Astrophysical Signatures of Particle Dark Matter

- positrons?
- anti-deuterons?
- γ-rays?

MACS J0025.4-1222

Rene A. Ong (UCLA)  McGill Astrophysics Seminar  26 Oct 2010
Outline

• Astrophysical evidence for dark matter.
• Motivation for a dark matter particle.
• Indirect Detection: $\gamma$, $\nu$, and anti-matter.
• Searching for the anti-deuteron – the why and how.
• GAPS: an anti-deuteron search using a novel technique.
• Future prospects.
Astrophysical Evidence for DM

- Zwicky (1933) saw large velocity dispersion of galaxies in Coma cluster.
- 1960’s & 1970’s: rotation curves of spirals (e.g. Rubin & Ford 1975) → clear evidence.
- Extended to ellipticals, LSB galaxies, MW.

- Galaxy clusters – velocity dispersions & X-ray measurements of hot gas.
- Strong gravitational lensing.
- Weak lensing – galaxy surveys.
- etc. …
Colliding Galaxy Clusters

1E 0657-56 (Bullet Cluster)

Optical (HST, Magellan)
Colliding Galaxy Clusters

1E 0657-56 (Bullet Cluster)

Optical (HST, Magellan) + X-ray (Chandra)
Colliding Galaxy Clusters

1E 0657-56 (Bullet Cluster)

Optical + Lensing (HST, Magellan, ESO WFI)
Colliding Galaxy Clusters

1E 0657-56 (Bullet Cluster)

Optical + Lensing (HST, Magellan, ESO WFI)
More Evidence

MACS J0025.4 -1222
(Chandra, HST)

Abell 520
(Chandra, CFH, Subaru)
Key Pieces from Cosmology

- CMB
- BBN
- Structure Formation (+ SN, Ho, etc.)

\[ \Omega_{M} h^2 = 0.133 \pm 0.006 \]

\[ \Omega_{h}^2 = 0.72 \pm 0.03 \]

- HDM – relativistic, forms large structures that fragment
- CDM – hierarchical, bottom-up

DM is non-baryonic. DM is not hot.
• There are “other” dark matter problems – e.g. in Galactic disk, the solar neighborhood, etc.

• There are problems with CDM, including:
  small scale features not observed – e.g. “cuspy” halos
  “missing satellites” problem …

• Alternatives to CDM include:
  WDM
  self-interacting DM
  decaying DM
  “fuzzy” DM
  strong-interacting DM
  etc. etc.

CDM hypothesis needs testing/verification. This motivates need to detect particle DM.
Many candidates:

- Primordial BH’s – possible, but production mechanism unknown.
- Axions – motivated by particle physics; searches underway.
- Weakly interacting massive particles (WIMPs):

Motivated by “fact” that present relic density is consistent with that expected for a particle that has weak-scale (~TeV) interactions.

i.e. WIMPs ($\chi$) were in thermal equilibrium and then “froze out”:

$$\Omega_\chi h^2 \approx 10^{-27} \, cm^3 s^{-1} / <\sigma_A v>$$

implies a suitable relic density for $\sigma_A$, $m_\chi$ at electroweak scale.

“WIMP Miracle”
Not to be confused with …
Another miracle?

There is the additional motivation from particle physics trying to explain electroweak symmetry breaking (EWSB):

\[ \text{New physics at } \sim \text{ TeV scale} \]

- This has spawned an enormous amount of theoretical activity and many viable candidates for CDM as a new particle, e.g.:
  - Supersymmetry (SUSY): WIMP = LSP
  - Kaluza-Klein theory (UED): WIMP = LKP (U(1) gauge boson)

Important point:
New particle physics models have many parameters, none of which are known. Thus, we have a:

\[ \text{large uncertainty in properties of DM particle (e.g. cross-sections).} \]
\[ \text{difficulty in placing meaningful constraints on theory.} \]

("You’re only allowed one miracle.", L. Rosenberg, 1990.)
Actually, we have no idea!

... and we really need to detect a DM particle.
Complementary Approaches

Produce DM particle in accelerators

Direct DM Detection

LHC at CERN

Xe Detector

Astrophysical Indirect Detection

Annihilation \((\sigma_A)\)
\(\chi\chi \rightarrow \gamma's, \nu's,\) anti-matter

Sextens dwarf galaxy
Why Different Approaches?

LHC could well see evidence for a new particle and measure its mass, but LHC will not:

• tell us whether this particle is stable,
• measure the couplings/interactions of this particle in detail, or
• tell us whether this particle makes up all/any of the DM.

