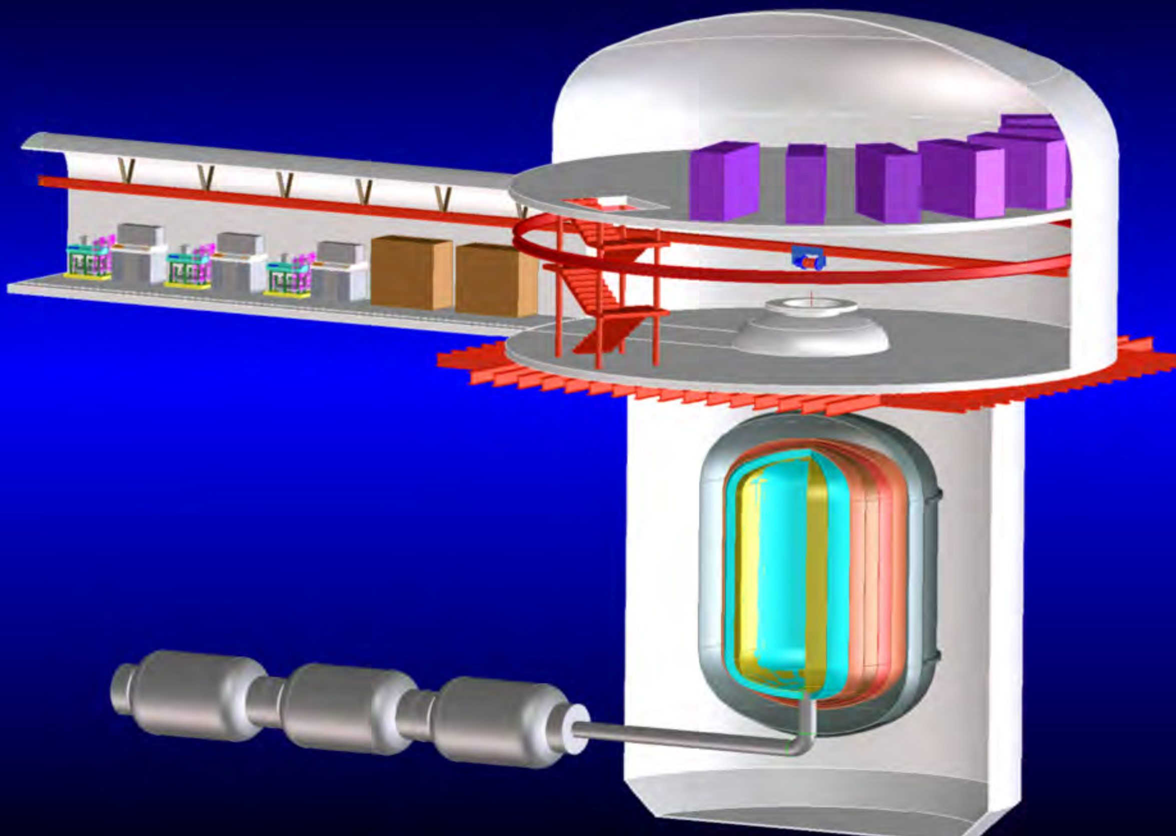
L. Gastaldo, S. Kempf, J. Jaeckel, C. Enss
Heidelberg University

DELight: Direct Search Experiment for Light Dark Matter

A Superfluid Helium Detector



HERON HElium-ROton detection of Neutrinos

A superfluid helium based detector designed to investigate solar neutrinos

HERON as Dark Matter detector

R. E. Lanou, H. J. Maris, and G. M. Seidel, PRL **58**, 2498 (1987).

J. Adams *et al*., Proc. XXXIst Moriond Conference, p. 14, (1996) .

T. M. Ito, G.M. Seidel, PRC **88**, 025805 (2013).

HERON-like Detectors for Dark Matter

W. Guo, D.N. McKinsey, PRD 87, 115001 (2013)

H. J. Maris, G. M. Seidel, D. Stein, PRL **119**, 181303 (2017)

S. Hertel et al., PRD **100**, 092007 (2019)

Why Superfluid Helium?

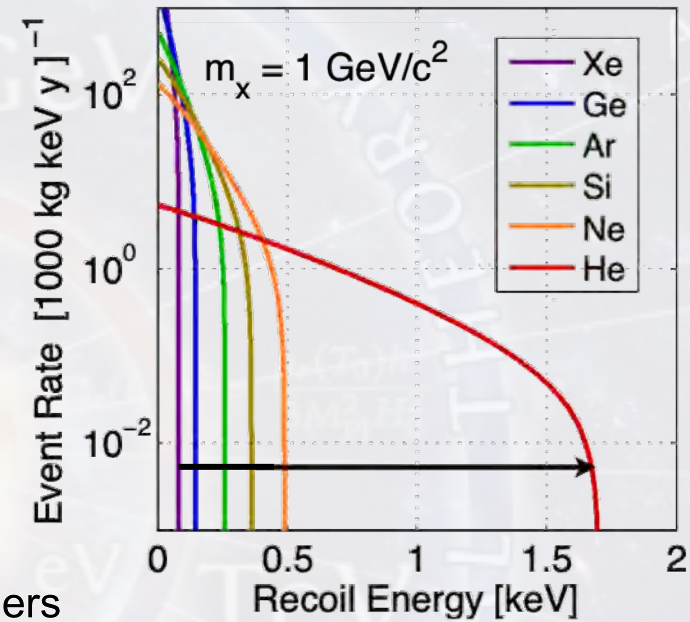
Favourable properties of superfluid helium

- light baryonic target

$$E_{nr} = \frac{2\, m_x^2\, m_n\, v^2}{(m_x + m_n)^2} cos^2\theta$$

10 GeV → 10 keV – 100 keV recoil energy

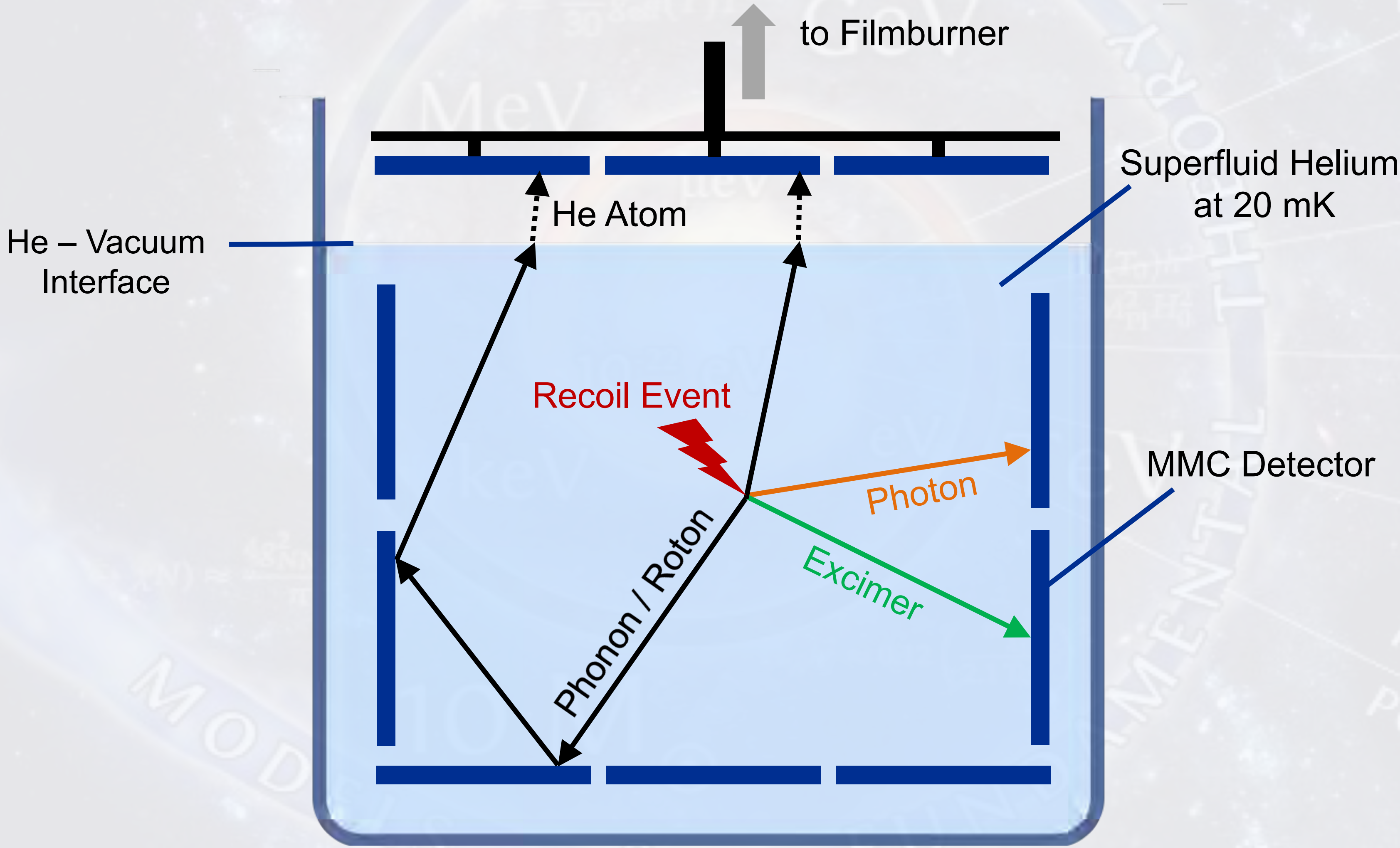
- ultrapure – no internal background
- multiple signals, phonon & rotons, photons, excimers
- discrimination of nuclear and electronic recoil
- event location: coded aperture array
- fiducial cuts possible
- directionality possible
- helium immune to muon spallation/capture



