Advanced Pair Telescope Concept

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Talk Plan

- Primary Science: WIMP Dark Matter
- Requirements from Science
- APT Straw-Man Concept
- Technical Approach, Cost
- Estimated Performance
- Secondary Science: GRBs, Pair Halos and Extended Galactic sources
APT v1.0 Concept for 2010 Decadal

## Science Drivers

- **Dark Matter:** Test hypothesis that the DM is a WIMP and thermal relic. A complementary approach with a portfolio of direct, indirect and collider probes is key.

- Space and ground-based gamma-ray observations provide measurements of annihilation spectra and angular distributions needed not only to constrain but to *identify* the DM particles and connect laboratory measurements with astrophysical DM halos.

- Instrument should cover the natural mass and cross-section range. This can be accomplished with an instrument with ~10x Fermi LAT geometry factor and some improvement in angular resolution (background rejection).

- Instrument design parameters are driven by the primary DM science, but APT would still result in major technical advances for a number of secondary science objectives:

  - **Transient Phenomena:** Up to 4.8 str instantaneous FoV for *all-sky temporally dense measurements of transient phenomena* (GRBs, LIV, Pop-III SNe, EM counterparts of gravity wave sources.)

  - **Intergalactic Magnetic Fields:** Make measurements of *pair halos* around AGNs, providing first solid constraints on primordial magnetic fields, with chirality probe CP violation in early universe, *baryogenesis / matter-antimatter asymmetry in the universe*

  - **Extended Galactic Sources:** Make *spatially resolved images of galactic sources* such as the GC region, SNR and PWN - survey objects across the galaxy.
Gamma Rays from DM Annihilation

\[ \Phi_\gamma (E, \Delta \Omega) = J (\Delta \Omega) \times \Phi^{PP} (E) \]

Particle Physics Input

\[ \Phi^{PP} (E) = \frac{1}{2} \frac{\langle \sigma v \rangle}{4 \pi m_\chi^2} \sum_f \frac{dN_f}{dE} B_f \]

Astrophysics/Cosmology Input

\[ J (\Delta \Omega) = \int_{\Delta \Omega} d\Omega \int_{1.o.s.} dl \rho^2 (l, \Omega) \]

Line-of-sight integral of \( \rho^2 \) for a Milky-Way-like halo in the VL Lactea II \( \Lambda \)CDM N-body simulations (Kuhlen et al.)
Masses below this are already constrained by Fermi

- Sensitivity requirements are very well defined by DM science. 10x Fermi sensitivity needed to probe natural cross section for a thermal WIMP between current limit, and the regime best probed by ground-based instruments like CTA (near the natural maximum).

• Figure: Fermi and CTA sensitivity to a high mass WIMP from a Dwarf galaxy, but...

• Crossover around 200 GeV - for spectral measurements - for high mass WIMPs still need better ground-based instrument!

• Spectral resolution of 15% sufficient for resolving important features. For line-like features above 200 GeV, ground-based instruments would have the best sensitivity following a detection by APT.

• Measuring the universal DM annihilation spectrum from two objects would be key
Comparison of Direct and Indirect Detection

Direct Detection: WIMP scattering rate $\sim n_{\text{nuclei}} \frac{\rho_X}{m_X} \langle \sigma_{\text{SI}} v_{\text{rel},\chi n} \rangle$

Indirect Detection: WIMP annihilation rate $\sim \left( \frac{\rho_X}{m_X} \right)^2 \langle \sigma_{\chi\chi \rightarrow q\bar{q},l^+l^-,\gamma\gamma,v_{\text{rel}}} \rangle$

Direct Detection:
- WIMP scattering rate
- $\sim n_{\text{nuclei}} \frac{\rho_X}{m_X} \langle \sigma_{\text{SI}} v_{\text{rel},\chi n} \rangle$

