Dark Matter Searches with GLAST

Larry Wai
SLAC
Representing the GLAST LAT collaboration
The GLAST “Large Area Telescope” (LAT) a.k.a. the large area silicon strip detector
A broad GLAST Science Menu

- Active Galactic Nuclei
- Extragalactic Diffuse Background Radiation
- Pulsars
- Supernova Remnants
- Unidentified Gamma-ray Sources
- Gamma-Ray Bursts
- Solar Physics
- Dark Matter
Talk overview

1. What is GLAST?
2. How does dark matter shine in gamma rays?
3. Where should we look for dark matter with GLAST?
GLAST Mission

Mission Management: NASA/GSFC
Launch: August 2007
5-year mission (10-year goal)

Large Area Telescope (LAT)
20 MeV - 300 GeV
PI: Peter Michelson (Stanford U)
NASA - DoE Cooperation

GLAST Burst Monitor (GBM)
5 keV - 25 MeV
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Spacecraft
Spectrum Astro

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NASA - DoE Cooperation

Sweden
Italy
France
Germany
USA
Japan
LAT Collaboration
(~160 collaborators total)

**United States**
- California State University at Sonoma (SSU)
- University of California at Santa Cruz - Santa Cruz Institute of Particle Physics (UCSC/SCIPP)
- Goddard Space Flight Center – Laboratory for High Energy Astrophysics (NASA/GSFC/LHEA)
- Naval Research Laboratory (NRL)
- Ohio State University
- Stanford University – Hanson Experimental Physics Laboratory (SU-HEPL)
- Stanford University - Stanford Linear Accelerator Center (SU-SLAC)
- Texas A&M University – Kingsville (TAMUK)
- University of Washington (UW)
- Washington University, St. Louis (WUSTL)

**France**
- Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules (CNRS/IN2P3)
- Commissariat à l'Energie Atomique / Direction des Sciences de la Matière/ Département d'Astrophysique, de physique des Particules, de physique Nucléaire et de l'Instrumentation Associée (CEA/DSM/DAPNIA)

**Italy**
- Agenzia Spaziale Italiana (ASI)
- Istituto di Astrofisica Spaziale (IASF, CNR)
- Istituto Nazionale di Fisica Nucleare (INFN)

**Japan GLAST Collaboration (JGC)**
- Hiroshima University
- Institute for Space and Astronautical Science (ISAS)
- RIKEN

**Swedish GLAST Consortium (SGC)**
- Royal Institute of Technology (KTH)
- Stockholm University
On-orbit particle environment

Protons (85%), alphas (14%), heavier ions (1%),..., electrons
4KHz (avg) outside South Atlantic Anomaly (SAA)
40MHz inside SAA

Albedo gammas, charged particles
250-750 Hz

Isotropic/galactic diffuse gammas

Point source gammas

After onboard filters... <500Hz events downlinked
the “finest” detector elements

- Silicon strip detector
  - UCSC (lead), INFN, Hiroshima, SLAC

- Calorimeter
  - NRL (lead), France, Sweden

- Cosmic ray shield
  - GSFC

- Plastic scintillator tile

- Front end electronics

- Silicon strips

- Fabrication
- LAT I&T
- LAT + S/C
- Launch!

Timeline:
- 2005
- 2006
- 2007
Putting it all together

Installing a tracker module

Rotating the LAT upside-down

Installing a calorimeter module

Installing electronics modules
How GLAST works

Charged particle shield - 4% R.L.
- 89 scintillating tiles
- 8 scintillating fiber ribbons
- efficiency (>0.9997) for MIPs

Tracking detector - 1.5 R.L.
- 16 tungsten foils (12x3%R.L., 4x18%R.L.)
- 18 pairs of silicon strip arrays
- 884736 strips! (228 micron pitch)

Calorimeter - 8.5. R.L.
- 8 layers cesium iodide logs
- 1536 logs total (1200kg)
gammas in the detector (courtesy of Bill Atwood)
Beyond EGRET…

