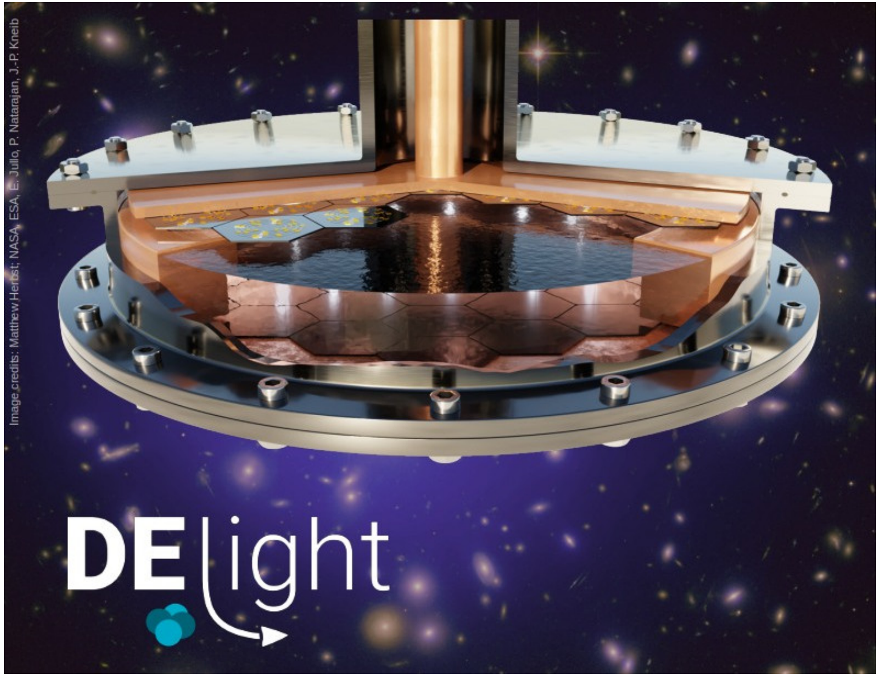
Searching for Sub-GeV Dark Matter with superfluid helium using DELight



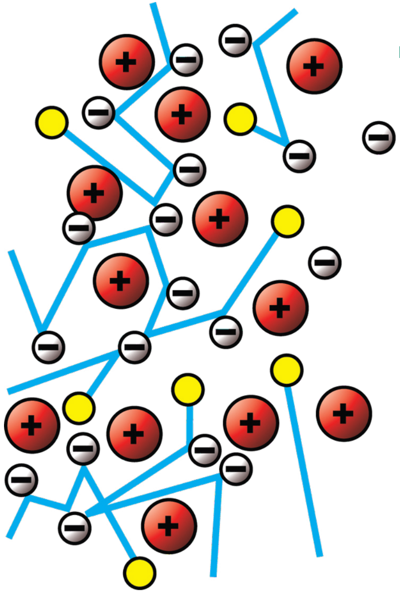
Felix Kahlhoefer
Institute for Astroparticle Physics (IAP)

Quantum Metrology and Fundamental Physics
Tübingen, 15 July 2026

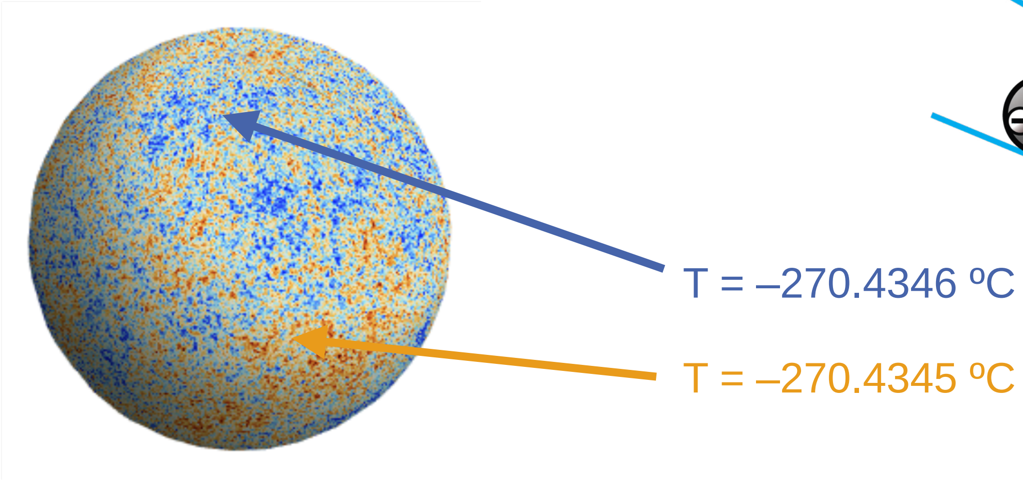
Outline

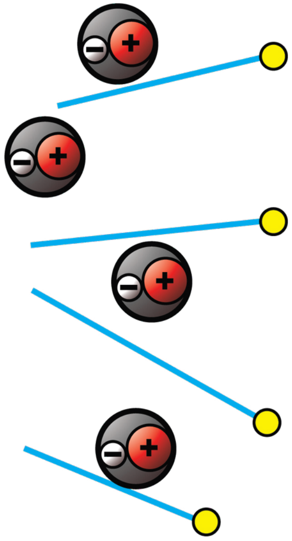
- Motivation: Dark matter
- Methodology: Direct detection
- Pushing to smaller masses and energies
- The DELight experiment
- Going lower: The Migdal effect
- Can we go even lower?

Cosmic Microwave Background



- Emitted when protons and electrons form neutral hydrogen
  - → Snapshot of the universe 380,000 years after Big Bang
  - → Thermal bath of nearly uniform temperature
  - → Temperature fluctuations at the level of $\delta T/T \sim 10^{-5}$ reflect density perturbations $\delta\rho/\rho \sim 10^{-5}$





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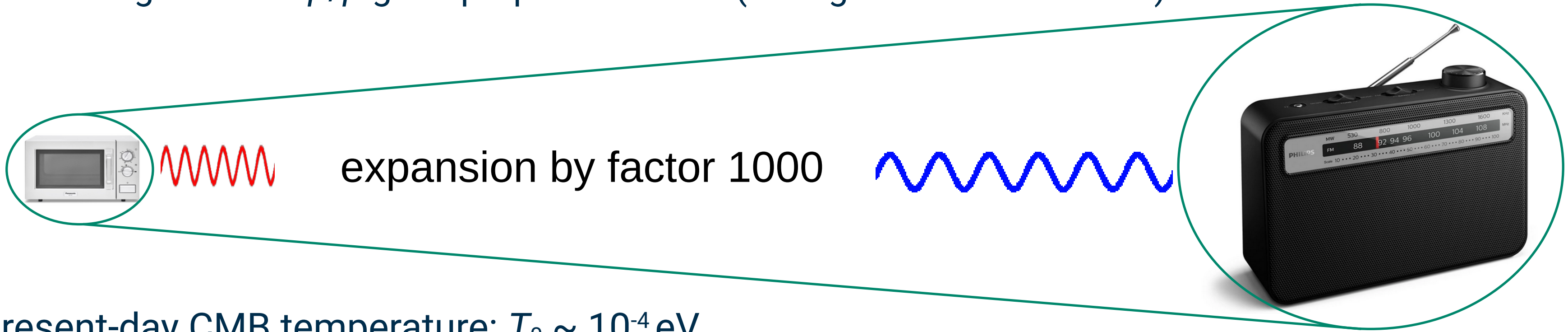
Expanding universe

- General relativity tells us how the universe evolves after recombination:
  - ➞ Expansion proportional to scale factor a
  - ➞ CMB temperature decreases proportional to a^{-1}
  - ➞ Inhomogeneities $\delta\rho/\rho$ grow proportional to a (during matter domination)



- Present-day CMB temperature: $T_0 \sim 10^{-4}$ eV
  - ➞ $a_0 / a_{\mathrm{CMB}} \sim 1000$
  - ➞ Expect inhomogeneities at the level $\delta\rho/\rho \sim 0.01$
  - ➞ Dramatic disagreement with data!

