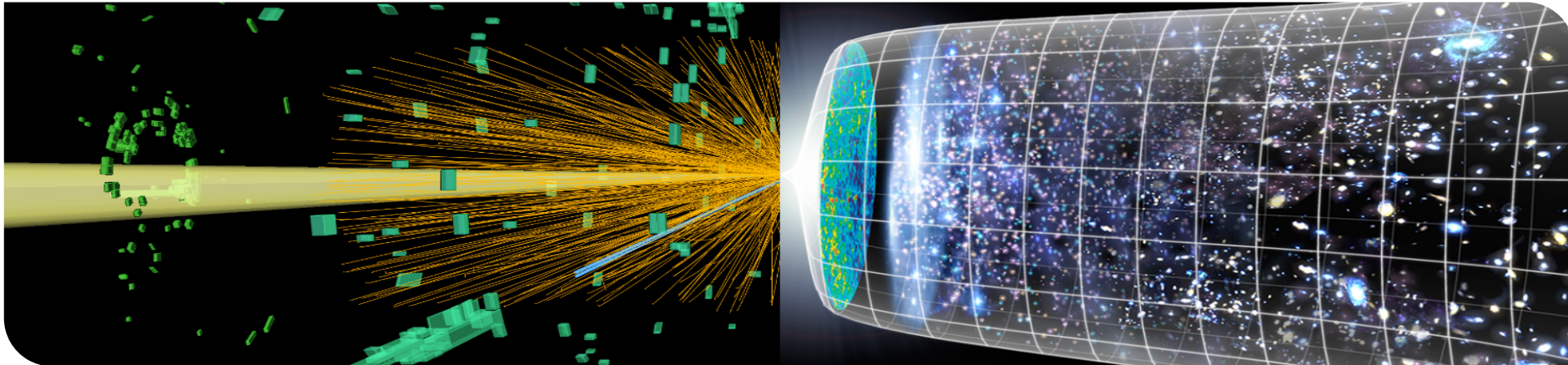


Overview of dark matter theories

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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

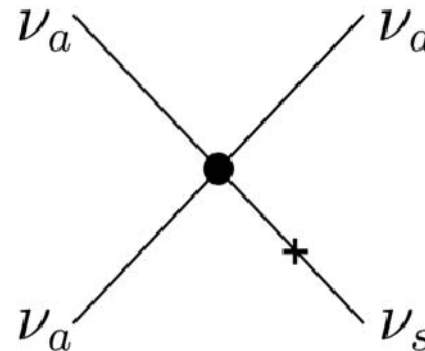


<https://bwsyncandshare.kit.edu/s/pmLHArMzMJNYP6Q>

Example: Sterile neutrino

- Instead of a heavy neutrino that directly couples to the Z boson, consider a heavy neutrino that mixes with active neutrinos

→ Any process that produces active neutrinos can also produce sterile neutrinos with probability $\sim (\text{mixing})^2$