Similarly, direct detectors could well find a dark matter candidate and measure its interaction cross-section, but they will not:

• determine the particle decay modes and couplings or
• study the DM distribution outside the vicinity of Earth.

Indirect detection experiments can provide important information relating to the astrophysics and particle physics of DM. It’s a promising approach … … but significant difficulties (e.g. backgrounds) exist.
Indirect Detection

Telescopes
- VERITAS, HESS, Fermi …
- IceCube

Cosmic Ray Expts
- e⁻: ATIC, Fermi …
- e⁺: Pamela, AMS
- p: HEAT, Pamela, AMS
- d: GAPS

WIMP Annihilation (e.g. GC)
Recent Interesting Results

e⁻/e⁺

ATIC e⁻ “bump”

Fermi e⁻ “non-bump”

WMAP “haze”

Pamela e⁺ excess

(Chang et al., Nature 456, 362 (2008))

(Abdo et al., PRL 102, 181101 (2009))

(Hooper, Finkbeiner & Dobler, PRD 76, 083012 (2007))

(Adriani et al., Nature 458, 607 (2009))

VERITAS Limits
(also Fermi, HESS, & MAGIC)

Fermi GC excess


(Goodenough & Hooper, arXiv:0910.2998v2)

Pamela anti-protons

(Adriani et al., PRL 102, 051101 (2009))
ATIC (2008, 2010)

Balloon expt. (Antarctica)
Tracker, BGO Calorimeter (18 X₀)
• No magnet

Clearly see a “feature”.
Experimental difficulties:
• No particle ID redundancy.
• No direct measurement of background rejection.
Fermi (2009)

Large Area Telescope (LAT)
- Si-strip tracker
- CsI Calorimeter (10 X₀)
- Very detailed shower simulation

Fermi/HESS see possible enhancement in e spectrum, but no “bump”.

Many possible explanations – relatively easy to produce e⁻ astrophysically:
- Local sources (SNRs, pulsars).
- Shrouded sources.
- “Special” location.
- Secondary e⁻ model incorrect (GALPROP).

Dark matter models require
- “Leptophilic” models
- Boost factors of 10² – 10³.

Dark matter hypothesis is shaky.
Anti-proton flux agrees with predictions for secondary particle production.

Satellite instrument (launch 2006).
- Particle ID: TOF, Tracker, Calorimeter
- Magnet (0.45T) for +/- separation.

Excellent anti-proton identification.
From G. Tarle (UCLA DM Meeting 2010):

Local pulsar
(Yuskel, Kistler, & Stanev, PRL 103, 051101 (2009)).

Bkgd Rejection = 10^{-4}
(important because of flux and index of protons)

DM Model
(Grajek et al., PRD 79, 043506 (2009))

Significant enhancement in Positron fraction above 10 GeV.

Real effect? But no independent verification of bkgnd rejection.

Very possibly background or a local source.
# Summary of cosmic-ray probes

<table>
<thead>
<tr>
<th>Particle</th>
<th>Kinematic Range</th>
<th>Experimental Challenges</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻</td>
<td>&gt; 100 GeV</td>
<td>particle ID</td>
<td>e⁻’s are ubiquitous in CR’s !</td>
</tr>
<tr>
<td>e⁺</td>
<td>&gt; 20 GeV</td>
<td>p background</td>
<td>local sources secondary production</td>
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<tr>
<td>p</td>
<td>&gt; 20 GeV</td>
<td>large aperture</td>
<td>secondary production</td>
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<tr>
<td>d</td>
<td>&lt; 2 GeV</td>
<td>low flux</td>
<td>no known backgrounds</td>
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</table>

The unique possibilities of anti-deuterons as a background-free probe of new physics → a big interest from theoretical community, e.g.:

- H. Baer & S. Profumo, Astroparticle Phys. 12, 008 (2005)
- ... and many more.
Why Anti-deuterons?

Unlike anti-protons, which are easy to produce as secondary particles, anti-deuteron secondaries are severely suppressed at low energies.

Primary Component (DM):
\[ \chi \chi \rightarrow \gamma, \bar{p}, \bar{d} \]

Secondary Component:
\[ pA \rightarrow \bar{d} X \text{ [via } p(pn)n] \]
where A = p, He

Anti-deuterons provide extremely clean signature, but low fluxes result in a daunting experimental challenge!

→ New experiment
→ General AntiParticle Spectrometer (GAPS)
GAPS anti-D Sensitivity Reach

• Cosmic anti-D have never been detected. Could be produced by new physics.

