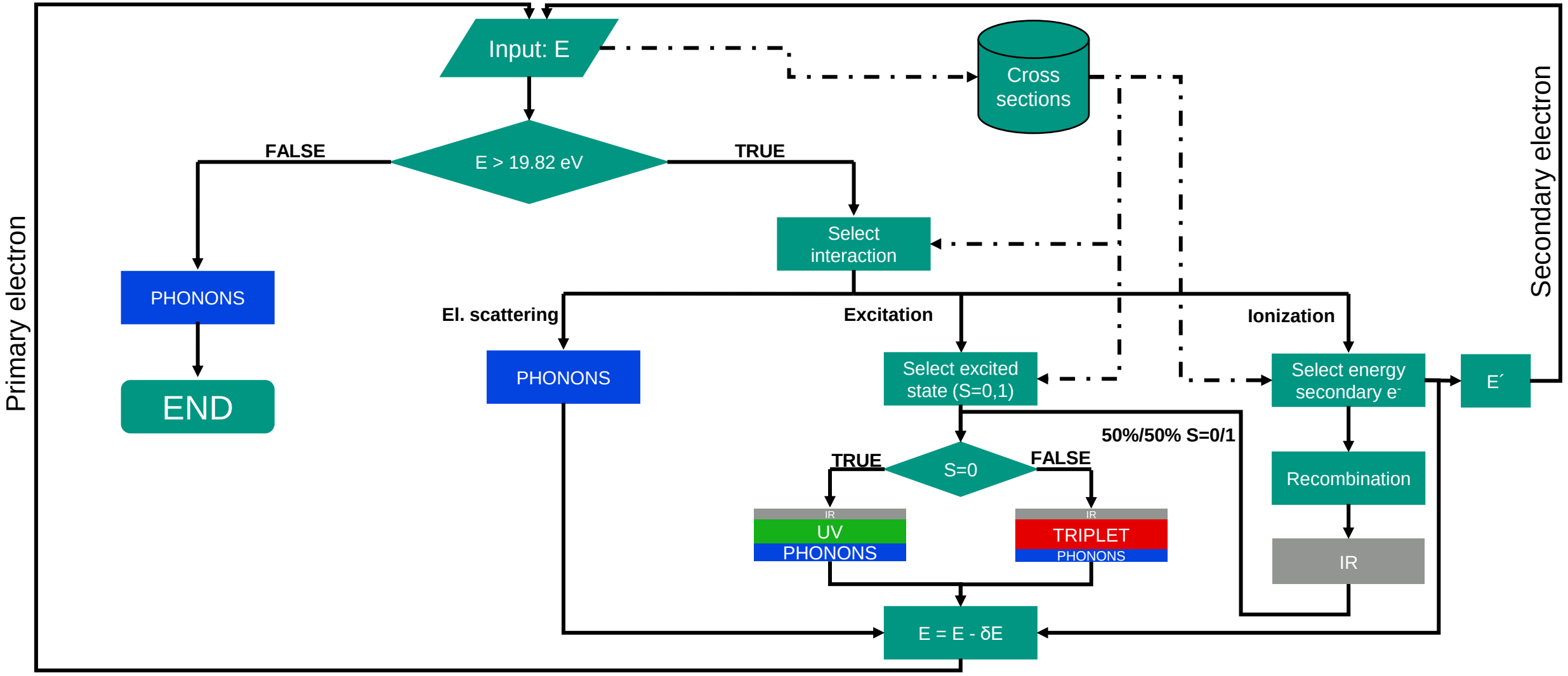


From interactions to signal quanta (ER)

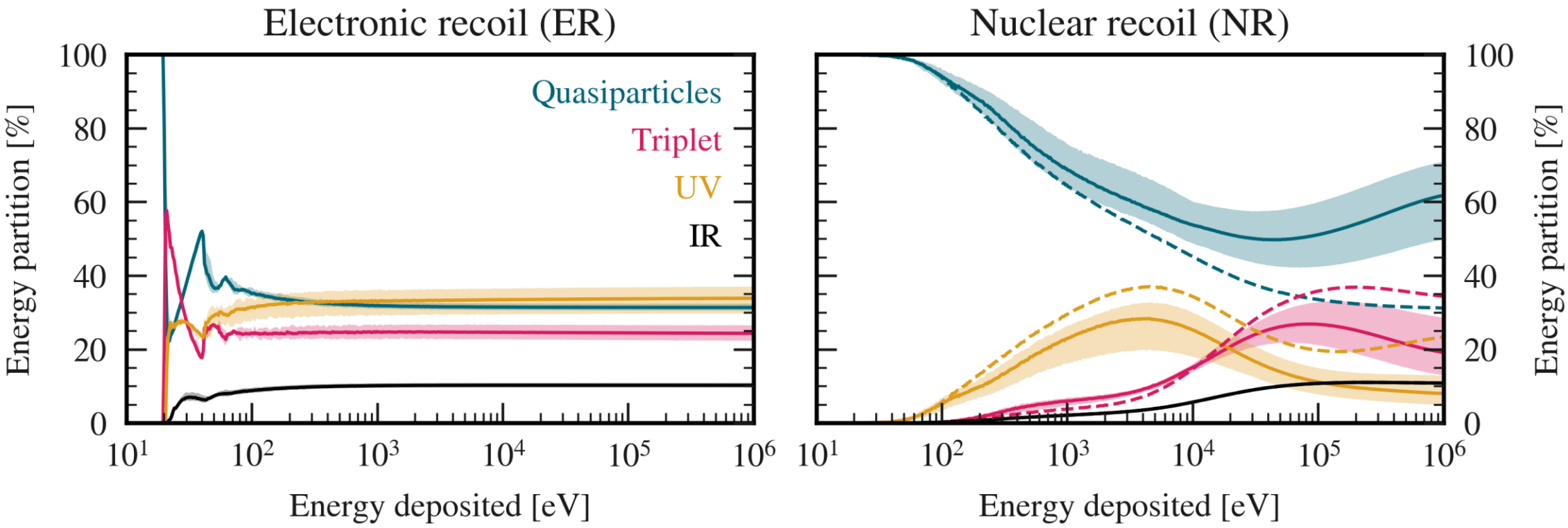




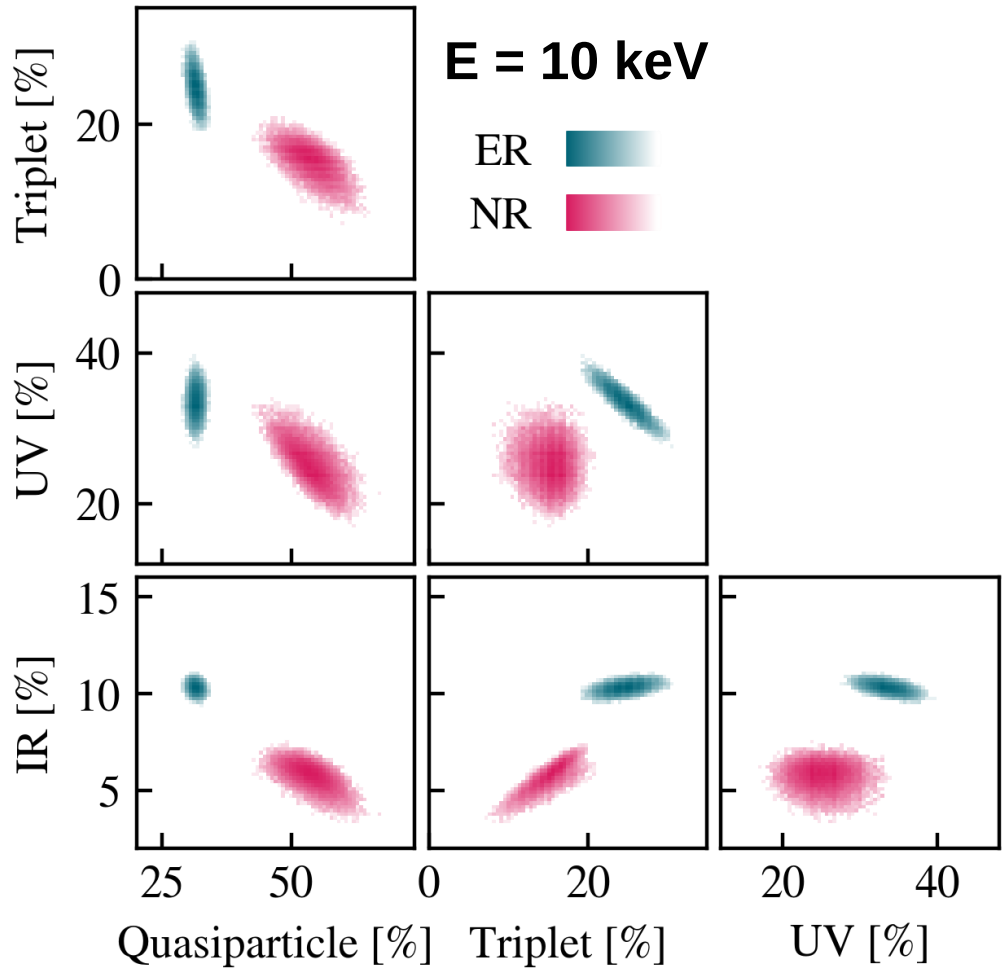
From interactions to signal quanta (ER)



