Dark Matter and Dark Energy components chapter 7

Lecture 4

See also Dark Matter awareness week December 2010
http://www.sissa.it/ap/dmg/index.html
The early universe

chapters 5 to 8


5. The expanding universe
6. Nucleosynthesis and baryogenesis
7. Dark matter and dark energy components
8. Development of structure in early universe

Slides + book http://w3.iuhe.ac.be/~cdeclerc/astroparticles
Overview

- Part 1: Observation of dark matter as gravitational effects
  - Rotation curves galaxies, mass/light ratios in galaxies
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  - Gravitational lensing
  - Bullet cluster

- Part 2: Nature of the dark matter:
  - Baryons and MACHO’s
  - Standard neutrinos
  - Axions

- Part 3: Weakly Interacting Massive Particles (WIMPs)

- Part 4: Experimental WIMP searches

- Part 5: Dark energy
Previously – \( \Lambda \)CDM model

- Universe is flat \( k=0 \)
- Dynamics given by Friedman equation
  \[
  H^2 t^2 = \left( \frac{\dot{R}}{R} t \right)^2 = \frac{8 \pi G N}{3} \rho_{\text{tot}} t
  \]
- Size of universe at given time and today, \( t_0 \)
- Closure parameter relates density to critical density
- Energy density evolves with time, and so does \( H \)

\[
1 + z = \frac{R}{R_0} \frac{t_0}{t}
\]

\[
\Omega t = \frac{\rho t}{\rho_c t}
\]

\[
H^2 t^2 = H_0^2 \left[ \Omega_m t_0 + 1 + z^3 + \Omega_r t_0 + 1 + z^4 + \Omega_\Lambda t_0 + \Omega_k t_0 + 1 + z^2 \right]
\]

\[\Omega_k = 0\]
Energy budget of universe today

• Today only 5% of the matter-energy consists of known particles

• 18% is Cold Dark Matter = new type of particles

• 76% is completely unknown

\[ H^2 t^2 = H_0^2 \left[ \Omega_m t_0 \left( 1 + z \right)^3 + \Omega_r t_0 \left( 1 + z \right)^4 + \Omega_\Lambda t_0 \right] \]

\[ \Omega_{rad} = 10^{-5} \]

\[ \Omega_{matter} = 0.24 \]
Previous lecture : Dark Matter

- **Observation of dark matter** as gravitational effects

- **Nature of dark matter** particles is still unknown
  - Baryons
  - MACHOs = Massive Compact Halo Objects
  - Neutrinos
  - Axions
  - WIMPs = Weakly Interacting Massive Particles

- **Identifying dark matter**:
  direct and indirect detection experiments
Where should we look?

• Search for WIMPs in the *Milky Way halo*
  
  ➢ *Indirect detection*: expect WIMPs from the halo to annihilate with each other to known particles
  
  ➢ *Direct detection*: expect WIMPs from the halo to interact in a detector on Earth
Identify the nature of dark matter with experiments

PART 4: WIMP DETECTION
DIRECT DETECTION EXPERIMENTS
Principle of direct detection

- Earth moves in WIMP ‘wind’ from halo
- Elastic collision of WIMP with nucleus in detector
  \[ \chi + N \rightarrow \chi + N' \]
- Recoil energy
  \[ E_{\text{Rec}} = \frac{v^2}{m_N} \mu^2 (1 - \cos \theta) \leq 50\text{keV} \]
- Velocity of WIMPs \( \sim \) velocity of galactic objects
  \[ v_{\chi} \sim 270\text{ km s}^{-1} \sim 10^{-3}c \]

\[ \mu = \frac{m_{\chi}m_N}{m_{\chi} + m_N} \]
Cross section and event rates

- Event rate depends on density of WIMPs in solar system

\[ R \propto N \frac{\rho_\chi}{m_\chi} \left\langle \sigma_\chi p \right\rangle \]

- Rate depends on number \( N \) of nuclei in target

\[ \rho_\chi \sim 0.3 \text{GeV/cm}^3 \]

- Rate depends on scattering cross section – present upper limit

\[ \sigma_\chi p < 10^{-44} \text{cm}^2 = 10^{-8} \text{pb} \]

Weak interactions!
Direct detection challenges

\[ R \propto N \frac{\rho \chi}{M \chi} \langle \sigma \chi p \rangle \]