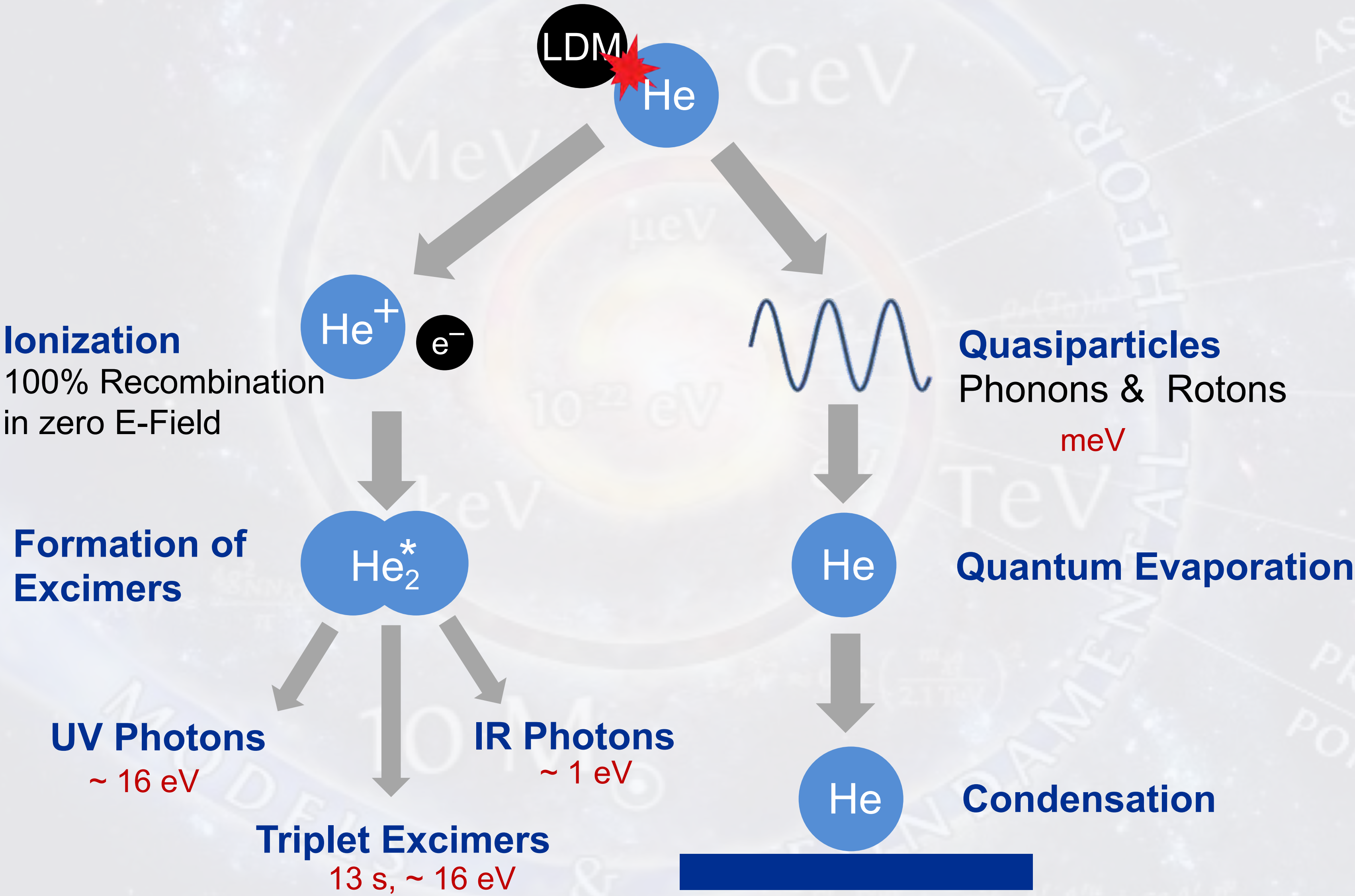
Overall concept has been demonstrated

S. Bandler *et al.* PRL **78**, 2429 (1992)
C. Enss *et al.* Physica B 1**94-196**, 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)