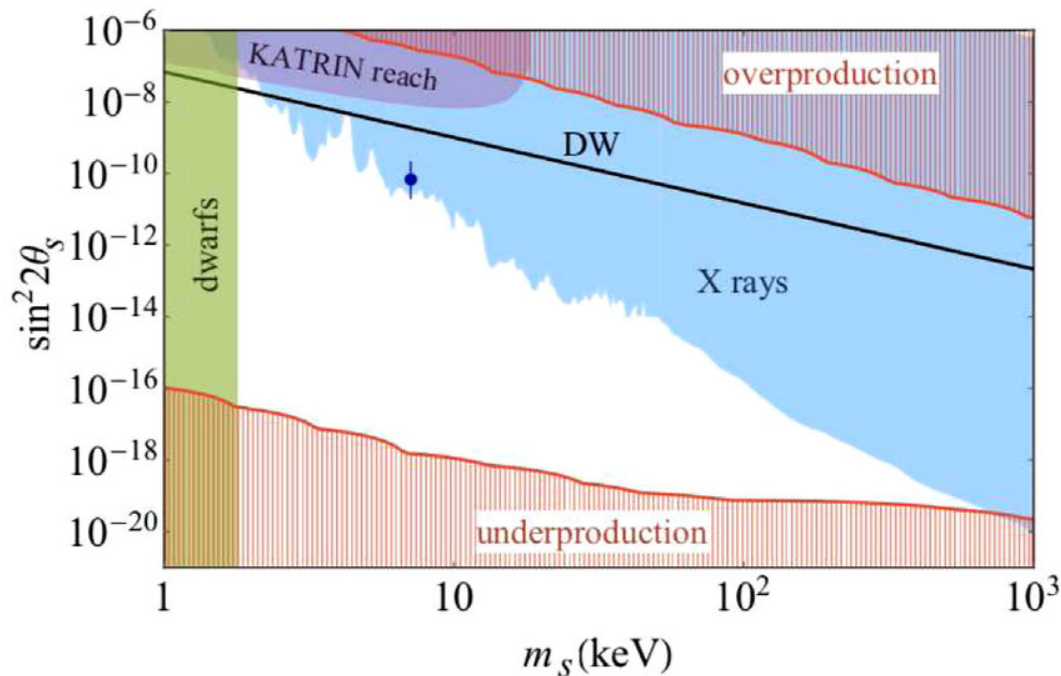


- For sufficiently small mixing, sterile neutrinos do not thermalise and evade the BBN bound

Constraints on sterile neutrinos

■ Main constraints:

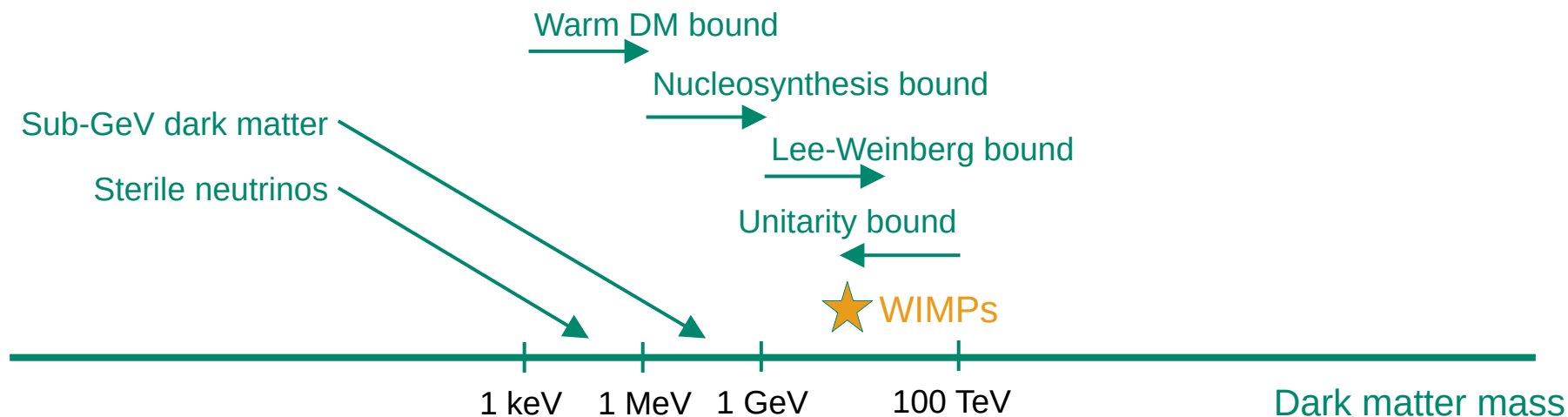
- Observed DM relic abundance
- Sterile neutrino decays (into active neutrinos + x-ray photons)
- Warm dark matter bounds (structure formation): $M_\nu > \text{keV}$



