Dark matter awareness week: Dark matter and particle physics

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Outline of the talk

- Introduction: A consistent picture takes shape
- Evidence for dark matter
  - Evidence for DM on galactic scales
  - Evidence for DM on cluster scales
  - Evidence for DM from CMB
- WIMPs: Candidates for particle DM
- Direct and indirect WIMP search
- Conclusions

Introduction:
A consistent picture takes shape

Evidence for DM from following observations:

1. Rotational speed of galaxies
2. Orbital velocities of galaxies within clusters
3. Gravitational lensing
4. Cosmic microwave background
5. Large-scale structure
6. Light-element abundances

- 1932 Jan Hendrik Oort: thickness of galactic disc smaller than one would expect from gravity of observed mass
- 1933 Fritz Zwicky: DM in galaxy clusters

Remarks:

- DM has gravitational interaction
- Local DM densities from observations 1,2,3
- Mean cosmic DM density from observations 4,5
- Total baryon density from observation 6

Modern consistent picture of cosmology: ΛCDM model

Λ = cosmological constant, CDM = cold dark matter

Energy fractions of different types of matter:

- 4% baryonic matter
- 23% cold dark matter
- 73% dark energy

Luminous matter ~ 0.002, photons $\sim 5 \times 10^{-5}$, neutrinos < 0.015

Cosmic Concordance:

good concordance among different cosmological data
CMB = cosmic microwave background
LSS = large scale structure
BBN = big bang nucleosynthesis (light-element abundances: ^{2}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li)
SN Ia measurements (Hubble constant H_0)

Cold dark matter

Definition 1:

Non-relativistic at time $t_{\rm rec}$ of decoupling of matter and radiation
$t_{\rm rec} \sim 380000\,y \longrightarrow$ formation of atoms
CDM consistent with formation Large Scale Structure $\longrightarrow$
filaments and voids

Definition 2:

Non-relativistic since $T \sim 1\,\mathrm{MeV}$

Definition 3:

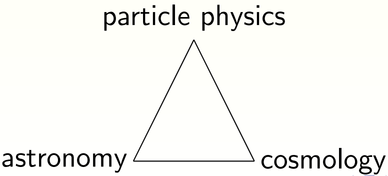
$T^X_{\rm dec}$ decoupling temperature of dark matter particles X
$m_X \ll T^X_{\rm dec} \Rightarrow$ hot DM
$m_X \gg T^X_{\rm dec} \Rightarrow$ cold DM

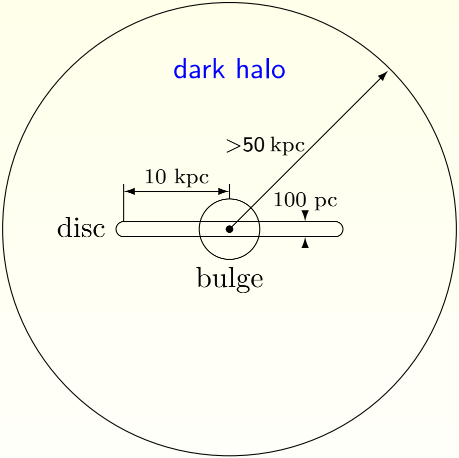
Local DM density:

DM accumulation in galaxies, galaxy clusters, stars, . . . by gravitation
Could galactic DM consist of baryons?
DM density in local neighbourhood: $0.3\,\mathrm{GeV\,cm}^{-3}$
Limits on MACHO density from microlensing: CDM more than 80%
MACHO = massive astrophysical compact halo object
Molecular hydrogen clouds?

Dark matter

- non-baryonic
- consists of hitherto unknown DM particles!




dark halo
>50 kpc
10 kpc
100 pc
disc
bulge

Proposed condidates for DM particles:

Particles with zero electric charge, stable or lifetime much longer than the age of the universe

- WIMPS = weakly interacting massive particles:
  $M \sim 100 \div 1000\,\text{GeV}$, produced in thermal equilibrium
  Could be bosons (spin 0, 1) or (Majorana) fermions (spin 1/2, 3/2)
- Axions: $M < 10^{-3}\,\text{eV}$, scalar produced out of thermal equlibirium
- Sterile neutrinos: Majorana neutrinos with $M \sim 1 \div 50\,\text{keV}$, non-thermal production, warm or cold dark matter
- WIMPZILLAS: $M > 10^{10}\,\text{GeV}$, non-thermal production during inflation, could have only gravitational interactions $\rightarrow$ gravitational wave background