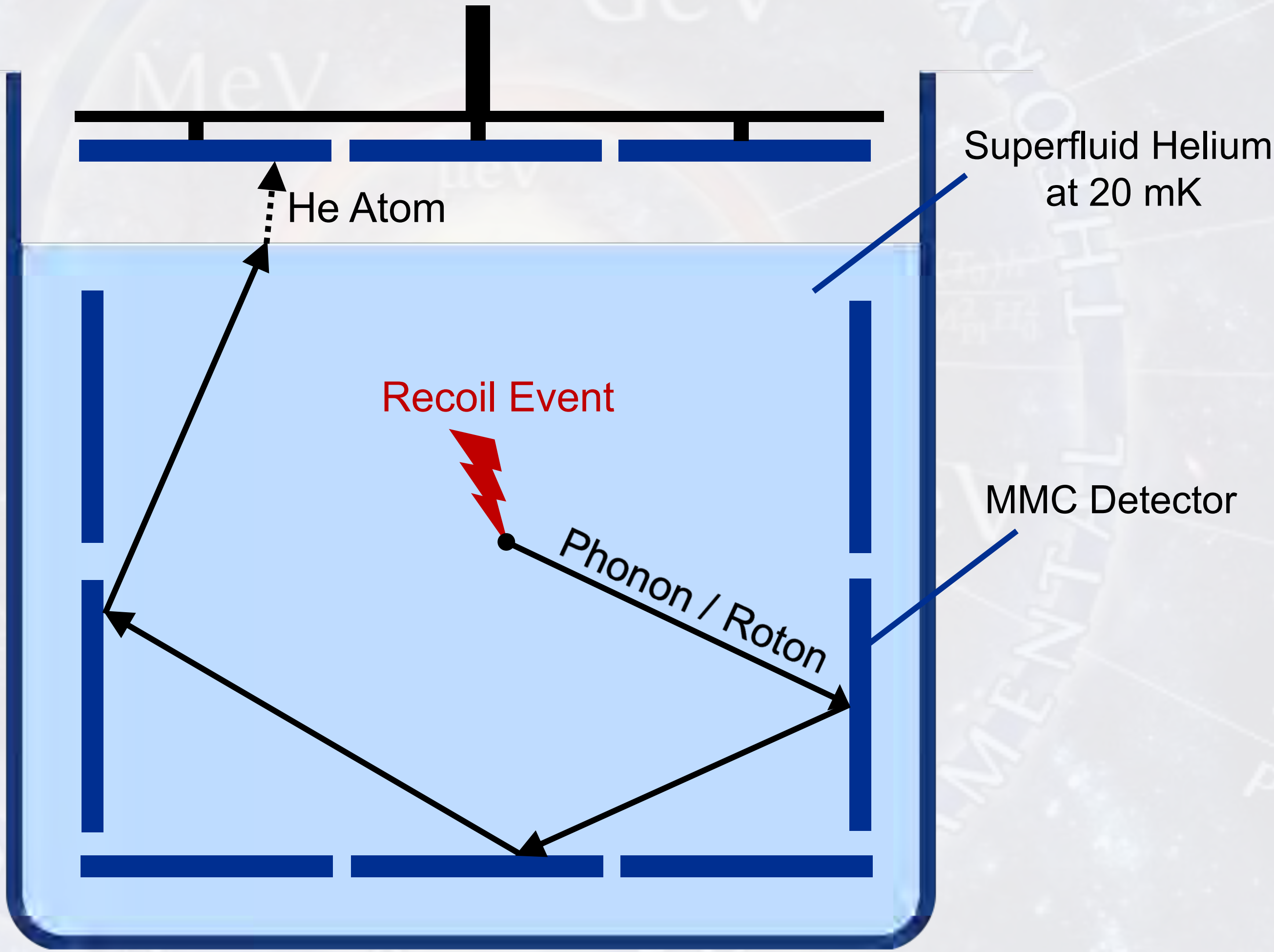
Basic Concept and Available Signals



Multiple Signals and Signal Chains

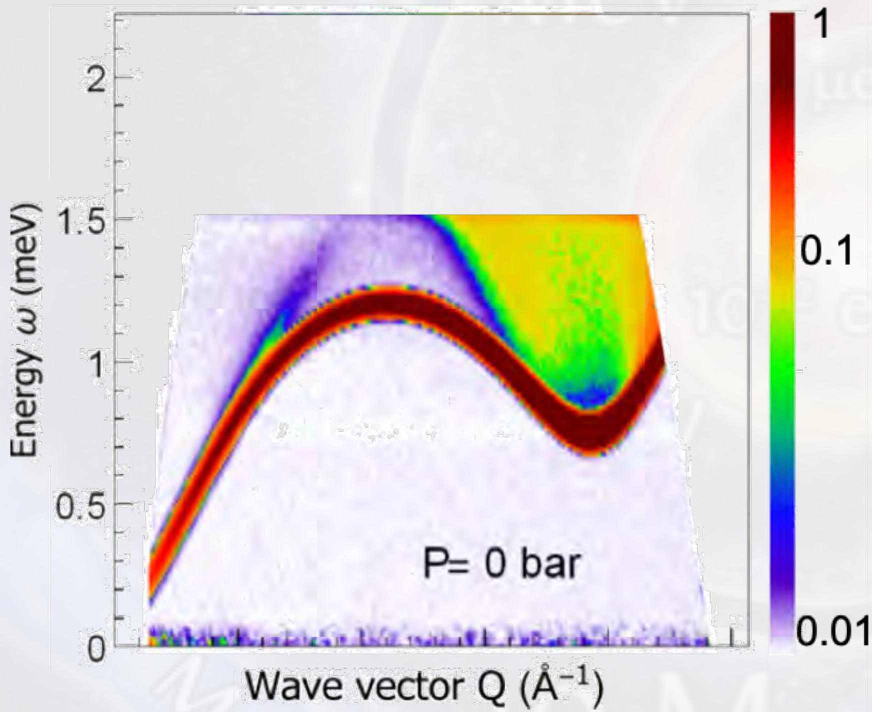


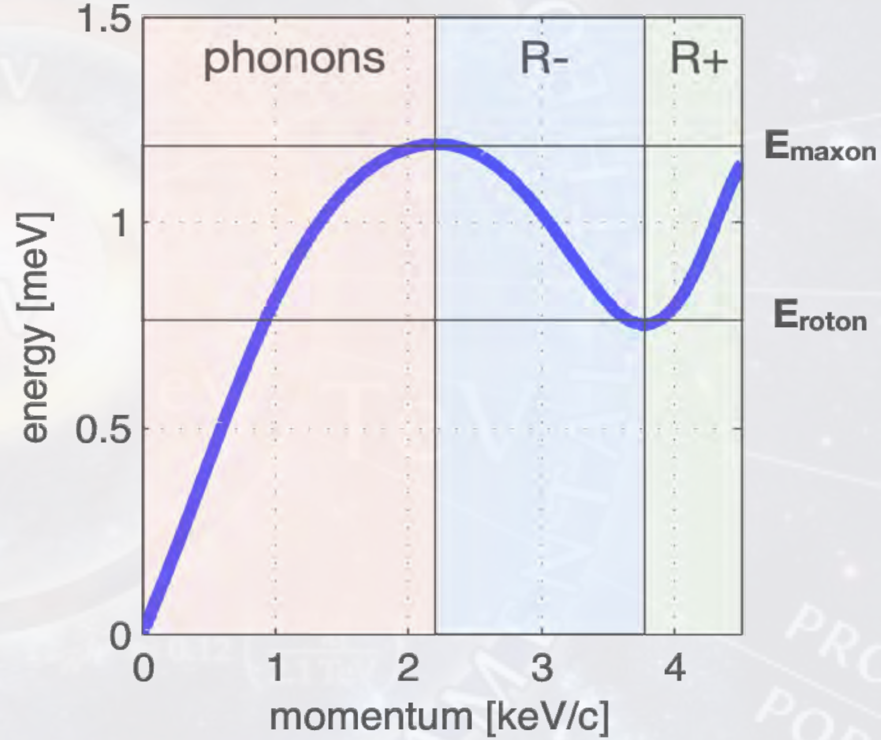
Quasi-Particles and Quantum Evaporation



Quasi-Particles: Phonon and Rotons

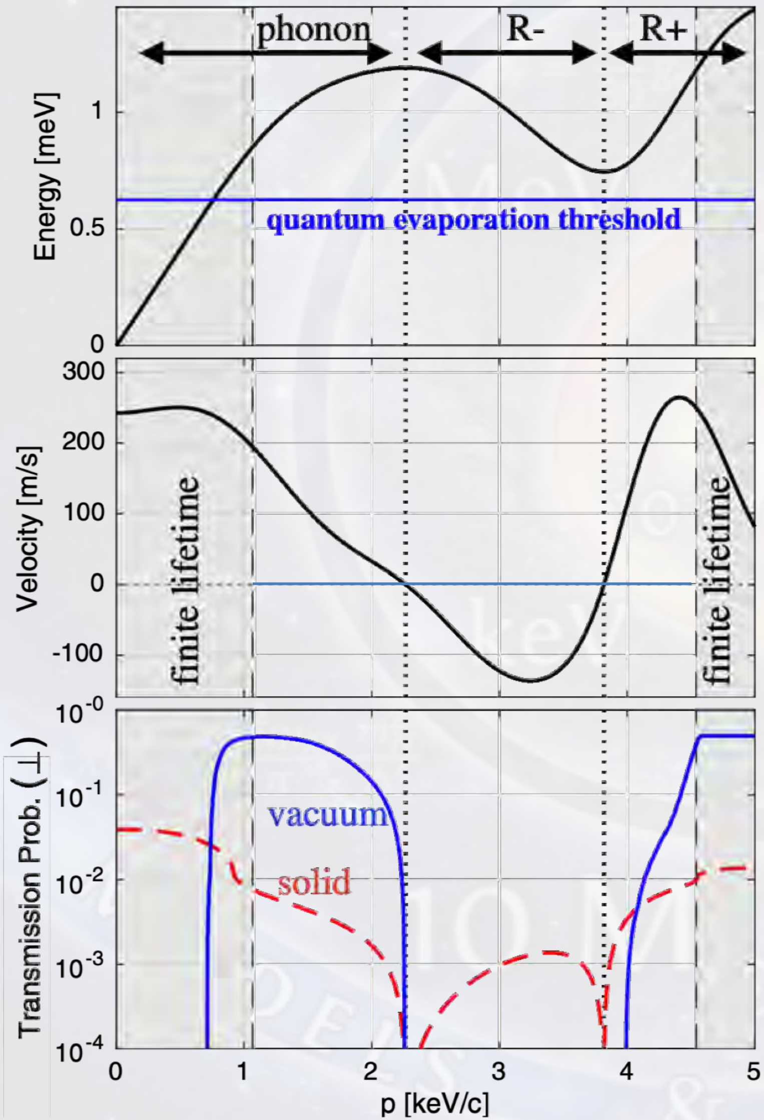
Phonon-Roton Dispersion in Superfluid Helium





K. Beauvois *et al.* PRB **97**, 184520 (2018)

Quasi-Particles: Phonon and Rotons



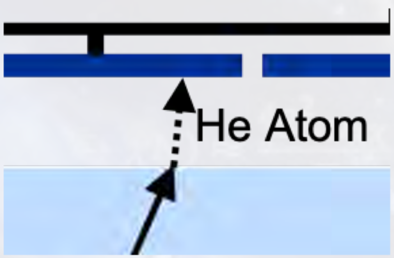
S. Hertel *et al.*, PRD **100**, 092007 (2019)

Quantum Evaporation: Gain Factor

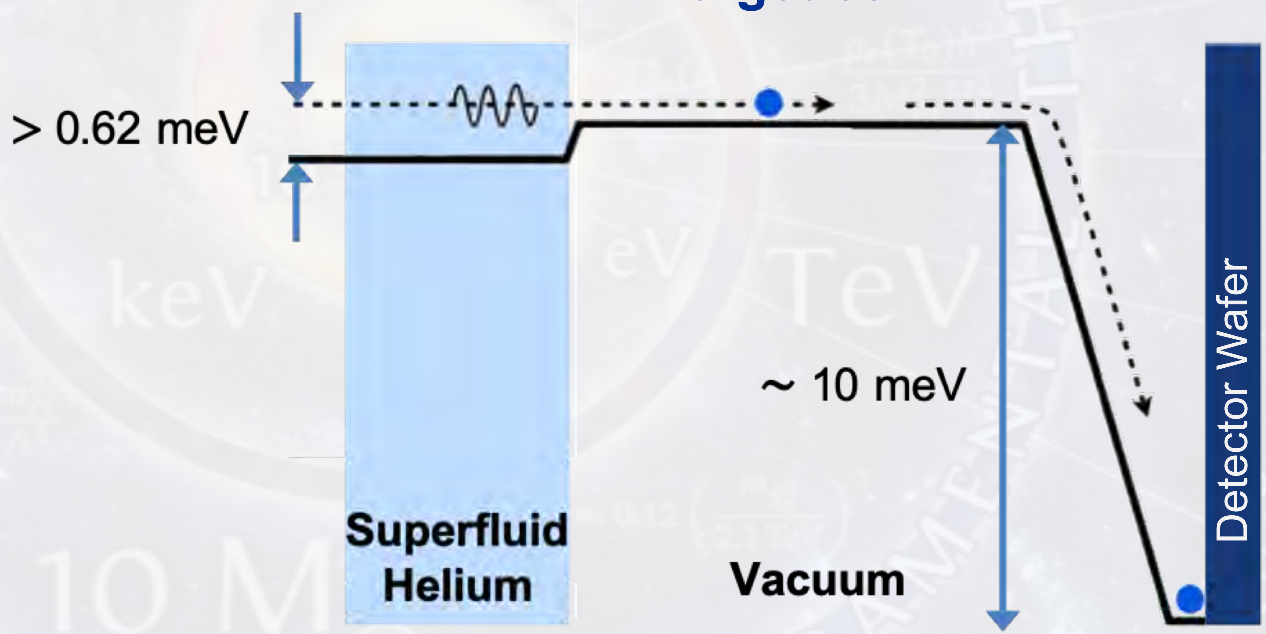
Phonon/Roton → **Free He-Atom** → **He-Atom on Solid**

