THE GRAMS PROJECT
DUAL MEV GAMMA-RAY AND DARK MATTER OBSERVATORY

TSUGUO ARAMAKI, SLAC
OUTLINE

Dark Matter Search with Antimatter
- Current status and recent results of indirect dark matter search
- Why is antimatter survey important?
- Antimatter-based dark matter search with GAPS and GRAMS

MeV Gamma-Ray Observations
- Current status of MeV gamma-ray observations
- Why are MeV gamma-ray observations important?
- MeV gamma-ray observations with GRAMS

GRAMS Current Status and Future Prospects
- R&D Program
- Application to other fields

Summary

Accepted in Astroparticle Physics
Aramaki et al., 2019
DARK MATTER IN ASTROPHYSICAL PHENOMENA

EVIDENCE FOR DARK MATTER

GALAXY CLUSTERS

ZWICKY IN 1930S COMA CLUSTER

GALAXIES MOVING TOO FAST!

INVISIBLE/MISSING MASS FOR HIGH VELOCITY

GRAVITATIONAL LENSING

IMAGE OF DISTANT OBJECT

DISTANT OBJECT

GALAXY IN A CLUSTER

IMAGE OF DISTANT OBJECT

INVISIBLE/MISSING MASS FOR DISTORTED FIELD

INVISIBLE/MISSING MASS = DARK MATTER
**COMPOSITION OF THE UNIVERSE**

- **Atoms**: 5%
- **Dark Matter**: 27%
- **Dark Energy**: 68%

**COSMIC MICROWAVE BACKGROUND**

**SNAPSHOT OF THE EARLY UNIVERSE**
when electrons and protons were recombined

**NO DM, NO LIFE.**

**PLANCK**

**TEMPERATURE FLUCTUATION PROVIDES COMPOSITION/EVOLUTION OF THE UNIVERSE**

**27% OF OUR UNIVERSE IS DARK MATTER (DM)**

Large scale structure and galaxy clusters were created by dark matter density fluctuation in early universe
ASTROPHYSICAL PHENOMENA INDICATE THAT DM SHOULD BE:

1) **LONG LIFETIME**
   - Stable particle on galactic time scale
   - Otherwise DM wouldn't be seen in Astrophysical phenomena

2) **VERY SMALL INTERACTION WITH NORMAL MATTER**
   - Or else DM would have been easily detected long time ago

3) **NON RELATIVISTIC (SLOW)**
   - Otherwise there would be lower density fluctuation in the early universe and less large scale structures in the present

VARIOUS DM MODELS ARE PROPOSED TO EXPLAIN ASTROPHYSICAL PHENOMENA
**POPULAR DARK MATTER CANDIDATES (m>10 GeV)**

WEAKLY INTERACTING MASSIVE PARTICLE = WIMP (> 10 GeV)

(I) THERMAL (CHEMICAL) EQUILIBRIUM

IN EARLY UNIVERSE

<table>
<thead>
<tr>
<th>DM</th>
<th>SM</th>
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<td>DM</td>
<td>SM</td>
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SM = Standard Model Particle
DM = Dark Matter Particle

MIXED IN HOT SOUP

(II) UNIVERSE EXPANDED AND COOLED DOWN

<table>
<thead>
<tr>
<th>LEFTOVER</th>
<th>DM</th>
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<td>DM</td>
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ISOLATED THEN DM IS FROZEN OUT

Larger the cross-section = Less Relic DM
Smaller the cross-section = More Relic DM

FREEZE-OUT

RELIC ABUNDANCE (LEFTOVER)

WIMP weak-scale interaction cross-section coincidentally gives right dark matter relic abundance seen in astrophysical phenomena

NO SIGNS OF DETECTION IN DM SEARCH → MORE FOCUS ON LOW-MASS DM
**DIRECT DM SEARCH**
- DM interaction inside the detector
- Measure scintillation, charge, phonon
- Underground lab to minimize cosmic-rays

**COLLIDER SEARCH**
- Artificially produce DM particles
- Measure missing energy/momentum
- Mono-X search to trigger events

**INDIRECT DM SEARCH**
- Measure DM annihilation/decay products

**COMPLEMENTARY SEARCHES ARE CRUCIAL TO ILLUMINATE THE NATURE OF DM**
INDIRECT DARK MATTER SEARCH

MEASURE DM ANNIHILATION/DECAY PRODUCTS

DM → q, h, W, e⁺, γ, ν, p, d, n...