• Primary anti-D production:
  Supersymmetry (LSP)
  Kaluza-Klein UED (LKP)
  Warped ED (LZP)
  Primordial BH’s!

• Sub-GeV region essentially background free; the detection of even a single, clean event is important.

• **GAPS will extend sensitivity reach by 2-3 orders of magnitude.**
Synergy with Direct Detection

- Anti-D search provides important complementary capability to direct detection.
- GAPS can probe DM models not easily accessible otherwise.
- Both direct and indirect expts suffer from significant theoretical uncertainty.
- >25 direct detection expts 2 anti-D expts (GAPS, AMS).
GAPS Collaboration

(+ LLNL, Univ. of Latvia)


Collaboration meeting, UCB May 2010
GAPS Concept

GAPS consists of two detectors (acceptance ~2.7 m²sr):

Si(Li) Detector (target and tracker):
- Si(Li) tracker: 13 layers of Si(Li) wafers
- relatively low Z material
- good X-ray resolution
- circular modules segmented into 8 strips → 3D particle tracking
- 270 per layer (total: ~3500)
- timing: ~50 ns
- dual channel electronics
  - 5-200 keV: X-rays (resolution: ~2 keV)
  - 0.1-200 MeV: charged particle

Time of flight and anticoincidence shield:
- plastic scintillator with PMTs surrounds tracker
- track charged particles, dE/dX
- velocity measurement
- anticoincidence for charged particles

Designed for low-energy anti-deuterons:
- no need for a magnet
  (heavy, complicated/expensive … e.g. AMS)

LDBalloon flight planned in 2014
GAPS Detection Technique

- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).

- GAPS introduces an original method. GAPS utilizes the de-excitation sequence of exotic atoms.

![Diagram showing anti-deuteron orbiting around a nucleus]
GAPS Detection Technique

- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).

- Detection principle was verified and high X-ray yield was shown in accelerator tests (KEK antiproton beam, '04 - '05).

1. Once $\bar{D}$ is slowed down and stopped in the target,
2. an excited exotic atom is formed,
3. which deexcites with emitting X-rays,
4. and annihilates with producing a pion shower.

- Atomic Transitions

  - Auger e$^-$
  - Refilling e$^-$
  - Ladder Deexcitations $\Delta n=1$, $\Delta l=1$

  $$E_\gamma = (zZ)^2 M R^2 \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

- Nuclear Annihilation
Main Challenges for GAPS

- Basic detection technique has been established, but the difficulty is to translate to a full-scale instrument.
  - Large scale Si(Li) production at reasonable cost.
  - Building a hermetic detector (i.e. no cracks, etc.).
- Rare-event detector → backgrounds need to be fully modeled and understood.
- A prototype / test experiment is essential: pGAPS (2011).
- Additional note: there is significant uncertainty in anti-D flux estimation arising from:
  - Dark matter halo profile.
  - Modeling the nuclear reactions (coalescence model).
  - Propagation of anti-D through Galaxy to Earth.
  (last item is believed to give largest uncertainty).
Backgrounds

GAPS needs very reliable particle identification:

- Identification uses:
  - TOF velocity and tracks
  - depth in tracker
  - X-rays
  - pions from annihilation

- Important background sources for anti-deuteron events:
  - anti-protons
  - protons, electrons, neutrons in coincidence with cosmic X-rays
  - atmospheric production of antideuterons
  - etc...

Very detailed Monte-Carlo simulation is required.
GAPS Timeline

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Prototype Experiment

Prototype GAPS (pGAPS) goals:

- demonstrate stable, low noise operation of components at float altitude and ambient pressure.
- demonstrate the Si(Li) cooling approach and verify thermal model.
- measure incoherent background level in a flight-like configuration.

2011 scheduled flight from Taiki, Japan
Si(Li) Tracker

- 7 commercial Semikon detectors.
- 2 homemade detectors (test for the bGAPS fabrication).
- Energy resolution < 3 keV @ 60keV.
- Operation at ambient pressure. (8mbar).
- Cooling system delivers: -35°C.

Semikon: N+: Lithium contact
P+: Boron implanted (strips)

Homemade: N+: Lithium contact (strips)
Au contact with shallow well
Si(Li) Detectors

- Performance check in a vacuum chamber.
  - Energy resolution $\Delta E: < 3\text{keV}$.
  - Pre-amplifier
    individual read out for each strip
    with dual E range (for X-ray and $\pi$).
  - Surface coating -operation in vacuum.
  - SEMIKON-made vs. home-made.