...GLAST – the next generation

• Field of View ~20% of sky, factor 4 greater than EGRET

• Minimize rejection of $E>10\text{GeV}$ gamma rays due to backscatter into cosmic ray shield

• Point Spread function factor > 3 better than EGRET for $E>1\text{GeV}$. On axis $>10\text{ GeV}$, 68% containment < 0.12 degrees

• Large effective area, factor > 5 better than EGRET

• **Results in factor > 30 improvement in sensitivity**

• Much smaller deadtime per event (27 µsec, factor ~4,000 better than EGRET - 0.1 s)

• No expendables (EGRET had spark chamber gas) ➞ long mission without degradation (5 year requirement, 10 year goal).
Review of the large area telescope

- The GLAST large area telescope detectors are integrated and working! Launch in 2007!

- Large area silicon tracker – huge effective area, excellent angular resolution
- Segmented calorimeter – high energy gamma shower measurement
- Segmented cosmic ray shield – rejection of charged particle background while preserving high energy gammas
- On-board filter to reduce 4kHz event rate to 400Hz sent to the ground
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Different signs of dark matter everywhere!

- Velocity dispersions – galaxies within clusters
- Cluster X-ray temperature profiles
- Large scale structure
- Others...

Rotation curves of galaxies

Cluster Gravitational lensing

Cosmic microwave background anisotropies
## Dark matter as WIMPs

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Production Process</th>
<th>Mass</th>
<th>Observation methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axions</td>
<td>Big Bang Non-thermal</td>
<td>$\sim 10^{-5}$ eV</td>
<td>Direct conversion to radio waves</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>Big Bang Thermal</td>
<td>$\sim 10^{-1}$ eV</td>
<td>Large scale structure says neutrinos don’t contribute much to the (cold) dark matter</td>
</tr>
<tr>
<td>WIMPs</td>
<td>Big Bang Thermal or non-thermal</td>
<td>$\sim 10^{2}$ GeV</td>
<td>Direct scatter; annihilation radiation detection</td>
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- **Axions**
  - Production Process: Big Bang Non-thermal
  - Mass: $\sim 10^{-5}$ eV
  - Observation methods: Direct conversion to radio waves

- **Neutrinos**
  - Production Process: Big Bang Thermal
  - Mass: $\sim 10^{-1}$ eV
  - Observation methods: Large scale structure says neutrinos don’t contribute much to the (cold) dark matter

- **WIMPs**
  - Production Process: Big Bang Thermal or non-thermal
  - Mass: $\sim 10^{2}$ GeV
  - Observation methods: Direct scatter; annihilation radiation detection
GLAST – a complementary way to observe WIMP signals

- Direct detection experiments: WIMPs at the earth
- Neutrino observatories: WIMPs at the earth, sun
- Anti-matter detectors: WIMPs in the galaxy, diffusion
- Atmospheric cherenkov telescopes: large area in the WIMP “line” range
- Others...

GLAST
- Large field of view allows “Imaging” of dark matter clumps
- Large fraction of WIMP mass conversion to GLAST energy range
- Low background because of cosmic ray shield

Simulated WIMP Annihilation in the Gamma Ray Sky Stoehr, et.al. (2003)
Gammas from neutral pions

• If $\rho_{\text{WIMP}} \sim \rho_{\text{anti-WIMP}}$ or WIMP = anti-WIMP, expect tree-level annihilation to quark pairs

\[
\begin{align*}
\chi & \rightarrow q \quad \text{time} \\
\chi & \rightarrow q
\end{align*}
\]
2 photon final state, a.k.a. the “line” spectral feature

- Line energy = WIMP mass

**WIMPs are neutral!**
- occurs at higher order (loop diagrams)
- Branching fraction highly model dependent (“typical” branching fraction $10^{-3}$)
Ingredients of WIMP annihilation

\[
d\Phi / dE / d\Omega = \left( \sum_i dN/dE \ B_i \right) / M_{\text{WIMP}}^2 \ \times \ <\sigma v> / 2 \ \times \ \left( \int \rho^2(r,l,b) \ dr \right) / 4\pi
\]

