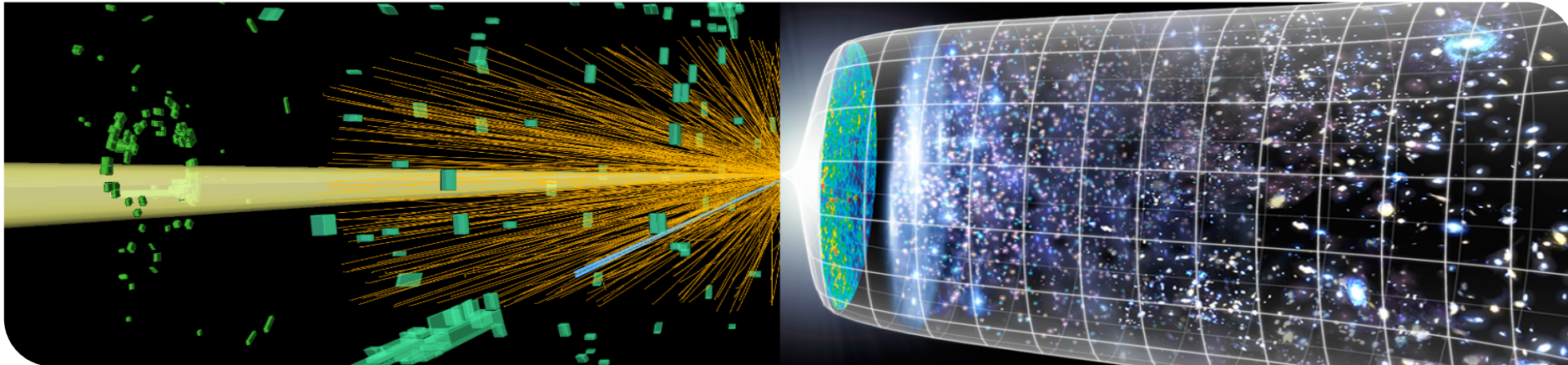


Overview of dark matter theories

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



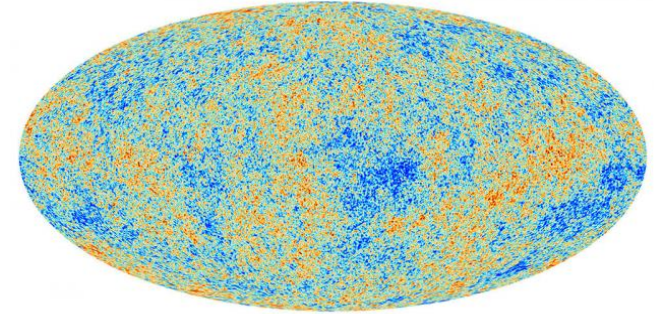
<https://bwsyncandshare.kit.edu/s/pmLHArMzMJNYP6Q>

Literature recommendations

- Balazs, Bringmann, Kahlhoefer, White: A Primer on Dark Matter (<https://arxiv.org/pdf/2411.05062>)
- Cirelli, Strumia & Zupan: Dark Matter (<https://arxiv.org/abs/2406.01705>)
- Marsh, Ellis & Mehta: Dark Matter: Evidence, Theory, and Constraints (ISBN-13: 978-0691249520)
- Profumo: An Introduction to Particle Dark Matter (ISBN-13: 978-1786340016)
- Mambrini: Particles in the Dark Universe (ISBN-13: 978-3-030-78138-5)
- Bauer & Plehn: Yet Another Introduction to Dark Matter (<https://arxiv.org/pdf/1705.01987.pdf>)

Evidence for dark matter: Cosmology

- Almost perfect black-body radiation created during recombination at $T_{\text{CMB}} = 0.3 \text{ eV}$
- Observed today with a redshifted temperature of $T_{\text{CMB}}^{\text{today}} \sim 2.7 \text{ K} \sim 0.2 \text{ meV}$
 - Universe has grown by a factor 1000 since recombination