Quantum Evaporation — Condensation

Schematic



Energetics



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

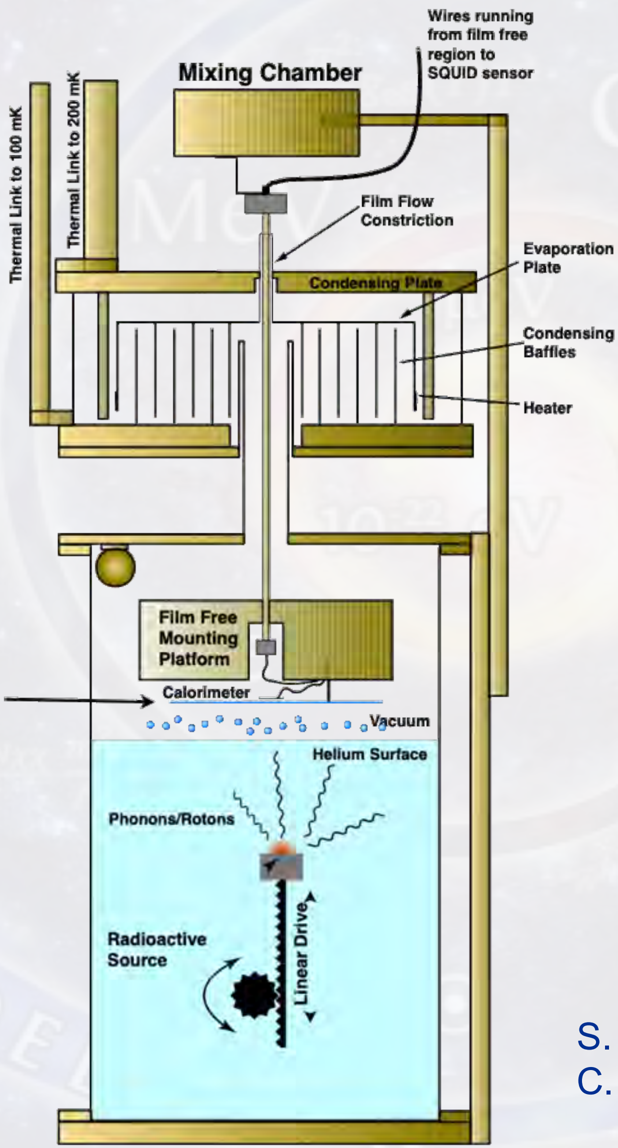
HERON Detector

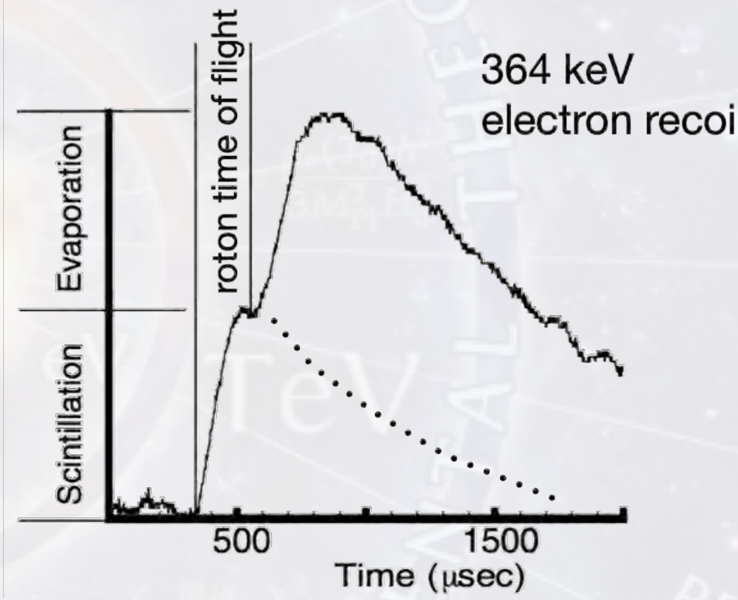
He film burner

wafer calorimeter

NTD sensors

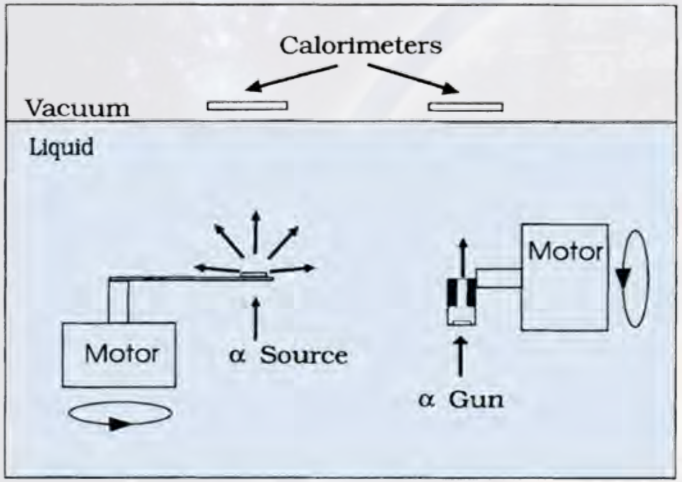
kg-scale
LHe mass

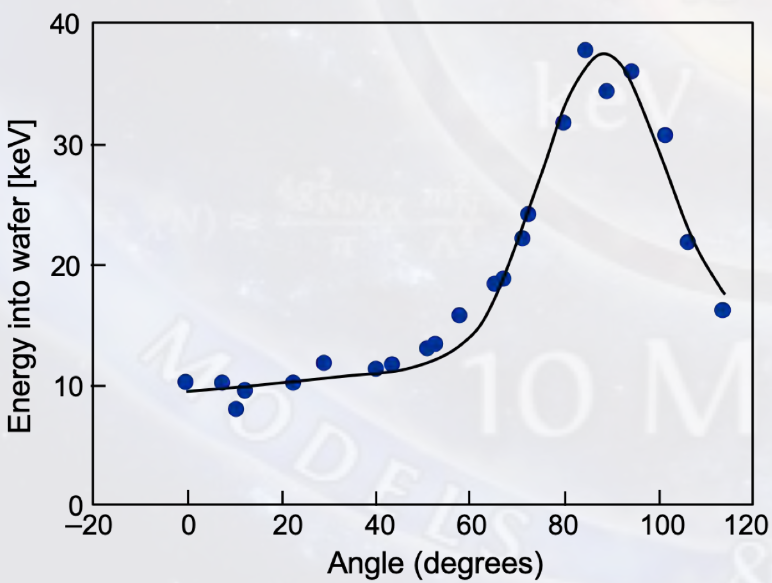


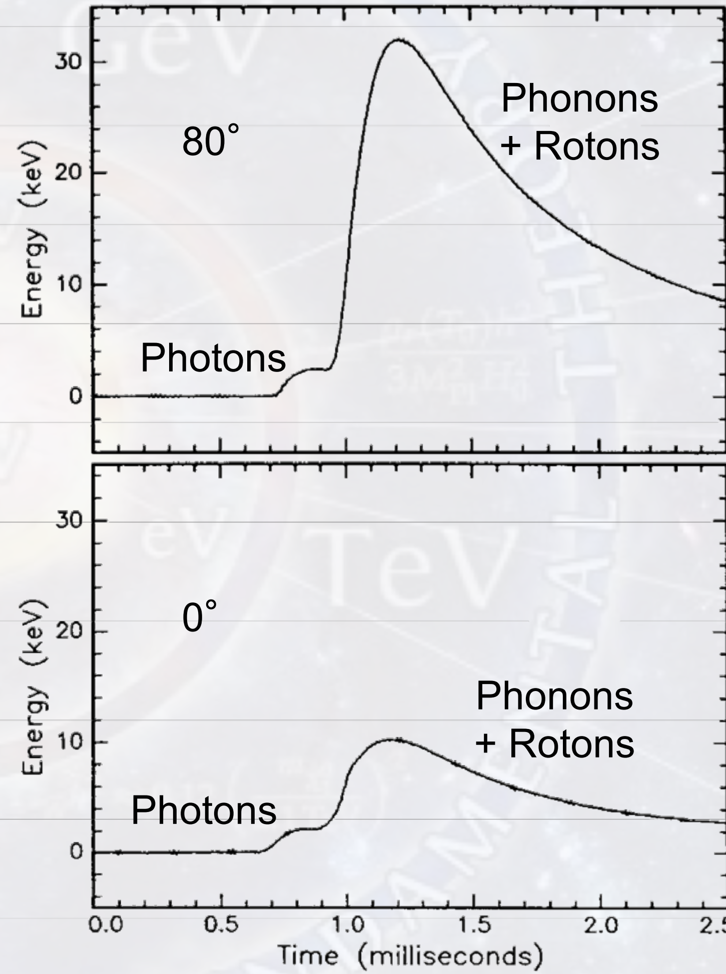


S. Bandler *et al.*, PRL **74**, 3169 (1995)
C. Enss *et al.*, Physica B 1**94-196**, 515 (1994)

HERON Detector: Directionality

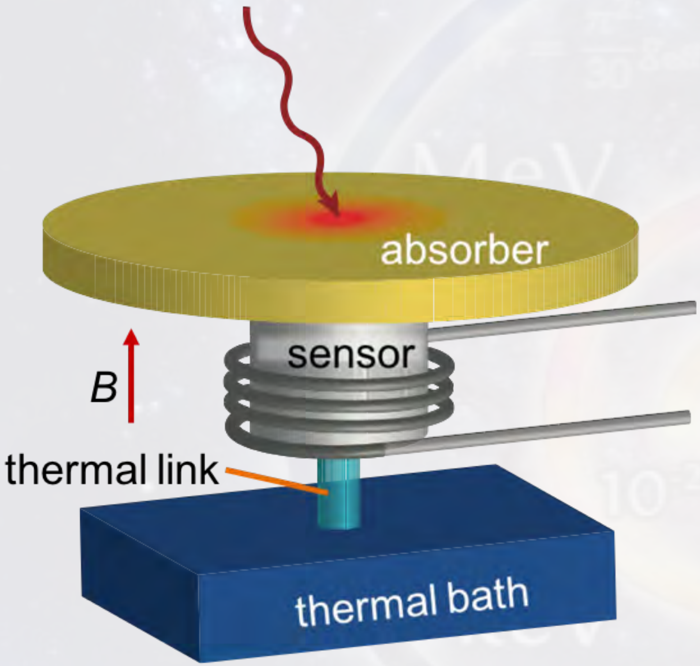






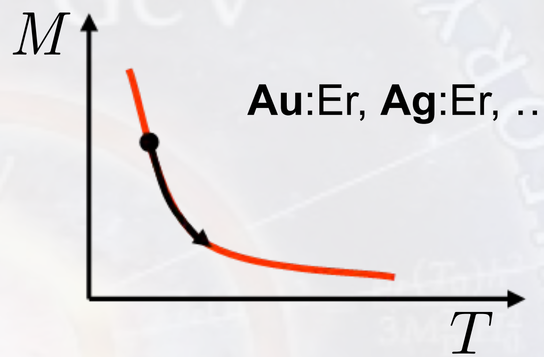
S. Bandler *et al.* PRL **74**, 3169 (1995)

Metallic Magnetic Calorimeters (MMCs)