POSITRON: AMS-02, PAMELA, DAMPE...
GAMMA RAY: FERMI-LAT, VERITAS, CTA, GRAMS...
NEUTRINO: ICECUBE, ANTARES...

ANTIPROTON: AMS-02, PAMELA, BESS, GAPS, GRAMS
ANTIDEUTERON: AMS-02, BESS, GAPS, GRAMS
ANTIHELIUM: AMS-02, GRAMS

COMPLEMENTARY SEARCHES WITH DIFFERENT DETECTION METHODS AND BACKGROUND MODELS ARE CRUCIAL TO VALIDATE DM SIGNATURES
Recent Results from Fermi-LAT

Launched in June 2008, targeting 20MeV - 300GeV gamma-rays

Possible DM signatures from Galactic Center Region (GCE)
Inconsistent with dwarf spheroidal galaxy (dSph) observations
(recent observations for new dSphs show some small excess)

Difficult to verify DM signatures due to mimic signal from background
Need a new approach/experiment to validate the results

Fermi Galactic Center Excess (GCE)
~50GeV DM or astrophysical objects?
Launched in May 2011, targeting cosmic-rays including antiparticles

Possible DM detection in antiproton measurements
Possible detection of antiheliums and antideuterons

Antiproton excess: ~50GeV DM (consistent with Fermi GCE) or cosmic-ray interaction?
Antihelium detection:
  ▶ If from DM, a large excess should be seen in the antiproton/antideuteron fluxes?
  ▶ Antimatter clouds in our galaxy?

NEED A NEW APPROACH, EXPERIMENT TO VALIDATE THE RESULTS
WHY ANTIDEUTERONS?

BACKGROUND-FREE DM SEARCH AT LOW-ENERGY

Antideuteron Flux \([\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} (\text{GeV/n})^{-1}]\)

- GAPS
- AMS-02
- AMS-02
- BESS upper limit
- DM, \(m_X = 30\text{GeV}\)
- background

\[\sim 400x\]

LSP: Donato et al., 2008
BKG: Ibarra et al., 2013

Kinetic Energy per Nucleon \([\text{GeV/n}]\)

0.1 1 10 100

GAPS FIRST SCIENCE FLIGHT IS SCHEDULED FROM ANTARCTIC IN 2021
GRAMS: NEXT GENERATION EXPERIMENT

PRIMARY FLUX
DM ANNIHILATION/DECAY

DM
q,h,W…
\(\bar{\nu}\)

HADRONIZATION PROCESS
COALESCEENCE PROCESS \((P_C)\)

SECONDARY FLUX
COSMIC RAY INTERACTION

\(p (\text{CR}) + H (\text{ISM}) \rightarrow p + H + p + n + \bar{p} + \bar{n}\)
GAPS/GRAMS DETECTION CONCEPT

MEASURE ATOMIC X-RAYS AND ANNihilation PRODUCTS

Plastic Scintillators, TOF (time-of-flight)

A time of flight (TOF) system tags candidate events and records velocity

The antiparticle slows down & stops, forming an excited exotic atom

De-excitation X-rays provide signature

Annihilation products provide additional background suppression

\[ E_f = (zz')^2 \frac{M^*}{m_e} R_H \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \]

Aramaki, et al., 2013

Concept proven with accelerator beam test
X-ray yields measured with different targets
Cascade model developed to predict X-ray yields