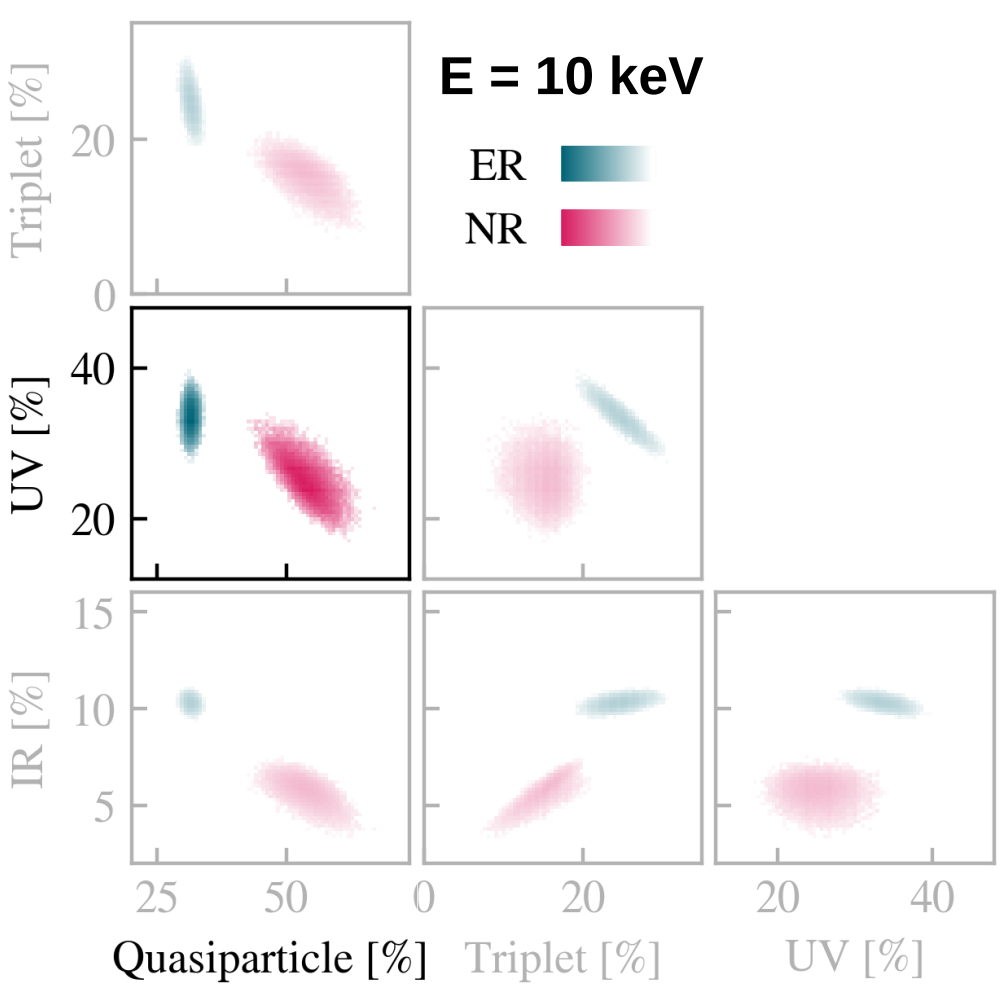
Signal partitioning in superfluid ^{4}He

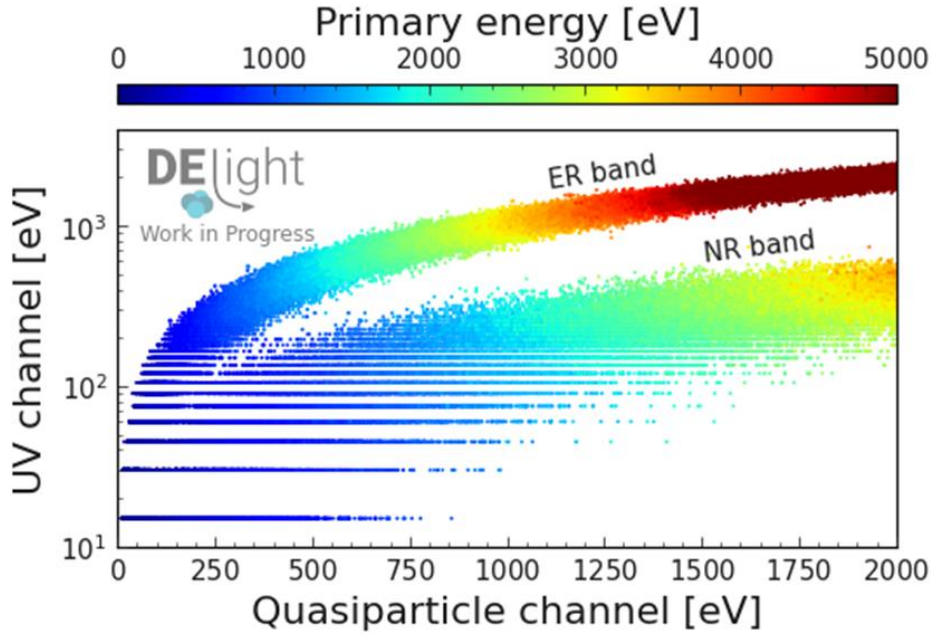


Signal correlation in superfluid ^{4}He



Signal correlation in superfluid ^{4}He



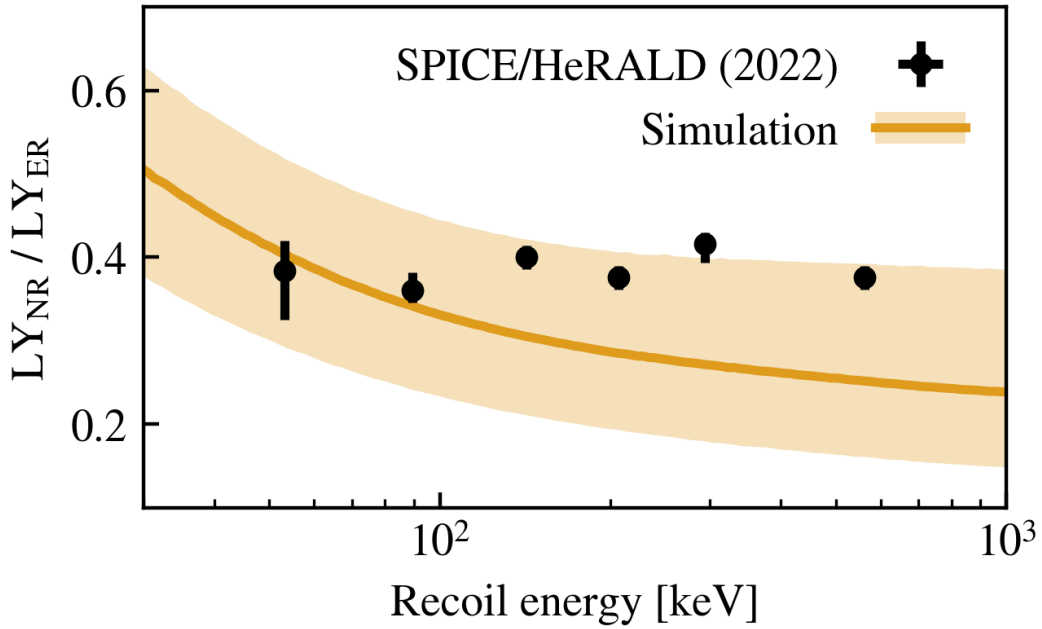


Great potential for **ER/NR discrimination**

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

Comparison with available measurements

- Average energy to produce e^--ion pair (W ~ 43 eV) well reproduced
- Difference with measured UV light yield ratio NR/ER might come from **Penning quenching** model
  - Penning affects NR LY, but not W value

