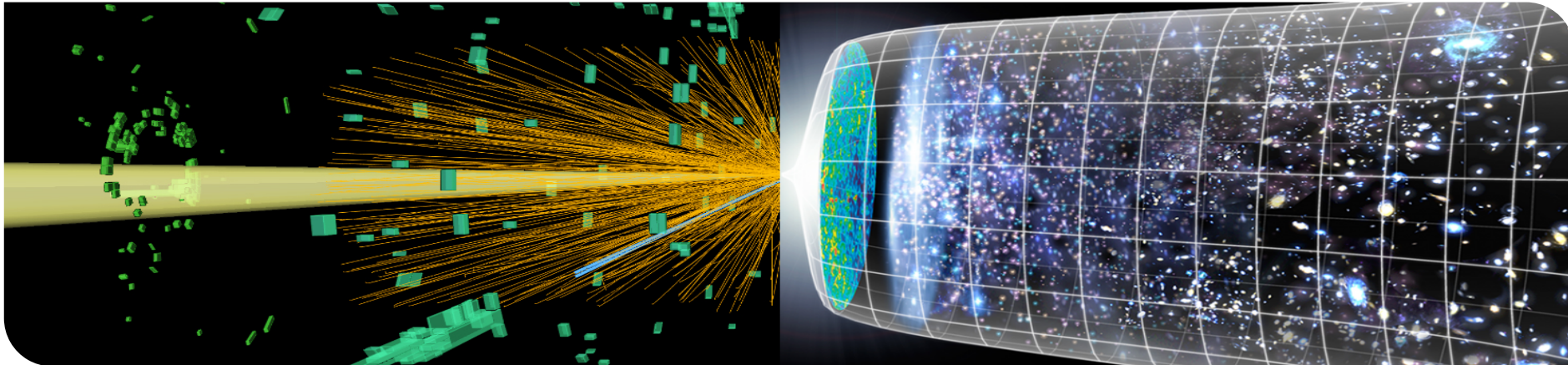


# Overview of dark matter theories

**Felix Kahlhoefer**

BND Graduate School, 17 September 2026



# Outline

## ■ Lecture 1: The basics

- Cosmological and astrophysical evidence for dark matter
- Dark matter production in the early universe

## ■ Lecture 2: Thermal dark matter

- The freeze-out mechanism and the WIMP “miracle”
- Dark sectors and sub-GeV dark matter

## ■ Lecture 3: Non-thermal dark matter

- The freeze-in mechanism and sterile neutrinos
- The misalignment mechanism and axions



<https://bwsyncandshare.kit.edu/s/pmLHArMzMJNYP6Q>

# Case study: Heavy neutrino

■ For heavy neutrinos with  $M_\nu > M_Z$  one finds  $\langle \sigma v \rangle \approx \frac{g^4}{16\pi M_\nu^2}$

→ Observed dark matter density reproduced for  $M_\nu \sim 1 \text{ TeV}$

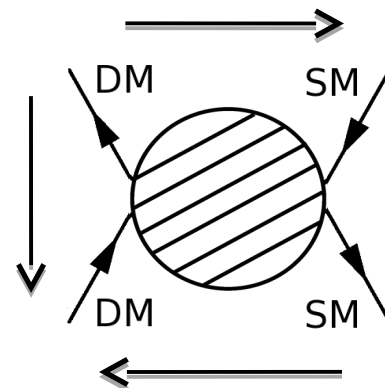
→ Intriguingly close to the electroweak scale (250 GeV)