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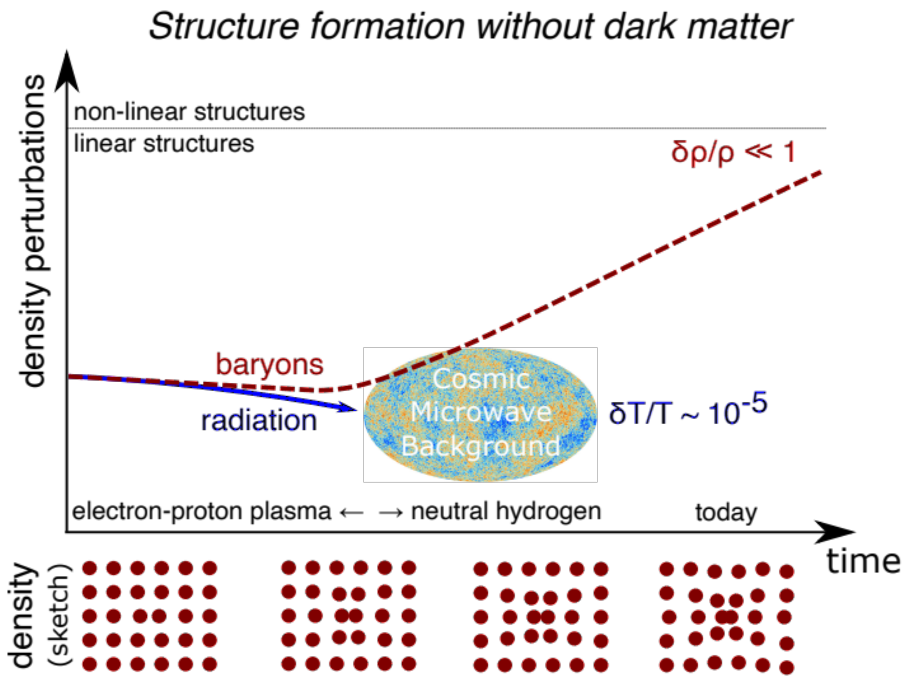
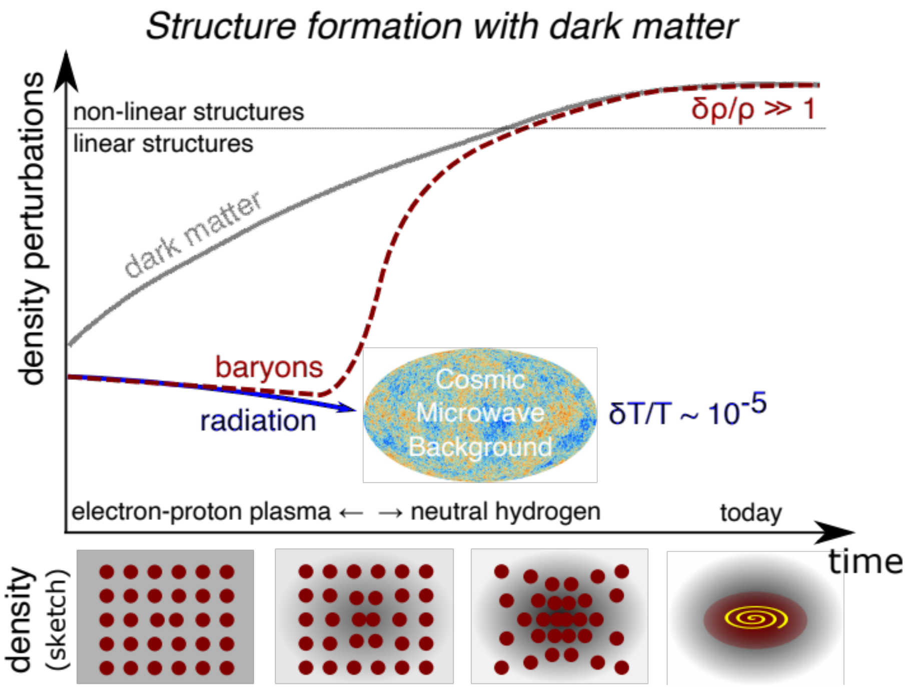
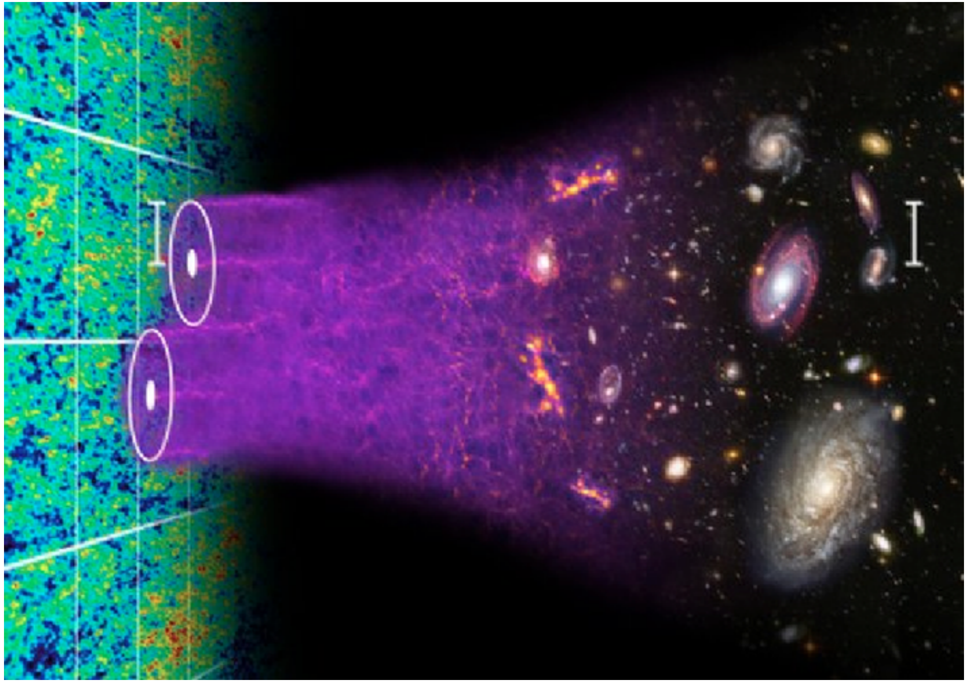
Why we need dark matter

See “A Primer on Dark Matter”
Balasz, FK et al., arXiv:2411.05062

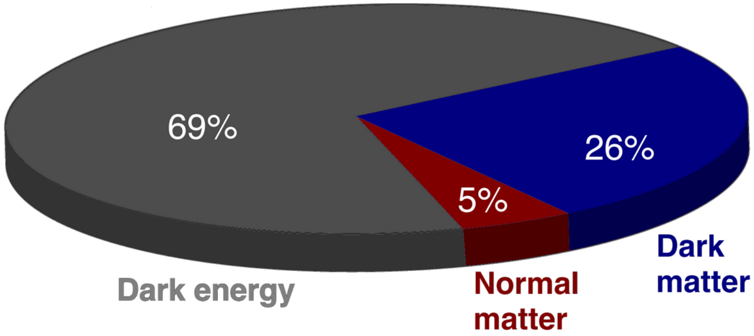




Structure formation



- Dark matter starts forming overdensities already before recombination
- Creating of potential wells that act as seeds for subsequent structure formation
- Need approximately five times more dark than visible matter



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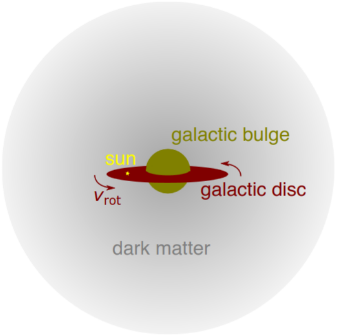
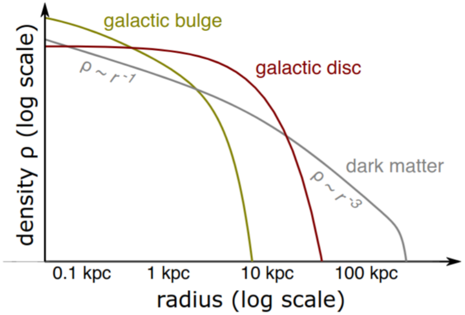
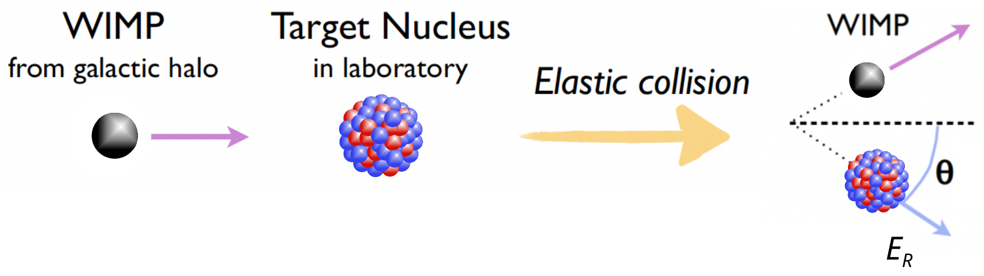
Dark matter direct detection