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Annihilation products provide additional background suppression

\[ \pi^- \pi^+ \]

\[ \pi^- \pi^+ \]
**GAPS/GRAMS ANTIDEUTERON IDENTIFICATION TECHNIQUE**

**CR p, e± REJECTION: ANTIPROTON AND ANTIDEUTERON SELECTION**

Select **slow particles** with TOF

Simultaneous detection of secondary/annihilation products (pions/protons)
- Slow CR p and e± **may not be able to produce secondary particles**

**ANTIDEUTERON IDENTIFICATION FROM ANTIPROTONS**

- **atomic X-rays** from exotic atom
  - different energy
- **pion/proton multiplicity**
  - more for antideuterons
- **stopping range (depth sensing)**
  - antideuterons go deeper
- **dE/dX** energy deposit in layers
  - more for antideuterons

**EXPECTED BACKGROUND/MIMIC EVENTS ~0.01**
**GAPS DETECTOR**

**Si(Li) DETECTOR:** 4 inch, 2.5mm thick wafer
- 10 layers, about 140 Si(Li) detectors/layer
- Segmented into 8 strips
  > 3D particle tracking
- Energy/timing resolution: 4 keV, ~100 ns
- Operation temperature: -40°C
  cooled with oscillating heat pipe (OHP)
- Dual channel electronics
  - 20–80 keV: X-rays
  - 0.1–50 MeV: charged particles

**TOF PLASTIC SCINTILLATORS:** 18cm x 1.6m x 5mm
- Identify incoming charged particles
- 1m separation between inner/outer TOF
- Timing resolution: 0.5ns, SiPMs on each end

**WELL-STUDIED, WIDELY-USED Si(Li) AND PLASTIC SCINTILLATORS SUCCESSFULLY DEMONSTRATED THE PERFORMANCE IN THE ENGINEERING FLIGHT**
**LArTPC DETECTOR SURROUNDED BY PLASTIC SCINTILLATORS**

**LArTPC MEASURES SCINTILLATION LIGHT AND IONIZATION ELECTRONS**

- Plastic Scintillators: **TOF** – measure velocity and incoming angle
- **LArTPC**: Calorimeter and particle tracker
  - Scintillation light at **SiPMs** to trigger events
  - Wires/pads on anode plane \((X, Y)\), drift time \((Z)\) to provide a **3D image/track**
  - Well-studied, widely-used in large-scale DM/neutrino experiments

Scintillation light localized by segmentation to reduce coincident background
GRAMS SENSITIVITY IN DM PARAMETER SPACE

STRONG TENSIONS WITH FERMI GCE/DSPHS AND AMS-02

GRAMS COULD FULLY INVESTIGATE FERMI GCE AND AMS-02 ANTIPROTON EXCESS
CURRENTLY EVALUATING GRAMS ANTIHELIUM SENSITIVITY
MEV GAMMA-RAY OBSERVATION
CURRENT STATUS OF MEV GAMMA-RAY OBSERVATIONS

GAMMA-RAYS IN MEV REGION POORLY EXPLORED = “MEV GAP”

Takahashi et al., 2013
**ASTROPHYSICAL OBJECTS**
- Neutron stars: high matter density
- Magnetars: strong magnetic field
- AGNs/Blazars: powerful jets
- Cosmic MeV gamma-ray background

**GAMMA-RAY LINE STUDY**
- Positron annihilation: 511 keV
- Nuclear lies are typically in ~MeV
- Radioactive isotopes provide physical condition during nucleosynthesis
  - Core-collapse SNe: $^{26}$Al (1809keV), $^{60}$Fe (1173keV, 1333keV), $^{44}$Ti (1157keV)
  - Thermonuclear SNe: $^{56}$Co (847keV)
  - Neutron capture: $^2$H (2223keV)
  - Cosmic-ray interactions: $^{12}$C* (4438keV)