Evidence for dark matter

Rotation curves of galaxies

Rotation in galactic disc: gravitational force = centrifugal force

$$v(r) = \sqrt{\frac{GM(r)}{r}} \quad \text{with} \quad M(r) \equiv 4\pi \int_0^r \rho(r')r'^2 dr'.$$

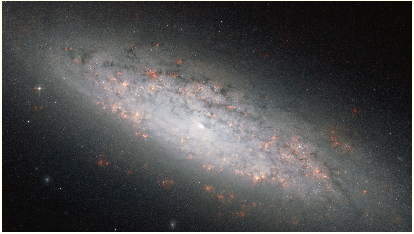
If galaxy consisted of visible matter only:

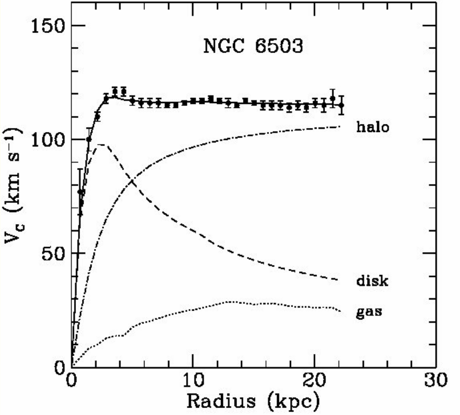
$$v(r) \propto \frac{1}{\sqrt{r}} \quad \text{for large } r,$$

but one finds

$$v(r) \simeq \text{const for large } r \quad \Rightarrow \quad \rho(r) \propto \frac{1}{r^2} \quad \text{for large } r$$

Rotation curve of NGC 6503





Refs.: Hubble Space Telescope,
Bertone G., Hooper D., Silk J. *Particle Dark Matter: Evidence, Candidates and Constraints*. arXiv: hep-ph/0404175

Evidence for dark matter on cluster scales

Zwicky 1933: velocities of galaxies in cluster (indirect evidence)

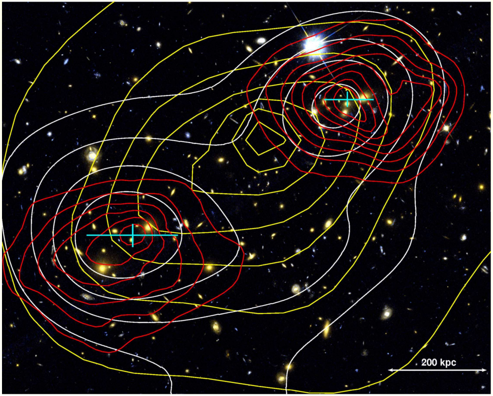
Recently more direct evidence:
Displacement of gas relative to to dark matter

Collisions of clusters: stars, CDM, gas (= dominant baryonic matter)
Stars, CDM interact only graviationally $\Rightarrow$ non-collisional
Hot gas ($\sim 10^8\,\mathrm{K}$) interacts electromagnetically $\Rightarrow$ gets displaced by collision

Measurement:
CDM $\rightarrow$ gravitational lensing
gas $\rightarrow$ X-rays

Bullet cluster

Bullet cluster: Gravitating matter in blue, X-ray emitting matter in red



Cluster MACS J0025.4-1222: Optical image,
mass density countours from gravitational lensing in red,
X-ray brightness in yellow

Evidence for dark matter from CMB

Evidence for dark matter on cosmological scales:

- CMB and its two-point correlation function of temperature fluctuations
- Large scale structure

CMB: last-scattering surface at $t_{\rm rec} \sim 380000\,\mathrm{y} \Rightarrow$
Formation of atoms, universe transparent for primordial photons $\Rightarrow$
imprint of density variations $\Leftrightarrow$ correlations of T_γ fluctuations

overdense region $\Rightarrow$ photon red-shifted
underdense region $\Rightarrow$ photon blue-shifted

Basics of general relativity

Einstein-equations:

$$R_{ik} - \frac{1}{2} g_{ik} R = -8\pi G\, T_{ik} + \Lambda g_{ik}$$

Cosmological principle (isotropy around every point) $\Rightarrow$
Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = g_{ik} dx^i dx^k = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$

scale factor $a(t)$

- $k = 0$: Euclidian space,
- $k = +1$: Riemannian sphere,
- $k = -1$: hyperbolic space.