- Key prediction: Galaxies are embedded in dark matter halos
  - ➙ We can estimate the local dark matter density and velocity distribution from stellar kinematics
  - ➙ Dark matter particles are constantly passing through the Earth (~10^9 particles/s/m^2)
- Almost all particles have no interactions
- But even very rare events may be detectable!
- Bosonic (wave-like) dark matter
  - ➙ Look for conversion/absorption
- Fermionic (particle-like) dark matter
  - ➙ Look for scattering







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Differential event rate

- Interaction rate proportional to
  - Flux of dark matter particles $j_\chi = n_\chi \cdot v = \rho_\chi \cdot v / m_\chi$
  - Number of target atoms $N_T = m_T / m_N$
  - Scattering cross section σ
- Accounting for velocity distribution gives

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\rho_0}{m_\chi m_N} \int \mathrm{d}^3 v \, v \, f(\mathbf{v}, t) \, \frac{\mathrm{d}\sigma}{\mathrm{d}E}$$

- Key observation: Kinematic threshold for scattering

$$v_{\min} = \left| \frac{\Delta E}{q} + \frac{q}{2 m_\chi} \right|$$

ΔE: Energy transfer
q: Momentum transfer

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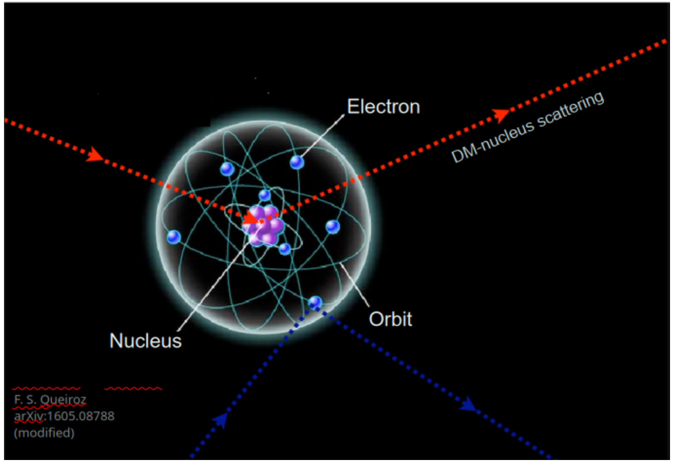
Elastic nuclear scattering

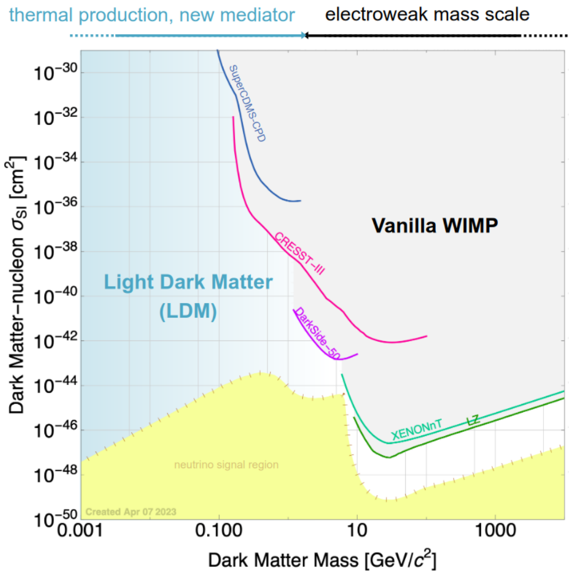


$$v_{\min} = \sqrt{m_N E_R/(2\mu^2)}$$

with

$$\mu = m_N m_\chi/(m_N + m_\chi)$$

m_N: nucleus mass
m_χ: dark matter mass



- Scattering possible only if $v_{\min}$ is smaller than the Galactic escape velocity v_{esc} ~ 600 km/s ~ $2 \cdot 10^{-3}$ c
- For fixed detector threshold ($E_R > E_{thresh}$): Loss of sensitivity for light dark matter ($m_\chi << m_N$)

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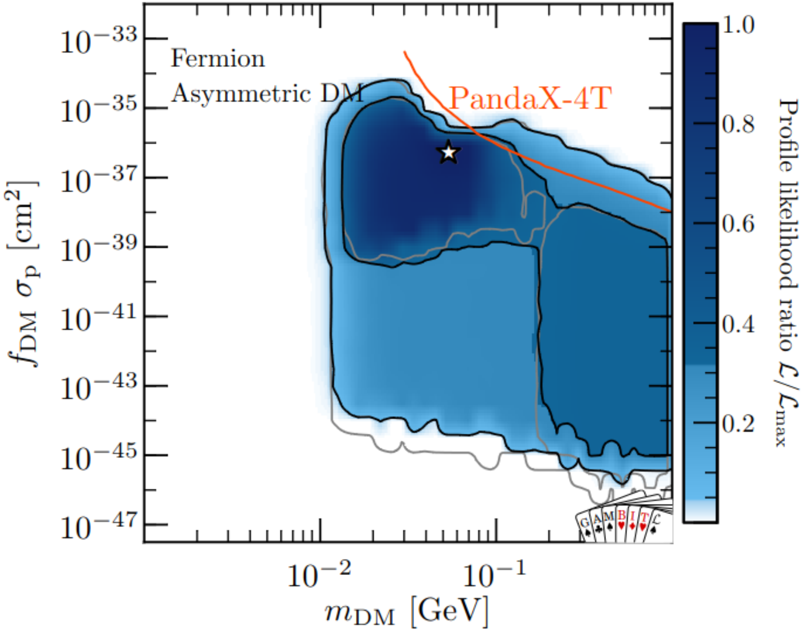
Models of Sub-GeV dark matter

- The Lee-Weinberg bound states that Sub-GeV dark matter particles cannot interact exclusively via the known forces of the Standard Model
  - ➙ Need new exchange particles
- Simplest example: Dark photon
  - ➙ Similar to visible photon but massive
  - ➙ Stability of dark matter via dark charge conservation
  - ➙ Interactions with visible matter via kinetic mixing
- Large (but finite) viable parameter space



Balan, FK et al., arXiv:2405.17

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Institute for Astroparticle Physics

Possible avenues

- Scattering on electrons
- Lower detector threshold
- Lighter target nuclei

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Institute for Astroparticle Physics

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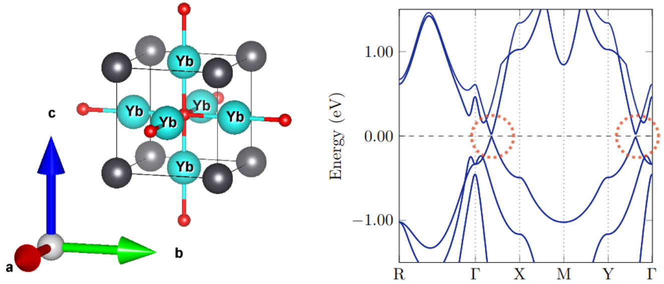
Semiconductors,
Dirac materials, …
→ not this talk



Geilhufe, FK et al., arXIv:1910.02091

Possible avenues

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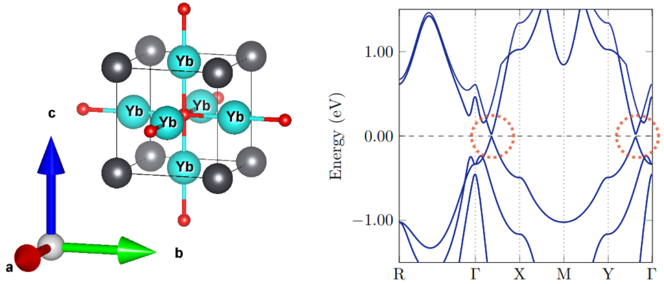