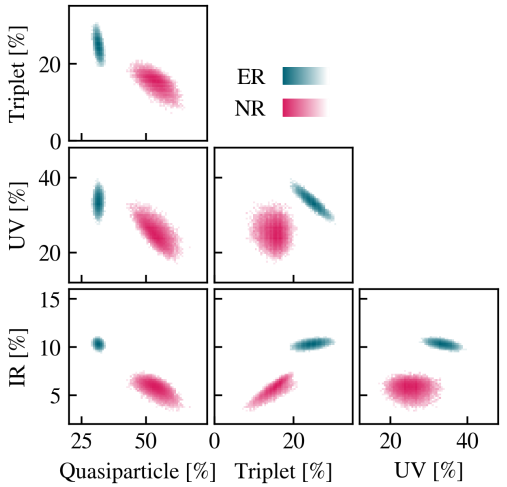


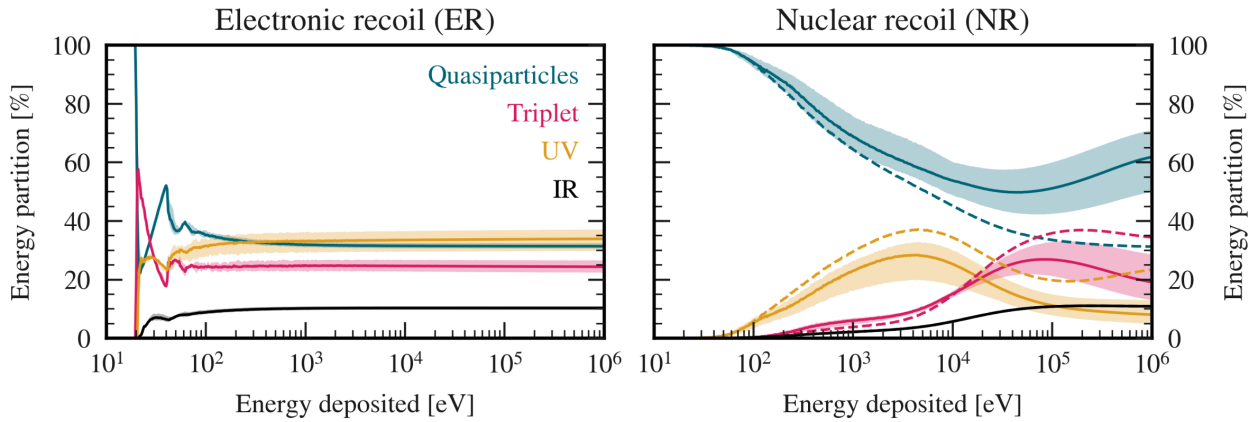
Penning quenching

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

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
  → published on PRD: **Phys. Rev. D 111, 032013**
- Implemented in our simulation framework
- Limited results for comparison
  → we need measurements!

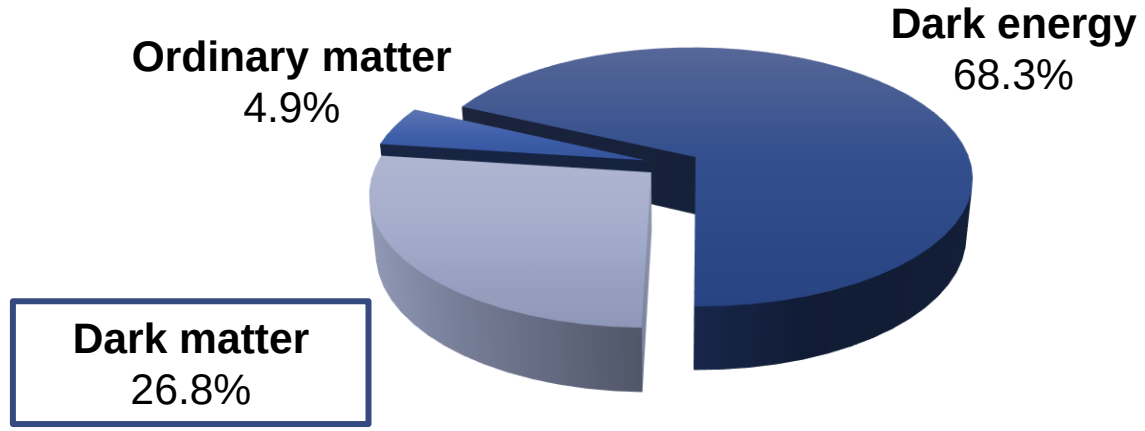


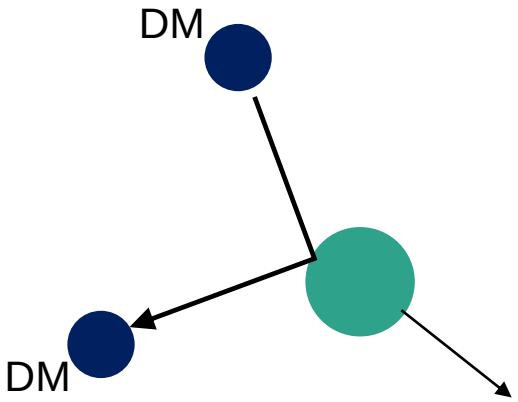


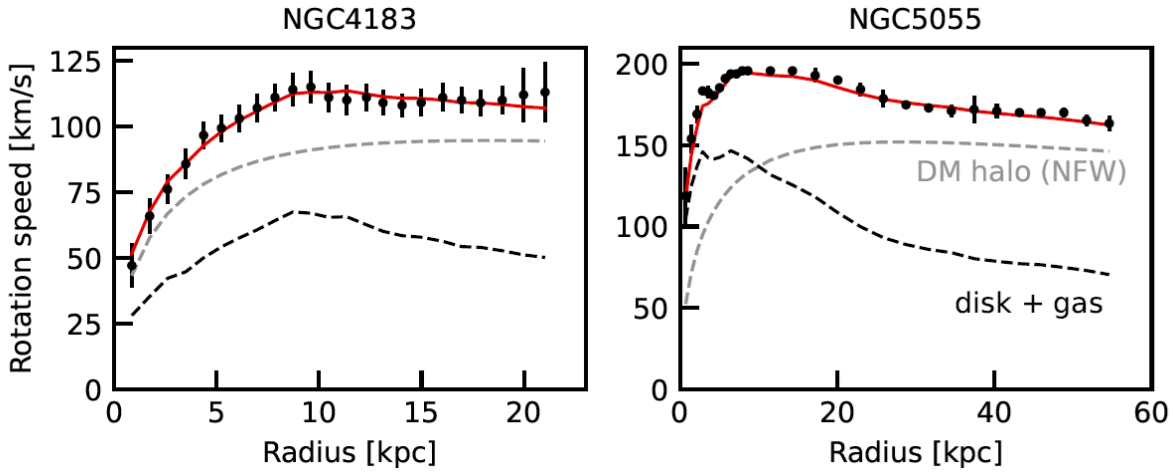
Back-up slides

Dark Matter

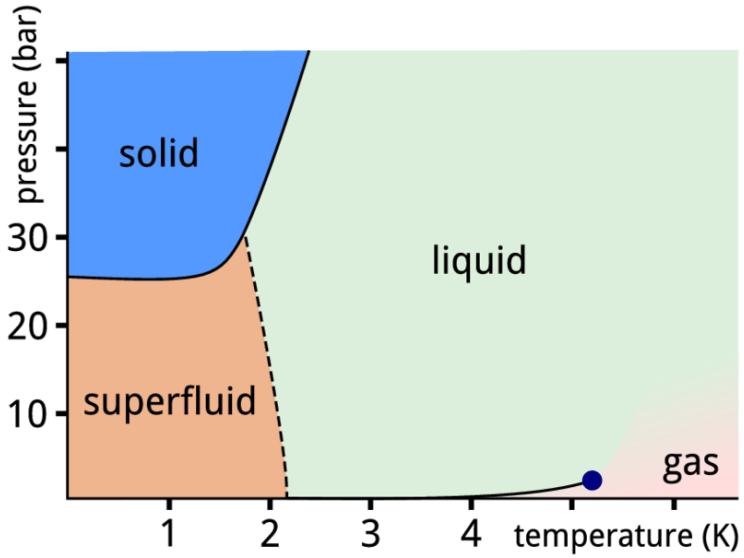
- No electromagnetic interaction → **dark**;
- Evidences of gravitational nature → **massive**;
- No particle candidate in SM → **BSM physics**;
- Direct searches for DM-nucleus scattering.