- Si(Li) fabrication.
  - In-house, mass fabrication.
Time-of-Flight System

- 3 planes of TOF.
  - 1 plane consists of $3 \times 3$ crossed panels.
  - 1 panel has 2 PMTs.
  - = 18 panels and 36 PMTs
- 3mm scintillator from Eljen (EJ-200) or Bicron (BC-408).
- Hamamatsu R-7600 PMT (UBA).
- timing resolution: $< 400 \text{ps}$
- charge resolution: $< 0.30 \text{e}$
- MOP value: ~15 photo electrons
- angular resolution: $8^\circ$
Simulations

**cosmic antideuterons**

**atmospheric simulation**

**detector simulation**

**exotic atomic physics**

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**Atmospheric and geomagnetic simulations with PLANETOCOSMICS based on GEANT 4.9.2**

- Geomagnetic simulations as a function of position and direction.
- Atmospheric fluxes are in good agreement with measurements.

**Instrument simulation with GEANT, ROOT output format:**

- Electromagnetic, hadronic, optical physics are completed.
- Basic components are implemented, frames/structures must be added.
- Ion and exotic physics are under development.

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More details at Geant4 Space Users Workshop 2010, Seattle
Taiki Aerospace Research Field (TARF)
Taiki Aerospace Research Field (TARF)

- Airstrip (L 1,000m)
- Sliding Launcher on Rails (L 460m)
- Meteorological Equipments
- Handling Area
- Balloon Operation Building (BOB)
- Hangar (W30m, H35m, L83m)
- Facilities for Aircraft Operations

Pacific Ocean
Future Prospects

GAPS Program:
- Prototype instrument to be flown in 2011 from Taiki.
- Plan for LDB instrument in 2014/15. Cost ~$6-8M.
- ULDB (300 day) flights, when available, would improve sensitivity reach.
- (Possible future satellite instrument).

Alpha Magnetic Spectrometer (AMS-2)
- AMS-I had space shuttle flight in 1999. AMS-II, a much more sophisticated detector, was scheduled for deployment on ISS in 2005, but postponed numerous times.
- 2010: failure of cooling system forced delay, replacement of SC magnet by conventional magnet. Impact ??
- AMS-II scheduled for (last) shuttle flight in February 2011.
- Overall cost ~ $1.5B ??

Other future missions
Space: CALET (e)
Balloon: CREST(e), PEBS (e⁺, e⁻, p)
Main science goal: anti-HE search.
Extend range of positron, anti-proton measurements.
anti-deuteron search.
# anti-D vs Mass:  
(generic new physics model, tt channel)  

Mass reach of experiments:  

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\bar{q}q$</th>
<th>$\bar{t}t$</th>
<th>$h^0h^0$</th>
<th>$gg$</th>
<th>$W^+W^-$</th>
<th>$N_{\text{crit}}$</th>
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<tr>
<td>AMS-02 high (3\sigma)</td>
<td>50</td>
<td>&lt; $m_t$</td>
<td>&lt; $m_h$</td>
<td>100</td>
<td>&lt; $m_W$</td>
<td>3</td>
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<tr>
<td>AMS-02 low (3\sigma)</td>
<td>100</td>
<td>&lt; $m_t$</td>
<td>&lt; $m_h$</td>
<td>200</td>
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<td>GAPS (LDB) (3\sigma)</td>
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<td>200</td>
<td>140</td>
<td>300</td>
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<tr>
<td>GAPS (ULDB) (3\sigma)</td>
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<td>400</td>
<td>250</td>
<td>500</td>
<td>160</td>
<td>2</td>
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<tr>
<td>GAPS (SAT) (3\sigma)</td>
<td>500</td>
<td>700</td>
<td>500</td>
<td>900</td>
<td>240</td>
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Note: assumes “med” propagation parameters & background-free.
Summary

- Gravitational evidence for DM is very strong. The majority of DM is non-baryonic and is not hot.

- Particle DM has motivation from astrophysics & particle physics. WIMP CDM is a cool idea… it might even be right.

- Indirect detection is promising; it is able to directly test the particle hypothesis and is complementary to other methods.

- Anti-deuterons are a unique probe of DM, but as interesting is the question of whether they even exist in the cosmic rays.

- GAPS is a new balloon instrument using the exotic atom technique to search for anti-deuterons.
  Prototype flight scheduled for 2011.
  Science flight proposed for 2014.

“Great scientific discoveries have been made by men seeking to verify quite erroneous theories about the nature of things,” Aldous Huxley, 1929.