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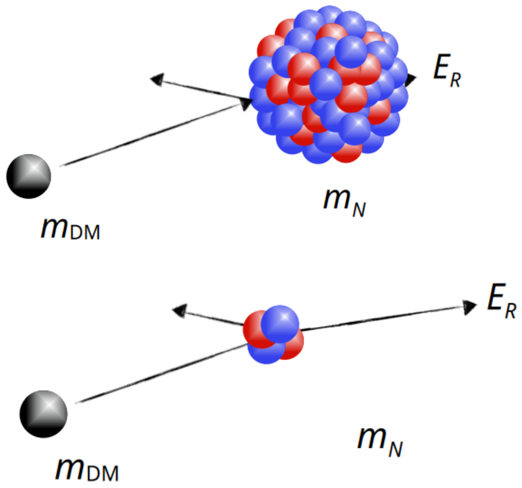
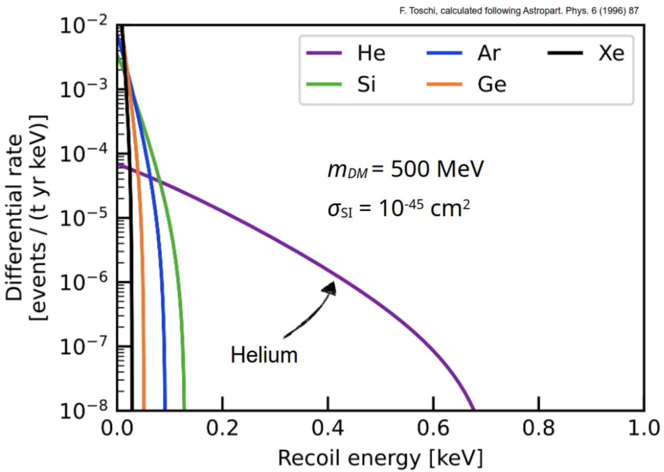
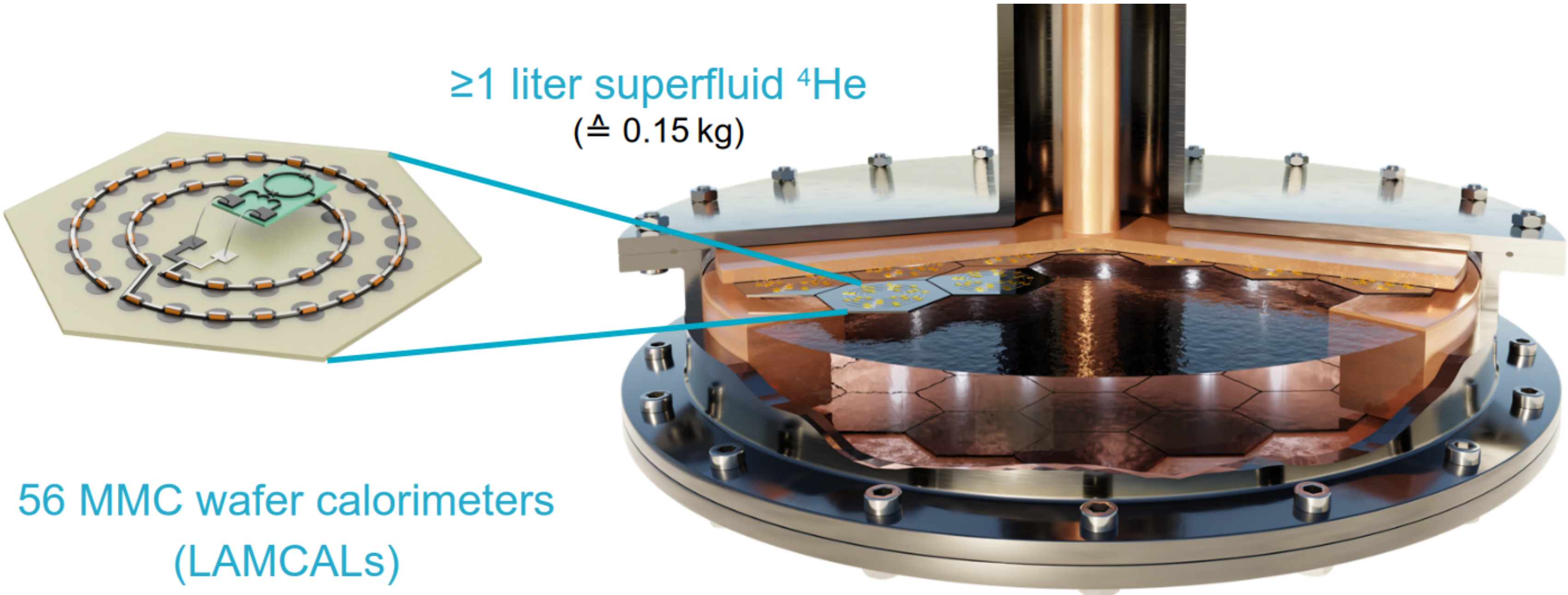




The DELight Experiment



56 MMC wafer calorimeters (LAMCALs)

(37 in top-array, 19 in bottom-array)

ca. 30 cm

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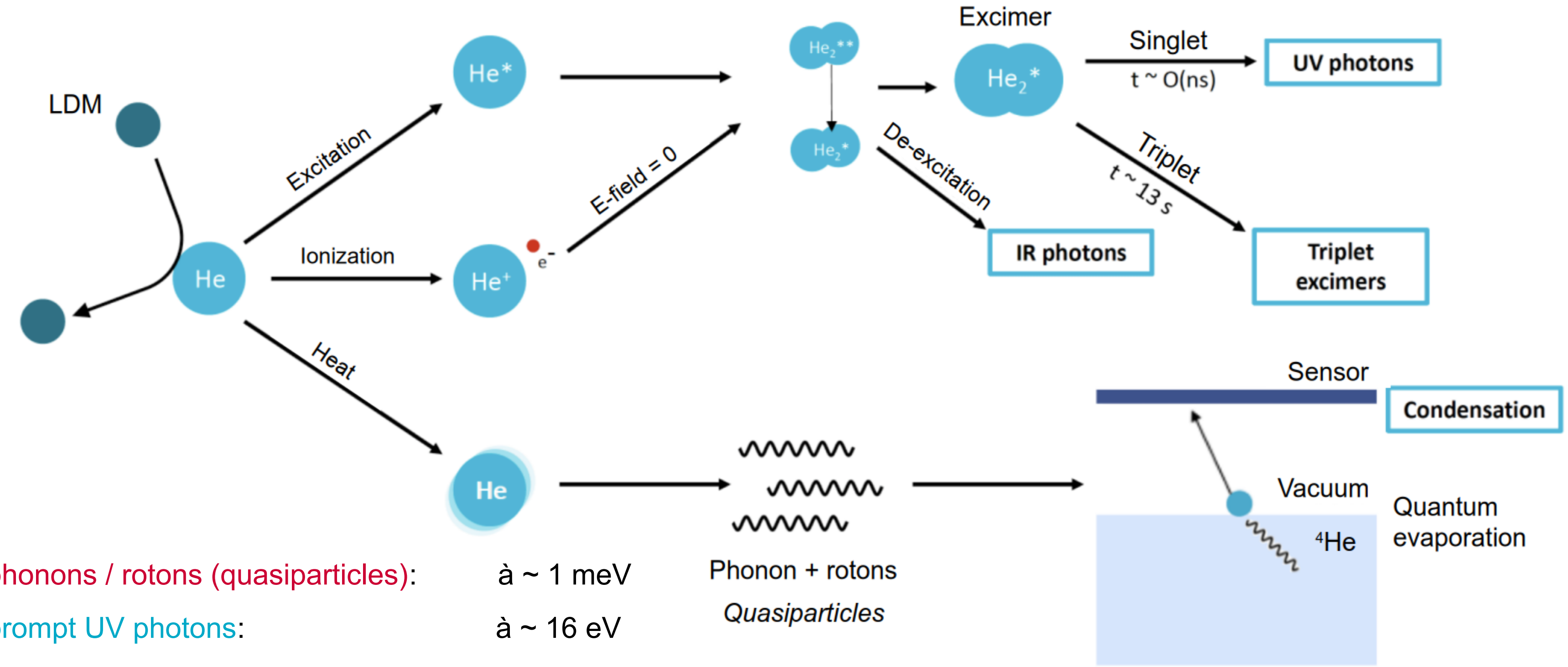
Signal generation in superfluid helium