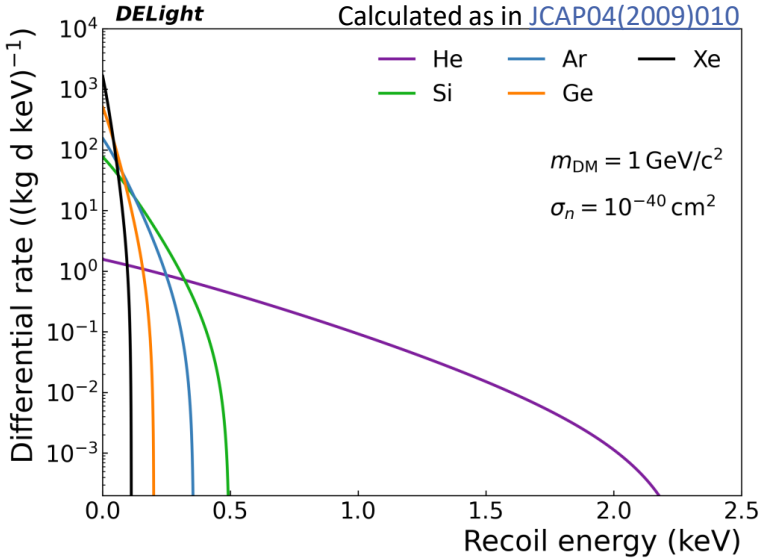






Superfluid ^{4}He as target

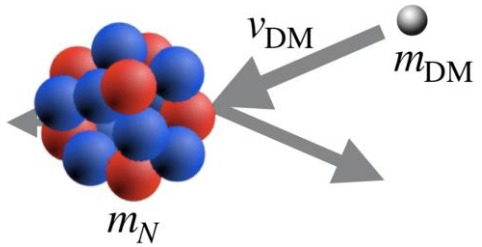




- Impurities freezing out (~20 mK)
- Multiple signals
- Unexpensive material and scalable technology

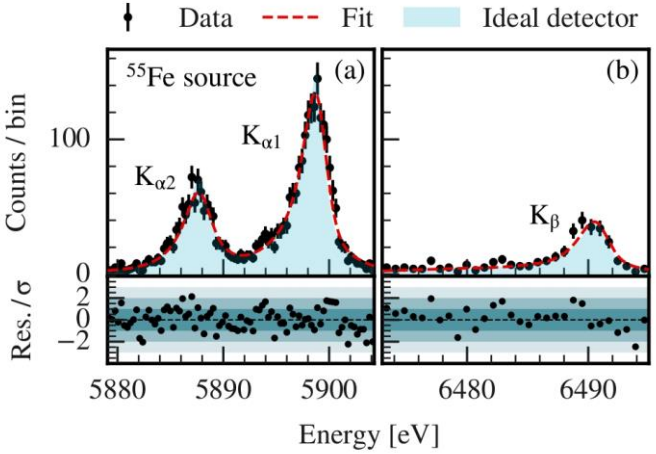
- Light nuclei maximize recoil energy for LDM

vs.

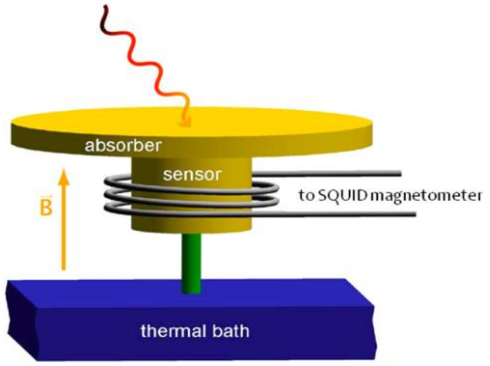


Magnetic Micro-Calorimeters (MMCs)

- 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)

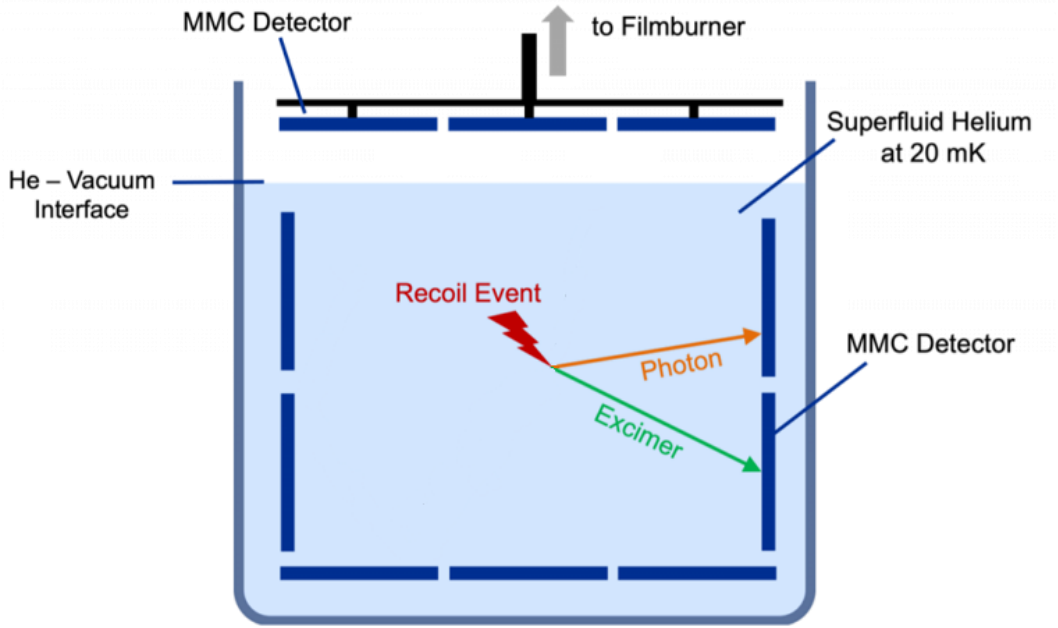


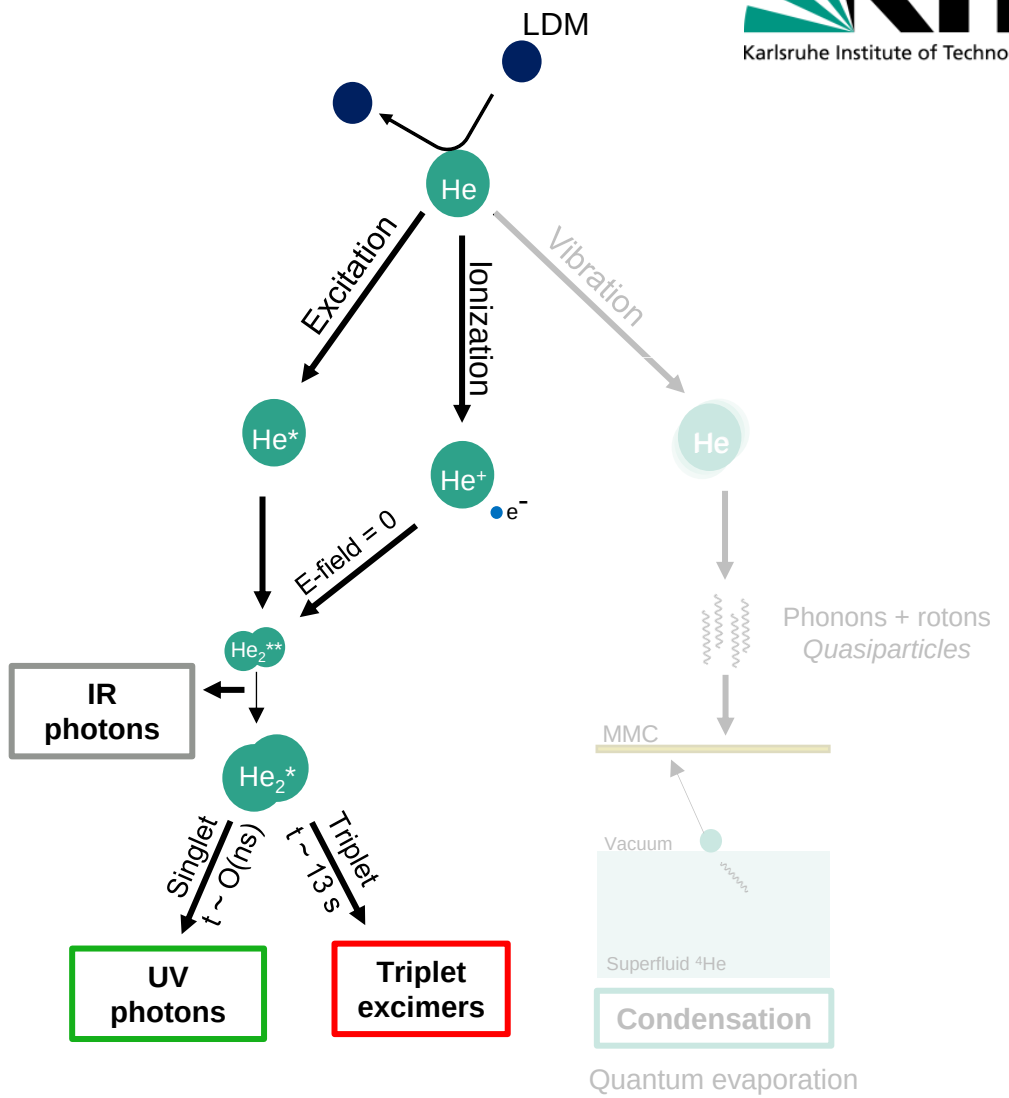
J. Low Temp. Phys. 193, 365-379 (2018)



