SUMMER SCHOOL IN COSMOLOGY AND
ASTROPARTICLE PHYSICS
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Strategies for dark matter detection
Part 4

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Search for Dark Matter

WIMPs: Indirect Detection

Gamma Rays
Positrons
Antiprotons
Neutrinos

Non Thermal Candidates
Deciphering the Nature of Dark Matter

- dark matter
  - baryonic
  - non-baryonic
  - thermal
  - non-thermal
  - Primordial Black Holes
  - MACHOs
  - Mirror branes
  - clumped H$_2$?
  - gas
  - dust

- non-baryonic
  - exotic particles
  - WIMPs
  - Light Neutrinos

- energy
  - $\Lambda$
  - Quintessence
  - Energy in bulk

- dark matter and energy
  - Axions
  - Wimpzillas

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Weakly Interactive Massive Particles

**Particles in thermal equilibrium**

+ decoupling when nonrelativistic

Freeze out when annihilation rate $\approx$ expansion rate

$$\Rightarrow \Omega_{\chi} h^2 = \frac{3 \cdot 10^{-27} \text{cm}^3/\text{s}}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

Cosmology points to $W\&Z$ scale

Inversely standard particle model requires new physics at this scale

(e.g. supersymmetry) $\Rightarrow$ significant amount of dark matter

We have to investigate this convergence!

**Directly fixes annihilation rate in halo**

$\gamma + X, \gamma\gamma, \gamma Z$

$e^+ X$

$\chi \bar{\chi} \rightarrow \bar{p} X, \bar{d} X$

$\nu, \bar{\nu}, \nu X$

**Sensitive to a number of details fixed by Astrophysics**

$\approx \text{density}^2$ i.e. cusp discussion is central

Confinement time

Astrophysics backgrounds (e.g. Supernovae remnants, black holes)
Gamma Rays

2 techniques
< 300 GeV GLAST
> 200 GeV Atmospheric Cerenkov

New Ground and Space Based Telescopes

High Energy Stereoscopic System
H.E.S.S.

CANGAROO III

VERITAS PROTOTYPE

MAGIC

GLAST
Exploring Nature's Highest Energy Processes with the Gamma-ray Large Area Space Telescope
GLAST

Launched 2007. All sky survey ≠ ACT

USA-France-Italy-Sweden-Japan-Germany collaboration, launch 2007

GLAST can search for dark matter signals up to 300 GeV. (It is also likely to detect a few thousand new GeV blazars …)
Atmospheric Cerenkov

Look at cosmic shower.
Select gamma rays by shape

Science 3 Sept 2004
Clumps in halo


Boost factor $B = \frac{n_{\text{clumpy}}^2}{n_{\text{smooth}}^2}$
Gamma Rays

The $\gamma$ ray sky from Dark Matter annihilation
Ted Baltz 2006 based on Taylor/Babul 2005

In SUSY
Annihilation cross section is relatively constant (50% cases maximal: Baltz)
$\neq$ elastic cross section

$$N_\gamma \propto J \frac{\langle \sigma v \rangle}{m} \text{ with } J \propto \int_0^r \rho^2 dr$$

$\Rightarrow$ Many unknown sources at high latitude: Smoking gun
$\Rightarrow$ Map the inhomogeneities of the galaxy
Gamma and Electron spectra

Baltz et al Astro-ph 0602187
For 2 models out of 4 nearly maximal
GLAST Discovery Potential

GLAST: All sky survey ≠ ACT

55-days GLAST in-orbit counts map (E>1GeV)

Optimistic case: 70 counts signal, 43 counts background

Galactic Center

30°

LSP WIMP (SUSY)
GLAST 5-yrs

no. clumps

number of sigma

LCC2

LCC4
Gamma Lines

For $\gamma\gamma$ Line, energy = WIMP mass

For WIMP masses $> M_Z/2$
   can also have $\gamma Z^0$ line

Branching fractions are in the range $10^{-2} - 10^{-4}$


$\Delta E/E=15\%$
Kaluza Klein

Harder spectra

Kaluza-Klein models
L.B., T. Bringmann, M. Eriksson & M. Gustafsson, PRL 2005

Quark fragmentation (e.g., SUSY)

From tau leptons

With internal Bremsstrahlung

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Has Dark Matter been Discovered

511 keV line from galactic center

EGRET Galactic gamma rays (50-70 GeV)

EGRET extragalactic background (500 GeV)

TeV Signal from Galactic Center
511 keV line from Galactic Center

Very difficult to imagine a few MeV particle

**Conventional explanation:** radioactivity of SN 1a; positrons transported from disk to bulge via magnetic fields N. Prantzos, 2005
 Galactic Excess “seen” by EGRET

Wim de Boer ≠ EGRET team

Fit only KNOWN shapes of BG + DMA, i.e. 1 or 2 parameter fit
NO GALACTIC models needed. Propagation of gammas straightforward

If normalization free, only relative point-to-point errors of ≤ 7% important,
not absolute normalization error of 15%. Statistical errors negligible.
Galactic Excess “seen” by EGRET

No what you expect from dark matter

Would point to problem with cosmic ray propagation model

GALPROP: Moskalenko, Strong, Reimer
Galactic Excess “seen” by EGRET

Too large an antiproton flux
Bergström et al Astro-ph 0603632

Solar modulation: 610 MV

$M_\chi = 50.1$ GeV

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Extragalactic EGRET Excess

need steep profile of subhalo
+ fine tuning to get annihilation rate

Wait for GLAST!

