Dark Matter — Theory

Why do we need Dark Matter ?

- Rotation curves of galaxies
  - can be explained by Modified Newtonian Dynamics (MoND)
  - the gravitational dark matter could be macroscopic:
    - brown stars, planets, compact dust, . . .
    - Massive Compact Halo Objects (MaCHOs)

- Gravitational lensing
  - only needs the gravitational potential, not particles

- Mass balance in the expansion
  - todays measured value of the matter density id $\Omega_m \sim 0.27$
  - the visible mass (luminous and gas) has only $\Omega_{\text{lum}} \sim 0.04$

⇒ Structure formation and Baryon Acoustic Oscillations (BAO)

Structure formation

- density fluctuations grow through gravitational interaction:
  - overdense regions contract
    $\Rightarrow$ they become hot
  - underdense regions expand
    $\Rightarrow$ they cool down

- "gas pressure" counteracts the contraction of dense regions
  - the density contrast δ follows the equation

$$\ddot{\delta} + [\text{Pressure} - \text{Gravity}]\,\delta = 0$$

  - if Pressure $<$ Gravity $\Rightarrow$ exponential collaps
    * star formation; time of the collaps comparable to the Hubble time: $\sim \frac{1}{100} t_H$
  - if Pressure $>$ Gravity $\Rightarrow$ oscillations

  $\Rightarrow$ Baryon acoustic oscillations (BAO)

Structure formation

- in the radiation era
  - most components are in thermal equilibrium
  - temperature defines the thermal speed of particles
  - most particles move fast enough to be ”radiation”

  ⇒ hence ”radiation era”

- overdensities are washed out through the free streaming of ”radiation”
- the universe as a whole expands and cools down
  - particle species drop out of thermal equilibrium
    - and usually decay, thereby reheating the rest
  - stable non-relativistic particles form the matter density Ω_m
    - they should have no pressure

  ⇒ their interaction has to be small

Dark Matter — Theory

Structure formation — observation

- galaxies (nebulae) are formed before the individual stars
  - star formation happens in the overdense nebulae
    - ∗ by fluctuatiuons in the overdense region

- the later the formation starts, the smaller the objects

⇒ at the start of structure formation
  - the free streaming length should be smaller than a galaxy
    - ∗ otherwise structure formation would not start . . .

- the cross section σ determines the mean-free-path of a particle
  = the length between two scattering events of the particle
    - ∗ the cross section σ is a measure for the interaction strength
  - if $\sigma|\vec{v}| < H_{\text{local}}$ the mean-free-path grows bigger than ℓ_H

  ⇒ the particles effectively do not interact ⇒ no pressure

Structure formation — Dark Matter properties

- only a component already present in the radiation era can trigger structure formation
  - $\Rightarrow$ it has to be described by the Einstein-Boltzmann equations
    - $\Rightarrow$ Dark Matter ... and not macroscopic objects

- Dark Matter has nearly no pressure
  - does not participate in gravitational oscillations
    - * described by the density contrast equation $\ddot{\delta} + [\text{pressure} - \text{gravity}]\,\delta = 0$
  - influences the BAO by providing additional gravitational attraction
    - * effect is seen in the CMB spectrum

$\Rightarrow$ Dark Matter should not actively distort the CMB spectrum

- $\Rightarrow$ Dark Matter has to be electrically neutral
  - * and can only very weakly interact with the CMB photons

Dark Matter — Theory

Structure formation — Dark Matter properties

- Big Bang Nucleosynthesis (BBN) happens in the radiation era
  - is successfully described by the Einstein-Boltzmann equations
  - Dark Matter should not spoil this success

    ⇒ Dark Matter cannot interact by the nuclear force

⇒ Dark Matter can at most interact with the weak interactions

  ⇒ Weakly Interacting Massive Particles (WIMPs)