- low rate \(\rightarrow\) large detector
- very small signal \(\rightarrow\) low threshold
- large background: protect against cosmic rays, radioactivity, …

WIMP Scattering Rates

- 18 events/100-kg/year \((E_{\text{th}}=5 \text{ keVr})\)
- 8 events/100-kg/year \((E_{\text{th}}=15 \text{ keVr})\)

\[ M_\chi = 100 \text{ GeV}, \sigma_{\chi - p} = 10^{-45} \text{ cm}^2 \]
Annual modulation

• Annual modulations due to movement of solar system in galactic WIMP halo – 30% effect
• Observed by DAMA/LIBRA – not confirmed by other experiments

\[ R \propto N \frac{\rho \chi}{M_{\chi}} \langle \sigma v \rangle \]

\[ v_{\chi} \sim 270 \text{ km s}^{-1} \]

Against the wind in June higher rate

In direction of the wind in December Lower rate
From event rate to cross section

\[ R \propto N \frac{\rho_\chi}{M_\chi} \left\langle \sigma_{\chi p} \right\rangle \]

Some experiments claim to see a signal at this mass and with this cross section.

Other experiments see no signal and put upper limits on the cross section.

Expected cross sections for models with supersymmetry.

XENON100 (2012)
- observed limit (90% CL)
- Expected limit of this run:
  - $\pm 1 \sigma$ expected
  - $\pm 2 \sigma$ expected

DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
ZEPLIN (2009-12)
CDMS (2010/11)
XENON10 (2011)

WIMP-Nucleon Cross Section [cm$^2$]

WIMP Mass [GeV/c$^2$]
INDIRECT DETECTION EXPERIMENTS
Indirect detection of WIMPs

- Search for signals of *annihilation of WIMPs in the Milky Way halo*
- Accumulation near galactic centre or in heavy objects like the Sun or Earth due to gravitational attraction
- Detect the produced antiparticles, gamma rays, neutrinos

\[ \chi \chi \rightarrow q \bar{q}, l \bar{l}, \rightarrow \nu_\mu, \gamma, e^+, \ldots \]

\[ W^\pm, Z, H \]
neutrinos from WIMP annihilations : IceCube

- Neutrinos from WIMP annihilations in the Sun
- Neutrinos from WIMP annihilations in galactic halo, galactic centre, dwarf spheroidal galaxies
- Neutrinos from WIMP annihilations in the centre of the Earth
WIMPs accumulated in the Sun

1. WIMPs are captured

\[ C_{SUN} \propto \frac{\rho \chi \sigma_{\chi N}}{v^3 m_\chi^2} \]

Capture rate

\[ \chi + \chi \rightarrow q\bar{q}, l\bar{l}, \ldots \]
\[ \rightarrow \nu_\mu \]

2. WIMPs annihilate

\[ \Gamma_{ANN} = \frac{1}{2} C_{SUN} \]

Annihilation rate

Detector

\[ \nu \text{ interaction} \]
Search for GeV-TeV neutrinos from Sun

A few 100,000 atmospheric neutrinos per year from northern hemisphere

Max. a few neutrinos per year from WIMPs in the Sun

~10^{11} atmospheric muons per year from southern hemisphere
No excess above known background

Data

Background

Number of events

• No significant signal found
• Rate is compatible with atmospheric background
• Set upper limit on possible neutrino flux and annihilation rate
Combining direct and IceCube searches

\[ \sigma_{SD} \chi p \left[ cm^2 \right] \]

\[ \Gamma_{Ann} \sim C_{SUN} \sim \sigma_{\chi N} \]

IceCube

\[ \chi + \chi \rightarrow W^+ + W^- \]

A selection of SuperSymmetry models
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• **Part 5: Dark energy**
Part 5: Dark Energy

Observations
The nature of Dark Energy

$\Omega^\Lambda$
Energy budget of universe today

- Today only 5% of the matter-energy consists of known particles.
- 18% is Cold Dark Matter = new type of particles.
- 76% is completely unknown.

\[ H^2 = H_0^2 \left[ \Omega_m t_0 + 1 + \frac{z^3}{1 + z^2} + \Omega_r t_0^2 + \Omega_{\Lambda} t_0 \right] \]

- \( \Omega_{rad} = 10^{-5} \)
- \( \Omega_{matter} = 0.24 \)
OBSERVATIONS

SNIa surveys
Link to cosmological parameters
The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".