phonons / rotons (quasiparticles): à ~ 1 meV

prompt UV photons: à ~ 16 eV

delayed UV photons (from excimers): à ~ 16 eV

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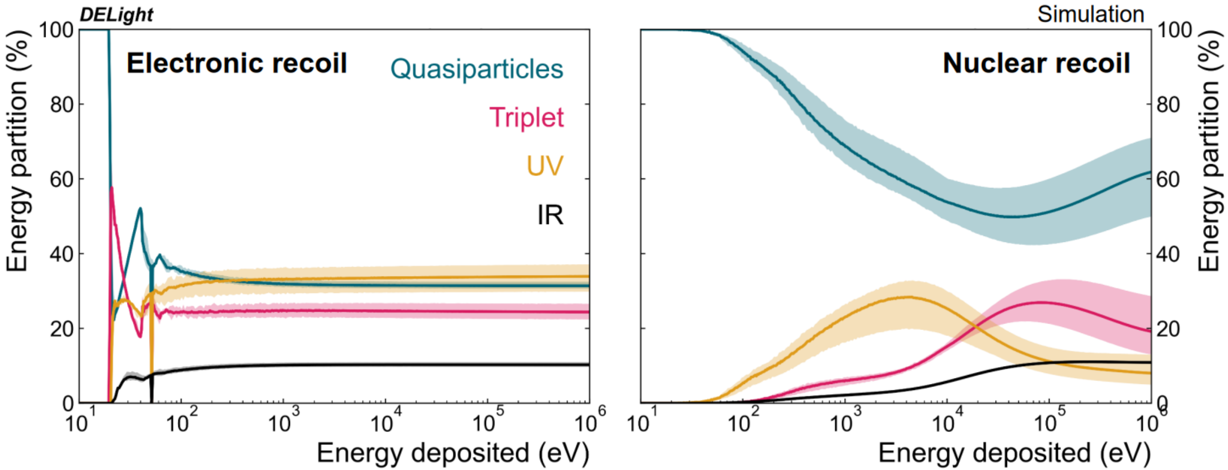
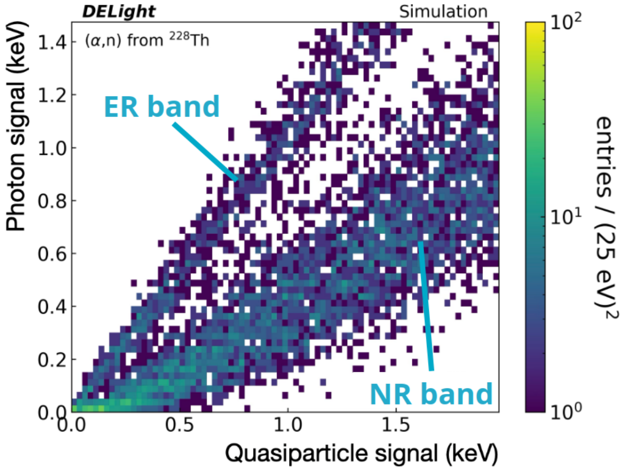
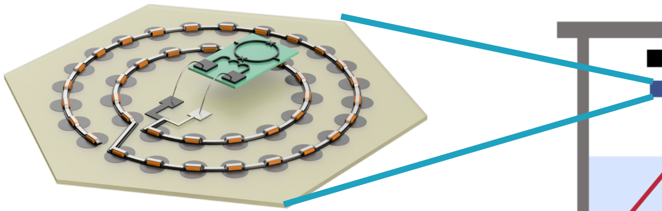
Energy partitioning

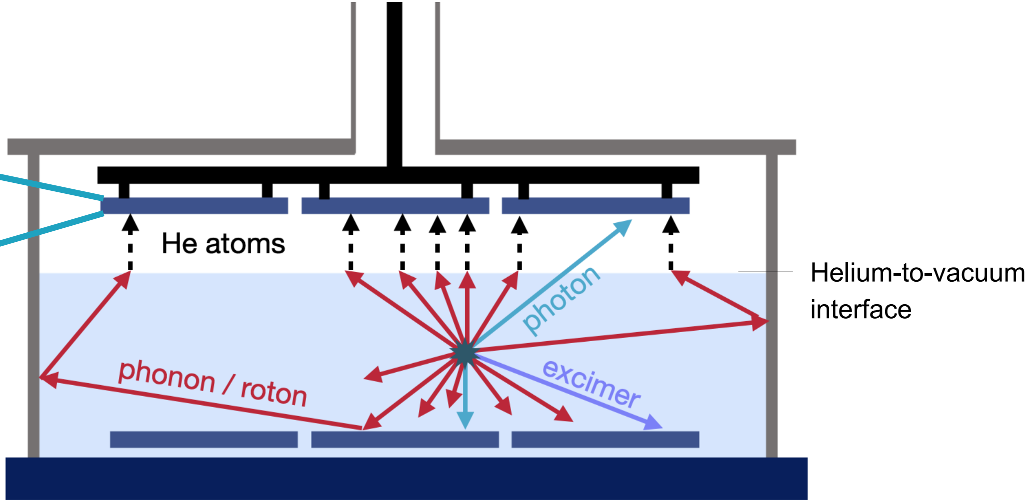


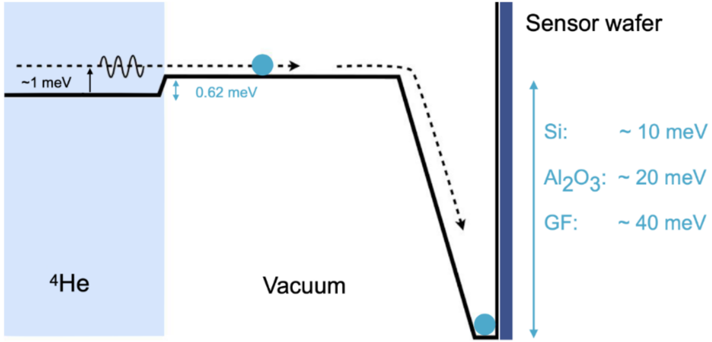


- Ratio of photon and quasiparticle signal differs for nuclear recoil (NR) and electron recoil (ER)!
  - → Potential discrimination of signal and background

Detection principle







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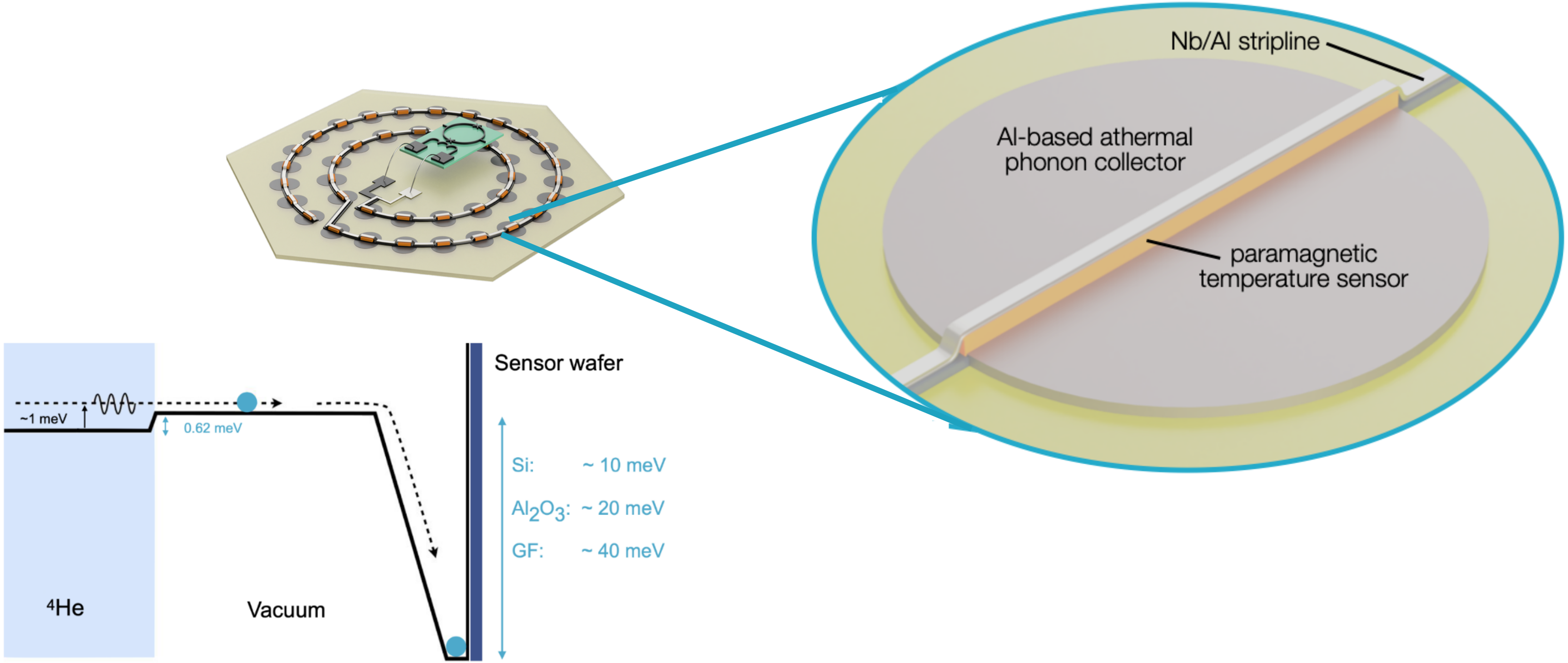