Indirect Detection:
- WIMP annihilation rate
- $\sim \left( \frac{\rho_X}{m_X} \right)^2 \langle \sigma_{\chi\chi \rightarrow q\bar{q},l^+l^-,\gamma\gamma,v_{\text{rel}}} \rangle$

Comparison of Direct and Indirect Detection

Direct Detection: WIMP scattering rate $\sim n_{\text{nuclei}} \frac{\rho_X}{m_X} \langle \sigma_{\text{SI}} v_{\text{rel},\chi n} \rangle$

Indirect Detection: WIMP annihilation rate $\sim \left( \frac{\rho_X}{m_X} \right)^2 \langle \sigma_{\chi\chi \rightarrow q\bar{q},l^+l^-,\gamma\gamma,v_{\text{rel}}} \rangle$
• DOE and NSF investments into G2 Direct Detection experiments should allow most of the natural nuclear recoil mass range to be covered. In the event of a detection, a gamma measurement would be needed for mass/particle ID, halo measurements. The only way to reach the required sensitivity on multiple sources is with a new space-based instrument.
APT Instrument Concept
Lessons from Fermi LAT

- Sweet spot energy for Fermi was around a few GeV, where angular resolution good enough, astrophysical backgrounds lower but statistics still adequate.

- APT aims to improve performance in this energy regime. Performance is scaled from Fermi, adding confidence in sensitivity requirements for science, and scaling laws to determine detector performance.

- Dark Matter science, extrapolated from Fermi, drives the instrument design.
Tail Calorimeter

- Design of future space mission, should acknowledge planned ground-based instruments and their capabilities.

- CTA will provide better continuum sensitivity to DM for masses above ~1 TeV, and could provide better line sensitivity above ~200 GeV. For future mission, can trade energy resolution and reach for better sensitivity in the 100 GeV to 1 TeV range.

- There are numerous purpose-built (narrow-field) optical telescopes, how about another narrow-field telescope for >100 GeV gamma-rays? To support APT, a dedicated fast-slewing, narrow field (6deg) array at an existing site might provide good “tail calorimetry” (with >4 o.m. in area!) at hundreds of GeV for an estimated cost ~ $30M, small compared to the total mission cost.
Pair Telescope Operation

Tracker

Calorimeter

1 \( X_0 \)
2 \( X_0 \)
3 \( X_0 \)
4 \( X_0 \)
5 \( X_0 \)
Strawman(men)

- Either one large massive 3m x 6m pair telescope in LEO (monolith), or back-to-back trackers with shared calorimeter (Orthrus - 2 headed brother of Cerberus) to minimize calorimeter cost/weight and maximize FoV in high orbit

- Large geometry factor >10x Fermi and instantaneous Area (monolith) or FoV=2x Fermi (Orthrus)

- Similar complexity to Fermi (same number of channels, all solid-state detectors)

- Challenge: Large mass and high orbit, very large passive volume needs to fit in Probe class mission
Orthrus in LEO

- Orthus in 1000 km Orbit (JPL A-team).
Monolith Concept

• Compared with Orthrus, twice instantaneous area, half FoV

• Calorimeter more massive and more expensive, but with current launch vehicles even heavier instrument in LEO is most realistic (baseline) option.
**Energy Resolution and Maximum Energy**

- **Question:** Fermi was already a probe class mission - how can we achieve 10x GF without going over $1\text{G}$?!

- **Give up energy resolution and use simpler tracker technology**

- Need >7 radiation lengths to reach >~100 GeV.

- Energy resolution is sacrificed to reduce weight. Still get better than 15% resolution up to 200 GeV.

- At high energies, energy resolution is limited by leakage of electromagnetic shower out of the back of calorimeter, at low energies, by fluctuations and absorption in passive converter.
- Angular resolution over most of energy range dominated by multiple Coulomb scattering.

- Using fibers, holding tracker thickness at 1.5 radiation lengths (Fermi) can increase from 18 (Fermi) to 50 layers, improving angular resolution by a factor of 1.4
- Scale model (line) to Fermi (points). Use Fermi Aeff, angular resolution, and published values of CR, electron and gamma-background rejection (adjust to fit), then scale using APT parameters.