→ Exactly where we would expect to find new particles beyond the SM

→ So-called WIMP miracle

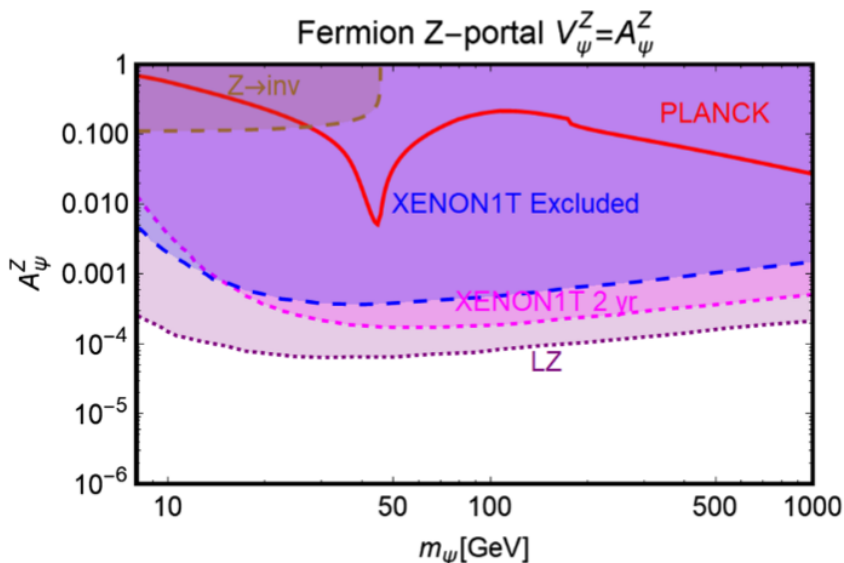
# Experimental tests of WIMPs

- The WIMP idea requires sizable interactions of DM with SM particles
- Can be tested experimentally
- Three strategies:
  - Indirect detection: Dark matter energy density in astrophysical objects converted into SM particles that travel to Earth
  - Direct detection: Dark matter energy density in the solar neighbourhood converted into observable signals in laboratory experiments
  - Accelerator searches: Use energetic known particles to produce dark matter



# Where Is My Particle?

■ In combination, these search strategies rule out heavy neutrinos



■ More generally, lack of DM signals puts pressure on the WIMP idea

■ What about alternatives to the WIMP paradigm?



# Case study: (Not so) heavy neutrino

■ For heavy neutrinos with  $M_\nu < M_Z$  one finds  $\langle \sigma v \rangle \approx \frac{g^4 M_\nu^2}{32\pi M_Z^4}$

→ Relic abundance increases as  $M_\nu$  decreases

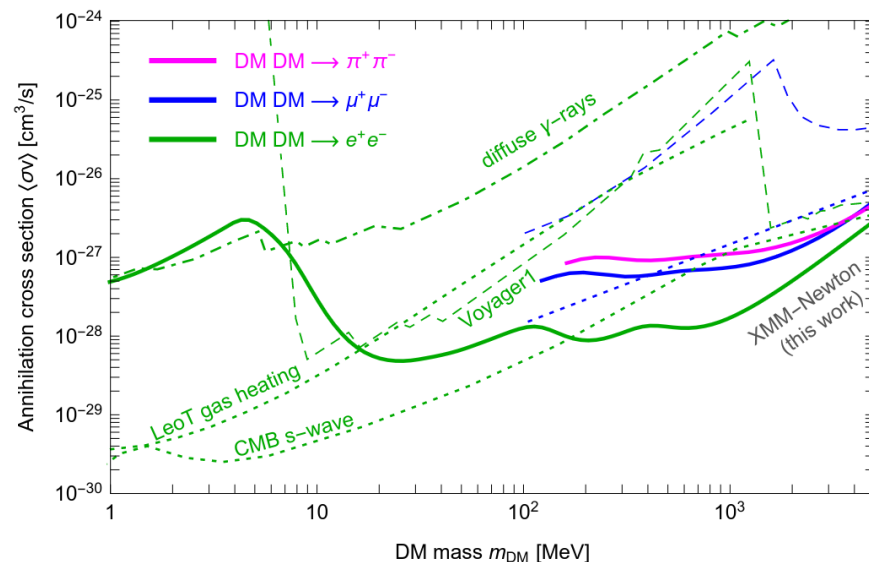
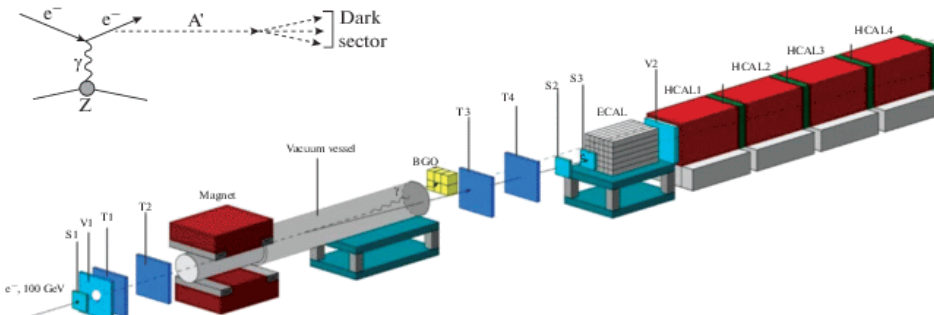
→ Cosmology gives lower bound  $M_\nu > 2 \text{ GeV}$  (Lee-Weinberg bound)

