Evidence, Candidates, and Searches for Dark Matter

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Department of Physics, National Tsing Hua University
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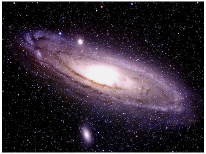
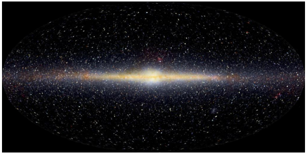
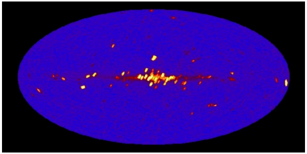
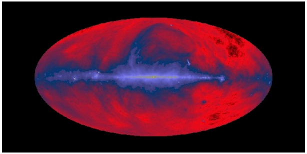
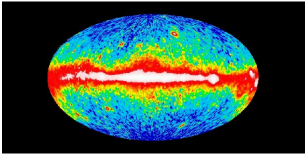
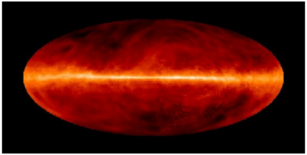
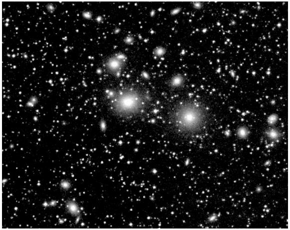
based on arXiv:0707.0488 [astro-ph]

Evidence for Dark Matter

Evidence for Dark Matter

- Clusters of galaxies

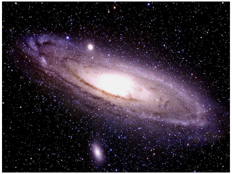


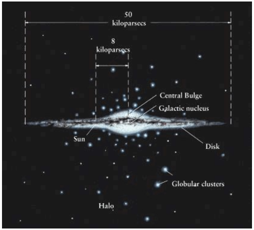
▲ The masses of the clusters of galaxies required to bind these galaxies are much larger than the sum of the luminous masses of the individual galaxies (1930s).

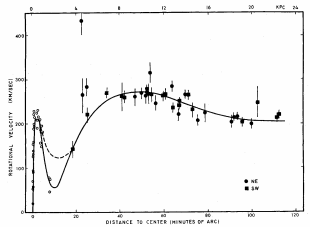
[F. Zwicky (1933); S. Smith (1936)]

Evidence for Dark Matter

- Rotation curves of spiral galaxies





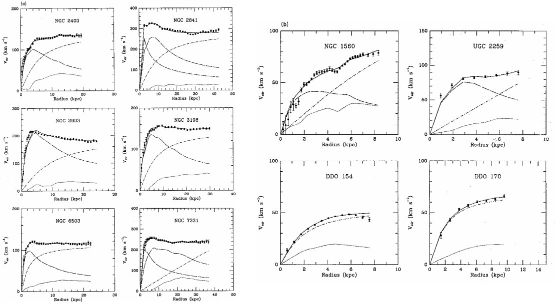


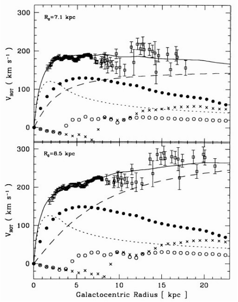
▲ The rotation curves of spiral galaxies are flat or even rising at distances far away from their stellar and gaseous components (1970s).

[V. C. Rubin, W. K. Ford (1970, 1980); S. M. Faber, J. S. Gallagher (1979)]

Evidence for Dark Matter

- Rotation curves of spiral galaxies



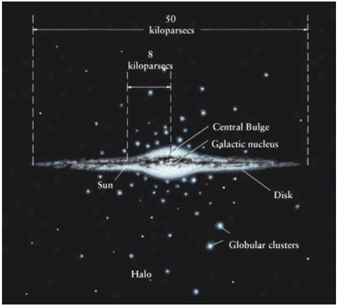


▲ The rotation curves of spiral galaxies are flat or even rising at distances far away from their stellar and gaseous components (1970s).

[K. G. Begeman, A. H. Broeils, R. H. Sanders (1991); R. P. Olling, M. R. Merrifield (2000)]

Evidence for Dark Matter

- Escape velocity from the Milky Way



▲ The escape velocity from the Milky Way is much larger than can be accounted for by the luminous matter in our Galaxy (1990s).