Photos: Copyright © The Nobel Foundation
SN Ia as standard candles (see lecture 1)

• Supernovae Ia are very bright - very distant SN can be observed

• All have roughly the same luminosity curve which allows to extract the absolute magnitude $M$

• $\rightarrow$ effective magnitudes yield luminosity distance

$$ M = -2.5 \log L + \text{cst} $$

$$ m(z) - M = 5 \log_{10} \left( \frac{D_L}{1 \text{Mpc}} \right) + 25 $$

• Network of telescopes united in

  – Supernova Cosmology Project SCP, (Perlmutter) up to $z=1.4$ – have now data from 500 SN (http://supernova.lbl.gov/)

  – High-z SN search HZSNS (Schmidt & Riess, in 1990’s)
Luminosity distance vs redshift - 1

- SN at redshift $z$ emits light at time $t_E$ – is observed at time $t_0$
- Light observed today travelled during time $(t_0 - t_E)$
- Distance travelled depends on history of expansion
- Proper distance $D_H$ from SN to Earth (lecture 1, horizon distance)

$$D_H \ t_E = R \ t_0 \ \int_{t_E}^{t_0} \frac{c \ dt}{R \ t}$$
$$dt = - \frac{dz}{1 + z \ H}$$

- For flat universe ($k=0$) with negligible radiation content

$$H^2 \ z = H^2(t) = H_0^2 \left[ \Omega_m \ t_0 + \frac{1 + z^3}{t_0} + \Omega_\Lambda \right]$$
Luminosity distance vs redshift - 2

\[ D_H(z) = \int_0^z \frac{c \, dz}{H(z)} = \frac{c}{H_0} \int_0^z \frac{dz}{\Omega_m \, t_0 + 1 + z^3 + \Omega_{\Lambda} \, t_0} \left[ \frac{1}{2} \right] \]

- Luminosity distance

\[ D_L(z) = 1 + z \cdot D_H(z) \]
Luminosity distance $D_L$ vs redshift $z$

- Neglect radiation at low $z$ – different examples

<table>
<thead>
<tr>
<th>Dominant component</th>
<th>$\Omega_m$</th>
<th>$\Omega_\Lambda$</th>
<th>$\Omega_k$</th>
<th>$D_L H_0/c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matter (Einstein–de Sitter universe)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$2(1 + z)[1 - (1 + z)^{-1/2}]$</td>
</tr>
<tr>
<td>Empty universe</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$z \left(1 + \frac{z}{2}\right)$</td>
</tr>
<tr>
<td>Vacuum</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$z(1 + z)$</td>
</tr>
<tr>
<td>Flat, matter + vacuum</td>
<td>0.24</td>
<td>0.76</td>
<td>0</td>
<td>Numerical integration giving best fit to data (see Fig. 7.14)</td>
</tr>
</tbody>
</table>

\[
\sum \Omega_i = \Omega_m + \Omega_\Lambda + \Omega_k = 1
\]
normalise to empty universe

- normalise measurements to empty universe

\[
\Omega_k \ t_0 = 1, \quad \Omega_m \ t_0 = 0, \quad \Omega_\Lambda \ t_0 = 0
\]

\[
D_L \text{ empty} = 1 + z \frac{c}{H_0} \int_0^z \frac{dz}{\left[1 + z^2\right]^{1/2}} = \frac{c}{H_0} \left[ z \left(1 + \frac{z}{2}\right) \right]
\]

- Deceleration parameter is zero – universe is ‘coasting’

\[
q \ t = \frac{\Omega_m \ t}{2} + \Omega_r \ t - \Omega_\Lambda \ t = 0
\]

\[
q \ t = -\frac{\ddot{R} \ R}{\dot{R}^2} = -\left(\frac{\ddot{R}}{R}\right)\left(\frac{R}{\dot{R}}\right)^2
\]

\[\ddot{R} = 0\]
Hubble plot with high z SNIa

Vacuum dominated & flat

Empty universe:
\[ \Omega_m = \Omega_r = 0 \]
\[ \Omega_k = 1 \]
No acceleration
No deceleration

Matter dominated & flat

Far away & dimmer
Influence of cosmological parameters

- Best fit
- Empty universe

\[ D_\text{L} - D_\text{L}^{\text{empty}} \]

Difference between measured \( \log D_\text{L} \) vs \( z \) and expected \( \log D_\text{L} \) vs \( z \) for empty universe