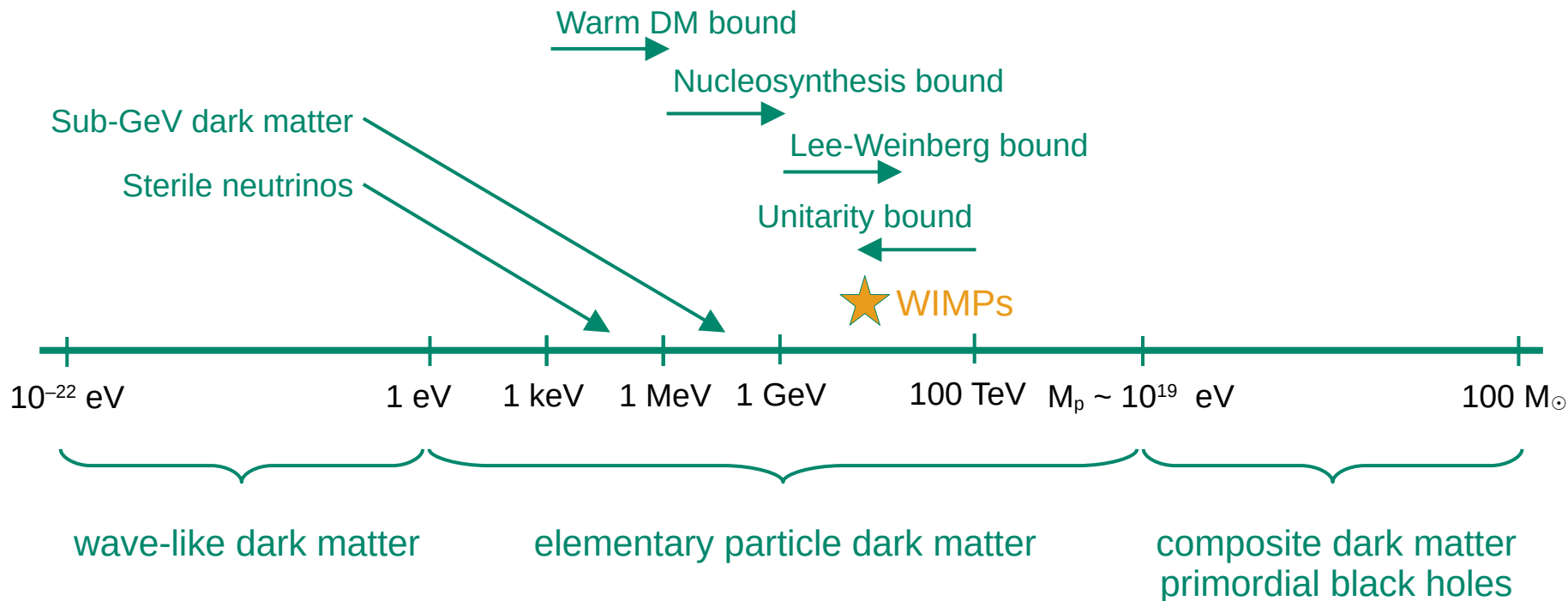
The universe as a dark matter laboratory

- Cosmological observations can even constrain DM models with negligible interactions with SM particles
 - **Free-streaming:** Relativistic particles escape from overdensities
 - Suppression of small-scale structure (no dwarf galaxies)
 - **Self-interactions:** Strongly coupled particles create friction and heat transport
 - Modification of DM halo density profiles (core formation)
 - **Dark radiation:** DM may decay or annihilate into lighter invisible states
 - Modification of the universe's expansion history