$$\Delta T \propto \Delta M \propto \Delta\phi \propto \Delta U$$

paramagnetic sensor:



signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E}{C_{\mathrm{tot}}}$$

energy resolution:

$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

A. Fleischmann, Adv. Solid State Phys. **41**, 577 (2001)

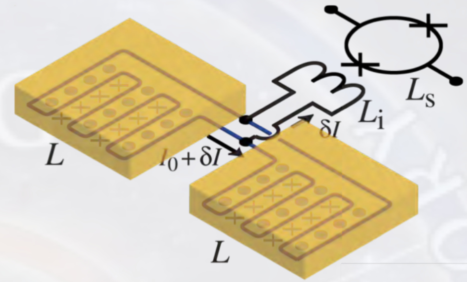
main difference to resistive calorimeters:

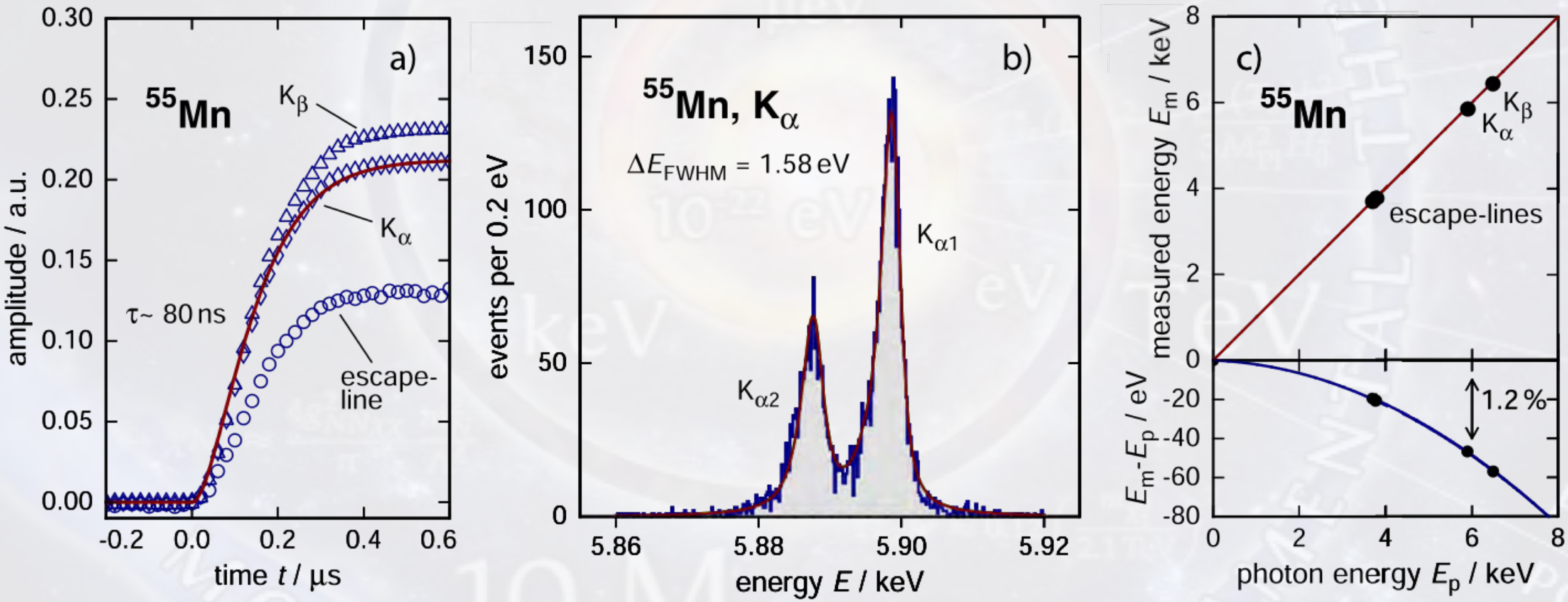
no dissipation in the sensor
no galvanic contact to the sensor

MMC Performance at 6 keV

250 µm × 250 µm Gold, 5 µm thick

98% Quantum Efficiency @ 6 keV





record speed **record resolving power** **record linearity**

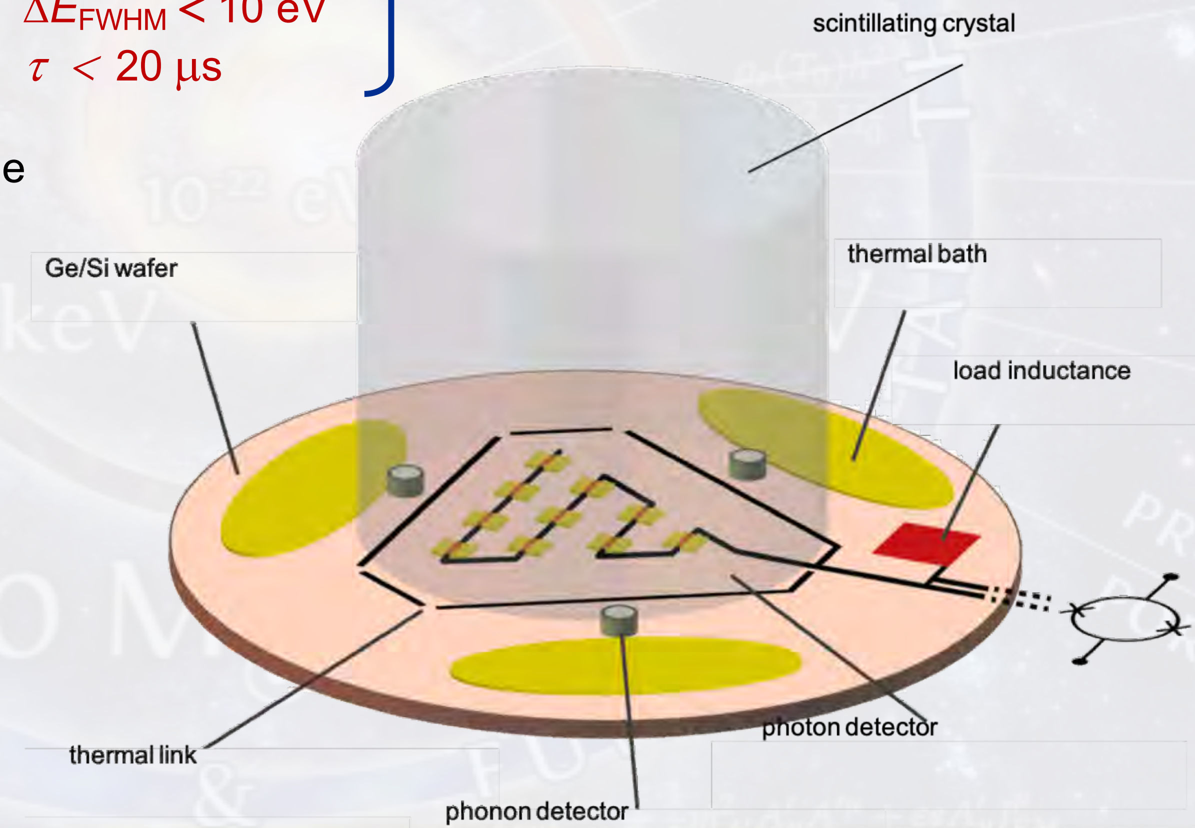
S. Kempf, A. Fleischmann, L. Gastaldo, C.E., J. Low Temp. Phys. **193,** 365 (2018)