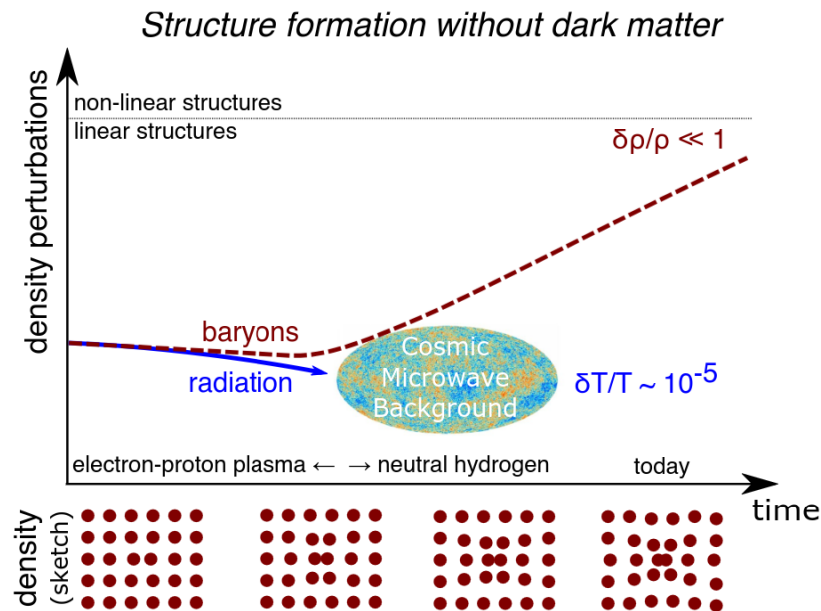
- The CMB exhibits tiny temperature fluctuations $\Delta T/T \sim 10^{-5}$ resulting from density fluctuations in the baryon-photon fluid: $\delta_r(t_{\text{CMB}}) \simeq \delta_b(t_{\text{CMB}}) \sim 10^{-5}$

Evidence for dark matter: Cosmology

- Cosmological perturbation theory predicts that these perturbations should grow linearly as the universe expands:

$$\delta_{\text{today}} \sim a_{\text{today}} / a_{\text{CMB}} \cdot \delta_b(t_{\text{CMB}}) \sim 10^{-2}$$

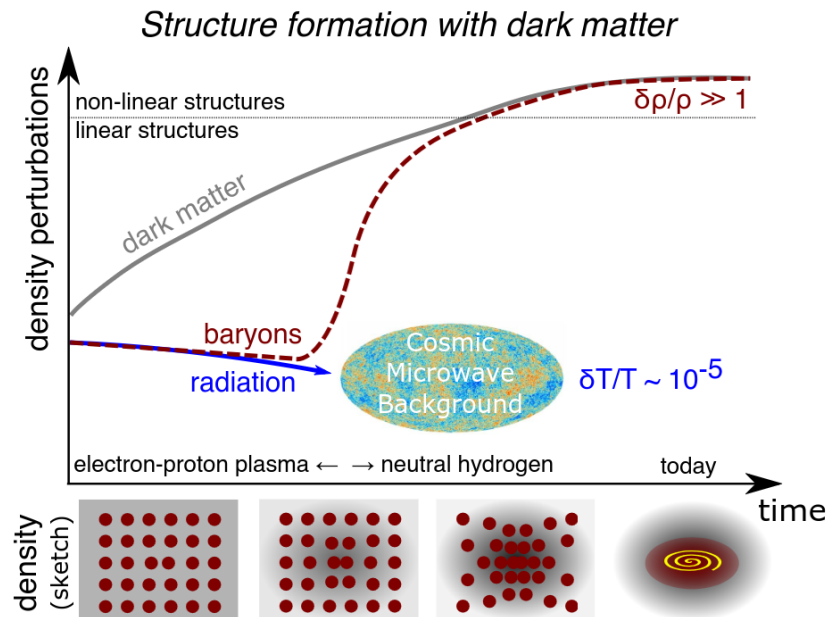
- Expect present universe to be nearly homogeneous
- Clear contradiction with observations



