Status and Future of Dark Matter Searches
The “hidden mass” problem becomes a “key problem” of modern cosmology.

- Studies kinetic energies of 8 galaxies of the Coma Cluster
  - finds velocities are much larger than expected (théorème du viriel)
  - apparently Coma cluster contains 200 x more mass than is visible in form of galaxies

Fritz Zwicky, 1937
Doppler shift of star light and of HI distribution

$M_{\text{halo}} > 10 \times (M_{\text{lum}} + M_{\text{gas}})$

For $v_{\text{rot}} = ct$, $M(r)$ must increase linearly with $r$

For large $r$ halos of galaxies start to overlap

Vera Rubin, 1974

$\frac{v_{\text{rot}}^2}{r} = \frac{GM(r)}{r^2}$
DARK MATTER IN OUR MILKY WAY

\[ M(r) = \frac{v_{rot}^2 r}{G} \]

\[ \rho_{DM} \sim 0.3 \, m_p/cm^3 \]

...only 5-10% of matter visible!

1 kpc = 3.259 \times 10^3 Ly
DARK MATTER FURTHER OUT

- Size of Local group 2.2 MLy
- MW & M31 dominate Local Group
- Enormous gravit. pull between the two galaxies
- Invisible mass > 10 x $M_{MW}$
- Local group at fringe of Virgo cluster

- Size of Virgo cluster 50MLy
- Local group pulled towards Virgo cluster
- Invisible mass > 10 x $M_{vis}$

Virgo Cluster pulled towards an invisible “Great Attractor”
VIRGOHI21: A GALAXY OF DARK MATTER! (50 M Ly)

- Visible spectrum
- RF-hydrogen emission

1000 x more Dark Matter than hydrogen!

$M \sim 0.1 \, M_{MW}$

(Feb. 2005)
DARK MATTER AROUND CLUSTERS OF GALAXIES

Abell 2029 (~ 100 Mpc)
- a cluster of thousands of galaxies
- surrounded by gigantic clouds of hot gas
- $T \sim 10^6$ K

Stellar mass 15% of galaxy masses
DM mass 95% of cluster mass
DARK MATTER AT AT LARGER SCALES

Gravitational lensing

- grav. potential $\varphi$ causes time delay of light (Shapiro) → refractive index $n$

$$n = 1 - \frac{2\varphi}{c^2}$$

$$\Delta \Phi = \frac{2}{c^2} \int \nabla \perp n dl = \frac{2}{c^2} \int \nabla \perp \varphi dl$$

- provides evidence of large masses between source and MW

- recently 3D reconstruction of clusters of Dark Matter
High velocity merger of clusters of galaxies 4500 km/s $10^8$K

$M_{\text{dark}} > 49 M_{\text{vis}}$

M. Markewitch et al: HST, Magellan, Chandra (August 2006)
DM & DEVELOPMENT OF STRUCTURE

- BB creates DM + ord. Matter
- DM decouples early
- DM clumps
- Ordinary matter flows in
- Galaxies form
- Galaxies trace DM distribution
DO GALAXIES TRACE THE DM DISTRIBUTION?

COSMOS EVOLUTION SURVEY: (Jan. 2007)

- First large scale 3D reconstruction of DM distribution
- HST, ESO VLT, Magellan, Subaru, XMM Newton

Near infra red HST
Grav. lensing

DM > six times more abundant than ordinary matter
3 slices of red shift

Growing clumpiness of DM & ordinary matter flowing in
SLOAN DIGITAL SKY SURVEY

WHAT IS THE STRUCTURE AT LARGE SCALE

- 2.5m telescope Apache Point
- 120 Megapixels
- 2008 1.6 M galaxies
- 2011 map covers 35% of sky

> 100 Mpc
WHAT KIND OF MATTER CAN EXPLAIN LSS?