- *Sensitivity at high energies (photon counting limit) scales with geometry factor, at low energies improved by angular resolution and $\sqrt{\text{area}}$*

- Possible to achieve a factor of 5 to 10 over entire energy range. Estimate is conservative at ~100 MeV where more continuous tracker could help (need detailed GEANT simulation)
## Straw-man Specifications

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Requirement</th>
<th>Orthrus</th>
<th>Monolith</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry Factor</td>
<td>&gt;10 x Fermi</td>
<td>8.8 x Fermi</td>
<td>8.9 x Fermi</td>
<td>33 m² str</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>&lt; Fermi</td>
<td>Fermi/1.4</td>
<td>Fermi/1.4</td>
<td>for all events</td>
</tr>
<tr>
<td>Effective Area</td>
<td></td>
<td>4 x Fermi</td>
<td>8 x Fermi</td>
<td></td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>&lt;15 %</td>
<td>8-15%</td>
<td>8-15%</td>
<td>0.4 to 200 GeV</td>
</tr>
<tr>
<td>Maximum Energy</td>
<td>&gt;30 GeV</td>
<td>173 GeV</td>
<td>39 GeV</td>
<td>50% leakage - Fermi = 860 GeV</td>
</tr>
<tr>
<td>Field of View</td>
<td></td>
<td>2 x Fermi</td>
<td>1.1 x Fermi</td>
<td>4.8 str</td>
</tr>
<tr>
<td>Dimensions</td>
<td>&lt; Fairing</td>
<td>3m x 3m</td>
<td>3m x 6m</td>
<td></td>
</tr>
<tr>
<td>Tracker Aspect Ratio</td>
<td></td>
<td>0.4</td>
<td>0.4</td>
<td>same as Fermi</td>
</tr>
<tr>
<td>Total Height</td>
<td></td>
<td>2.5m</td>
<td>1.2 m</td>
<td></td>
</tr>
<tr>
<td>Tracker Thickness</td>
<td></td>
<td>1.5 r.l.</td>
<td>1.5 r.l.</td>
<td></td>
</tr>
<tr>
<td>Calorimeter Thickness</td>
<td></td>
<td>5.5 r.l.</td>
<td>5.5 r.l.</td>
<td>Fermi CsI bricks</td>
</tr>
<tr>
<td>Total Thickness</td>
<td></td>
<td>8.5 r.l.</td>
<td>7 r.l.</td>
<td>10.1 r.l for Fermi</td>
</tr>
<tr>
<td>Number Channels</td>
<td>~884,736 (Fermi)</td>
<td>923,000+cal</td>
<td>923,000+cal</td>
<td></td>
</tr>
<tr>
<td>Fiber Thickness</td>
<td></td>
<td>1.3 mm</td>
<td>1.3 mm</td>
<td>2-layers+centroid⇒pitch</td>
</tr>
<tr>
<td>Mass (Instrument)</td>
<td></td>
<td>6400 kg</td>
<td>10,600 kg</td>
<td>Falcon 9 OK for LEO</td>
</tr>
</tbody>
</table>
• **Silicon** - Proven technology used in Fermi. Channel count, cost, complexity scales like volume - naive scaling from Fermi cost of $700M leads to mission cost well over $1B, but using a past experience and savings in non-recurring costs, may still be viable.

• **Scintillating Fibers** - Low cost, good TR level, SiPMs with 50% QE and ASICs imply solid state readout with ~20 p.e. per MIP with 1.3mm fibers.

• **High pressure or liquid noble TPCs** - Excellent angular resolution and good polarization sensitivity but small effective area, triggering/DAQ issues, limited mission life, not optimized for DM science.
Budget

- **My Reading of Paul Hertz’s sand chart...**

- Highest priority is to create a probe line in the next Decadal survey and come up with a short list of mission concepts that address a range of key science topics.