Summary so far



Going beyond

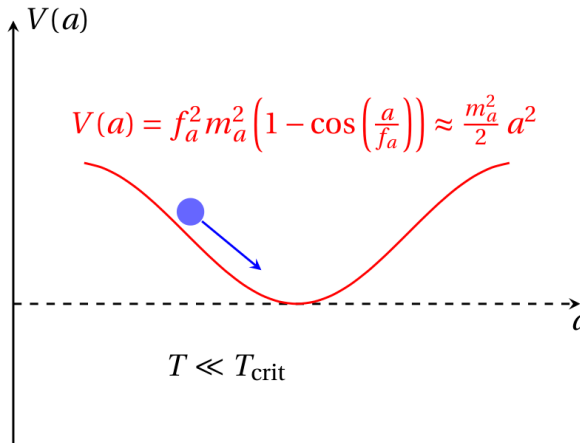
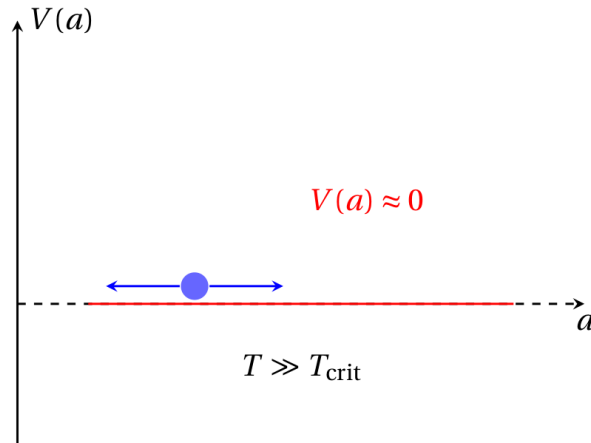


Wave-like dark matter

- To achieve successful structure formation for ultra-light particles ($\ll \text{keV}$), we need a large number of particles in the same quantum state
 - Impossible for fermions (Pauli exclusion)
 - Can be achieved for bosons
- Such large occupation numbers lead to classicalisation
 - DM can be modeled as a coherently oscillating scalar field
 - Energy density $\sim (\text{amplitude})^2$
 - Same equation of state as a collection of non-relativistic particles

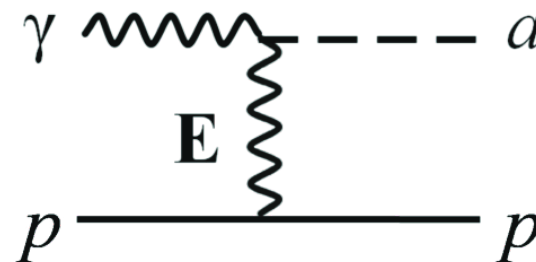
Example: Axions

- Pseudoscalar particles with the same quantum numbers as neutral pions but much smaller mass
- Produced in the early universe via the realignment mechanism
→ Scalar field displaced from potential minimum



Axion signals

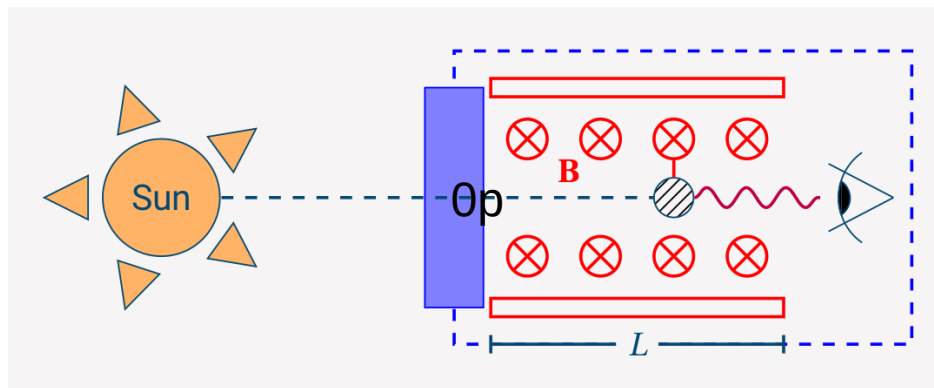
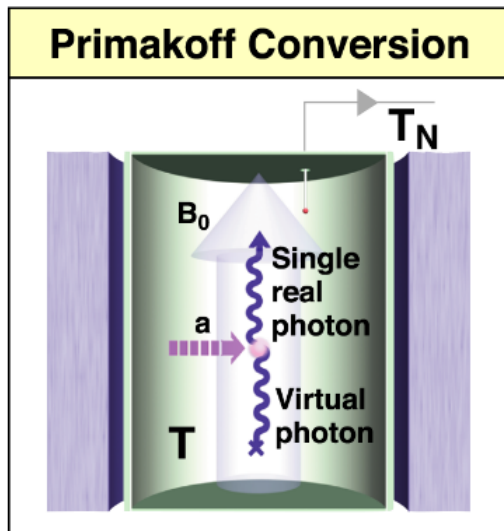
- In the presence of a magnetic field, axions can be converted into photons
- Prediction: Electromagnetic wave with frequency = axion rest mass