→ For smaller masses, new interactions are needed

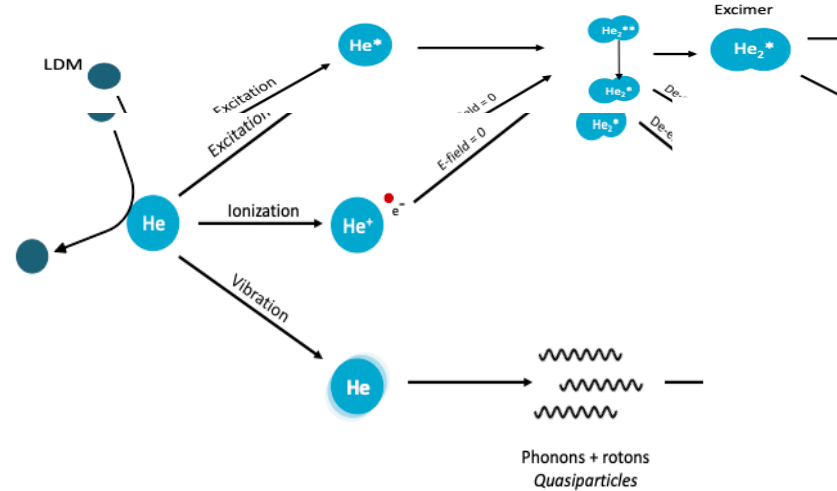
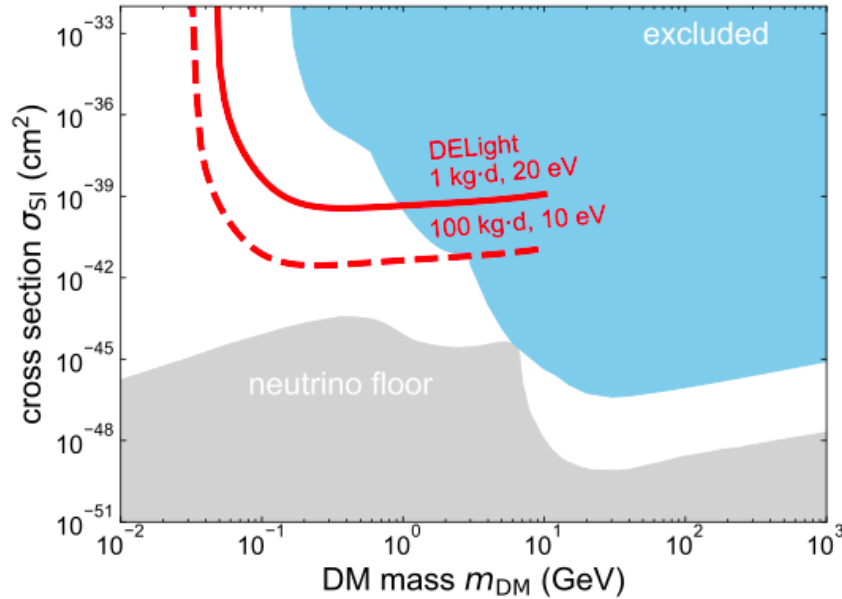