MMC based Phonon and Photon Detectors

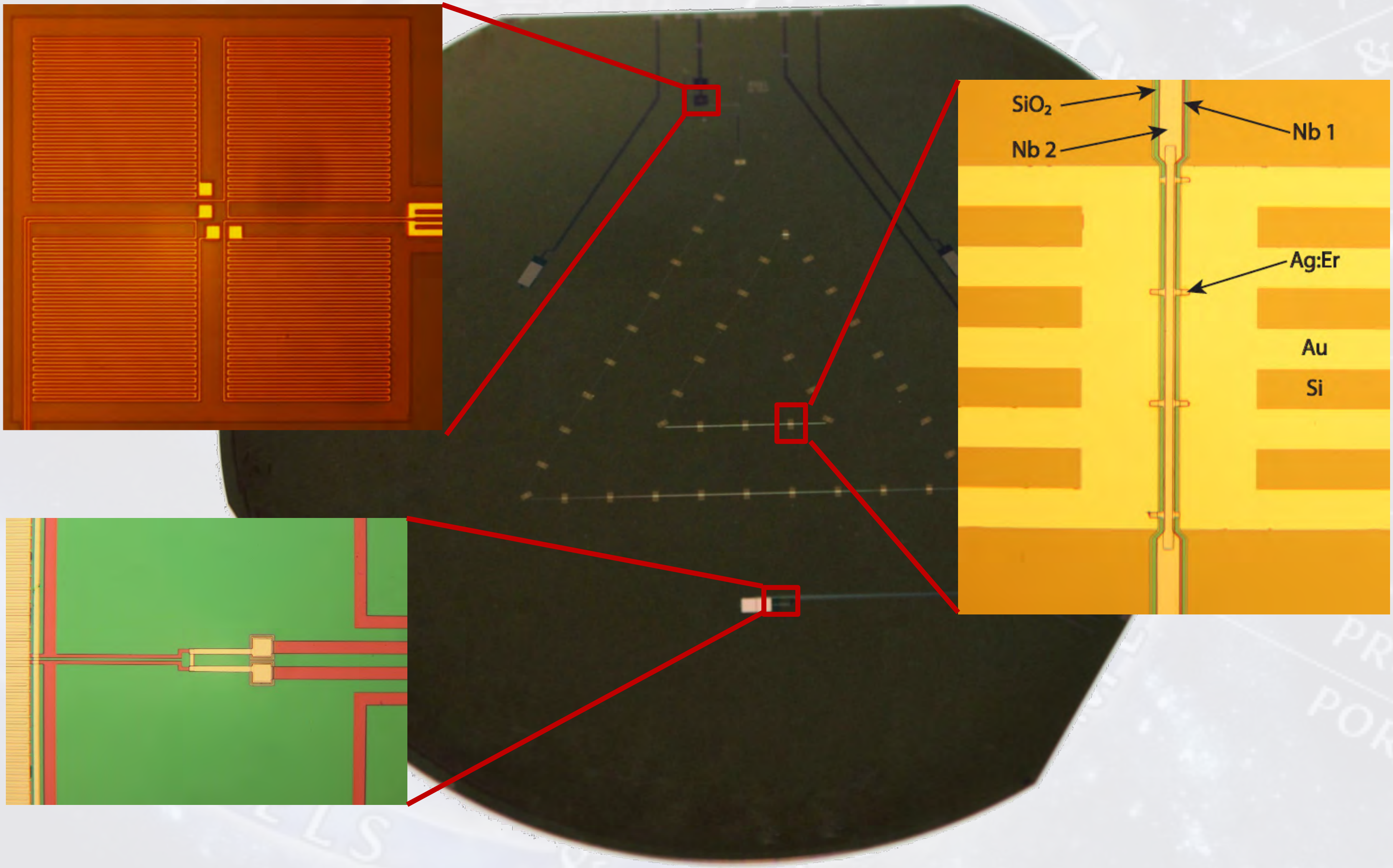
- Phonon detector:
  - energy resolution $\Delta E_{\mathrm{FWHM}} < 100$ eV
  - rise time $\tau < 200$ µs
- Photon detector:
  - energy resolution $\Delta E_{\mathrm{FWHM}} < 10$ eV
  - rise time $\tau < 20$ µs