[M. Fich, S. Tremaine (1991)]

Evidence for Dark Matter

- Dark: neither emits nor absorbs electromagnetic radiation.

- The observational evidence for the existence of Dark Matter are gravitational.

  - ▲ The masses of the clusters of galaxies required to bind these galaxies are much larger than the sum of the luminous masses of the individual galaxies (1930s).

  - ▲ The rotation curves of spiral galaxies are flat or even rising at distances far away from their stellar and gaseous components (1970s).

  - ▲ The escape velocity from the Milky Way is much larger than can be accounted for by the luminous matter in our Galaxy (1990s).

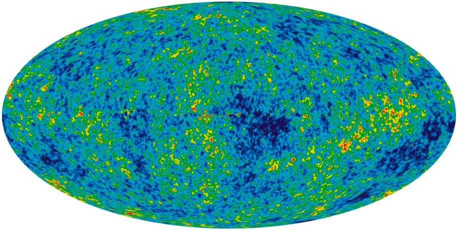
  ➥ The observed luminous objects can not have enough mass to support the observed gravitational effects.

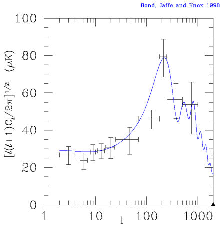
Evidence for Dark Matter

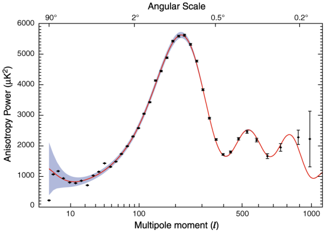
- Astronomical measurements
  - Cosmic microwave background (CMB)
  - Anisotropy of the CMB radiation (CMBR)
  - Age of the Universe
  - Present expansion rate of the Universe, Hubble constant
  - Abundances of the light elements: D, ^{3}He, ^{4}He, ^{7}Li
  - Opacity of the Lyman-α forest toward high-redshift quasars
  - Gas-to-total mass ratio
  - Mass-to-light ratio
  - Peculiar velocities of galaxies
  - Shape of the present power spectrum of density perturbations
  - Supernovae type Ia (SNe Ia) at high-redshift

Evidence for Dark Matter

- Anisotropy of the CMB radiation



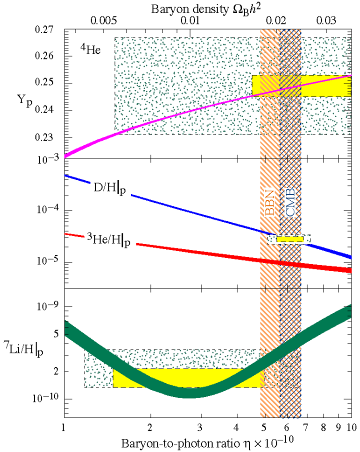




[M. S. Turner, arXiv:astro-ph/9904051 (1999); NASA/WMAP Science Team]

Evidence for Dark Matter

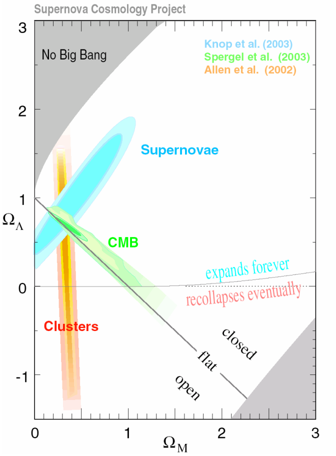
- Abundances of the light elements



[Review of Particle Physics 2006]

Evidence for Dark Matter

- Supernovae type Ia at high-redshift



[Supernova Cosmology Project]

Evidence for Dark Matter

- A large fraction of the mass/energy in our Universe is Dark!
  - Dark Energy: 76%
  - Dark Matter: 20%
  - Ordinary baryonic matter: 4%
  - Luminous matter: $\simeq 1\%$
  - Stars: $0.2\% \sim 0.5\%$
  - CMB photons: 0.0046%
  - Neutrinos: $< 1.4\%$

[Review of Particle Physics 2006]

Candidates for Dark Matter

- Non-luminous, non-baryonic, non-relativistic (cold), collisionless elementary particles which have not yet been discovered.
  - Dark Matter should move non-relativistically in the early Universe in order to allow it to merge to galactic scale structures.
  - So far we can observe (or "feel") the existence of Dark Matter only through its gravitational effects.
  - Dark Matter forms halos with an approximately spherical distribution around galaxies.
  - Dark Matter must be stable on cosmological time scales.
  - Dark Matter must have the right relic cosmological density.