Differential flux:

- Spectra, WIMP mass
- Annihilation cross-section
- Square of density – look in most dense regions
Estimate of gamma yield per WIMP pair annihilation

<table>
<thead>
<tr>
<th>$M_{\text{WIMP}}$</th>
<th>Total# $\gamma$</th>
<th>&gt;100MeV</th>
<th>&gt;1GeV</th>
<th>&gt;10GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GeV</td>
<td>17.3</td>
<td>12.6</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>100GeV</td>
<td>24.5</td>
<td>22.5</td>
<td>12.4</td>
<td>1.0</td>
</tr>
<tr>
<td>1 TeV</td>
<td>31.0</td>
<td>29.3</td>
<td>22.4</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Gamma ray yield per final state b-bbar
WIMP annihilation spectra

- WIMP Annihilation Prompt Gamma Spectrum
  - $M=10\,\text{GeV}$
  - $M=100\,\text{GeV}$
  - $M=1\,\text{TeV}$

- PP Prompt Gamma Spectrum
  - $M=10\,\text{GeV}$
  - $E_p = E^{-2.1}$
  - $E_p = E^{-2.6}$
  - $M=100\,\text{GeV}$
annihilation cross-section vs relic density

\[ \Omega_{\text{WIMP}} h^2 \approx 3 \times 10^{-27} \text{ cm}^3 \text{ sec}^{-1} / \langle \sigma_A v \rangle \]

For \( \Omega_{\text{WIMP}} = 0.25 \),

\[ \langle \sigma_A v \rangle \approx 2.3 \times 10^{-26} \text{ cm}^3 \text{ sec}^{-1} \]

At freeze-out, \( v \approx 10^8 \text{ cm/s} \), so

\[ \sigma_A \approx 5 \times 10^{-7} \text{ GeV}^{-2} \]

Electroweak interaction scale \( \approx \frac{\alpha^2}{M_{\text{weak}}} \approx 5 \times 10^{-9} \text{ GeV}^{-2} \)

Griest & Kamionkowski (2000)
Review of dark matter gamma emission

- ~10 gammas per WIMP pair annihilation in the GLAST energy range
- Very hard non-powerlaw spectrum
- Spectral cutoff, line at the mass of the WIMP
- Annihilation cross-section inversely proportional to relic density
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Where to look for WIMPs with GLAST?

- Galactic center
- Galactic satellites
- Galactic halo
- Extra-galactic
Galactic satellites – seen and unseen

Moore, et.al. (1999)

500 clumps
$M > 10^8 M_{\text{sun}}$
$R_{\text{tidal}} < 1 \text{kpc}$

Clumps we have found

Dark matter simulations predict many more clumps for our galaxy

$V = \left(\frac{GM_{\text{bound}}}{R_{\text{bound}}}\right)^{0.5}$

(Galaxies within Virgo)

$V_{\text{global}}$
Sagittarius Dwarf Galaxy

- Low Surface Brightness Dwarf Spheroidal
- Closest Milky Way satellite (25kpc)
- Location: $l = 5.6^\circ$, $b = -14^\circ$
- Extent: $8^\circ \times 4.8^\circ$

http://cossc.gsfc.nasa.gov/docs/cgro/egret/
Back of the envelope calculation for Sagittarius Dwarf Galaxy

\[ \int \left( \sum_i dN/dE \cdot B_i \right) dE \cdot M_{WIMP}^{-2} \times 
\begin{align*}
4\pi \int \rho^2(r)r^2 dr & \times \\
<\sigma v>/2 & \times \\
1/4\pi d^2 & \times 
\end{align*}
\]

\[ 10^{-3} \ \gamma \ \text{GeV}^{-2} \ (M=100\text{GeV}, \ E_{th}=1\text{GeV}) \]
\[ 10^{67} \ \text{GeV}^2 \ \text{cm}^{-3} \ (R_{core}=1\text{kpc}, \ 10^9 \ M_{\odot}) \]
\[ 10^{-26} \ \text{cm}^3 \ \text{sec}^{-1} \ (\Omega_{WIMP}=25\%) \]
\[ 10^{-47} \ \text{cm}^{-2} \ (d=25\text{kpc}) \]
\[ = \]
\[ 10^{-9} \ \text{cm}^{-2} \ \text{sec}^{-1} \]