Substrate: Ge or Si 3" wafer

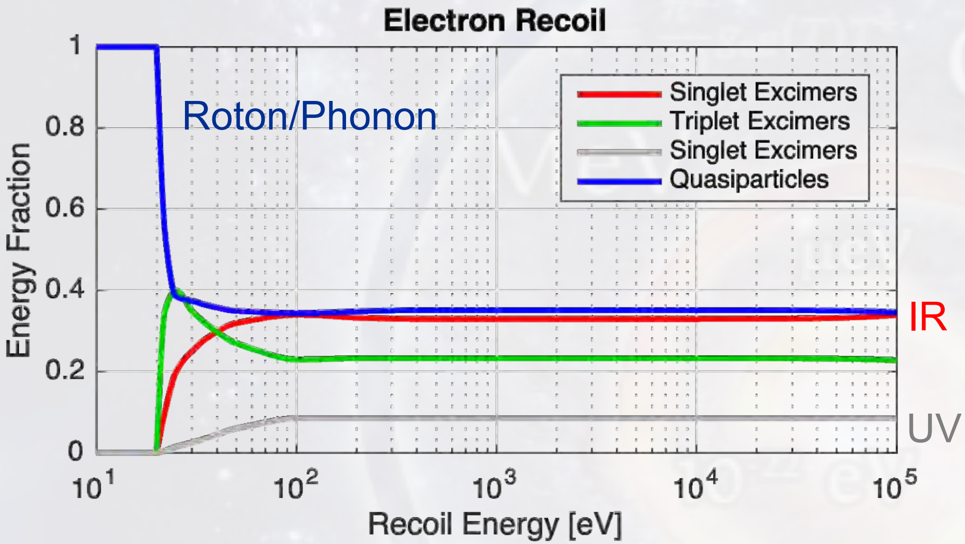
- Position sensitivity possible

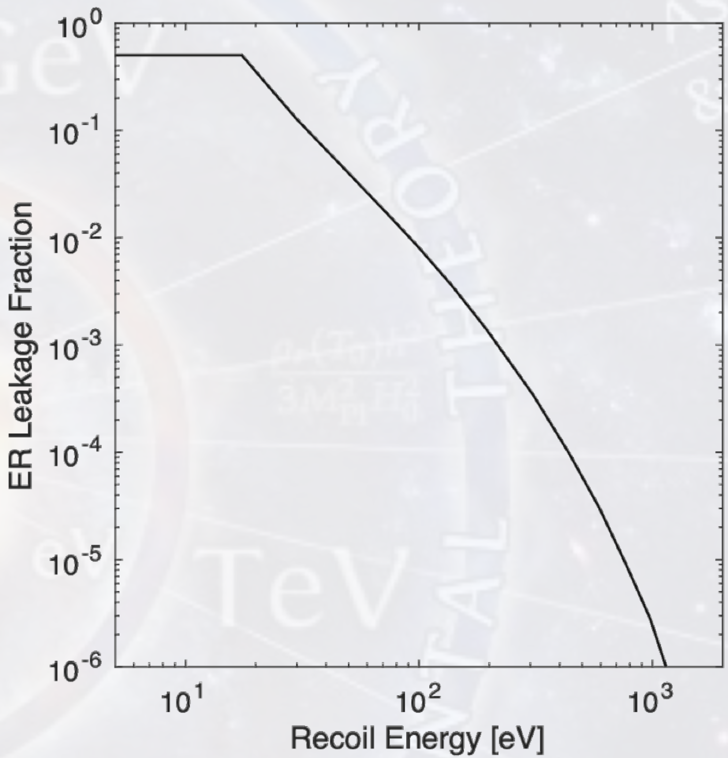


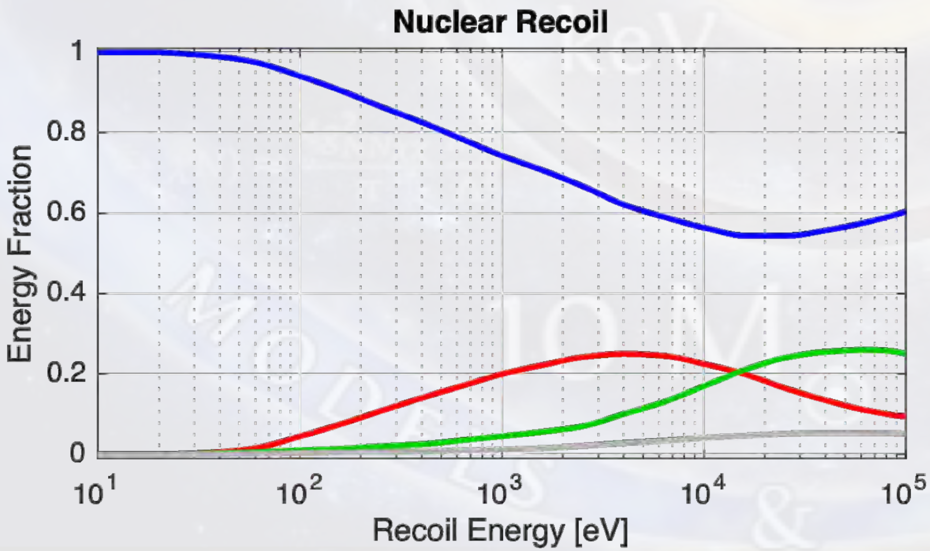
MMC based Phonon and Photon Detectors



Discrimination of ER and NR



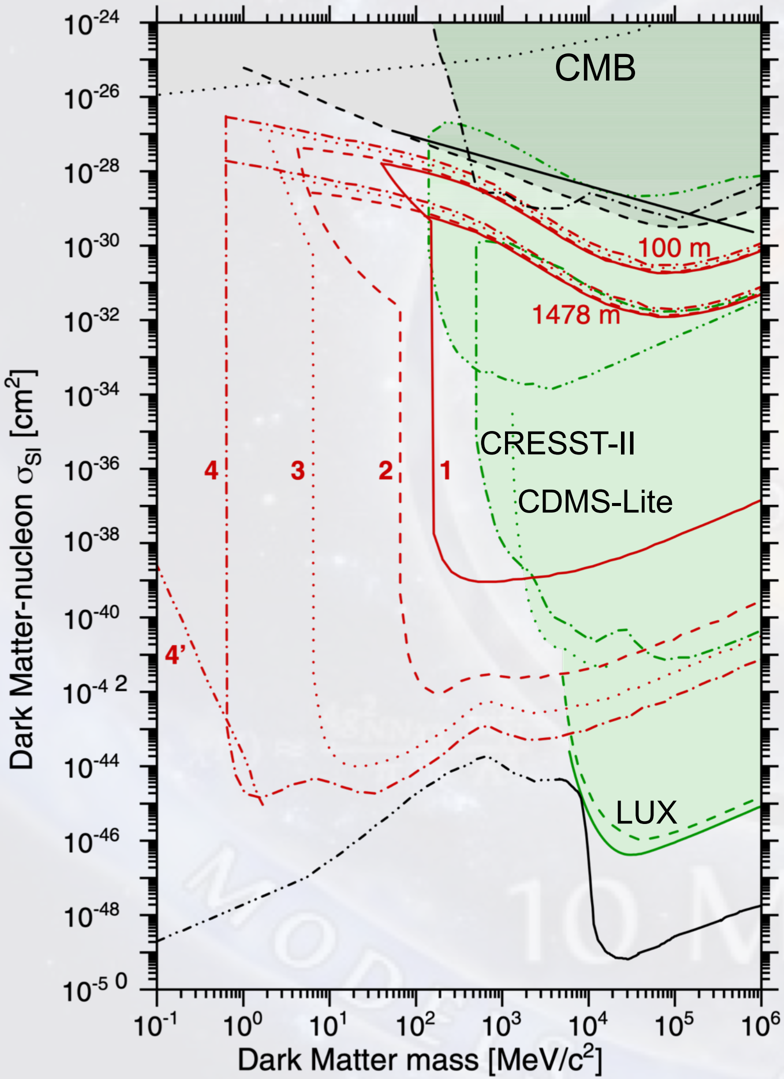




T.M. Ito, G.M. Seidel, PRC **88**, 025805 (2013)

S. Hertel *et al.*, PRD **100**, 092007 (2019)

Projected Sensitivity: Spin-independent Nuclear Scattering



DELight Phase 1

10 ℓ, 3 years, ΔE < 10 eV

→ 4 kg-yr 10 eV

1 kg-d 40 eV

1 kg-yr 10 eV

10 kg-yr 0.1 eV

100 kg-yr 1 meV

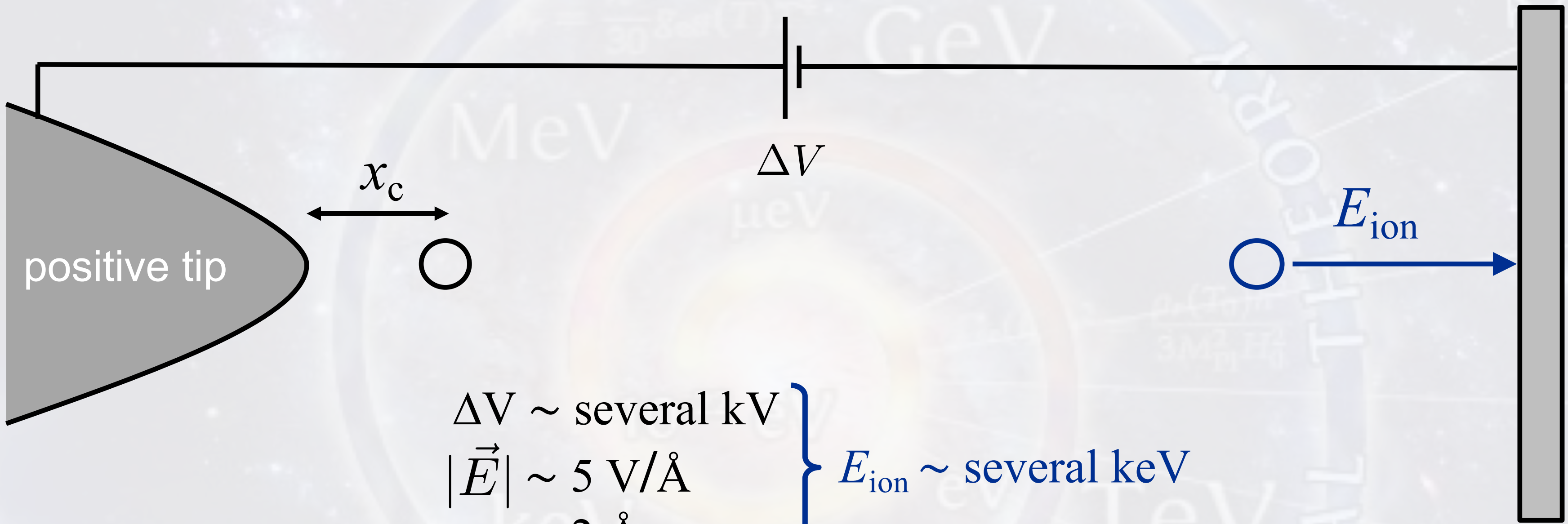
XENON-nT

HeRALD

helium roton apparatus for light dark matter

S. Hertel et al., PRD **100**, 092007 (2019)

Sensitivity Enhancement by Field Ionization



$$\left.\begin{array}{l} \Delta V \sim \text{several kV} \\ |\vec{E}| \sim 5\ \text{V/Å} \\ x_c \sim 2\ \text{Å} \end{array}\right\} E_{ion} \sim \text{several keV}$$

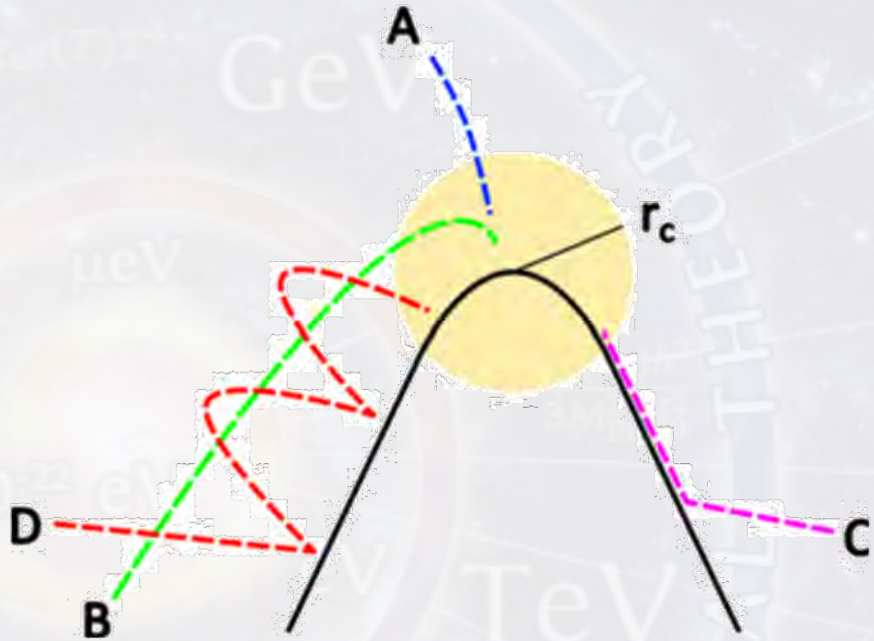
- helium becomes field-ionized when its highest electron tunnels through a field-distorted barrier into a charged metal tip.
- the resulting helium ion gains several keV of kinetic energy