Candidates for Dark Matter

- Cold Dark Matter (CDM)
  - moved non-relativistically at the matter-radiation decoupling time in the early Universe.
  - would form some small galactic scale structures due to their relatively slower velocities.
- Hot Dark Matter (HDM)
  - moved relativistically at the matter-radiation decoupling time in the early Universe.
  - would cover great distances and then form some very large scale structures due to their fast velocities.
- Dark baryons

Candidates for Dark Matter

Special relativity

Dirac → Charge-conjugation symmetry $\Longrightarrow$ Particles $\longleftrightarrow$ Antiparticles

Quantum mechanics

General relativity

SUSY models → Supersymmetry $\Longrightarrow$ Fermions $\longleftrightarrow$ Bosonic superpartners
Bosons $\longleftrightarrow$ Fermionic superpartners

Quantum field theory

Supersymmetry has been considered to solve the hierarchy problem in the Standard Model of particle physics: Why is the electroweak scale ($E_{\rm EW} \simeq \mathcal{O}(100~{\rm GeV})$) so small compared to the other known scales such as the grand unification scale ($E_{\rm GUT} \simeq 10^{16}~{\rm GeV}$) or the Planck scale ($E_{\rm Pl} \simeq 10^{19}~{\rm GeV}$)?

Candidates for Dark Matter

Particles of the Standard Model

SM particles			
Name	Symbol		
up-quarks	$u,\ c,\ t$		
down-quarks	$d,\ s,\ b$		
leptons	$e,\ \mu,\ \tau$		
neutrinos	$\nu_e,\ \nu_\mu,\ \nu_\tau$		
gluons	g		
photon	γ		
Z boson	Z^0		
Higgs boson	h		
W bosons	$W^\pm$		

Candidates for Dark Matter

Particles of typical supersymmetric models

Normal particles		SUSY partners		
Name	Symbol	Name		Symbol
up-quarks	u, c, t	up-squarks		$\tilde{u}_L, \tilde{u}_R, \tilde{c}_L, \tilde{c}_R, \tilde{t}_L, \tilde{t}_R$
down-quarks	d, s, b	down-squarks		$\tilde{d}_L, \tilde{d}_R, \tilde{s}_L, \tilde{s}_R, \tilde{b}_L, \tilde{b}_R$
leptons	e, μ, τ	sleptons		$\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L, \tilde{\mu}_R, \tilde{\tau}_L, \tilde{\tau}_R$
neutrinos	ν_e, ν_μ, ν_τ	sneutrinos		$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
gluons	g	gluinos		$\tilde{g}$
photon	γ	photino $\tilde{\gamma}$	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
Z boson	Z^0	Z-ino $\tilde{Z}$		
light scalar Higgs	h^0	neutral higgsinos $\tilde{h}^0, \tilde{H}^0$		
heavy scalar Higgs	H^0			
pseudoscalar Higgs	A^0			
charged Higgs	$H^\pm$	charged higgsinos $\tilde{H}^\pm$	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
W bosons	$W^\pm$	gauginos, W-inos $\widetilde{W}^\pm$		
graviton	G	gravitino		$\tilde{G}$
axion	a	axino		$\tilde{a}$

Candidates for Dark Matter

- Weakly Interacting Massive Particles (WIMPs) χ
  - arise in supersymmetric extensions of the Standard Model of electroweak interactions.
  - are stable particles and interact with ordinary matter only via weak interactions.
  - have masses typically presumed to be between 10 GeV and a few TeV.

- Neutralinos
  - are linear combinations of photino, Z-ino and neutral higgsinos.
  - The lightest neutralino is the most widely studied candidate for WIMP Dark Matter.
  - has the desired thermal relic density in at least four distinct regions of parameter space.