Baryonic matter at \( t = 225s \) (BBN) cannot clump to form voids (200MLy) filaments & superclusters

...structures thinned out by Hubble expansion

Assume DM decouples earlier at \( t < t_{BBN} \) and interacts weakly

- longer time to develop structure
- baryons fall into grav. troughs

- galaxy formation \( \text{ok} \)
- Large scale structure \( \text{ok} \)
LSS AND DARK MATTER SPEED

COLD DM
- non relativistic
- non-baryonic (CMB $\frac{\Delta T}{T} \sim 10^{-5}$)
- weak interaction with baryonic matter
- clump on small scale
- smaller clusters first

HOT DM
- non-baryonic (CMB $\frac{\Delta T}{T} \sim 10^{-5}$)
- relativistic
- weak interaction with ord. matter
- e.g. massive $\nu$'s
- before decoupling structures washed out
- superclusters form first
Convincing Evidence for Dark Matter at all Scales!

- Rotation curve
- Velocity flow
- Cluster kinematics
- Hot X-ray gas
- Lensing
- Bullet Cluster
- Large scale structure
- BB nucleosynthesis
- CMB anisotropy

rotation curve
velocity flow
cluster kinematics
hot x-ray gas
lensing
bullet cluster
large scale structure
bb nucleosynthesis
cmb anisotropy
The Concordance Model

\[ \Omega_\Lambda \]

\[ \Omega_M \]

No Big Bang

Supernovae

Clusters

CMB

expands forever

recollapses eventually

75% DARK ENERGY

21% DARK MATTER

4% NORMAL MATTER

Supernova Cosmology Project

Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
WHAT CAN DARK MATTER BE?

- cannot be baryons (CMB and light element abundance different)
- cannot be charged (CMB different)
- no MACHOS (are not there)
- stable or at least metastable (τ > 10 Gyr)
- must be cold or warm to explain structure
- must clump on small scale (dwarf galaxies M/L ~ 1000)
- no sub-keV particles (unless axions or BE scalar condensates)
- self-interaction constrained (σ/m < 1 cm²g⁻¹ by halo structures)

Guidance by theory?

MACHOS: massive compact halo objects
No Lack of Options…

Tim Tait, Dark Matter 2014
Dark Matter Candidates

- Hidden sector particles
- Dark photons
- Sterile neutrinos
- Asymmetric dark matter
- WIMP: Weakly Interacting Massive Particle
The WIMP Miracle Paradigm

After Big Bang: therm. equilibrium

• $\chi \bar{\chi} \rightarrow$ ord. matter $\rightarrow \chi \bar{\chi} \rightarrow \ldots$

• Add Hubble expansion

• $\sigma_{\text{ann}} \rightarrow$ freeze out $\rightarrow$ relic abundance

$$\Omega_x \sim \frac{0.1 pb}{\langle\sigma v\rangle h^2}$$

In order to get $\Omega_\chi \sim 0.2$

$\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

non- rel. speeds (CDM)!

...particles which annihilate with electro-weak scale cross-section and e.w. scale mass (100 GeV)

PRE LHC: WIMP - SUSY - LSP - Neutralino – basta!
The Neutralino: The preferred CDM Candidate

- $\chi_1$ can be lightest stable super symmetric particle – LSP
- Majorana particle
- interaction with matter electro-weak
- can provide closure density
- relic population from early BB

$$\chi_1 = N_{11} \tilde{\gamma} + N_{12} \tilde{Z} + N_{13} \tilde{H}_1^0 + N_{14} \tilde{H}_2^0$$

- “photino”
- “zino”
- “higgsino”
- “higgsino”

$M_\chi \sim 10 \text{ GeV} - 7 \text{ TeV}$

SUSY structure  

cosmology
General Experimental Approaches

DIRECT SEARCHES

INDIRECT SEARCHES

ACCELERATOR SEARCHES

Dark matter scattering

Dark matter annihilation

Dark matter production
Complementarity !!!

- Discovery of cosmological dark matter (WIMP) does not prove yet SUSY etc \(\rightarrow\) accelerator searches
- LHC signal does not yet prove CDM discovery \(\rightarrow\) (in) direct searches
- Candidate must meet astrophysical constraints
Searches for DM Particles

Production in situ at accelerators

Indirect detection via DM annihilation in Sun, Earth, Galaxy, $\nu$, $\gamma$-rays, anti-protons, $e^+$

Direct detection of galactic halo DM in terrestrial laboratories
Interaction rate: \[ R = N_T \cdot v_x \cdot \rho_x \cdot \sigma \]

- $\chi$ in self gravitating halo
- Maxwellian $v$-distr.
- $\rho \sim R^{-2}$
- $\rho_{\text{sun}} \sim 0.3$ GeV / cm$^3$
- annual variation!
- extragalactic streams?
$\sim 10^9$ particles traverse us on earth per second!