**MULTI-MESSENGER ASTRONOMY**
- EM counterparts of NS-NS mergers
- r-process in neutron star mergers/remnants

**DARK MATTER SEARCH**
- MeV gamma rays from DM annihilation
Why is it difficult to measure MeV Gamma-rays?

- Compton scattering dominates in the MeV energy region
- Both energy & position resolutions need to be good for event reconstruction
- Challenging to have a large-scale detector

\[
E = E_1 + E_2
\]

\[
\cos \theta = 1 - m_ec^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)
\]
PREVIOUS EXPERIMENTS: COMPTEL AND COSI

COMPTEL
(The Imaging Compton Telescope)
- launched into space in 1991
- installed on Compton Gamma-Ray Observatory
- energy range: 0.75 - 30 MeV
- spacial resolution: ~ 40cm³
- Detected ~30 sources
- 12 HPGe crystals (2x2x3), double-sided stripped
- energy range: 0.2 - 5 MeV
- spacial resolution: ~ 2mm³
- 1st balloon flight from Antarctica in 2014
- 2nd flight from New Zealand in 2016

COSI
(The Compton Spectrometer and Imager)
- Liquid Scintillator
- Nal Crystal
- ~1.6m
- Z. Andreas
LArTPC DETECTORS HAVE BEEN WELL-STUDIED AND WIDELY-USED FOR LARGE-SCALE NEUTRINO/DARK MATTER SEARCH EXPERIMENTS

3D particle tracking in LArTPC
- Measure both scintillation light and ionization electrons
- Scintillation light is detected in PMTs
- Ionization electrons drift and are collected in anode wire planes

2 paths for scintillation light

Excitation → Excited Molecule

Ionization → Ionized Molecule

e⁻ → Recombination

Ar → Ar²⁺ → Ar²⁺

~6ns

~1600ns

Credit: Bo Yu
**Plastic Scintillators**: Veto incoming charged particles

**LArTPC**: Compton camera and calorimeter (for pair-production)

- Scintillation light at **SiPMs** to trigger events
- Wires/pads on anode plane (X, Y), drift time (Z) to provide a 3D image/track

**Signal localized by segmentation to reduce coincident background**

**Neutron events can be separated based on the pulse shape**
One Compton Scattering
+ Photoabsorption

Compton Circle

\[ E = E_1 + E_2 \]
\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \]

Two Compton Scatterings
+ Photoabsorption

Compton Circle

\[ E = E_1 + E_2 + E_3 \]
\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2 + E_3} - \frac{1}{E_1 + E_2 + E_3} \right) \]
\[ \cos \theta' = 1 - m_e c^2 \left( \frac{1}{E_3} - \frac{1}{E_2 + E_3} \right) \]
\[ E_3' = -\frac{E_2}{2} + \sqrt{\frac{E_2^2}{4} + \frac{E_2 m_e c^2}{1 - \cos \theta'}} \]

Three Compton Scatterings
+ Escaping Photon

Compton Circle

\[ E = E_1 + E_2 + E_3' \]
\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2 + E_3'} - \frac{1}{E_1 + E_2 + E_3'} \right) \]
**LArTPC vs. Semiconductor Detector**

<table>
<thead>
<tr>
<th></th>
<th>LArTPC</th>
<th>Semiconductor (Si/Ge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>1.4</td>
<td>2.3/5.3</td>
</tr>
<tr>
<td>$T_{\text{operation}}$</td>
<td>$\sim$80K</td>
<td>$\sim$240K/$\sim$80K</td>
</tr>
<tr>
<td>Cost</td>
<td>$$</td>
<td>$$$</td>
</tr>
<tr>
<td>Signal</td>
<td>scintillation light + Ionization electrons</td>
<td>electrons, holes</td>
</tr>
<tr>
<td>X, Y Positions</td>
<td>wires on anode plane (X-Y)</td>
<td>double-sided strips</td>
</tr>
<tr>
<td>Z position</td>
<td>from drift time</td>
<td>from layer #</td>
</tr>
<tr>
<td># of Layers</td>
<td>1 layer</td>
<td>multi-layers</td>
</tr>
<tr>
<td># of Electronics</td>
<td>#</td>
<td>###</td>
</tr>
<tr>
<td>Dead Volume</td>
<td>almost no dead volume</td>
<td>detector frame, preamps</td>
</tr>
<tr>
<td>Neutron bkg</td>
<td>Identified with pulse shape</td>
<td>No rejection capability</td>
</tr>
</tbody>
</table>