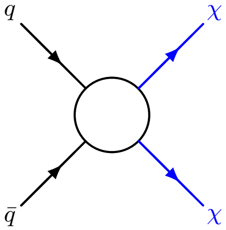
Candidates for Dark Matter

Particles of typical supersymmetric models

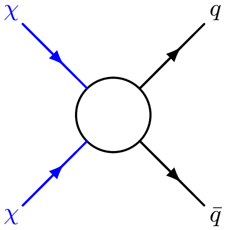
Normal particles		SUSY partners		
Name	Symbol	Name		Symbol
up-quarks	u, c, t	up-squarks		$\tilde{u}_L, \tilde{u}_R, \tilde{c}_L, \tilde{c}_R, \tilde{t}_L, \tilde{t}_R$
down-quarks	d, s, b	down-squarks		$\tilde{d}_L, \tilde{d}_R, \tilde{s}_L, \tilde{s}_R, \tilde{b}_L, \tilde{b}_R$
leptons	e, μ, τ	sleptons		$\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L, \tilde{\mu}_R, \tilde{\tau}_L, \tilde{\tau}_R$
neutrinos	ν_e, ν_μ, ν_τ	sneutrinos		$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
gluons	g	gluinos		$\tilde{g}$
photon	γ	photino $\tilde{\gamma}$	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
Z boson	Z^0	Z-ino $\tilde{Z}$		
light scalar Higgs	h^0	neutral higgsinos $\tilde{h}^0, \tilde{H}^0$		
heavy scalar Higgs	H^0			
pseudoscalar Higgs	A^0			
charged Higgs	$H^\pm$	charged higgsinos $\tilde{H}^\pm$	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
W bosons	$W^\pm$	gauginos, W-inos $\tilde{W}^\pm$		
graviton	G	gravitino		$\tilde{G}$
axion	a	axino		$\tilde{a}$

Dark Matter Searches

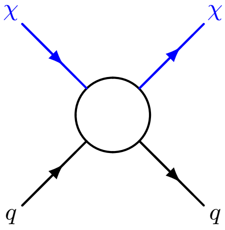
WIMPs should have small, but non-zero couplings to ordinary matter.



Colliders



Indirect Detection



Direct Detection

Direct detection: elastic WIMP-nucleus scattering

- WIMPs could scatter elastically from target nuclei and produce nuclear recoils which deposit energy in the detector.

  - The event rate depends on the WIMP density near the Earth, the WIMP-nucleus cross section, the WIMP mass and the velocity distribution of the incident WIMPs.

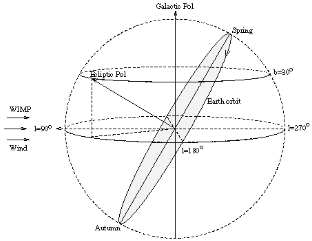
  - In typical SUSY models with neutralino WIMPs, WIMP-nucleus cross section is about $10^{-6} \sim 10^{-4}$ pb, the expected event rate is then at most 1 event/kg/day, or even less than 1 event/ton/yr.

  - The event rate drops approximately exponentially and most events should be with energies less than 40 keV.

  - Typical background noise due to cosmic rays and ambient radioactivity is much larger.

Direct detection: elastic WIMP-nucleus scattering

- Annual modulation of the event rate

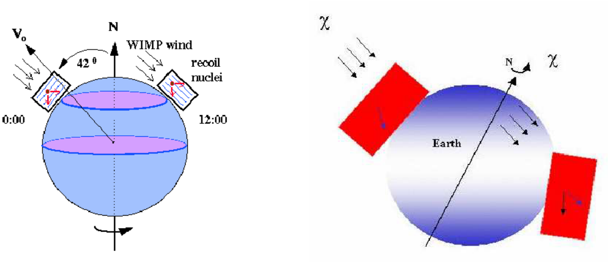


[Y. Ramachers, *Nucl. Phys. Proc. Suppl.* **118**, 341 (2003)]

- ▲ due to the orbital motion of the Earth around the Sun.
- ▲ cosinusoidal function with a one-year period, peaks around June 2nd, and a modulation amplitude $\sim 5\%$.
- ▲ The signal identification should also be performed, since the much larger background can also be subject to modulation!