DELight detection principle

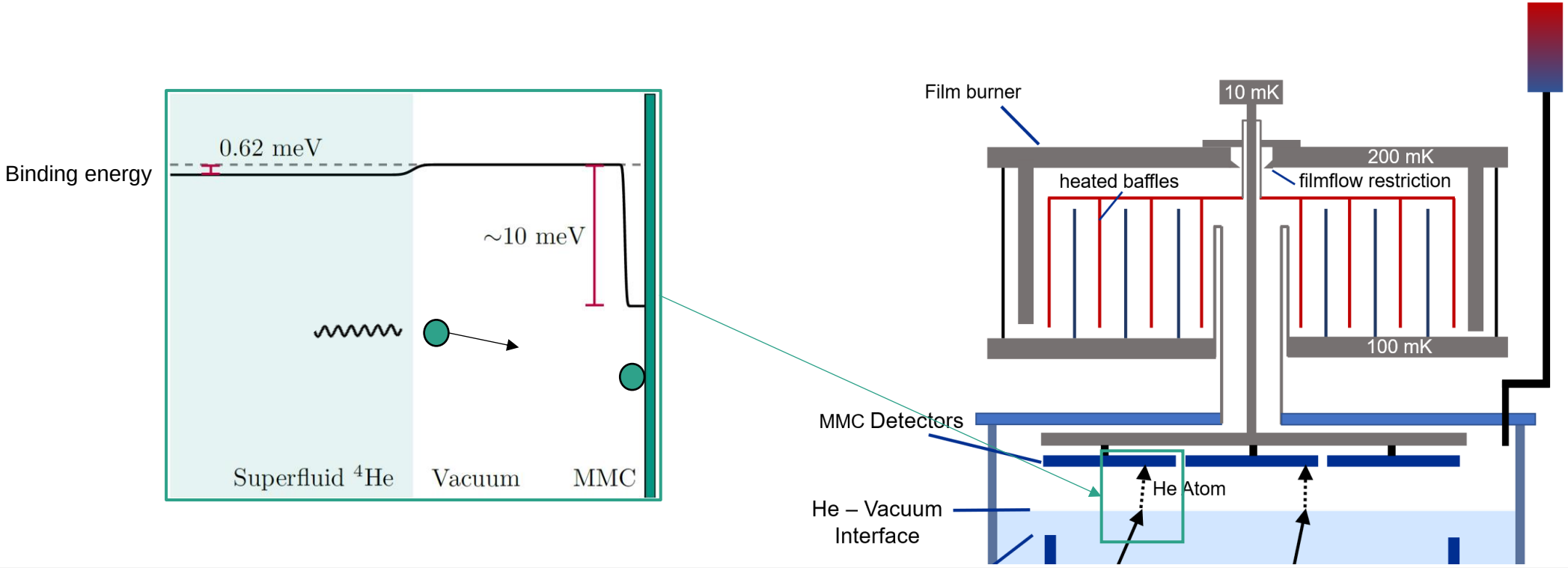
- Prompt detection of UV and IR photons
- Ballistic triplet excimer (13 s lifetime, O(m/s) speed)
  - Detected when in contact with MMC sensor



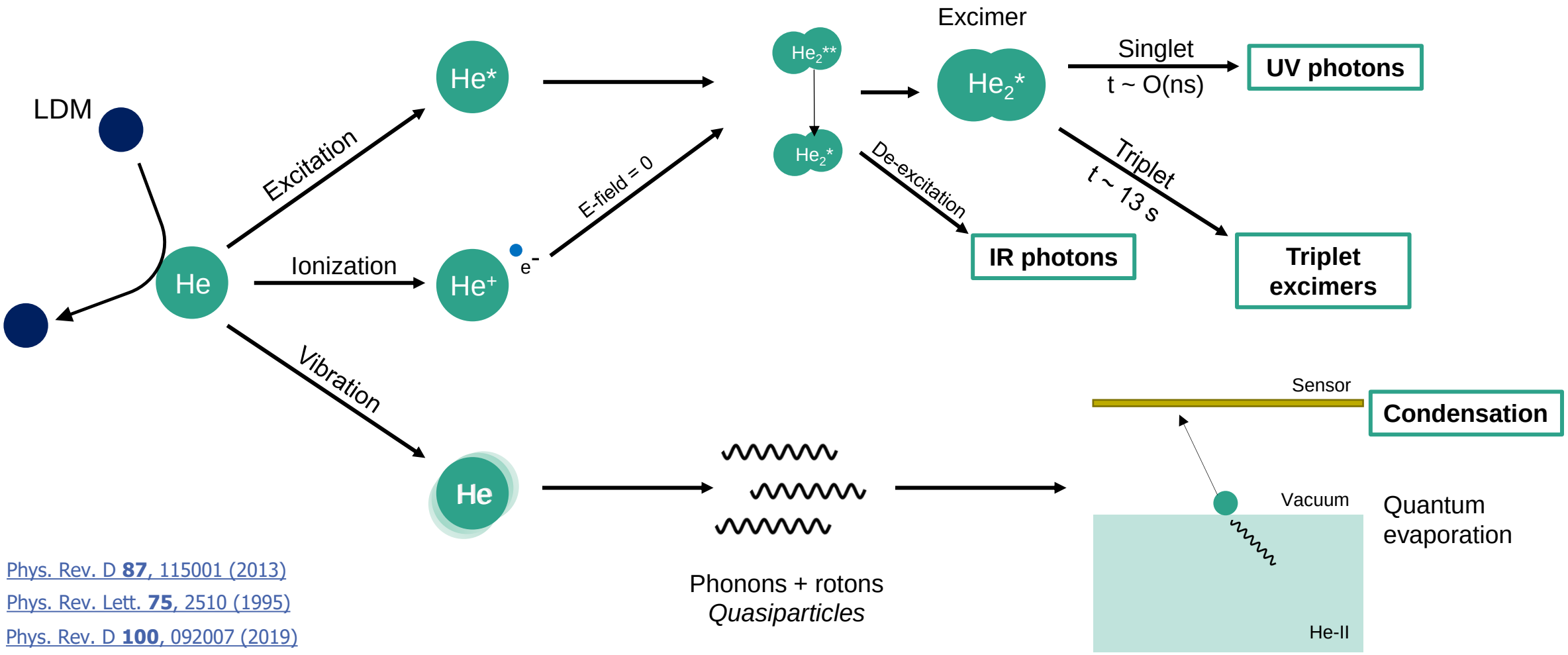


DELight quasiparticle detection principle

- 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



Superfluid ^{4}He as target

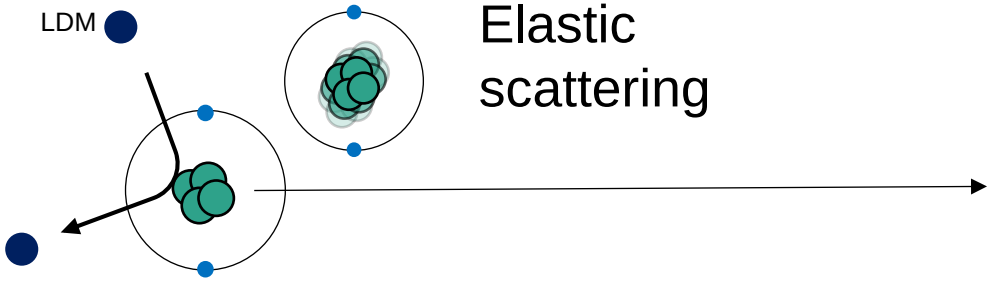


Phys. Rev. D **87**, 115001 (2013)

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

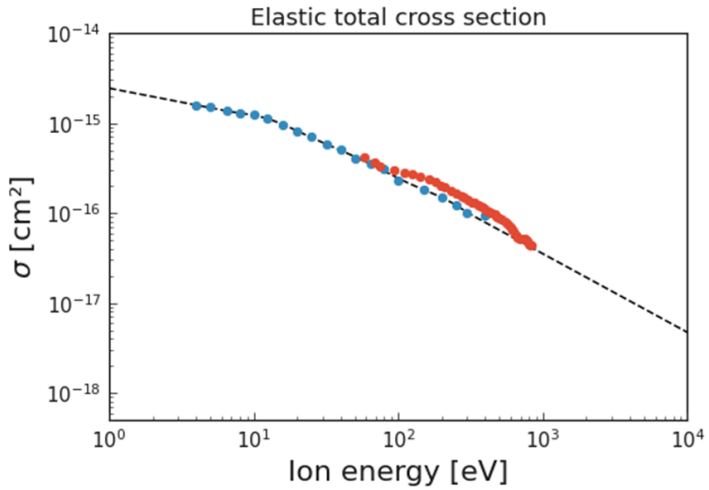
Phys. Rev. D **100**, 092007 (2019)