Basics of general relativity

Good model for the matter content of the universe: *ideal fluid*

$$T_{ik} = (\rho + p) u_i u_k + p g_{ik}$$

Some definitions

Hubble constant: $H(t) \equiv \frac{\dot{a}(t)}{a(t)}$

Total energy density: $\rho_T \equiv \rho + \frac{\Lambda}{8\pi G}$

Critical energy density: $\rho_c \equiv \frac{3H^2}{8\pi G}$

Energy densities in units of the critical energy density: $\Omega_i \equiv \frac{\rho_i}{\rho_c}$

$i = T$ (total), b baryonic, M (non-relativistic matter), Λ (dark energy), ...

Friedmann equation

Ideal fluid + Robertson-Walker metric $\Rightarrow$

Friedmann equation

$$\Omega_T(t) = 1 + \frac{k}{\dot{a}(t)^2}.$$

Universe is spatially flat $\Leftrightarrow k = 0 \Leftrightarrow \Omega_T(t) = 1$.

Photon redshift z and expansion:

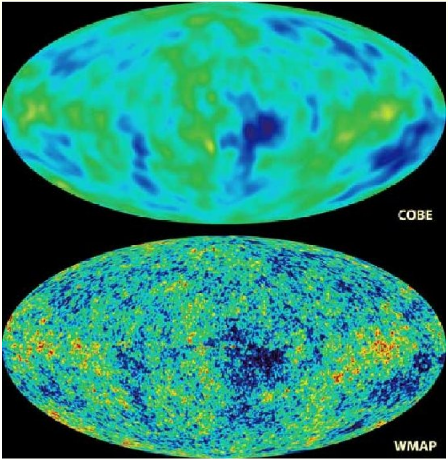
$$1 + z = \frac{\lambda_0}{\lambda} = \frac{a_0}{a}$$

λ = wavelenght at emission, λ_0 = present wavelenght
a = scale factor at time of emission, a_0 = present scale factor

Cosmic microwave background (CMB)

$T_0 =$
$2.725 \pm 0.001\,\mathrm{K}$

COBE, WMAP
measure
$\frac{\delta T(\theta,\phi)}{T_0}$



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CMB: temperature anisotropies

$$\frac{\delta T(\theta,\phi)}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}$$

$a_{00} = 0$, $a_{1m} \to$ dipole anisotropy, carries no cosmological information
Spherical harmonics correspond to angular variations $\Delta\theta \sim \pi/\ell$

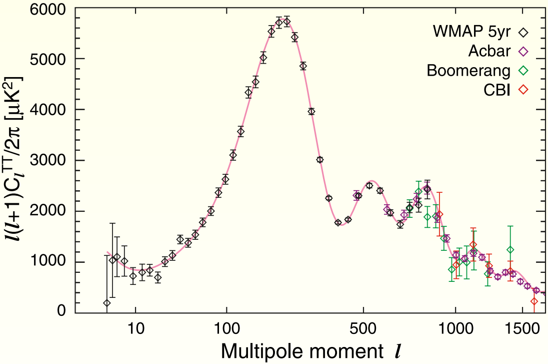
$$C(\theta) \equiv \left\langle \frac{\delta T(\theta_1,\phi_1)}{T_0} \frac{\delta T(\theta_2,\phi_2)}{T_0} \right\rangle_\theta \quad \text{with} \quad \theta = \angle(\vec{n}(\theta_1,\phi_1), \vec{n}(\theta_2,\phi_2))$$

Independent random variables $a_{\ell m}$:

$$\langle a_{\ell m} a_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'} \quad \Rightarrow \quad C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle$$

$$C(\theta) = \sum_{\ell=2}^{\infty} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta) \quad \text{with} \quad C_\ell = \int_{-1}^{1} \mathrm{d}\cos\theta \, P_\ell(\cos\theta) C(\theta)$$

CMB: temperature correlations



Oscillations of baryon - photon plasma on background of CDM

Acoustic peaks: position of first peak $\Rightarrow \Omega_T$, height $\rightarrow \Omega_b$

WMAP data combined with BAO + SN Ia

2dF Galaxy Redshift Survey, Sloan Digital Ska Survey $\Rightarrow$ LSS/BAO
Present day values of H, Ω_i

Observational data (5 years of WMAP (2008))

$$\Omega_b h^2 = 0.0227 \pm 0.0006$$
$$\Omega_{\mathrm{CDM}} h^2 = 0.113 \pm 0.003$$
$$\Omega_\Lambda = 0.726 \pm 0.015$$
$$h = 0.705 \pm 0.013$$

O.Lahav and A.R. Liddle in RPP (2010)

$$h = \frac{H}{100\ \mathrm{km\ s^{-1}\ MPc^{-1}}}.$$

Evidence for cold DM

- CMB
- Large scale structure: CDM $\Rightarrow$ bottom-up formation of structure $\Rightarrow$ voids and filaments in present-day universe

Movies!