Exposures:
EGRET=10^9\text{cm}^2\text{s} (2-week v.p.)
GLAST=2x10^{11}\text{cm}^2\text{s} (5-yr scan)
GLAST clump analysis

Baltz, Bloom, Taylor, Wai, Wang (in progress)

- Need to incorporate realistic background models
- Simulate milky way clump realizations

Calculate GLAST sensitivity to different clumps, WIMP masses (expect a few clumps visible to GLAST)
WIMP annihilation signals from Inverse Compton scattering

Baltz and Wai (2004); IC of starlight from WIMP annihilation

electrons

3kpc magnetic field \sim 3 \mu G

IC starlight

\pi^0 \rightarrow \gamma \gamma

e^{+/-}

Crossing time \sim diffusion time \sim 10^7 \text{ yr}
GLAST clump analysis: diffuse component

- For $\pi^0$ WIMP source flux $>10^{-8}$ cm$^2$ s$^{-1}$
- Diffuse emission from IC scattering $>2 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for $E>1$ GeV (>10% of diff. bkgd)

Angular distribution for diffuse emission:
- $100$ MeV $< E < 300$ MeV
- $1$ GeV $< E < 3$ GeV
- $10$ GeV $< E < 30$ GeV
- $E > 100$ GeV

160 GeV WIMP
Clump: 8 kpc distant
Velocity: 300 km/s
Milky Way halo and extragalactic signals
Galactic halo “sweet spot”

Where is the best place for GLAST to look for WIMP flux in the Milky Way halo?

- region from galactic center $25^0 < \theta < 35^0$ ($|b| > 10^0$); $3\sigma$ det.

$3\sigma$ detection limit: NFW, Galactic Center, 0.1 deg beam

MSSM models for $0.17 < \Omega_{DM} < 0.43$

Stoehr, et.al. (2003)
Extra-galactic Spectral Signatures

Ullio, et.al. (2002)

4-yr GLAST survey sensitive to feature

Spectral feature ~25% width

Combined WIMP annihilation spectrum over different $z$

- $M_\chi = 171$ GeV, $B_{2\gamma} = 0.0005$
- $M_\chi = 76$ GeV, $B_{2\gamma} = 0.06$
The galactic center
Dark matter density growth around black holes

- Black hole growth creates steep density profile for gravitationally bound dark matter, a.k.a. “the spike”
- \( \rho \sim r^{-\gamma} \rightarrow r^{-(9 - 2\gamma)/(4 - \gamma)} \)

Gondolo & Silk (1999)
EGRET source near the galactic center

- EGRET point source

Spatial analysis
• 100MeV-300MeV (I ~ -0.75deg)
• 300MeV-1GeV (I ~ -0.30deg)
• > 1GeV (I ~ 0.05deg)
• > 5GeV (I ~ 0.20deg)
review

• The GLAST large area telescope detectors are integrated and working
• GLAST – unique opportunity to observe WIMP annihilation
• 4 places to look for dark matter shining in gammas
“Connecting Quarks with the Cosmos”

Report by the committee on the physics of the universe
National Research Council (2003)

The 11 most profound, and ripe, questions in the universe!

1. What is dark matter? **LHC, direct detection,…,and GLAST!**
2. What is the nature of dark energy?
3. How did the universe begin?
4. Did Einstein have the last word on gravity?
5. What are the masses of the neutrinos?
6. How do cosmic accelerators work? **GLAST bread and butter**
7. Are protons unstable?
8. What are the new states of matter at high density/temp?
9. Are there additional space-time dimensions?
10. How were the elements from iron to uranium made?
11. Is a new theory of matter and light needed at the highest energies?