Gamma-Ray Telescopes

**Pair Production Telescopes**
EGRET/Fermi

- 0.1 - 100 GeV
- Space-Based (small area)
- Background free
- Large Aperture/High Duty Cycle
- All-sky survey & monitoring
- Extra-Galactic (AGN, GRB)
- Diffuse emission
- Dark matter

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**Atmospheric Cherenkov Telescopes**
H.E.S.S./VERITAS/MAGIC

- 50 GeV - 100 TeV
- Large Area
- Excellent background rejection
- Small Aperture/Low Duty Cycle
- Study known sources
- Deep surveys of limited regions
- Source morphology (SNRs)
- Fast transients (AGN flares)
- High resolution spectra
- Dark matter

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**Particle Detection Arrays**
Milagro/Tibet/ARGO

- 100 GeV - 100 TeV
- Large Area
- Good background rejection
- Large Aperture & Duty Cycle
- Partial sky survey & monitoring
- Extended Sources
- Transients (GRBs, AGN flares)
- Highest Energies (>10 TeV)
Science Goals of a Wide-Field Instrument

• Galactic Cosmic Ray Origins
  – Galactic Diffuse Emission
  – Highest Energies (10 - 100 TeV) for Galactic Sources

• Particle Acceleration in Jets
  – Gamma Ray Bursts at Highest Energies
  – AGN Flaring
  – Multi-wavelength and multi-messenger campaigns

• Complete Survey
  – Discovery potential
  – Alert system
Extensive Air Shower
Gamma Ray Telescopes

- Gamma rays interact in the atmosphere, form particle cascades
  - Particles produce Cherenkov light in water at ground level

- Reconstruct shower direction from timing of PMT hits across the detector

- Most triggers come from cosmic rays (1700 Hz in Milagro, 5 kHz expected in HAWC)

- Field of view ~2 sr

- Duty factor >95%
Extensive Air Shower Arrays

http://www.ast.leeds.ac.uk/~fs/photon-showers.html
Extensive Air Shower Arrays

- gammas
- electrons

1 TeV gamma-ray shower Longitudinal Profile

http://www.ast.leeds.ac.uk/~fs/photon-showers.html
Extensive Air Shower Arrays

• gammas
• electrons

Milagro
Extensive Air Shower Arrays

Milagro

1 TeV gamma-ray shower

Gammas
Electrons

http://www.ast.leeds.ac.uk/~fs/photon-showers.html
From Milagro to HAWC

• The High Altitude Water Cherenkov Observatory

• Redeploy Milagro detectors at Volcán Sierra Negra, México
  - Increase altitude from 2630 m to 4100 m
  - Increase area from 2,400 m² (bottom layer of pond) to 20,000 m²
  - Segment the Cherenkov medium: separate tanks instead of a single pond
  - Better angular resolution and background rejection, lower energy threshold

• Achieve 10-15 x sensitivity of Milagro
  - Detect Crab at 5σ in 6 hours instead of 3 months

• Cost: ~$10M
The HAWC Collaboration

**University of Maryland:** Jordan Goodman, Andrew Smith, Greg Sullivan, Jim Braun, David Berley

**Los Alamos National Laboratory:** Gus Sinnis, Brenda Dingus, John Pretz

**University of Wisconsin:** Teresa Montaruli, Stefan Westerhoff, Segev Ben Zvi, Juanan Aguilar, Dan Wahl

**University of Utah:** Dave Kieda, Wayne Springer

**Univ. of California, Irvine:** Gaurang Yodh

**Michigan State University:** Jim Linnemann, Kirsten Tollefson, Dan Edmunds

**George Mason University:** Robert Ellsworth

**Colorado State University:** Miguel Mustafa, Dave Warner

**University of New Hampshire:** James Ryan

**Pennsylvania State University:** Tyce DeYoung, Patrick Toale, Kathryn Sparks

**University of New Mexico:** John Matthews, William Miller

**Michigan Technical University:** Petra Hüntemeyer

**NASA/Goddard Space Flight Center:** Julie McEnery, Elizabeth Hays, Vlasis Vasiloudou

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**Universidad de Guadalajara:** Eduardo de la Fuente

**Universidad Michoacana de San Nicolás de Hidalgo:** Luis Vilaseñor, Humberto Cotti, Ibrahim Torres, Juan Carlos Arteaga Velázquez

**Centro de Investigación y de Estudios Avanzados:** Arnulfo Zepeda

**Universidad de Guanajuato:** David Delépine, Gerardo Moreno, Edgar Casimiro Linares, Marco Reyes, Luis Ureña, Mauro Napsuciale, Victor Mijene
Pico de Orizaba, altitude 4100 m, latitude 18° 59’ N
Two hours drive from Puebla, four hrs from México City
Site of Large Millimeter Telescope (infrastructure exists)
HAWC

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Two hours drive from Puebla, four hrs from México City
Site of Large Millimeter Telescope (infrastructure exists)
HAWC Site Location