From $z \simeq 30$ to present

$z \simeq 30$ corresponds to age of universe $\sim 10^8$ y

WIMPs: Candidates for particle dark matter

WIMPs: Candidates for particle dark matter

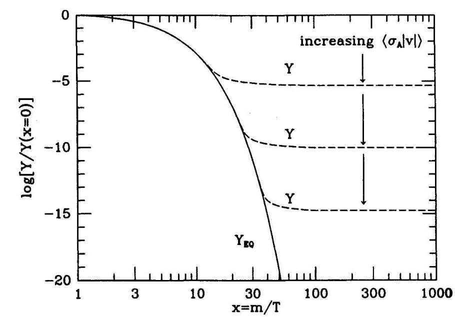
WIMPs = weakly interacting massive particles

Most compelling motivations for electroweak-scale particle dark matter:

- Many extensions of the standard model predict new particles at the electroweak scale and above ($100 \div 1000$ GeV)
- In many extensions of the standard model there are new stable particles, e.g.
  - SUSY with R-Parity (LSP)
  - Extra dimensions (Kaluza-Klein particles)
  - Little Higgs theories (lightest T-Parity odd particle)
  - Inert doublet model
- WIMPs are perfectly suitable for CDM in above mass range: **“WIMP miracle”**

The "WIMP miracle"

1. WIMPs χ initially in thermal equilibrium: $\chi\bar{\chi} \leftrightarrow f\bar{f}$
2. Universe cools: $\chi\bar{\chi} \to f\bar{f}$, $\chi\bar{\chi} \not\leftarrow f\bar{f}$
3. WIMPs freeze out: $\chi\bar{\chi} \not\to f\bar{f}$, $\chi\bar{\chi} \not\leftarrow f\bar{f}$



$\langle \sigma_A |v| \rangle$: thermally averaged total annihilation cross section
($|v|$ = relativ velocity between two WIMPs in their c.m.s.)
Freeze-out temperature $T_F \simeq m_\chi/20 \Rightarrow$ CDM!

The "WIMP miracle"

- Amount of dark matter $\propto \langle \sigma_A |v| \rangle^{-1}$
- Impose a "natural" relation: $\sigma_A = k\alpha^2/m_\chi^2$
- Remarkable coincidence:
  $\Omega_\chi h^2 \sim 0.1$ for $m_\chi \sim 0.1 \div 1\,\mathrm{TeV}$ ($k \sim 0.5 \div 2$)
  σ_A in pb range $\rightarrow$ nor far from typical weak cross section
  WIMP miracle!

Direct and indirect dark WIMP search

Direct and indirect observation of WIMPS

Principles:

- **Direct observation:** elastic WIMP - nucleus scattering
  - **Energies of recoiling nuclei:** phonons - ionization - scintillation
- **Indirect observation:** WIMP anti-WIMP annihilation products
  - WIMPs gravitationally bound in massive objects (galactic halo, galactic center, sun, earth,. . .)
  - photons, anti-protons, positrons, neutrinos, . . .

Annual modulation of direct WIMP signal

Goodman, Witten (1985): **Annual modulation of the scattering rate**

- WIMPs dragged along with rotation of galactic spiral arms
- Local WIMP density $\sim 0.3\,\mathrm{GeV/cm^3}$
- Local velocity of earth with respect to DM:

$$v_E = 220\ \mathrm{km/s}\ \times (1.05 + 0.07\cos(2\pi(t - t_m)))$$

Local movement of solar system $\rightarrow$ vega + earth orbital velocity
Maximal velocity on June 2, minimal at December 2

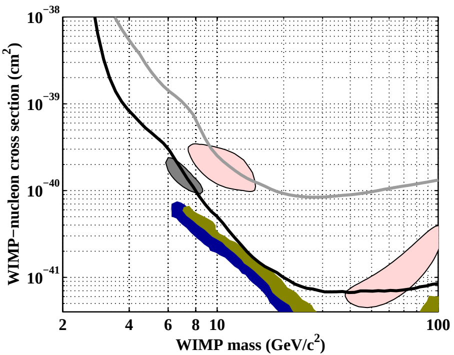
Annual variation of signal at percent level
Seen by DAMA/LIBRA experiment: 250 kg Na I (Tl) cistals
Not confirmed by other experiments!