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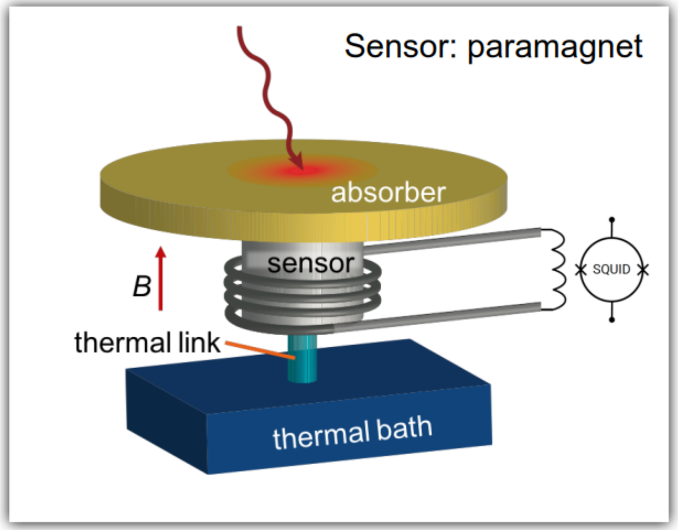
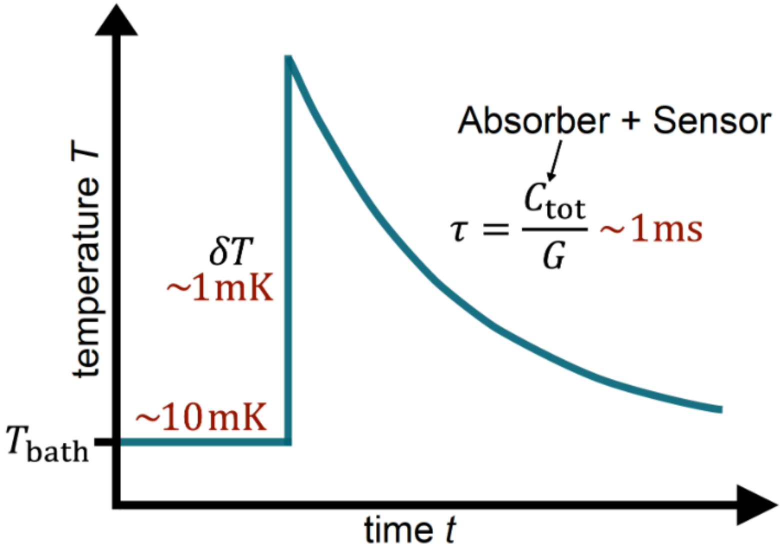
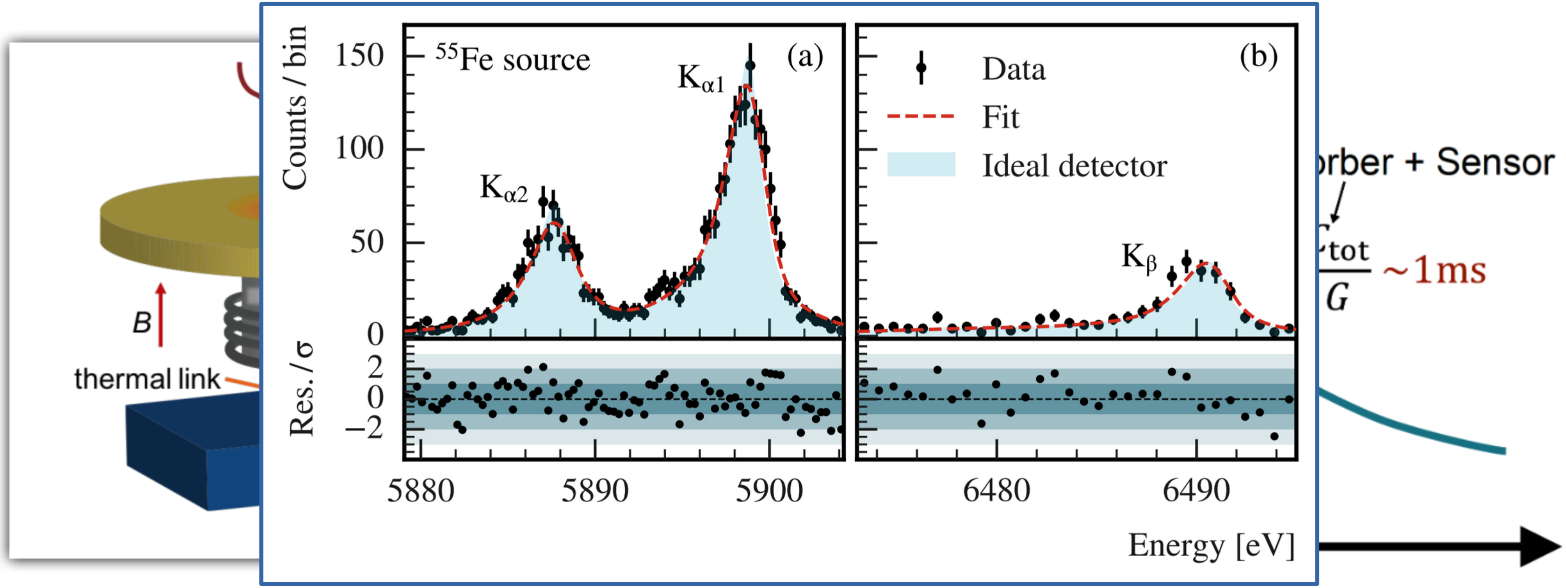
Magnetic MicroCalorimeters





Energy deposition → Temperature rise → Change in sensor magnetization → Magnetic flux change in SQUID

Magnetic MicroCalorimeters



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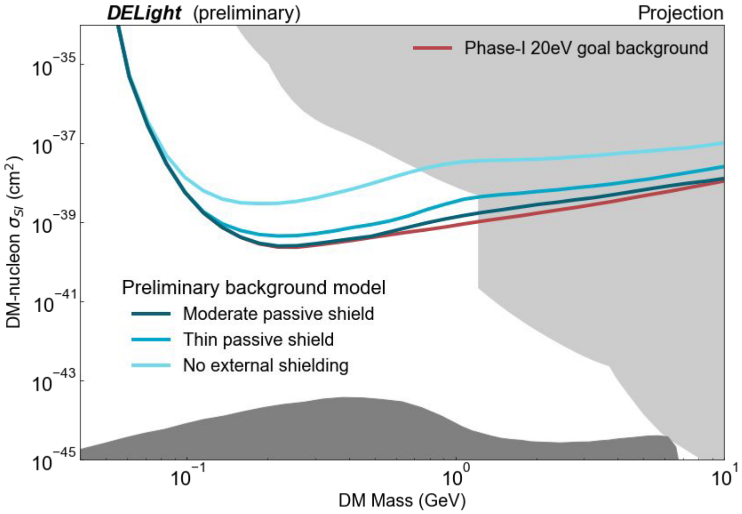
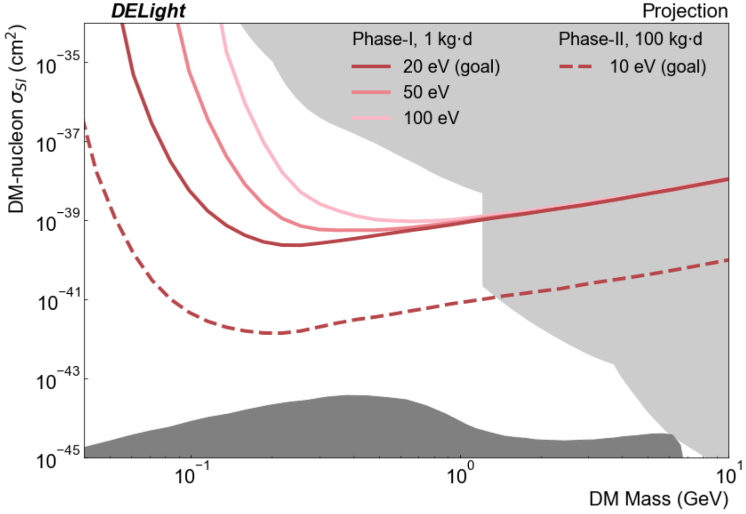
Projected sensitivities