GeV "bump"? (Moskalenko, Strong, Reimer, 2004)
TeV signal from the Galactic Center

Fig. 2. Centre of gravity of the VHE signal (triangle), superimposed on a 8.5' by 8.5' Chandra X-ray map (Munro et al. 2003) of the GC. The
TeV signal from Galactic Center

Bergström Marina Del Rey 2006

July 2004: H.E.S.S. data

MAGIC, 2006

Need 10 – 20 TeV particle:
SUSY would need finetuning
(S. Profumo, 2005; see also J. Hall & P. Gondolo, 2006)

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TeV signal from Galactic Center

Interpretation
Dark matter 10-20 TeV
Sagittarius A* (3 $10^6$ Black Hole)
Sag A* East (SN remnant)
Plerionic source
Interaction cosmic rays with Molecular Clouds
Aharonian and Neronov 2005

Note: another source seen on Galactic Center Ridge
Positrons

Spectral features possible
• annihilations to W pairs
• electron / positron line
  Tiny branching ratio in SUSY
  KK particles - dominant mode!

Features can survive diffusion and energy loss in the galaxy

HEAT excess?
PAMELA will sort this out soon

Unfortunately large uncertainty on propagation
Antiprotons and Antideuteron

Currently

Pamela, AMS

Unfortunately large uncertainty on propagation
High Energy Neutrino Detection

Look for Cerenkov light from muon
in ice: AMANDA→ Ice Cube (1km$^3$)
in deep sea: Antares, Nemo, Nestor + Baikal
Neutrinos from Sun/Earth

Capture by sun & earth
Trapped
⇒ annihilation in center

Observable: high energy neutrino
\[
\frac{dn}{dt} = \Gamma_{\text{elast}} n - \Gamma_{\text{ann}} n^2 \Rightarrow \text{in equilibrium } \Gamma_{\text{ann}} n^2 = \Gamma_{\text{elast}} n
\]
⇒ measure elastic scattering

More or less proportional
Sun (also spin dependent)

Earth

Depletion of low velocity WIMPs

SuperCDMS 25kg
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- Thermal
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  - Λ
- Energy
  - Mirror branes
  - Energy in bulk
  - VMO dust
Axions

**Invented to save QCD from strong CP violation**

Current experimental limits are such that if they exist, they have to be cosmologically significant.

Window: $10^{-6}$-$10^{-3}$ eV

**Produced out of equilibrium**

Theoretical discussion if Peccei Quinn symmetry breaking occurs after inflation

$\Rightarrow$ global strings which radiate axions. Technically difficult to compute (Shellard-Sikivie)

Loss mass region may be not favored

**Method of detection**

\[ n_a = 0.62 \text{eV} \left( \frac{10^7 \text{GeV}}{f_a} \right) \]

\[ L_{a\gamma\gamma} = \left( \frac{\alpha_{em}}{2\pi f_a} \right) \bar{E} \bar{B} \times O(1) \]

Tunable cavity: Most suitable for low mass region
Axion limits (Raffelt)
Axions

After 2 pilot experiments missing sensitivity

The US axion experiment
Livermore-MIT-UC Berkeley/LBNL
- U. Florida -U. Chicago/FNAL
- INR Moscow experiment
First data analyzed, published, PRL 98
demonstrated sensitivity to KSVZ axions
Currently scanning wider region

Approved upgrade : DC SQUID amplifiers
Allowing to reach DFZS

Kyoto experiment
Matsuki et al. (Rydberg atoms)
Starting in narrow region but high sensitivity
These experiments reach a cosmological sensitivity!
Potential Problem: one decade out three mass decades allowed

New idea (Adelberger et al.)
Torsion balance matter, magnetic field interaction
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  - ?

- VMO

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Other Candidates

WIMPZILLAs

\[ 10^{12} \text{ GeV/c}^2 \]

Gravitational production toward the end of inflation


Disruption of virtual pairs of particles/antiparticles (vacuum fluctuations) by fast expanding space

Resulting particle density independent of the interaction strength!

Can be electrically charged, strongly interacting etc...

Detection

May be responsible for high energy cosmic rays: fine tuning of decay time?
If strongly interacting, could lead to high energy \( \tau \) neutrino from sun/earth

Many Other Possible Candidates!

Proposed strategy

Investigate whether they are at all allowed by existing limits
Analyze existing data to put constraints
Only embark in major search program if there are at least two independent justifications and the model is generic
Conclusions

Fascinating time in cosmology
Extraordinary progress (CMBR, Large Scale Structure)
But profound mystery
What is the non baryonic dark matter?
What is this mysterious dark energy?
+ unnaturalness of the model which recalls the artificiality of epicycles

From this point of view: 2 scientific priorities
Detect Dark Matter: show that it is not an epicycle
   if we succeed this would be a second Copernican revolution!
   very much linked to fundamental particle physics
   Neutrino mass and see saw mechanism
   Supersymmetry
   May be even baryogenesis
Constrain better the nature of Dark Energy and if possible pin down its properties in the laboratory!
   Likely that we are touching some very fundamental underlying property of quantum gravity
Conclusions 2

Searches for WIMPs are essential

Theoretical convergence of Cosmology
Particle Physics

Also convergence of instrumental approaches:

Complementarity of Colliders
Direct Detection
Indirect Detection

Direct Detection Roadmap

Elastic scattering identifying event by event nuclear recoil

Phonon mediated detectors are leading the pack challenge: extrapolate to 100kg/1 ton

Importance => Development of other large mass technology
liquid Xe or Ar is best candidate but will need some time to master complex phenomenology

Best route to connection to galaxy is low pressure TPC: Particle Physics technology: we should be ready to make \( \approx 10000 \text{ m}^3 \) chambers

Indirect detection could provide important smoking gun

Eventually we might be able to have a full self consistent picture between colliders, direct and indirect detection: nature of Dark Matter