Direct detection: elastic WIMP-nucleus scattering

- Diurnal modulation of the event rate



[Y. Ramachers (2003); M. de Jesus, *Int. J. Mod. Phys.* **A 19**, 1142 (2004)]

  - ▲ due to the rotation of the Earth.
  - ▲ Directionality of the WIMP wind
    A daily forward/backward asymmetry of the nuclear recoil direction.
  - ▲ Shielding of the detector by the Earth of the incident WIMP flux.

Direct detection: elastic WIMP-nucleus scattering

- Target material dependence
  - Spin-independent (SI) coupling
    a scalar (and/or vector) interaction, the cross section for scalar interaction scales approximately as the square of the mass of the nucleus, so higher mass nuclei, e.g. Ge or Xe, are preferred for this search.
  - Spin-dependent (SD) coupling
    an axial-vector (spin-spin) interaction, the useful target nuclei are ^{19}F and ^{127}I.
  - For nuclei with $A \geq 30$, the scalar interaction almost always dominates the spin interaction.
  - The scattering event rate depends on the atomic mass of the target material directly.

Direct detection: elastic WIMP-nucleus scattering

- Induced signals
  - Ionization (charges)
  - Scintillation (light)
  - Heat (phonons)
  - Quenching factor (nuclear recoil relative efficiency)
    measured recoil energy: keV_{ee},
    true recoil energy: keV_{r}
  - Combinations of two different signals
    a powerful event-by-event rejection method for the background discrimination down to 5 to 10 keV recoil energy.

Direct detection: elastic WIMP-nucleus scattering

- Background and background discrimination
  - Cosmic muons
  - External/Internal natural radioactivity
  - Neutron induced nuclear recoils
  - Multiple-scatter events
  - Electron recoils
  - Surface events
  - Incomplete charge collection

Direct detection: elastic WIMP-nucleus scattering

- Cyrogenic detectors
  - CDMS
    Ge and Si, Soudan Underground Laboratory, Minnesota, USA.
  - CRESST
    $CaWO_4$, Gran Sasso National Laboratory (LNGS), Italy.
  - DAMA/NaI, DAMA/LIBRA
    NaI(Tl), LNGS, Italy.
  - EDELWEISS (EDW)
    Ge, Laboratoire Souterrain de Modane (LSM), France.
  - KIMS
    CsI(Tl), Yangyang Laboratory (Y2L), South Korea.
  - PICO-LON
    NaI(Tl), Oto Cosmo Observatory, Japan.

Direct detection: elastic WIMP-nucleus scattering

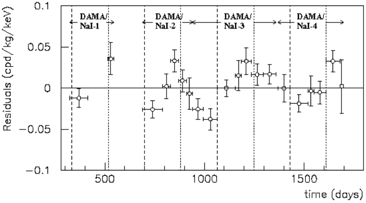
- Liquid noble gas detectors
  - ArDM
    dual-phase (gas-liquid) Ar, CERN, Switzerland.
  - WARP
    dual-phase Ar, LNGS, Italy.
  - XENON
    dual-phase Xe, LNGS, Italy.
  - XMASS
    single-phase Xe, SuperKamiokande, Japan.
  - ZEPLIN
    single-/dual-phase Xe, Boulby Laboratory, UK.

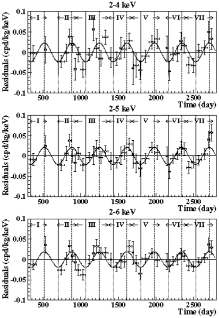
Direct detection: elastic WIMP-nucleus scattering

- Superheated droplet detectors (SDD)
  - COUPP
    CF_3I, C_3F_8, and C_4F_{10}, USA.
  - DRIFT
    low pressure Xe-CS_2 gas mixture TPC (time projection chamber), Boulby Laboratory, UK.
  - MIMAC-He3
    ^{3}He, Laboratoire de Physique Subatomique et de Cosmologie (LPSC), France.
  - PICASSO
    ^{19}F, SNO Underground Laboratory, Canada.
  - SIMPLE
    C_2ClF_5 and CF_3I, Laboratoire Souterrain à Bas Bruit (LSBB), France.