LArTPC is COST-EFFECTIVE AND EASILY EXPANDABLE TO A LARGER-SCALE, MUCH LESS CHANNELS/ELECTRONICS REQUIRED, ALMOST NO DEAD VOLUME.
Selection Cuts

- **Compton scattering**: interaction points should be separated by > 10 cm
- **Pair production**: both $e^+$ and $e^-$ should stop within detector, leave tracks > 2 cm
SINGLE BALLOON FLIGHT: AN ORDER OF MAGNITUDE IMPROVED
SATELLITE MISSION: COMPARABLE (BETTER) TO FUTURE MISSIONS
CURRENT STATUS AND FUTURE PROSPECTS
Grams Collaboration

Tsuguo Aramaki, SLAC
GAPS, SuperCDMS
GRAMS antimatter search

Hirokazu Odaka, U of Tokyo
Astro-H, Suzaku
GRAMS event reconstruction

Georgia Karagiorgi, Columbia U
MicroBooNE, SBND, DUNE
GRAMS LArTPC design

Yoshiyuki Inoue, RIKEN
Astrophysics theorist (AGN etc.)
GRAMS MeV gamma-ray science

Charles Hailey: professor at Columbia U, GAPS PI, NuSTAR Co-I
Pelle Hansson: former SLAC physicist/engineer, ATLAS, SuperCDMS, DUNE

Possible Future Collaborations
SLAC DUNE, LZ, Stanford nEXO, MIT/UCLA/UCSD/Hawaii GAPS, Columbia theory group...

First collaboration meeting in July 2019 at Columbia University, Nevis Lab
**TIME SCALE**

**R&D FOR PROOF OF CONCEPT – IN A FEW YEARS**
- Validate detection concept
- Develop event reconstruction technique

Submitted proposals to NASA APRA, SLAC LDRD programs

**FIRST BALLOON FLIGHT (STARTING WITH AN ENGINEERING FLIGHT) - IN 5-10 YEARS**
- MeV gamma-ray observations
  - Focusing on bright objects, Nuclear lines
- Antimatter-based indirect DM search
  - Possibly detect antideuterons from DM in the first flight
  - Investigate Fermi/AMS-02 results

**TPC DESIGN UPGRADE/DEVELOPMENT - IN 10 YEARS**
- Improve energy/position resolutions, event reconstruction
  - Finer pitch of anode wires/pads to track Compton scattered electrons
  - Add calorimeters to improve the performance of Energy measurement

“Event Circle” becomes “Event Arc”

**SATELLITE MISSION - IN > 10 YEARS**
- All sky survey in the MeV energy domain
- Antimatter-based (including antihelium) DM search
GRAMS is the first experiment to target both gamma-ray observations in the poorly explored MeV energy band and antimatter-based dark matter search.

With a cost-effective, large-scale LArTPC detector, the sensitivity to MeV gamma rays can be more than an order of magnitude improved compared to previous experiments.

GRAMS antideuteron measurements can provide essentially background-free dark matter signatures while deeply investigating and validating the possible dark matter detection indicated in Fermi GCE and AMS-02 antiproton excess.

The project is currently in the R&D phase and will demonstrate the detection concept using a small-scale prototype detector, MiniGRAMS.

Project will then become a balloon experiment, as a step forward to a satellite mission with detector upgrades.

GRAMS detector technology can also be applicable to other fields, such as nuclear medicine and homeland security.