  - WIMPs cannot decay quickly into Standard Model particles
    * otherwise the decay products would be energetic again
    * and disturb BAO and BBN
  - WIMPs are stable ... and form todays Dark Matter density

or

  - WIMPs decay into a hidden sector ...
    * which forms todays Dark Matter density

Properties of the Dark Matter density

- can be several components, but should sum up to $\Omega_{\text{DM}} \sim 0.23$
- Baryonic Dark Matter
  - brown stars, planets, compact dust, . . . MaCHOs
  - macroscopic objects $\Rightarrow$ non-relativistic

  $\Rightarrow$ cannot contribute to structure formation

  $\Rightarrow$ upper limit on contribution
- Non-Baryonic Dark Matter . . . particles
  - Hot Dark Matter . . . neutrinos or exotic very light particles (axions, axinos, . . .)
    - ultra-relativistic still today: $v \sim c$ or $E_{\text{kin}} \gg m_0$
    - strongly influences structure formation: severe limit on contribution
  - Warm Dark Matter . . . sterile neutrinos or gravitinos
    - relativistic still today: $E_{\text{kin}} \sim m_0$
    - also disfavoured by the current analysis
  - Cold Dark Matter (CDM) . . . WIMPs
    - non-relativistic today: $E_{\text{kin}} \ll m_0$
    - the "standard" Dark Matter: weakly interacting and $m > 10$ GeV

Particle Dark Matter

- Supersymmetric can provide all types

? How to get heavy particles stable ?

- the heavier a particle the quicker it decays:

muon	μ^-	0.105 GeV	$t_{1/2} =$	$2.2 \cdot 10^{-6}$ s
tau	τ^-	1.777 GeV	$t_{1/2} =$	$2.9 \cdot 10^{-13}$ s
top quark	t	172.2 GeV	$t_{1/2} =$	$5 \cdot 10^{-25}$ s

- a conservation law
  - for the Minimal Supersymmetric Standard Model (MSSM):
  - Matter parity $\mathcal{R}$
    - an assigned multiplicative quantum number
    - for each field f: $\mathcal{R}_f = (-1)^{3(B_f - L_f) + 2s_f}$

      with the baryon number B, the lepton number L and the spin s

$\Rightarrow$ the Lightest Supersymmetric Particle (LSP) is stable

Supersymmetric Dark Matter

- the LSP has to be neutral under $U(1)_{\text{em}}$ and $SU(3)_{\text{color}}$
  - a partner of the neutral gauge bosons γ or Z
  - a partner of the neutral Higgses h^0 or H^0
    - or a mixture of these: a fermionic neutralino $\tilde{\chi}_k^0$
    - the standard choice
  - a partner of the neutral leptons, the neutrinos ν
    - or a mixture of these: a bosonic sneutrino $\tilde{\nu}_i$
    - disfavored by model building

- including gravity to SUSY gives Supergravity (SUGRA)
  - the partner of the graviton can be the LSP, too: the gravitino $\tilde{G}$
    - even does not couple with the weak interaction
  - couples only gravitationally $\Rightarrow$ extremely weak: coupling $\sim \frac{E^2}{M_P^2} \sim 10^{-32}$
  - coupling not small in the GUT era with $kT \sim 10^{16}$ GeV

  $\Rightarrow$ thermal equilibrium at 10^{16} GeV and freeze-out during inflation ?

Supersymmetric Dark Matter

- the LSP could be the axino
  - the partner of the neutral axion
    - the Goldstone boson of the spontaneous broken symmetry of QCD vacua
  - the axion could couple to photons $\Rightarrow$ unstable

neutralino and sneutrino are weakly interacting — like the neutrino

- searching for Dark Matter particles
  - in Neutrino Telescopes or specialized experiments
  - signals reported from DAMA, CDMS, and CRESST
    - but the determination of the Dark Matter parameters is still incompatible
- producing Dark Matter particles at the LHC
  - detecting them in cascade decays
  - since they do not interact with the nuclear interaction
    - they are not directly produced