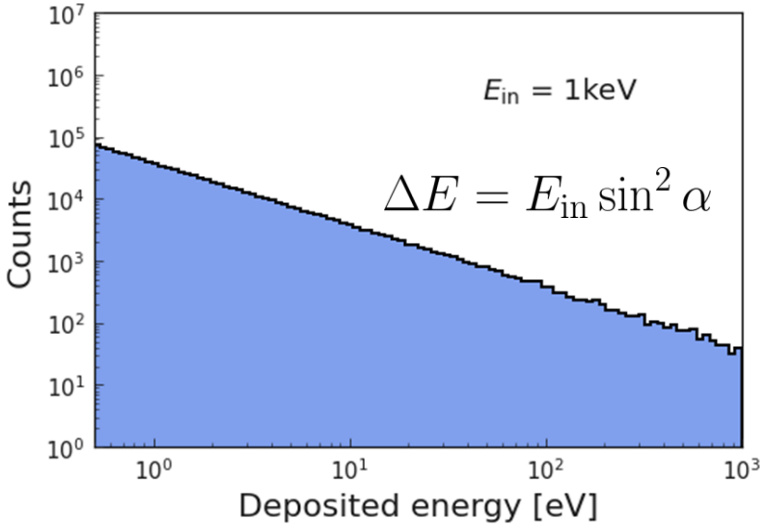
The journey of an helium ion



Elastic scattering

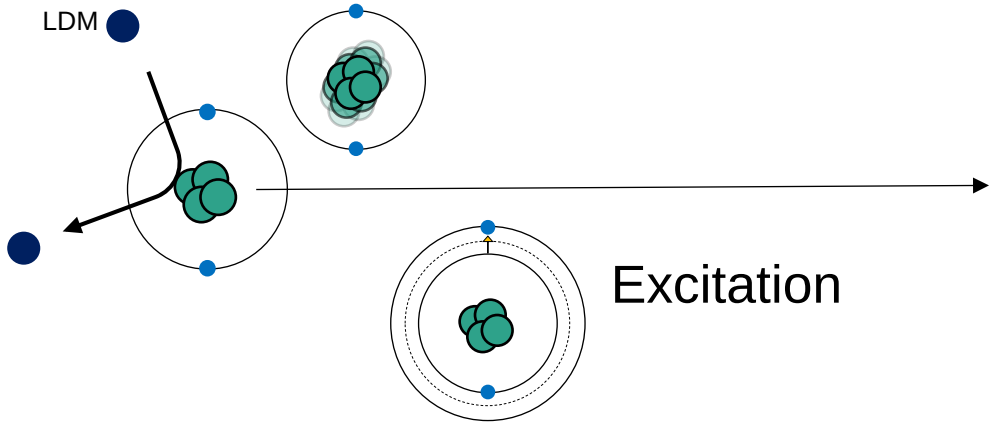
- Total cross section measurements from He^+;
- energy loss from non-relativistic collision;
- Rutherford-like angular distribution;
- large energy deposition possible (target = projectile).



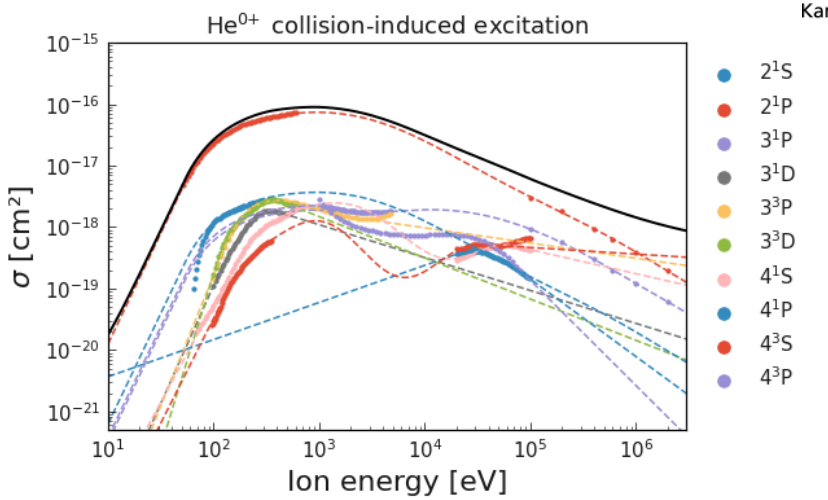


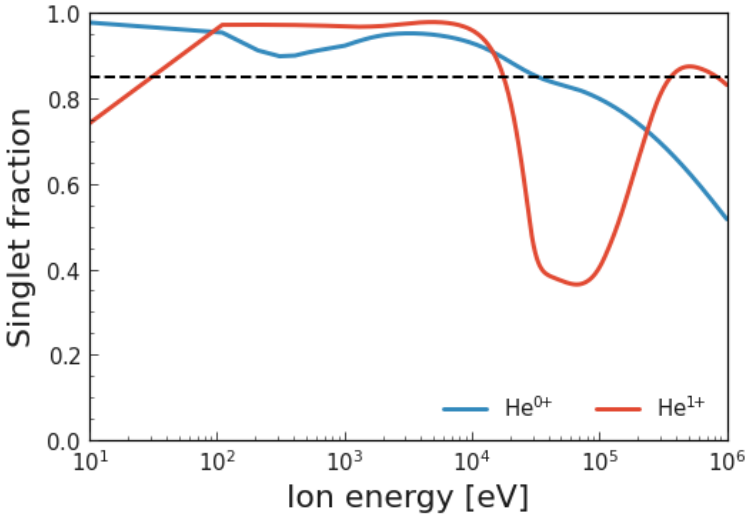
J. Chem. Phys. 26, 1272–1275 (1957)

The journey of an helium ion

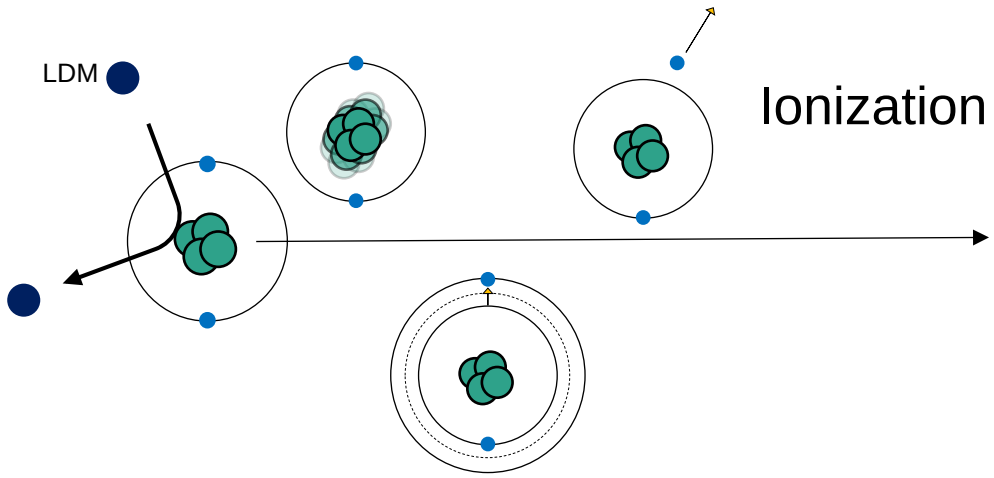


- Excitation of target neutral He;
- first accessible state is 2^3S (*1s2s*) at 19.82 eV*;*
- cross sections form database ALADDIN;
- singlet/triplet ratio from cross sections.