Evidence for dark matter: Cosmology

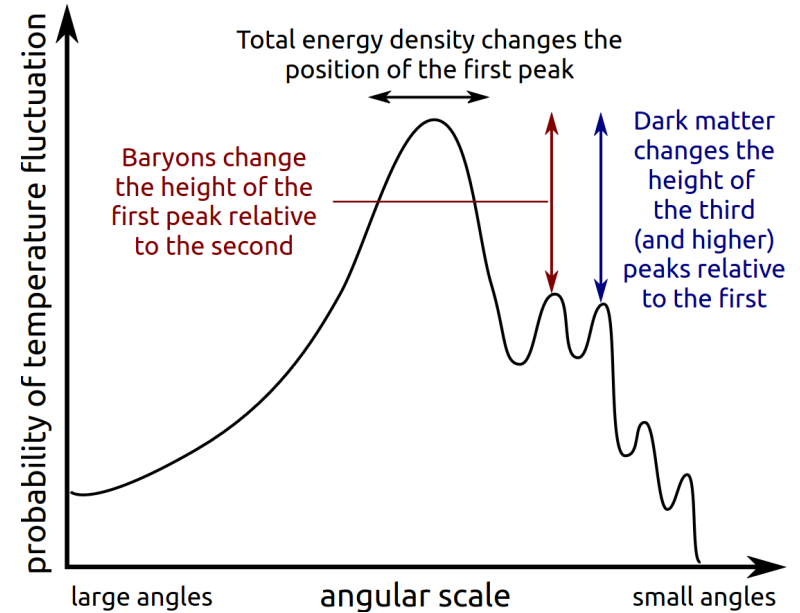
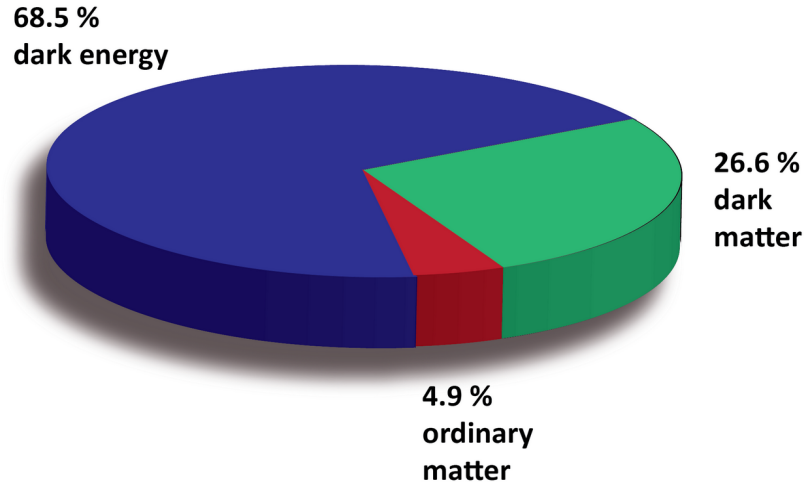
- **Conclusion:** Need a new form of matter that forms overdensities before recombination
- After recombination, baryons fall into the potential wells created by this matter
- Only possible if this new form of matter does not experience photon pressure

→ Dark matter



Evidence for dark matter: Cosmology

- Detailed analysis of the CMB reveals the total amount of dark matter in the universe



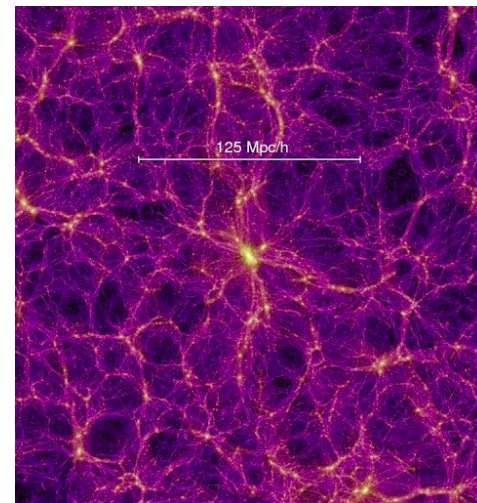
Evidence for dark matter: Astrophysics

- **Main conclusion:** Dark matter acts as seed for structure formation

→ Galaxies and galaxy clusters grow inside dark matter halos

- Non-linear structure formation can be studied with numerical simulations

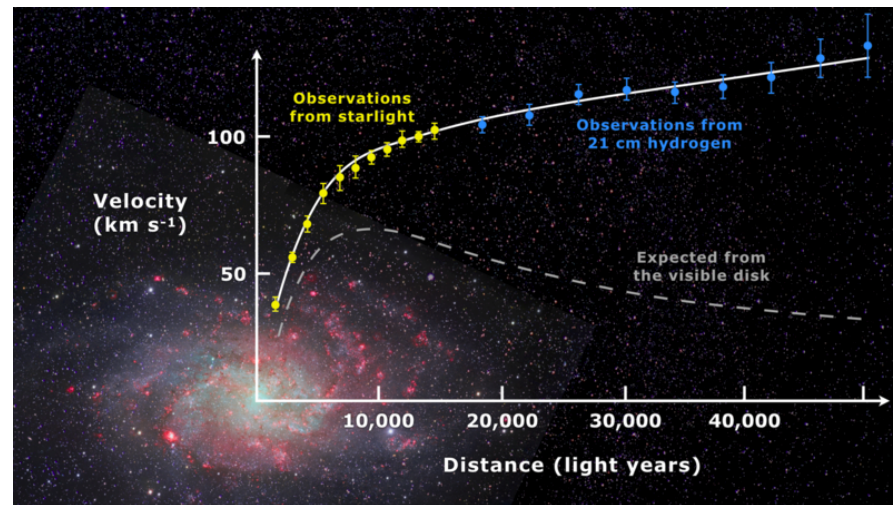
- **Key prediction:** Gravitational effects of dark matter should be observable in astrophysical systems



Evidence for dark matter: Astrophysics

■ Basic idea:

- Map out gravitational potential using kinematic data (e.g. rotation curves)
- Compare with gravitational potential created by visible matter