# Models of Sub-GeV dark matter

- Sub-GeV DM also evades most direct detection constraints, because the kinetic energy of the particles is too small to leave an observable signal in the detector
- Main constraints: Indirect detection and accelerator searches



## ■ New idea: Search for light dark matter scattering with superfluid helium-4

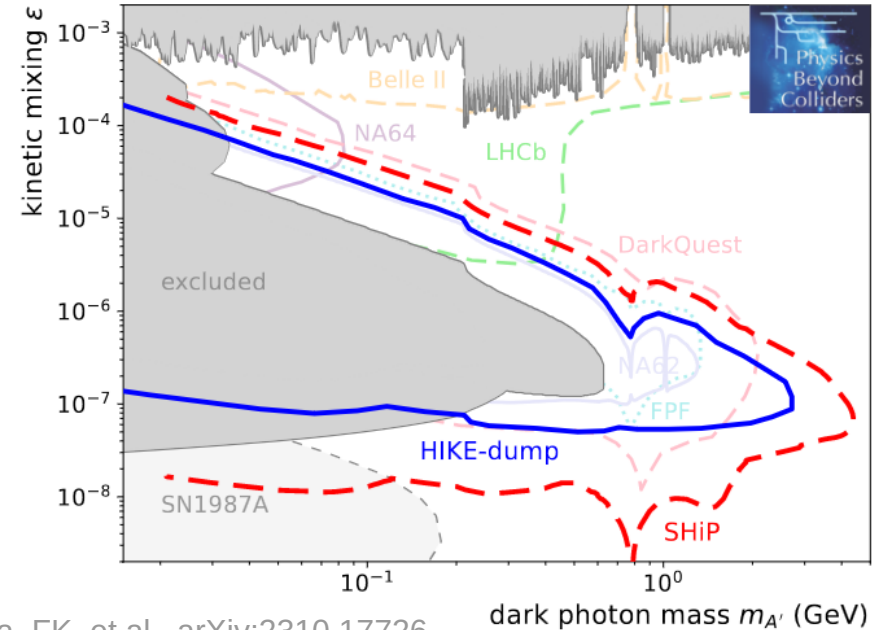
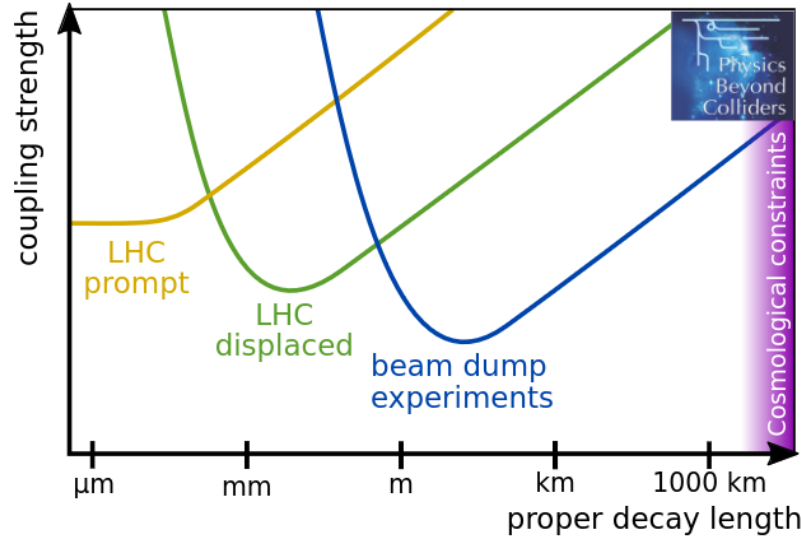


von Krosigk, FK, et al., arXiv:2209.10950



# Search for Hidden Particles (SHiP)

- Search for (long-lived) mediator of dark matter interactions



Ahdida, FK, et al., arXiv:2310.17726

- Recently approved by CERN!