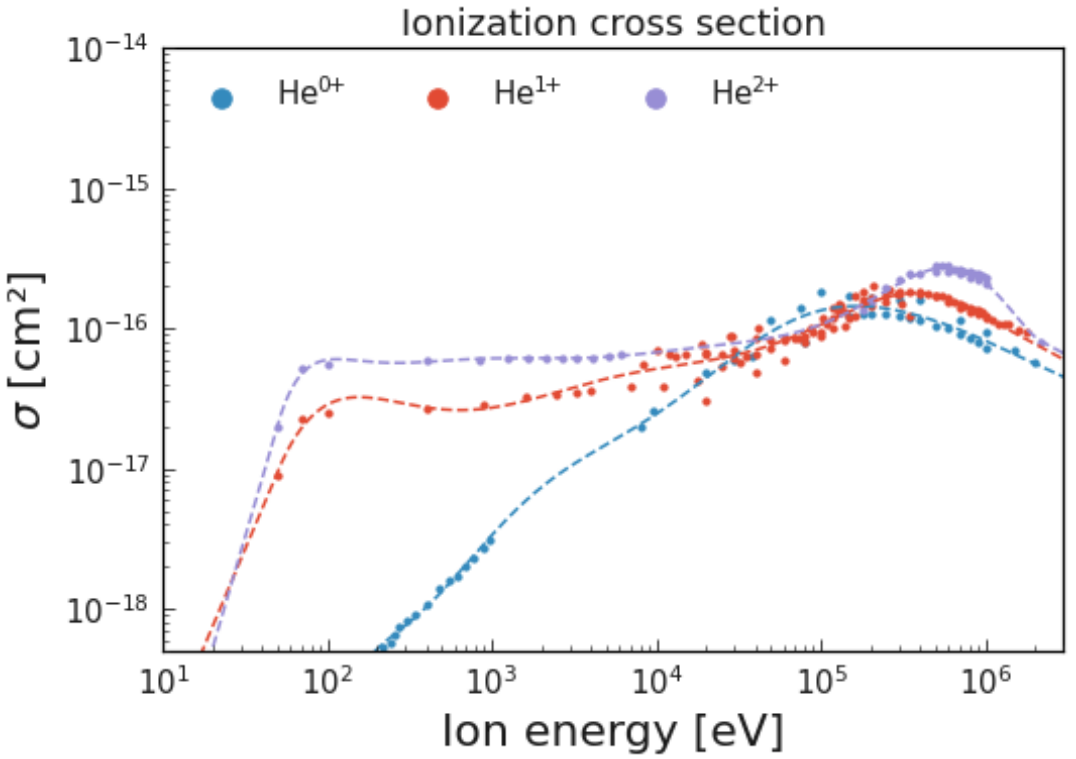




The journey of an helium ion

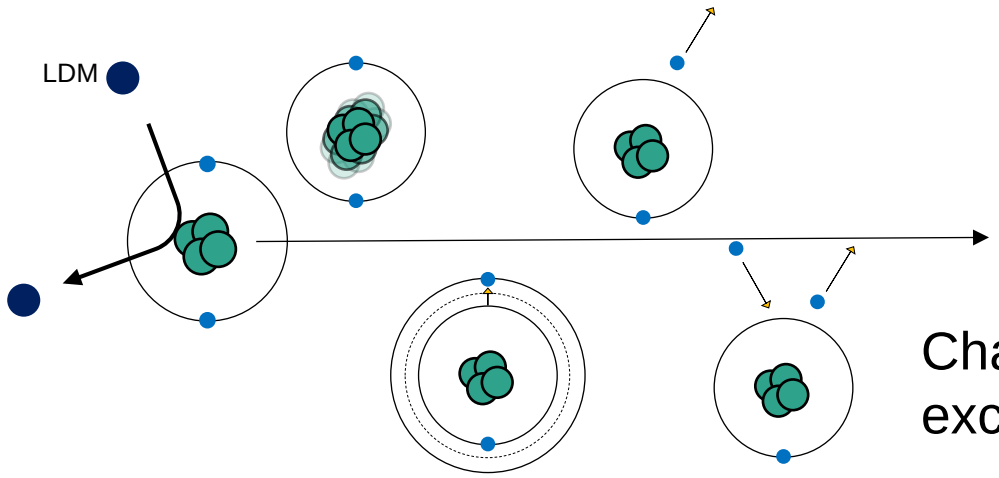


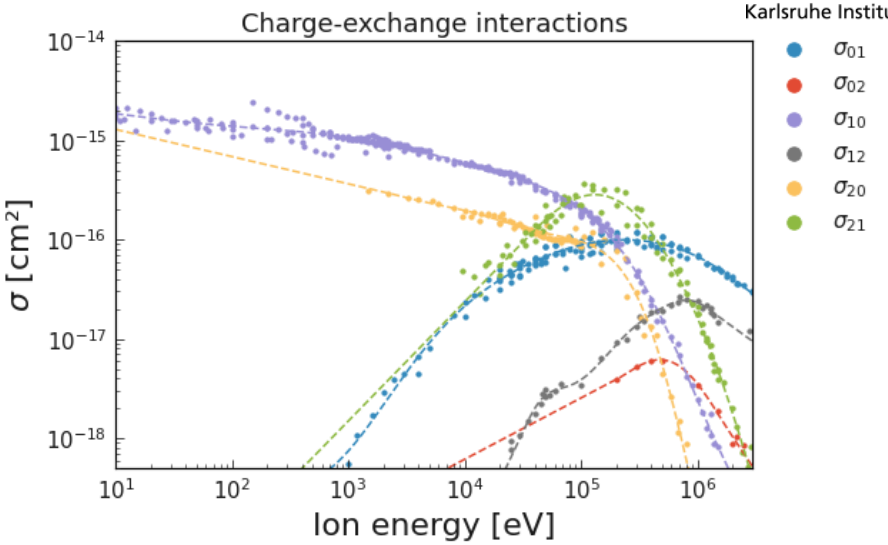
- Ionization of the target ground He;
- fit to measured cross section;
- measurements for different projectile charge states;
- negligible double-ionization.

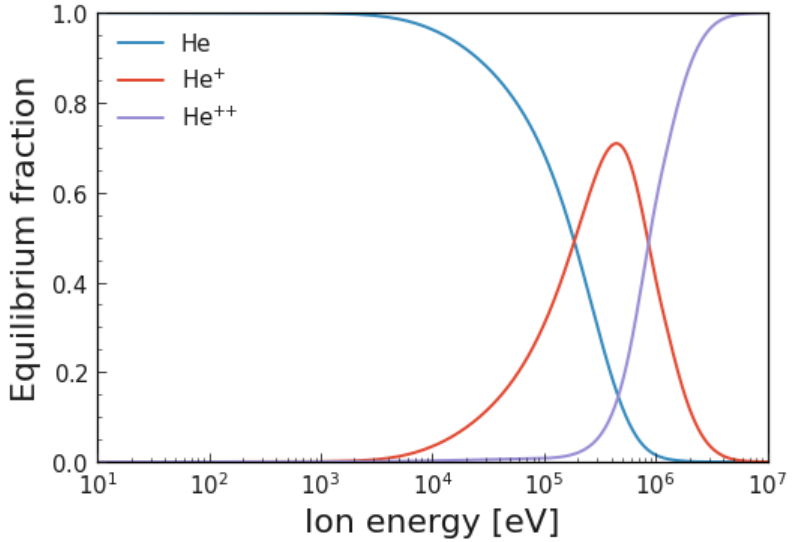


JAERI-M 9310 (1981)

The journey of an helium ion

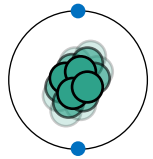




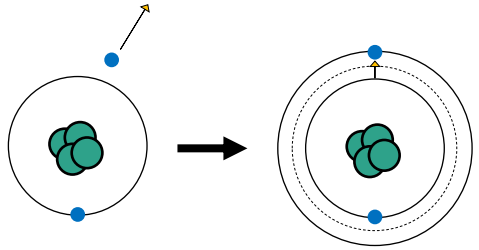


- Target and projectile He ions exchange electrons;
- projectile He changes charge state as it propagates;
- at low energy, projectile He is neutral.

From interactions to signal quanta



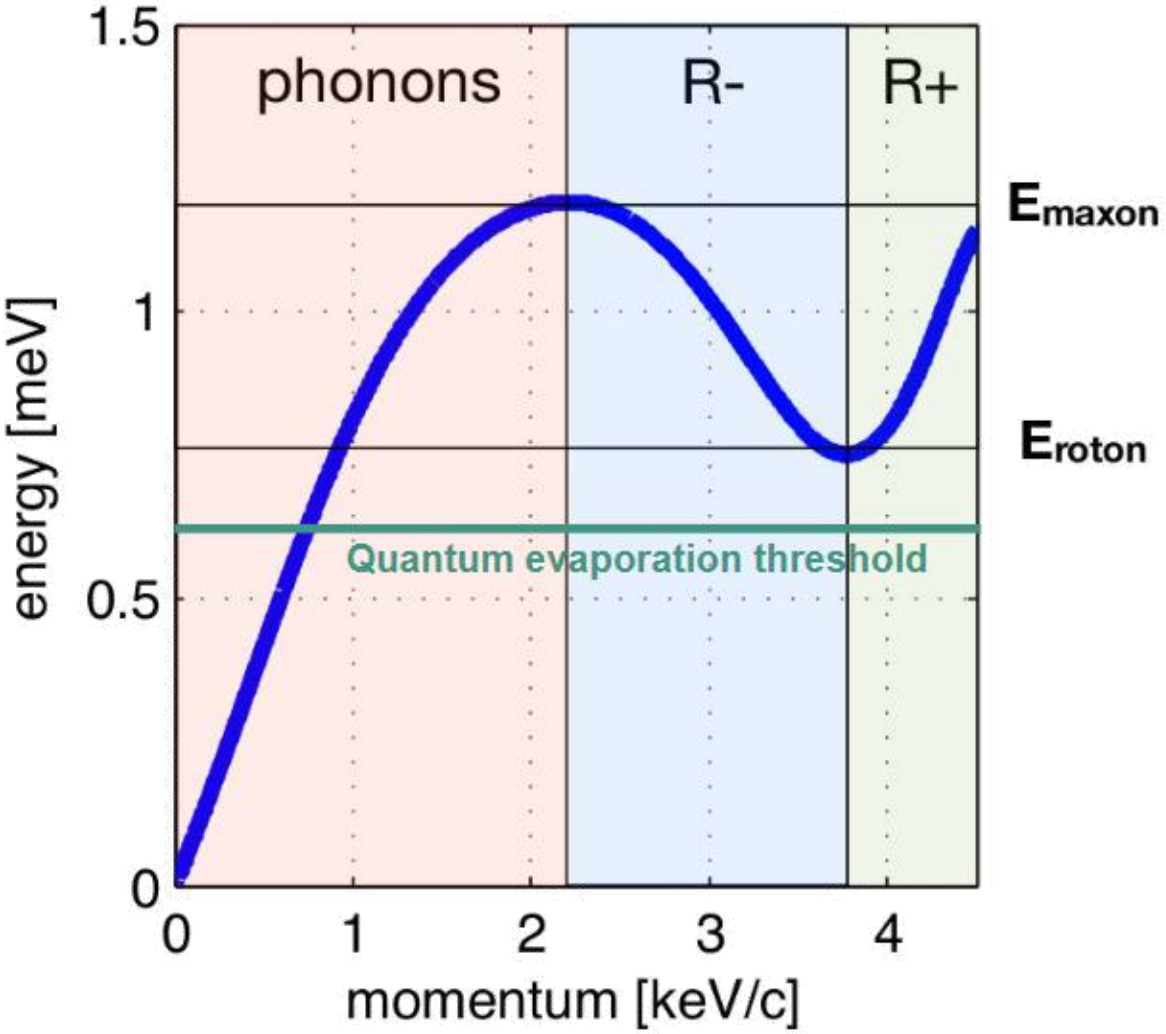
- Elastic scattering goes into quasiparticles (phonons and rotons)