Direct detection: elastic WIMP-nucleus scattering

- Results of the DAMA/NaI experiment



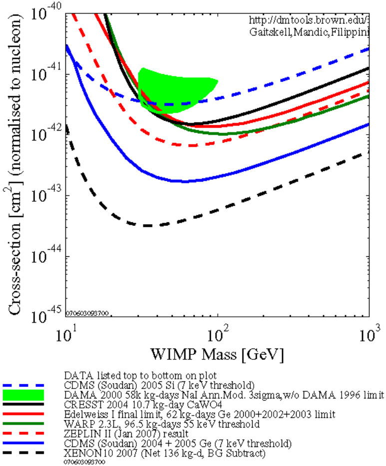


[R. Bernabei *et al.*, `arXiv:astro-ph/0305542`, `arXiv:astro-ph/0311046` (2003)]

- ▲ WIMP mass $m_\chi \simeq 52$ GeV$/c^2$
- ▲ WIMP-proton cross section $\sigma_{\chi \mathrm{p}} \simeq 7.2 \times 10^{-6}$ pb
- ▲ These results have been (almost) excluded!

Direct detection: elastic WIMP-nucleus scattering

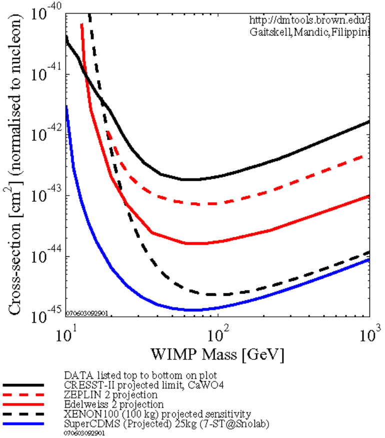
- Exclusion limits on the SI WIMP-nucleon cross section



[http://dmtools.berkeley.edu/limitplots/]

Direct detection: elastic WIMP-nucleus scattering

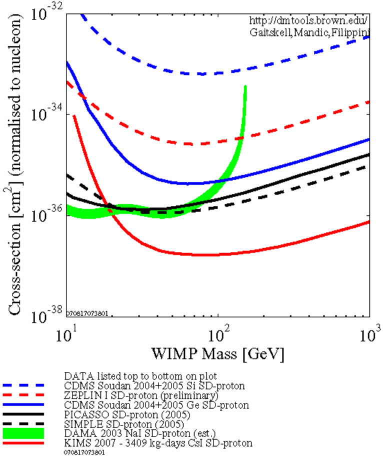
- Projected sensitivities of the SI WIMP-nucleon cross section



[http://dmtools.berkeley.edu/limitplots/]

Direct detection: elastic WIMP-nucleus scattering

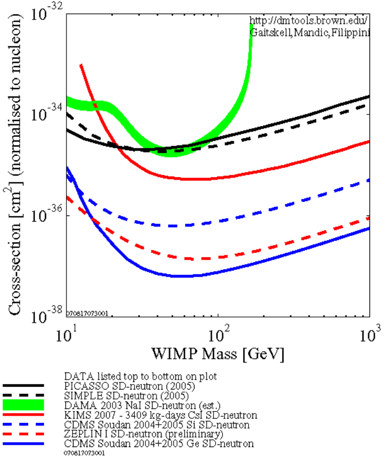
- Exclusion limits on the SD WIMP-proton cross section



[http://dmtools.berkeley.edu/limitplots/]

Direct detection: elastic WIMP-nucleus scattering

- Exclusion limits on the SD WIMP-neutron cross section



[http://dmtools.berkeley.edu/limitplots/]

Summary

- Astronomical observations and measurements show the existence of Dark Matter.
  - Rotation curves of spiral galaxies.
  - Anisotropy of the CMB radiation.

- Models in particle physics offer candidates for Dark Matter.
  - The lightest neutralino in most SUSY models.

- We are searching for Dark Matter by
  - producing new particle(s) at colliders.
  - indirect detection of the products of WIMP annihilations.
  - direct detection through the elastic WIMP-nucleus scattering.

Summary

Thank you very much for your attention.

[http://www.th.physik.uni-bonn.de/th/People/cshan/]