- Recoil energies: $< 100$ keV $\sim 10^{-7} E_{\text{kin}}$ (fruit fly)
- Rates: $\ll 0.1$ count /kgd
- Annual rate modulation $\approx 5 - 7\%$

A. Drukier, K. Freese, Spergel PRD 33(86)3495
Recoil Spectra & Rates

\[ \frac{dR}{dE_r} = C \cdot \exp \left( - \frac{E_r}{\langle E_r \rangle} \right) \]

\[ \langle E_r \rangle \approx 2 \cdot \left( \frac{M_N}{1\, \text{GeV}} \right) \cdot \left[ \frac{M_\chi}{M_\chi + M_N} \right]^2 \, [\text{keV}] \]

Info on WIMP mass using different target A!

Motivation for a rich variety of det. techniques!
Detecting WIMPS means fighting Backgrounds!

Neutrons look like WIMPs!

- $\mu$ spallation in det. material,
- in shielding, in surr. rock

Mitigated by going u/g

$U/Th (\alpha, n)$ reactions in rock

Mitigated by shielding

Other backg. $\alpha, \beta, \gamma$!

Mitigated by...

- Radiopurity of det. material
- $\leq 1$ ppb $U/Th$ required
- Shielding
- Active backg. discrimination

0.2 n / ton-y

0.05 n / kg-d

$0.1$ ppb ~ identify 1 person on the earth!
SNOLAB (Sudbury, Canada)

2 km below ground
Protected against cosmic rays
1000 particles / min / m²

Vale: Nickel min

Laboratory

20 min walk
Hand Cleaning!!! ..every pipe, every cable!!!
(Incomplete) Summary of Detection Activities

- Soudan: CDMS, CoGeNT
- Boulby: DRIFT
- Canfranc: ANAIS, ArDM, Rosebud
- Modane: EDELWEISS
- YangYang: KIMS
- Homestake: LUX
- SNOLAB: DEAP/CLEAN, PICASSO, COUPP
- Gran Sasso: CRESST, DAMA/LIBRA, DarkSide, XENON
- Jinping: Panda-X, CDEX
- Kamioka: XMASS
- South Pole: DM-ICE
- ANDES: (planned)
Tremendous Progress over the Years!

P. Cushman et al., arXiv: 1308327
Present & Future WIMP Searches (SI)

~ 1 event kg^{-1}d^{-1}

~ 1 event 1 tonne^{-1}yr^{-1}

~ 1 event 100 tonnes^{-1}yr^{-1}

P. Cushman et al., arXiv: 1308327
Unknnowns:
- Particle type
- Mass,
- Kind of interaction (SI,SD)
CDMS & SuperCDMS (Soudan-Mine)

- Ionisation + phonons + risetime
- 250 g Ge, Si ZIP detectors at 50 mK
- Total mass 4.5 kg Ge, 1.1 kg Si
- $\gamma$ rejection > 99.9998%, 99.75 for $\beta$'s

CDMS Lite

- Luke Neganov amplification
- $\rightarrow E_{th} < 170$ eV
- 0.6 kg sensitivity $< 4$ GeV

SuperCDMS (SNOLAB)

- 92 kg Ge, 11 kg Si
- 7 kg low thresh. Ge/Si

Combined with EDELWEISS $\rightarrow 200$ kg?
LUX  (SURF Homestake)

- Two phase detector
- 300 kg LXe
- Z-position from S1-S2 timing
- 3D imaging (mm resolution)
- $\gamma$, n – bckg. by self shielding
- Beta - gamma rejection > 99.5%

Currently best limits
light WIMPS ruled out

LZ at SURF

- Merger of LUX & ZEPLIN
- 7 tonne (fiducial) Xenon

G2 approval!
Excellent $\gamma$ - discrimination $\sim 10^{-10}$

Acoustic $\alpha$ - recoil discrimination

Superheated Liquids

PICASSO/PICO (SNOLAB)