- Alternative strategy: If particles couple to axions, their properties (e.g. dipole moments) might oscillate with the axion field
- Some models even predict a time variation of fundamental constants
→ Search for example with atomic clocks or atom interferometers

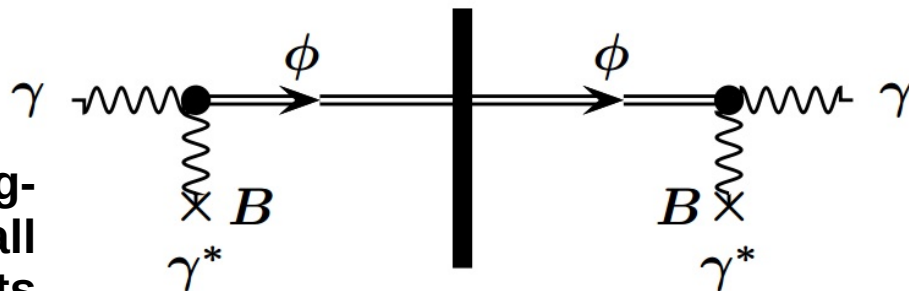
Axion searches

Haloscope



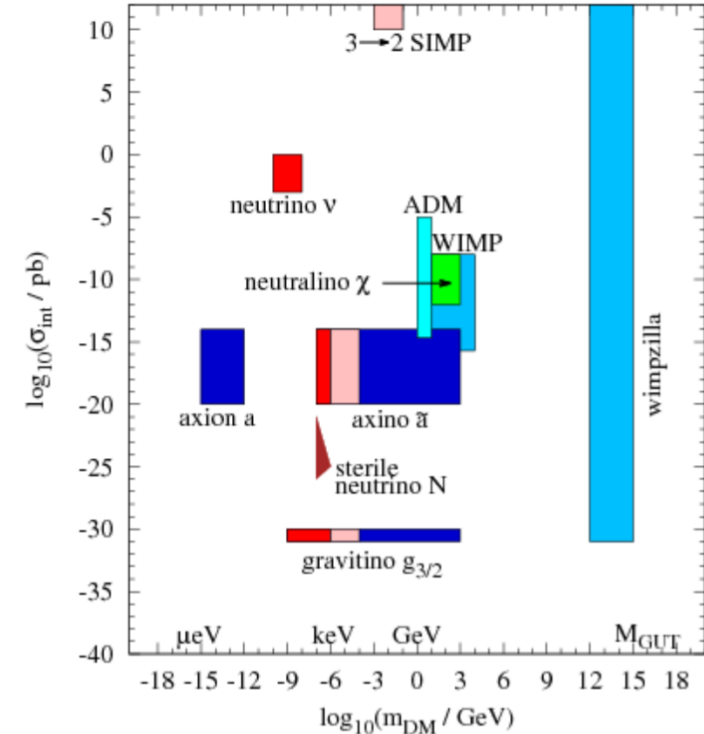
Helio- scopes

Light-shining- through-wall experiments



Summary: Dark matter models

- Viable and plausible DM models over many orders of magnitude in mass and coupling
- Many strong theoretical motivations
 - Hierarchy problem → WIMPs
 - Baryon asymmetry → GeV-scale DM
 - Neutrino mass → sterile neutrinos
 - Strong CP problem → axions
- Need a broad and diverse search programme!



Conclusions

- Cosmological and astrophysical evidence for DM implies new BSM physics
- Important class of models: Thermal DM via the freeze-out mechanism
 - Traditional WIMPs around the electroweak scale challenged by null results
 - New interactions/mediators allow for heavier and lighter particles
- Many alternative directions
 - Non-thermal dark matter (freeze-in mechanism)
 - Wave-like dark matter (realignment mechanism)
- Many opportunities for discovery