- Humility check: A gamma-ray (or X-ray) mission shouldn’t be the only astrophysics mission for the next decade. Does this fit in Probe class instrument?
Mass Estimate

This is a very rough breakdown based on coarse scaling; it is not a grass-roots estimate.

<table>
<thead>
<tr>
<th>Category</th>
<th>Mass (kg)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Element</td>
<td>12,260</td>
<td></td>
</tr>
<tr>
<td>Payload</td>
<td>11,145</td>
<td></td>
</tr>
<tr>
<td>Instrument</td>
<td>10,132</td>
<td></td>
</tr>
<tr>
<td>Tracker</td>
<td>1,825</td>
<td>Estimate is purely based on absorption length (no polystyrene, fiber, etc)</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>7,731</td>
<td>Also based purely on absorption length</td>
</tr>
<tr>
<td>ACD</td>
<td>576</td>
<td></td>
</tr>
<tr>
<td>Payload Primary Structure</td>
<td>1,013</td>
<td>10% of Instrument mass</td>
</tr>
<tr>
<td>Spacecraft</td>
<td>1,115</td>
<td>10% of Payload mass (very very rough estimate)</td>
</tr>
</tbody>
</table>
### Launch Vehicles?

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>Fairing Diameter (m)</th>
<th>Approx Static Envelop</th>
<th>Payload to LEO (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falcon 9</td>
<td>4.6</td>
<td>4.37</td>
<td>13150</td>
</tr>
<tr>
<td>Atlas V 521</td>
<td>5.4</td>
<td>5.13</td>
<td>13490</td>
</tr>
<tr>
<td>Atlas V 401</td>
<td>4</td>
<td>3.8</td>
<td>9797</td>
</tr>
<tr>
<td>Delta IV M+ (5,2)</td>
<td>5</td>
<td>4.75</td>
<td>12820</td>
</tr>
<tr>
<td>Dnepr-1</td>
<td>3</td>
<td>2.85</td>
<td>4500</td>
</tr>
<tr>
<td>Zenit 2</td>
<td>3.9</td>
<td>3.705</td>
<td>13740</td>
</tr>
</tbody>
</table>

- Size of instrument is constrained by available launch vehicles, achievable orbits
- Currently, can get heavier monolith into LEO, but can't quite get Orthus into L2 :(
- Must either be below or above the intense radiation zone (to avoid Mrads/year!)
- LEO or Lagrange point
• APT has a simple spacecraft design (no active repointing, 15 arcsec pointing knowledge with a star camera).

• With a $150M spacecraft, ATLAS V $250M, Science, Mission operations and ground data systems, project management, reserve etc. leaves about $250M for Payload.

• Initial cost estimates indicate that we could fit in a <1B$ probe line at a reasonable confidence level.

  - A-Team Cost estimate: John Elliott (Study Lead), Dr. Jonathan Murphy (Assistant Study Lead), Dr. Randii Wessen (Facilitator)

  - Disclaimer: This cost information is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

• If reuse Fermi Calorimeter design (removing nonrecurring costs) - At $3000/kg CsI - $14M (Orthus) to $27M (Monolith)

• Same number of channels as Fermi tracker, but relatively high gain SiPMs should make ASIC design straightforward. Readout on edges (not buried in towers)

• Big, simple, dumb brick of Plastic and CsI, with extrapolation from Fermicosting should
Technology
FiberGLAST Square Fiber/MAPMT Performance

FiberGLAST measurements with conventional MAPMTs

![FiberGLAST measurement graph]

APT measurements with UBA PMTs lower efficiency fibers (10 p.e./MIP)

![APT measurement graph]

A simple extrapolation implies that APDs may allow us to reach 20 p.e./MIP at 1 m
Fibers

- Number of detected photoelectrons, and attenuation length for 4m long, 1mm diameter double measured with 27% QE PMT.