- Latitude (19° N) gives access to over 1/2 the sky
  - 40% overlap with HESS Galactic Plane survey
  - 90% overlap with IceCube
- Longitude (97° W) gives simultaneity with
  - VERITAS
  - Pan-American Observatories

- Crab Nebula transits 3° from zenith
- Galactic Center visible at 48° zenith angle
HAWC

Array composed of 300 large steel water storage tanks
Plastic bladder (water in, light out) - non-reflective surfaces
7.3 m diameter 4.5 m height
Close-pack array (~1-2m spacing of tanks)
Design

- 300 large steel water tanks
- ~20,000 m² array area
- >60% of area instrumented
Design

- Each tank instrumented with 3 upward facing 8” PMTs
- 900 PMTs total
- Interior surfaces non-reflecting (maintain timing integrity)
HAWC Detectors

- Steel cylinders with liners, assembled in place
  - Light-tight, black plastic bladder to hold water
  - Water filtered and demineralized during fill
  - 3 upward looking PMTs with <1 ns time resolution

- 900 8” Hamamatsu PMTs and most electronics re-used from Milagro
Hadron Rejection

Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location.
Hadron Rejection

Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location
Hadron Rejection

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Gamma-Hadron Separation

- Parameter $C = \frac{n\text{Hit}}{\text{cxPE}}$ (\text{cxPE} = \text{largest nPEs >40m from core})
- $\sim 10x$ better rejection than Milagro

\begin{align*}
\text{Median Energy} &= 1.5 \text{ TeV} \\
\text{Median Energy} &= 20 \text{ TeV}
\end{align*}

G-H separation at 50% gamma efficiency
Energy Threshold and Effective Area

• Higher altitude leads to a lower energy threshold
  - Shower fluctuations (depth of first interaction) lead to soft threshold

• HAWC will be fully efficient above ~2 TeV
  - Still >100 m² effective area at 100 GeV

• Relative improvement even more significant after hadron cuts
Energy Resolution

• Uncertainty from two sources:
  - Measurement of energy deposited at ground level
  - Fluctuations in shower development in atmosphere (naturally log-normal)

• Higher elevation closer to shower max
  - Comparable resolution at ~1/10 the energy of Milagro
  - HAWC resolution approaches limit from shower fluctuations

Resolutions are log-normal:
50% resolution indicates 1σ range [.67,1.5] times measured value
Angular Resolution

- Significant increase over Milagro – limited by information in the particles that reach the ground
  - Based on Milagro algorithms – improvements possible (esp. at higher E)
Sensitivity to Point Sources

- Long integration times (1000 hrs/year)
  - excellent sensitivity at highest energies (> few TeV)

- $5\sigma$ sensitivity to
  - 10 Crab in 3 min
  - 1 Crab in 5 hr
  - 0.1 Crab in $\frac{1}{3}$ year

- 10-15x Milagro sensitivity
  - Lower energy threshold
  - Improved angular resolution
  - Improved energy resolution
  - Improved CR rejection
Measuring Spectra at the Highest Energies

- **HESS J1616-508**
  - 0.2 Crab @ 1 TeV, $\alpha=-2.3$
  - Highest energy $\sim20$ TeV
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- Simulated HAWC data for 1 year with no cutoff
Measuring Spectra at the Highest Energies

- **HESS J1616-508**
  - 0.2 Crab @ 1 TeV, $\alpha=-2.3$
  - Highest energy ~20 TeV

- Simulated HAWC data for 1 year with no cutoff

- ...or with a 40 TeV exponential cutoff
Transient Sensitivity
Assumed E^{-2} emission spectrum
Full HAWC simulation (5 σ or 10 photons)
Fermi-LAT assumed 0.8 m^2 effective area, no background
Sensitivity to High Energy Transients

- Fermi observation of GRB 090510 (z = 0.9) in GBM and LAT

- Simulated HAWC light curve assuming extension of spectrum with LAT index
  - EBL absorption included
  - Cosmic ray background included

- ~200 events expected above 30 GeV

- Detection (5σ) by HAWC if emission extended to 50 GeV
HAWC Construction Schedule

- **VAMOS**
  - Verification Assessment Measuring Observatory Subsystems (3 months)

- **HAWC-30**
  - Implementation of all subsystems (complete 2011)

- **HAWC-100**
  - Science operations with 2 times Milagro’s sensitivity (complete 2012/13)

- **HAWC-300**
  - Full detector (complete 2014)
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HAWC Status

• Evolution of Milagro: altitude, size, optical isolation
  - ~10-15x sensitivity of Milagro
  - Straightforward design

• Funding approved by NSF, DOE in US and by CONACyT in México
  - Site is approved for our use
  - 7 detector array (VAMOS) under construction, first detector operational
  - Plan for operation with 100 detectors in 2012
  - Full array of 300 detectors operational by 2014

• Wide field of view and high duty cycle at 100 GeV – 100 TeV
  - Excellent discovery potential
  - Complement to other current and future instruments