- 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

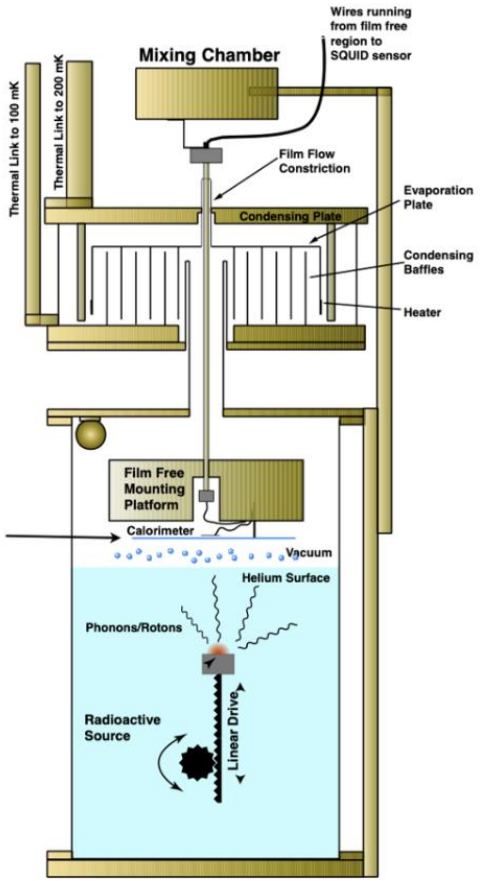


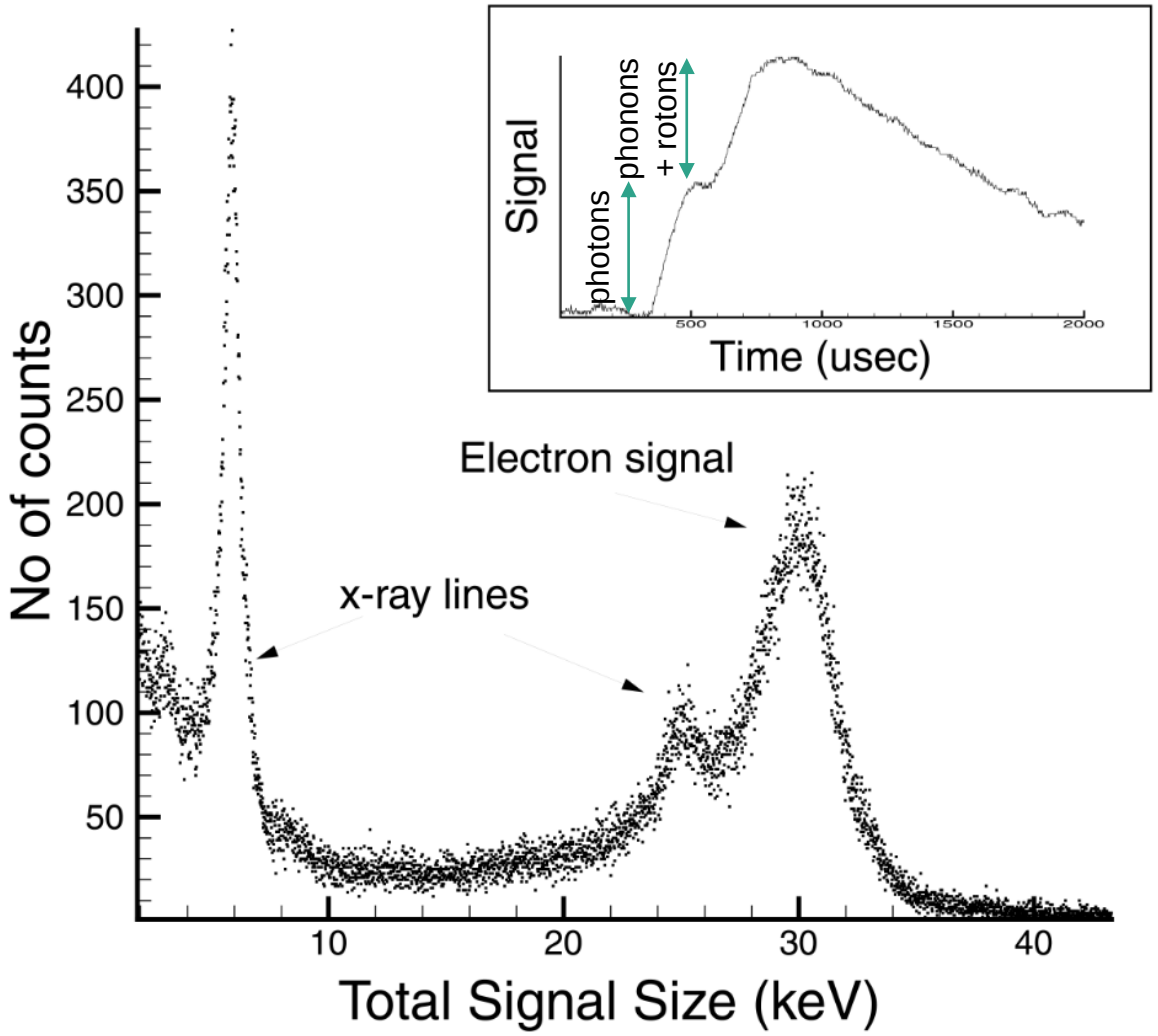
HERON

He film burner

wafer calorimeter

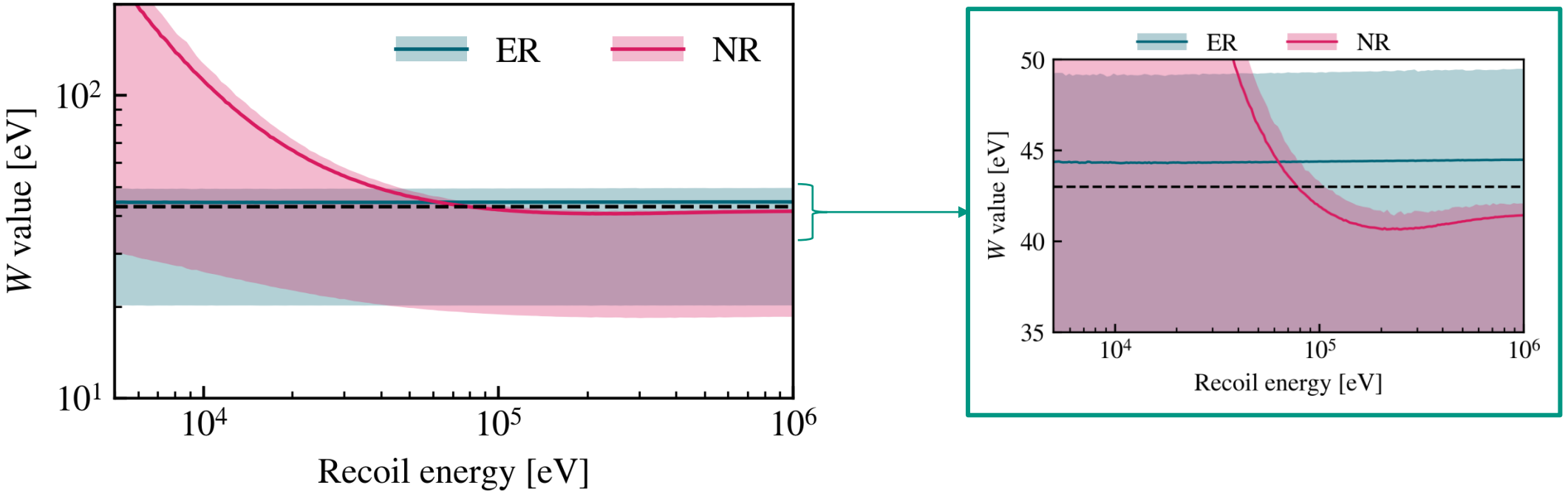
kg-scale
LHe mass





Comparison with available measurements

- *W* is the average energy needed to produce an electron-ion pair in superfluid ^{4}He
  - Measurements agree with an average value of ~43 eV



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