- Scaling from these results we expect \( N_{\text{pe}} = 9 \times (0.5/0.27) \times (1.3 \text{mm}/1 \text{mm}) > 20 \text{ p.e/MIP} \). The exact numbers will need to be determined using a bench test (underway) consisting of a dark box, radioactive source, and SENSL 3mm APD.

Photodetectors

- Current generation SENSIL C-series SiPMs (Geiger-mode APDs) can be optimized for PDE (photon detection efficiency) rather than dynamic range to achieve PDE~40% at the peak of the blue fiber spectrum.

- New C-series devices (to be released this summer) expected to achieve PDE~50%

- High dark count rates and cross-talk mean that threshold must be set well above 1 p.e.

- Excellent single p.e. resolution make devices self-calibrating for gain (p.e./d.c. ratio)

\[ \text{Counts} = 4000 \]

\[ \text{ADC channels} \]

\[ \text{Sr}^{90} \text{ Source @ 200cm from SENSIL A20HD SiPM (PDE = 0.082 ± 0.009)} \]

\[ N_{pe} = 4.47 ± 0.22 \]

Fig. 6. The number of photoelectrons as measured by the SiPM is shown when the \(^{90}\text{Sr}\) source and trigger counter is placed at a distance of 200 cm.
• ACE has been in orbit about the L1 libration point, and operating for 17 years (since 1998). Only small drop in signal intensity (could be fibers or image intensifier aging)

• Radiation dose calculated by extrapolating study using NRL creme code is 0.4 kRad/year.

• HEP testing of older fibers show insignificant damage up to ~50 kRads based on data available in 1999 (FiberGLAST proposal). New radiation resistant fibers may be better - accelerator studies needed.
Radiation Damage Test for FiberGLAST

Test of Radiation Damage to Fibers

- Dose to fibers over 10 year mission for 550km, 28 deg orbit and 3.4g/cm² Al equivalent shielding is ~1 kRad.
- Bicron blue emitting, 0.75mm, mirrorized fibers exposed to 4 kRads radiation (proton beam; E=42 MeV) at Indiana U. Radiation Effects Research Program (REAP) Facility.
- Fibers were uniformly exposed to dose over full 150 cm length.
- No observable damage occurred.
- Strong evidence that radiation damage is not a problem for fibers in the GLAST orbit, with the shielding.

Numbers of photoelectrons obtained from fibers for pre- and post-radiation at a dose level of 4kRads. The full length of the fibers (150 cm) was exposed to this dose. We see that there is no evidence of radiation damage to these blue emitting fibers.
• Use Fermi brick design. Will look into use of passive material to decrease mass of CsI/leakage (increase maximum energy) with some reduction in energy resolution and increase in backspash (NRL did similar studies for Fermi).

• Calorimeter design is conservative (based on normal incidence etc.). More careful simulations might allow a further reduction of mass needed to reach high orbit for Orthus approach.
Secondary Science with APT
Secondary Science:

- **Probe extreme spacetime:** All-sky, large area best sensitivity to *scalar* LIV (polarization more powerful, but cannot probe all terms in Lagrangian)

  \[
  \hat{Q}_{AB} = \sum_{I} \hat{Q}_{AB}^{I} \gamma_{I} = \hat{S}_{AB} + i \hat{P}_{AB} \gamma_{5} + \hat{V}_{AB} \gamma_{\mu} + \hat{A}_{AB} \gamma_{5} \gamma_{\mu} + \frac{1}{2} \hat{T}_{AB}^{\mu\nu} \sigma_{\mu\nu},
  \]

- **Inflation/Early Universe probe:** Search for helicity in IGMF to look for signatures of matter genesis in early universe.

- **Formation of structure:** Detection of transients: GRBs pair SNAae. Imprint of first stars on EBL (simultaneous spectra with space and ground-based instruments).

- **Census of objects in the Milky Way - All supernova remnants across the galaxy - More >GeV photons (with good angular resolution) key to identifying sources against diffuse background.**