Other direct detection experiments

- XENON
- CDMS
- CoGeNT
- ZEPLIN
- Edelweiss
- CRESST
- WARP
- COUPP

Cryogenic DM search (CDMS): Ge + Si detectors
Two sites:
Stanford underground facility $\rightarrow$ exclusion plot
Soudan mine: 2 WIMP candidates
(estimated background of 0.9 ± 0.2 events)

Exclusion plot of CDMS



Gray line: Si only, black line: Ge+Si
Pink: DAMA/LIBRA data interpreted by Savage *et al.*
Dark gray: simultaneous CoGeNT+DAMA/LIBRA fit by Hooper *et al.*
Blue+dark yellow: some SUSY model by Bottino *et al.*

Indirect detection experiments

γ-ray experiments:

- Main advantage: γ-rays are not deflected by magnetic fields! $\Rightarrow$ valuable angular information
- On galactic scales the spectrum of γ-rays is not attenuated $\Rightarrow$ observed spectrum on earth is the same as was generated in DM annihilation
- Energy spectrum of γ-rays depends on the type and properties of the annihilating WIMPs $\Rightarrow$ important information on the nature of DM

Antimatter experiments:

- WIMP annihilation in the galactic halo: e^+, $\bar{p}$, ...
- Particles charged $\Rightarrow$ influence of the galactic magnetic field $\Rightarrow$ no angular information
- Cosmic positrons attractive probes: lose majority of energy over typical length scales of kiloparsecs or less
  $\Rightarrow$ positrons sample local DM distribution.

γ-ray experiments

Satellite-based experiments:

- GLAST
- EGRET
- FermiLAT

Principle of ground based γ-ray experiments:

- γ-rays $\longrightarrow$ electromagnetic cascades

$\longrightarrow$ Secondary shower particles produce

$\longrightarrow$ Cerenkov light

Ground based γ-telescopes:

- HESS
- MAGIC
- VERITAS

Antimatter experiments

Examples for antimatter experiments

- HEAT (balloon observatory)
- PAMELA
- AMS-01, AMS-02

The PAMELA experiment

PAMELA is a satellite experiment.

Main specifications:

- Launched on 15 June, 2006
- collecting data since July 2006
- 350-610 km elliptic orbit around earth
- Mission shall last till at least December 2011

Scientific goals:

- Precision studies of the charged cosmic radiation over a wide energy range (100 MeV $\div$ several 100 GeV)
- Primary scientific goal: measurement of the positron and antiproton energy spectrum
- Search for primordial antinuclei

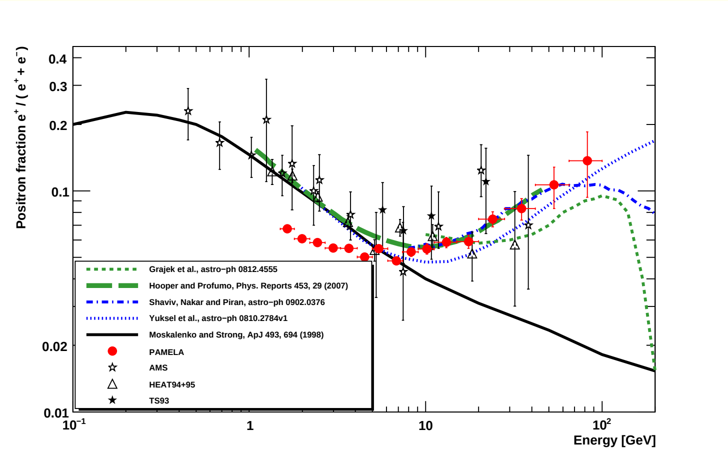
The PAMELA experiment

Low-cutoff orbit + long-term duration misson + specific orbit
$\Rightarrow$ ability for

- detection low-energy particles
- long-term time variations of the radiation intensity
- study the effect of the Earth's magnetic field on the incoming radiation

Interesting finding for DM:
Anomalous positron abundance between 10 GeV and 100 GeV!

The PAMELA experiment



Neutrino telescopes

- AMANDA
- ANTARES
- IceCube

Conclusions

- Cosmic concordance: firm evidence of non-baryonic cold DM
- On galactic and cluster scale: most likely non-baryonic
- Experimental status of WIMPs inconclusive