E. W. Müller, Z. Phys. **131**, 136 (1951)

How the Helium Arrives at the Tip

$$U_{\text{int}} = \frac{1}{2}\alpha|\vec{E}|^2$$

atomic polarizability



A) Direct impact

B) Orbital capture

C) Surface diffusion

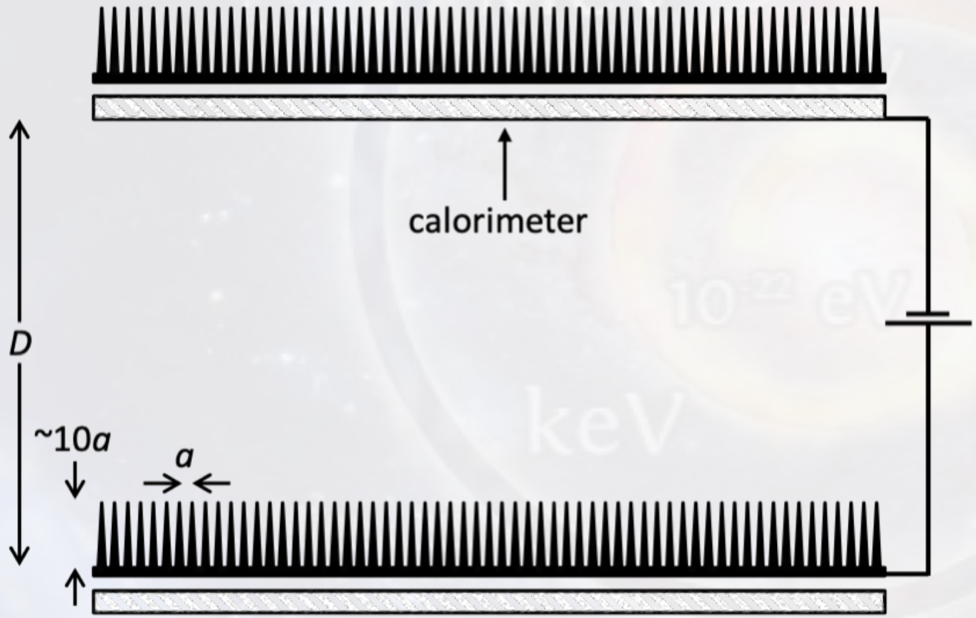
D) Bouncing

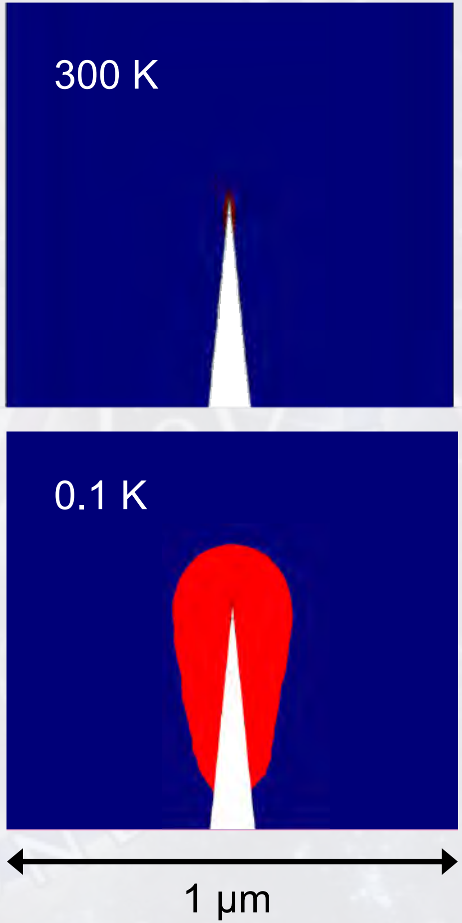
The polarization force draws helium to the tip, where the field gradient is highest

K.M. O'Donnell *et al.*, Meas. Sci. Technol. **22** 015901 (2011).

Sensitivity Enhancement by Field Ionization

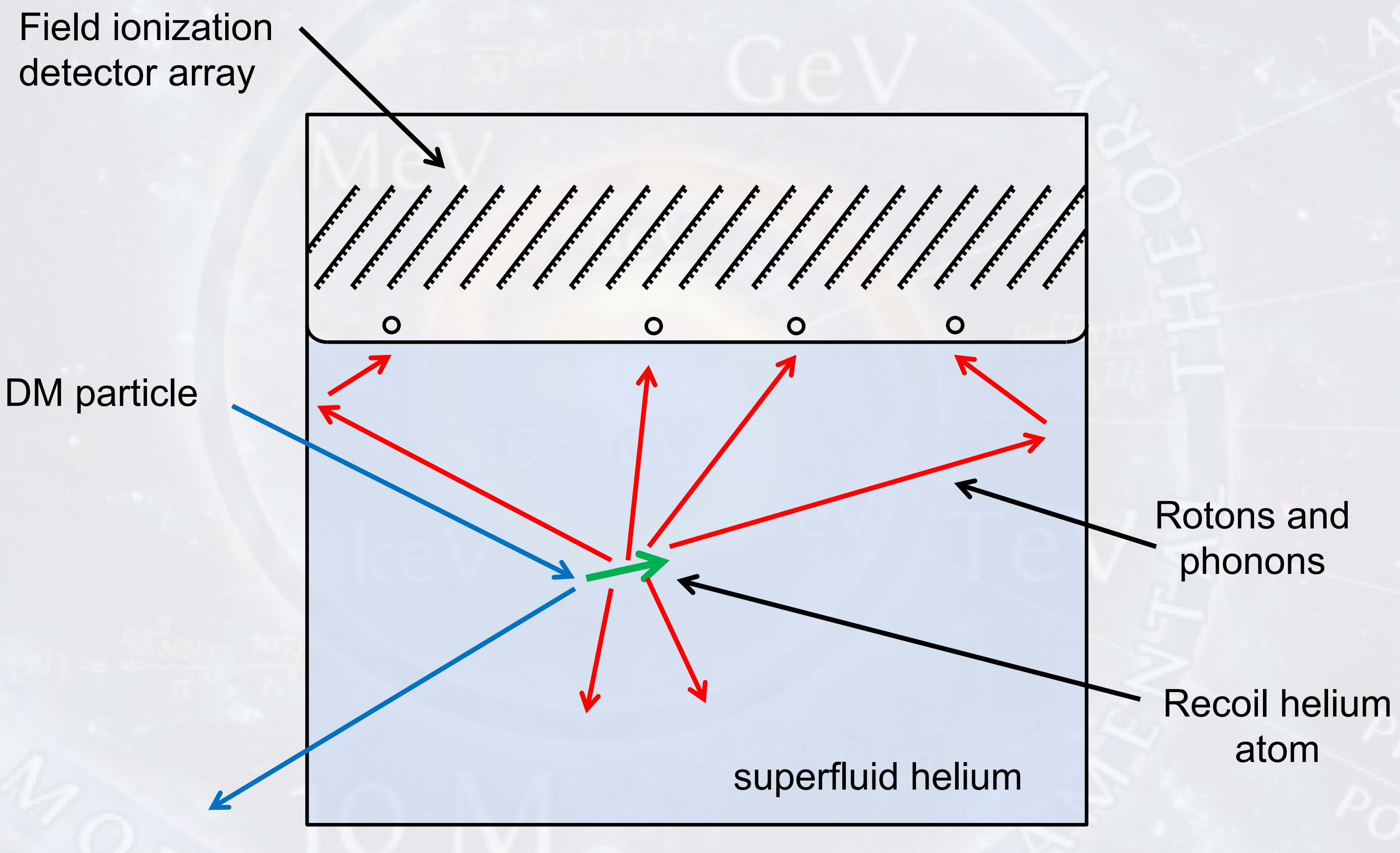
red region: $\frac{1}{2}\alpha|\vec{E}|^2 > k_\mathrm{B}T$





H. J. Maris, G. M. Seidel, D. Stein, PRL **119**, 181303 (2017)

Detector Arrays in a Chevron Configuration



H. J. Maris, G. M. Seidel, D. Stein, PRL **119**, 181303 (2017)

Conclusions

Superfluid helium based dark matter experiments have enormous potential for light dark matter searches

DELight is a new project to realize such an experiment

Thank you!