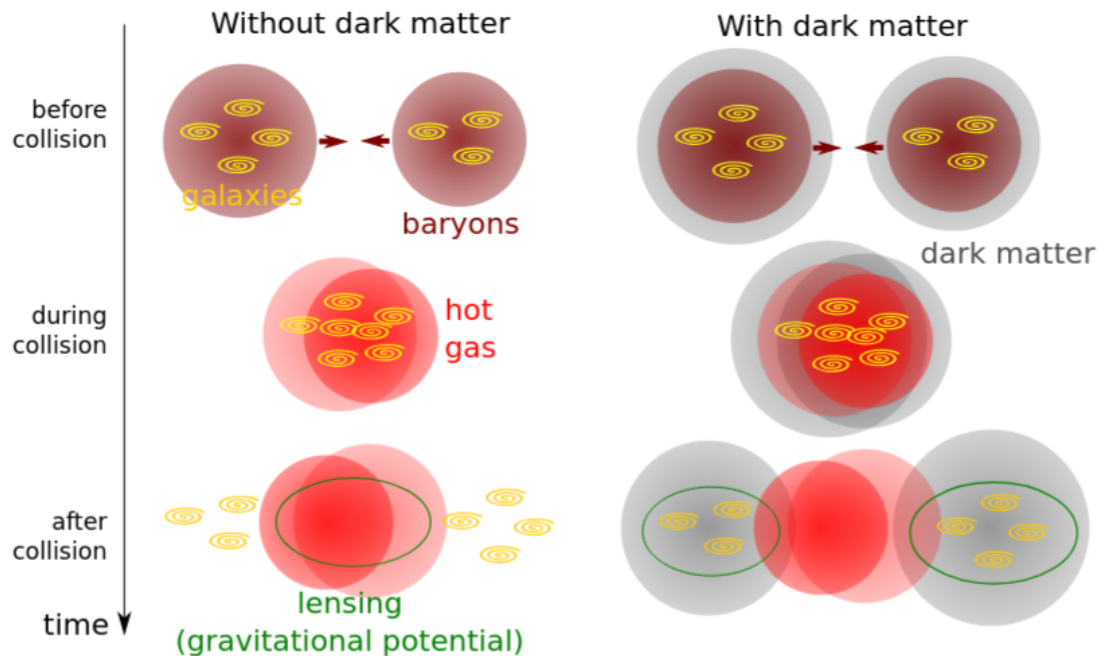
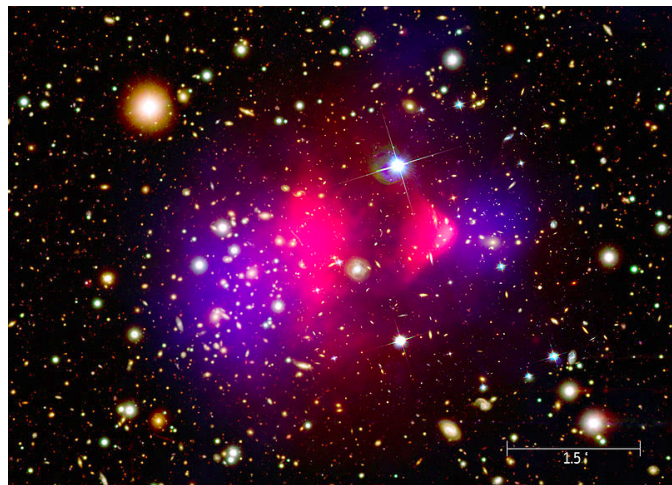


- Mismatch observed on all scales (galaxy clusters, galaxies, dwarf galaxies)
- Can be attributed to dark matter

Evidence for dark matter: Astrophysics

Alternative strategy:

Infer gravitational potential
using gravitational lensing



Implications for dark matter models

- CMB temperature anisotropies

- Dark matter has no (or at most a tiny) electric charge

- Bound on exotic energy injection

- Dark matter must be stable (or at least long-lived on cosmological timescales)

- Existence of small gravitationally bound objects (e.g. dwarf galaxies)

- Dark matter must be non-relativistic (cold) during structure formation

Dark matter from the Standard Model?

- **Neutrons:** Decay into charged particles
 - **Cold atoms (dust):** Would be ionised / dissociated in the early universe
 - **Neutrinos:** Experimental upper bounds on the neutrino mass imply that they cannot be cold dark matter
- No known particle has the right properties to be all of dark matter!

Case study: Heavy neutrinos

- Neutrinos are too light to be dark matter. What about a new heavy neutrino?
- Viable in principle. But can we produce enough of them in the early universe?
- Need to study the evolution of the dark matter number density including production and annihilation processes
→ Boltzmann equation