- PICASSO
  - 2.7 kg C4F10
  - 2L C3F8
  - 37 kg CF2I
  - > 3000 kgd

- PICO 2L
  - 350 kg C3F8

- COUPP 60
Present & Future WIMP Searches (SI)

~ 1 event kg\(^{-1}\)d\(^{-1}\)

~ 1 event 1 tonne\(^{-1}\)yr\(^{-1}\)

~ 1 event 100 tonnes\(^{-1}\)yr\(^{-1}\)

P. Cushman et al., arXiv: 1308327
...and if we hit the Neutrino Limit?
Last Resort: Exploit Directionality!

- Strong day/night modulations expected
- Low pressure TPC’s $\text{CF}_4$, $\text{CS}_2$
- Powerful backg. rejection

However:
- Very low density
- Low sensitivity
- Huge det. volumes required
- $>1000 \text{ m}^3$

But:
- Important to consolidate WIMP signals
- Important follow-up experiment

Maybe the ultimate WIMP experiment?!
DIRECT SEARCHES

INDIRECT SEARCHES

ACCELERATOR SEARCHES

OTHER ASTROPHYSICAL PROBES

χ - CDM?
ICECUBE – ANTARES -MAGIC- HESS - VERITAS....

\( \chi \chi \rightarrow \mu^+ \mu^- \quad \chi \chi \rightarrow \tau^+ \tau^- \)

**Spin Independent Interaction**

**Spin Dependent Interaction**

**IceCube**

**ICE Cube**

**ANTARES**

**MAGIC**

**VERITAS**

\( W^-, Z, b, \tau^-, t, h \ldots \rightarrow e^+, p, D \gamma, \nu \)

**Primary channels**

**Decay products**

\( W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightarrow e^\pm, p, D \gamma, \nu \)
FERMI (LAT) LARGE AREA TELESCOPE

- HE $\gamma$-ray spectrometer
- Launched in 2008

- Nov. 2012 spike at 130 GeV -> gal. center
- Reanalysis: CR induced $\gamma$'s in earth atm. ?
- Larger systematic uncertainty $\rightarrow$ no significant feature (2013)
• $\gamma$ rays peaked at gal. center with 7-12 GeV
• Consistent with thermal relics
• Emission distributed $\rho \sim r^{-1.3}$
• Spectrum not consistent w. msec pulsars and other backgrounds
ALPHA MAGNETIC SPECTROMETER (AMS)

Search for antimatter, $\bar{p}, e^+$, ...
Since 2012 installed on ISS
- E.m. spectrometer 7.5t
- Supraconducting magnet 1m Ø
- Range 500 keV – 1 TeV

- April 4, 2013: excess of $e^+$ announced
- Confirmed 09/2014
- Rate slope decreases > 20 GeV
- implies a heavy DM WIMP of ~ 1 TeV
- or a new mechanism of acceleration in pulsars

in 10 years from now
DIRECT SEARCHES

INDIRECT SEARCHES

ACCELERATOR SEARCHES

OTHER ASTROPHYSICAL PROBES

$\chi - \text{CDM}?$
DIRECT DETECTION & LHC \rightarrow MONO-JETS

- Tagging by $j/\gamma + E_{t}^{\text{miss}}$
- Search for excess
- Suppose contact interaction
- Relate to direct $\sigma_{\text{SI, SD}}$

Impressive limits….

BUT:

...works only well for mediator masses $> \text{few TeV}$
DIRECT SEARCHES

ACCELERATOR SEARCHES

INDIRECT SEARCHES

OTHER ASTROPHYSICAL PROBES

$\chi$ - CDM ?
… and search for other Candidates!

Axions!

- Solution to strong CP problem
- Early U. produced at QCD phase transition/string decays
- Form a Bose condensate
- \( m_a \approx 10^{-6} - 10^{-4} \text{ eV} \)
- extremely weakly interacting
- couple to e.m. field → astrophysics, lab experiments
  - axion DM can resonantly decay into 2 photons
Summary and Caveats

• Rapid progress in field
• Direct detection most promising
• Complementarity (collider, direct, indirect searches)
• Maybe DM not as simple as thought!
• Light WIMPS theoretically well motivated!
• New paradigms (asym DM, hidden sector, axions…)
• Need different techniques & targets
• Lots of astrophysical uncertainties (halo composition)
• ….but discovery possible any time!