Measurements
Measurements up to $z=1.7$

- **Best fit**
  \[
  \Omega_m \ t_0 = 0.27 \quad \Omega_\Lambda \ t_0 = 0.73
  \]

\[
\log D_L \text{ measured} - \log D_L \text{ empty}
\]

\[
\Delta(m-M) = \Delta D_L
\]

$q(t)<0$ acceleration

$q(t)>0$ deceleration

--- **Best fit**

$\Omega_m = 1.0, \Omega_\Lambda = 0.0$

$(\Omega_m = 0.27, \Omega_\Lambda = 0.73)$

--- **Empty**

$\Omega_\Lambda = 0$

Present

Past
SN observations show acceleration

\[
q(t) = \frac{\Omega_m}{2} t + \Omega_r t - \Omega_\Lambda t
\]

- **Early universe**: universe dominated by matter decelerates due to gravitational collapse:
  \[
  q(t) \sim \Omega_m t > 0 \implies \ddot{R} < 0
  \]

- **Recently**: universe dominated by vacuum energy accelerates
  \[
  q(t) \approx -\Omega_\Lambda t < 0 \implies \ddot{R} > 0
  \]

- Acceleration = zero around \( z=0.5 \) when
  \[
  \frac{\Omega_m}{2} t + \Omega_r t = \Omega_\Lambda t
  \]

- \( \rightarrow \) Switch from deceleration (matter dominated) to acceleration (dark energy dominated)

2012-13

Dark Matter - Dark Energy
Related to cosmological constant?

problems

THE NATURE OF DARK ENERGY
• Observed present-day acceleration means that Dark Energy generates a negative pressure

• Yields gravitational repulsion like vacuum energy

• Equation of state (see lecture 1)

\[ P_{\text{vac}} = -\left( \frac{\delta E}{\delta V} \right)_S = -\rho c^2 = \text{cst} \]

\[ w = \frac{P}{\rho c^2} \]

\[ w = -1 \]

• Fits to SNIa data yield that \( w \) is compatible with vacuum energy

\[ w < -0.85 \quad \text{at 95\% C.L.} \]
Related to cosmological constant $\Lambda$

- In $\Lambda$CDM – $\Omega_\Lambda$ is constant and related to Einsteins cosmological constant

- **If Universe contains constant vacuum energy density related to $\Lambda$** then we set

\[ \Lambda = 8\pi G \rho_{\text{vac}} \]

- In very early Universe there was only vacuum energy

- **At Planck energy scale** gravity becomes strong

- energy and length scales

\[ M_{\text{PL}}^2 = \left( \frac{\hbar c^5}{G} \right)^{\frac{1}{2}} = 1.2 \times 10^{19} \text{GeV} \]

\[ L_{\text{PL}} = \frac{\hbar}{M_{\text{PL}} c} = 1.6 \times 10^{-35} \text{m} \]

- And expected energy density

\[ \rho_{\text{vac}} c^2_{\text{exp}} = \frac{M_{\text{PL}}^2}{L_{\text{PL}}^3} \sim 10^{123} \text{GeV m}^{-3} \]
Cosmological constant problem

- Today vacuum energy density is of order of critical density

$$\rho_{\text{vac}} c^2 \approx 0.76 \times \rho_{\text{crit}} c^2 \approx 5 \text{ GeV } \text{m}^{-3}$$

$$\rho_{\text{vac}} c^2 \exp \sim 10^{123} \text{ GeV } \text{m}^{-3}$$

- Discrepancy of 100 orders of magnitude !!!
- Did vacuum energy evolve with time?
- There is no explanation yet
- need high statistics data:
  - ESA EUCLID mission – launch 2015-20 ([http://www.esa.int](http://www.esa.int))
Alternatives

• Quintessence – 5th force: acceleration is due to potential energy of a dynamical field

\[ \frac{P}{\rho c^2} = \omega_t \]

\[ -1 < \omega_t < -\frac{1}{3} \]

• Vacuum energy density varies with time

• Mechanism analogue to inflation in early universe

• Maybe general relativity works differently at large distances
Observations of SNIa emission show that the universe presently accelerates.

This can be explained by a constant dark vacuum energy contribution which dominates today.

In the $\Lambda$CDM model the dark energy is related to the cosmological constant introduced by Einstein.

There is yet no satisfactory explanation for the observed magnitude of the dark energy.
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