- Phase-I (years 1-4): 1 kg•d exposure, 20 eV threshold
- Phase-II (years 5-8): 100 kg•d exposure, 10 eV threshold

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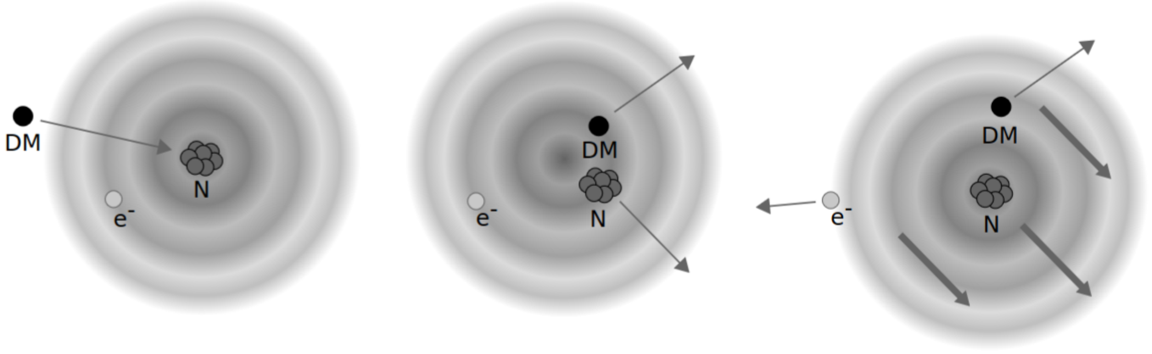
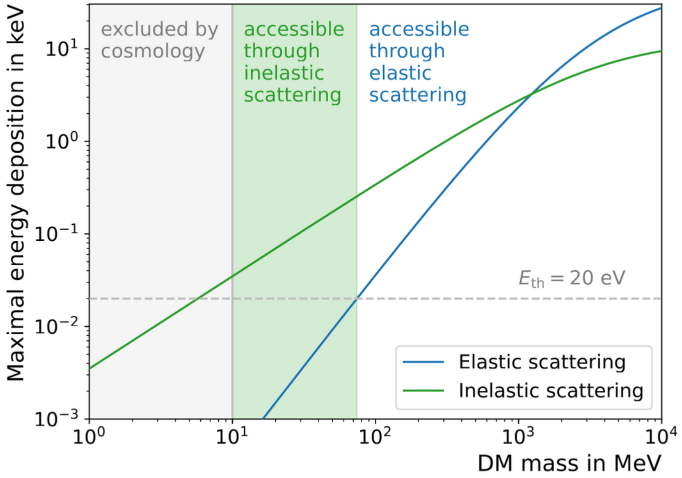
Going lower: The Migdal effect

- **So far:** Assumed factorisation of fundamental scattering process and subsequent excitations
- **But:** Possible to have scattering and excitation at the same time





- Different kinematics: Inelastic scattering means that entire kinetic energy can be deposited

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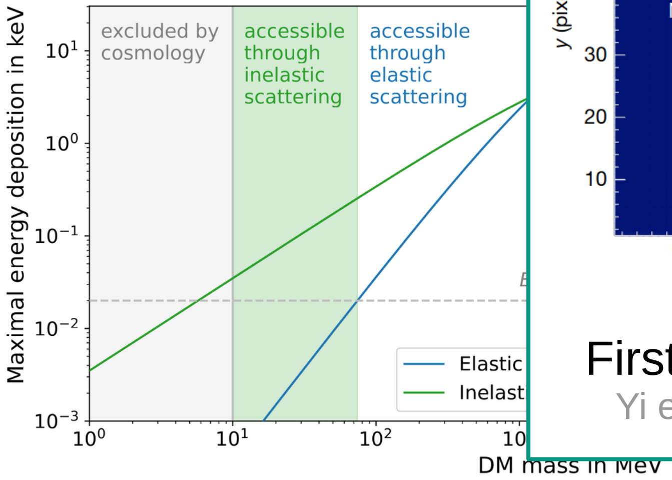
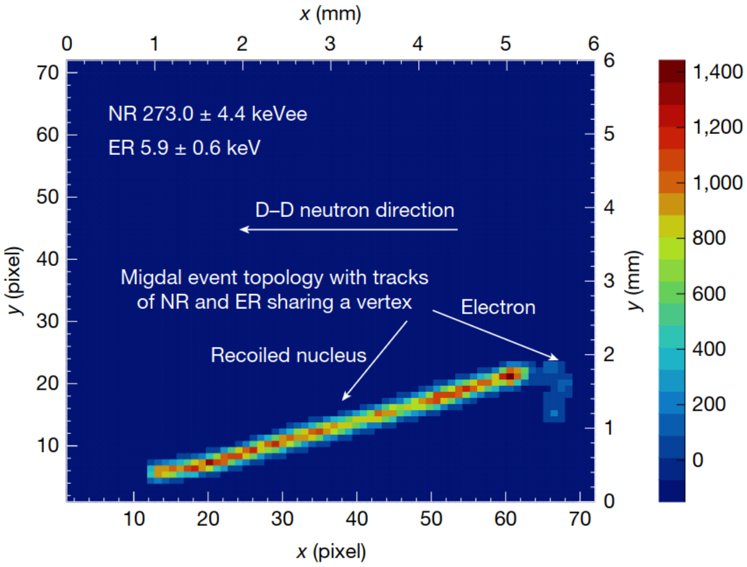
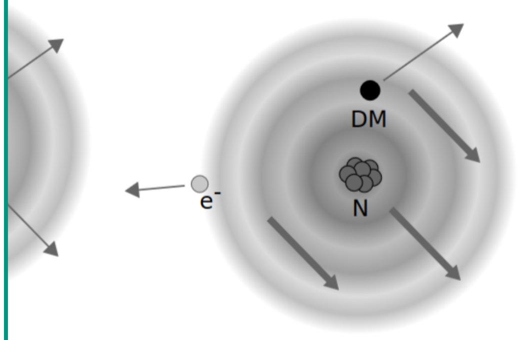




First direct observation recently

Yi et al., Nature 649, 580-583 (2026)



scattering means that
eposited

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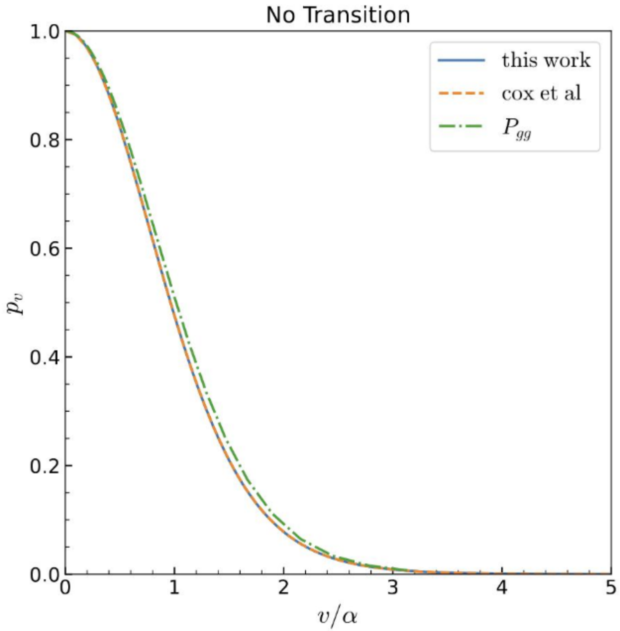
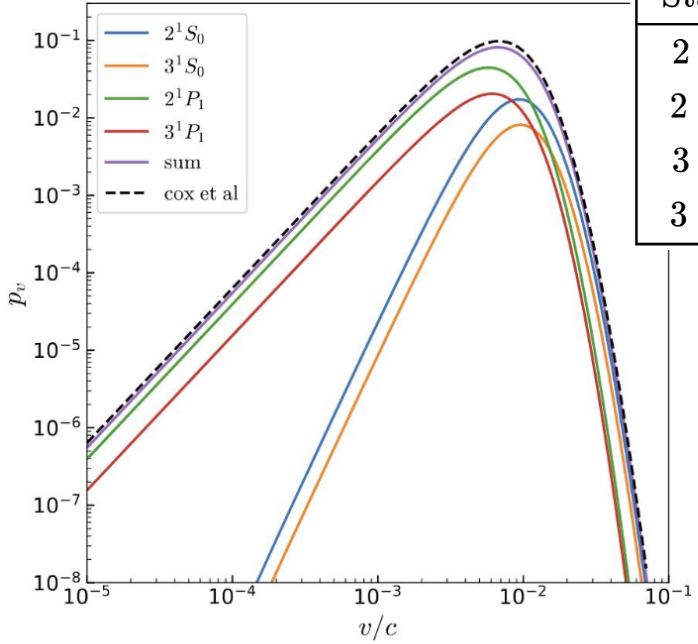
Transition probability



$$P_{gg} = \frac{1}{[1 + (8v/27\alpha)^2]^8},$$



State	$\lvert E_{exc}\rvert$[eV]
$2\ ^1\mathrm{S}$	20.616
$2\ ^1\mathrm{P}$	21.218
$3\ ^1\mathrm{S}$	22.920
$3\ ^1\mathrm{P}$	23.087

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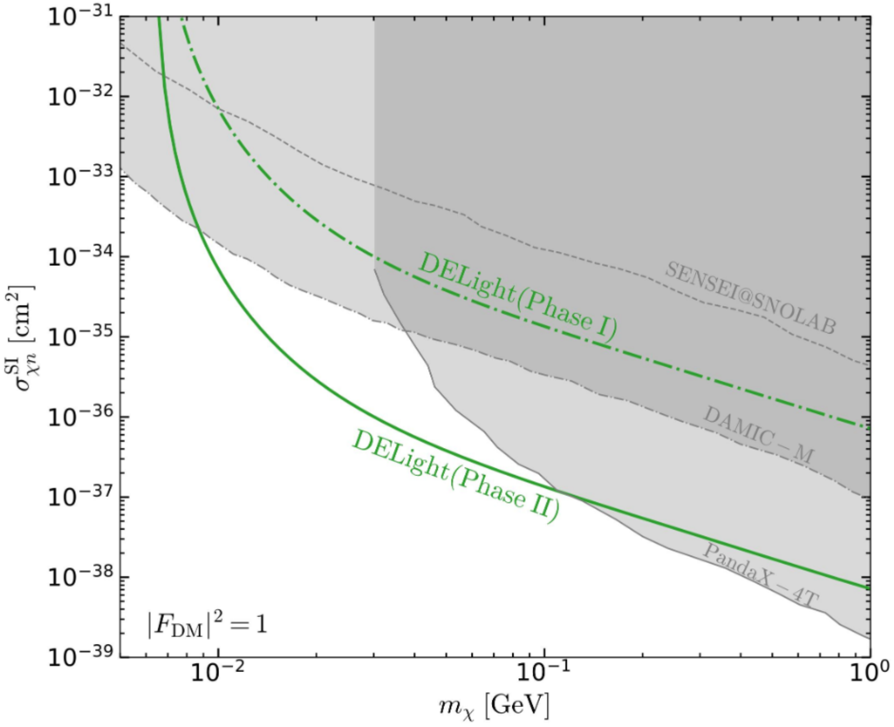
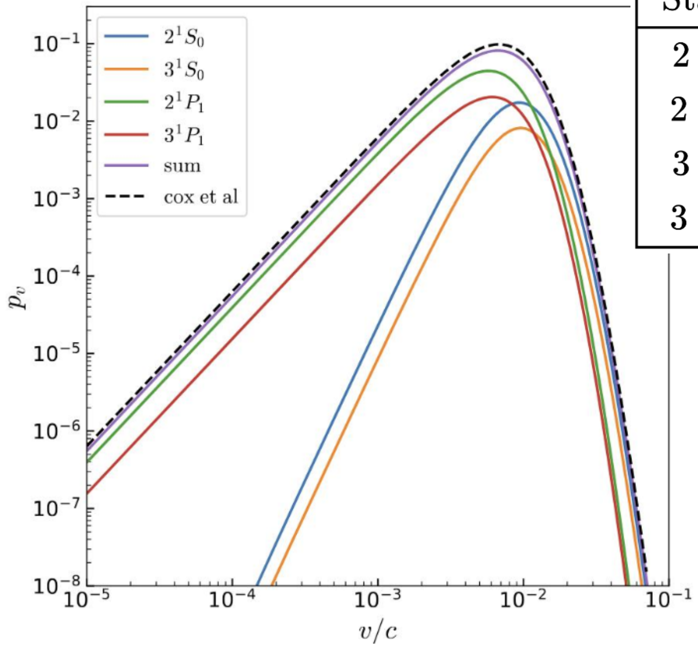
Sensitivity projections





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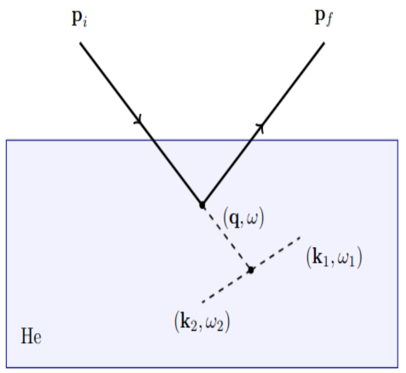
Going even lower

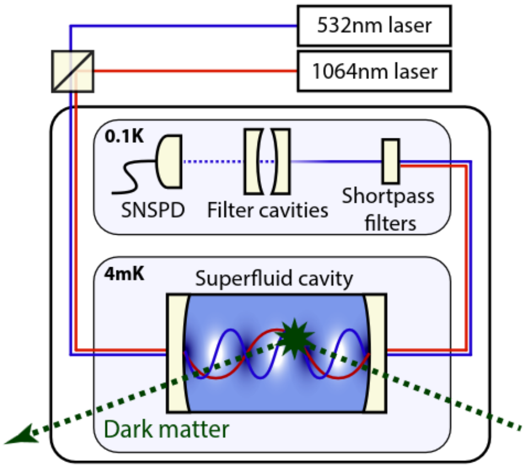
- For sub-eV recoils: Effective field theory of superfluid ^{4}He
  - Direct coupling of dark matter to collective modes
  - Creation of one-phonon and two-phonon excitations
  - ➞ Tiny energy deposition (<< eV)



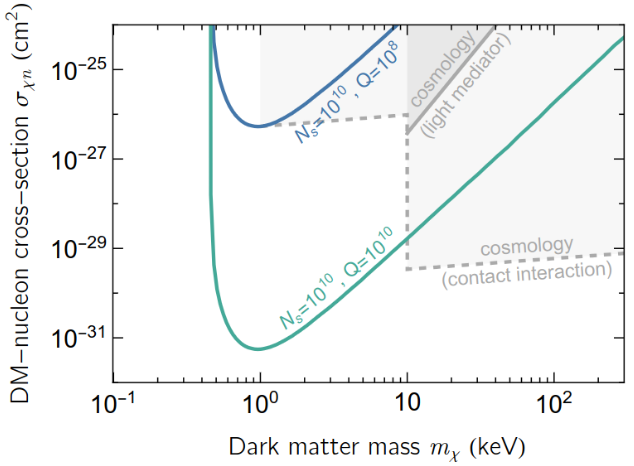
Knapen et al., arXiv:1611.06228

- How to detect this?

- Idea: optomechanical cavity
  - ➞ Dark matter scatters off highly populated phonon mode
  - ➞ Scattered phonon converted into photon
  - ➞ Single-phonon detection!



Baker et al., arXiv:2306.09726



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Conclusions

- Nature of dark matter among the most important open questions of fundamental physics
- Promising direction: Sub-GeV dark matter (e.g. with dark photon mediator)
- Requires lower thresholds, lighter targets (or both)
  - → Superfluid helium
- **DELight:** Simultaneous detection of UV photons from eximers and evaporation from quasiparticles
- Future directions:
  - – Direct excitations via the Migdal effect
  - – Single-phonon detection in optomechanical cavities

The DELight collaboration (2026)

Felix Kahlhoefer
Institute for Astroparticle Physics