VHE Astrophysics

- Energy range 10 GeV – 10 TeV
- Non thermal processes in the universe
- Highly variable sources
- Particle acceleration
- Physics of extreme objects
  - Supernova remnants
  - Active galactic nuclei
  - Gamma ray bursts
- Fundamental Physics
  - Quantum gravity
  - Extragalactic background light
  - Dark Matter
- Poorly explored energy range
  - Discoveries likely
  - New types of sources revealed

Gus Sinnis Los Alamos National Laboratory
Active Galactic Nuclei

- Supermassive Black Hole $10^8-10^{10} M_{\text{sun}}$
- Rotating magnetic field converts rotational energy of hole into kinetic energy.
- Shocks propagate along jets and accelerate particles. $\Gamma \sim 50$
- $10^{48}$ ergs/sec
- Highly variable in VHE band
Mrk 501 Longterm Variability

Gus Sinnis Los Alamos National Laboratory
AGN Spectra

![Graph showing AGN spectra with various data points and curves labeled Mrk 501, BeppoSax, CAT, EGRET, and Whipple. The graph plots Log νF(ν) [erg cm⁻² s⁻¹] against Log ν(Hz)].

Gus Sinnis Los Alamos National Laboratory
Gamma-Ray Bursts

- Discovered in 1960’s – VELA spy satellites at Los Alamos
- Intense bursts of $\gamma$-rays coming from seemingly random directions
- Last from milliseconds to 100’s of seconds
- Over >2500 observed to date
- Cosmological origin
- Most energetic phenomena known - $10^{-51}$ ergs
- Counterparts in other wavelengths (optical, radio, GeV, TeV?)
Gamma-Ray Burst Properties

Spatial Distribution

Duration Distribution

GRB Positions in Galactic Coordinates

Gus Sinnis Los Alamos National Laboratory
GRB Profiles

Gus Sinnis Los Alamos National Laboratory
GRBs: High Energy Emission

18 GeV photon

GRB 970417a – Milagrito

$10^{-3}$ chance probability

$>650$ GeV photons
GRB Models

Central Engine:
hypernovae (death of a very massive star)
neutron star - neutron star merger
black hole - neutron star mergers

Emission Spectra:
Fireball: internal or external shocks convert energy into electromagnetic radiation.
Quantum Gravity

• Quantum gravity may violate Lorentz invariance
• Most theories predict energy dependent speed of light
  – Interactions with Planck mass particles distort spacetime: yielding larger distances for HE gammas
  – Planck scale vacuum fluctuations probed by HE gammas
• Dynamics of the theory unknown
• Explore possible modifications to dispersion relation (Amelino-Camelia et al.)

\[ m^2 \approx E^2 - p^2 \left( 1 - \frac{\eta E}{E_{QG}} \right) \]

For photons this leads to an energy dependent velocity

\[ v \approx c \left( 1 - \frac{\eta}{2} \frac{E}{E_{QG}} \right) \]
# Quantum Gravity & GRBs

For $E = 1$ TeV: $E/E_{QG} = 10^{-16}$

Distant sources of HE $\gamma$-rays can amplify this effect

$$\Delta t \approx \eta \frac{LE}{cE_{QG}} = 40\eta zE_{TeV} \text{ sec}$$

Figure of Merit: $E_{probe} = 4 \times 10^{17} \frac{zE_{GeV}}{\Delta t_{sec}}$

<table>
<thead>
<tr>
<th>GLAST</th>
<th>Milagro</th>
<th>HAWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E = 30$ GeV</td>
<td>$E = 300$ GeV</td>
<td>$E = 50$ GeV</td>
</tr>
<tr>
<td>$\Delta t = 1$ sec</td>
<td>$\Delta t = 1$ sec</td>
<td>$\Delta t = 1$ sec</td>
</tr>
<tr>
<td>$z = 1$</td>
<td>$z = 0.2$</td>
<td>$z = 1$</td>
</tr>
<tr>
<td>$E_{probe} = 1.2 E_{Planck}$</td>
<td>$E_{probe} = 2.5 E_{Planck}$</td>
<td>$E_{probe} = 2 E_{Planck}$</td>
</tr>
</tbody>
</table>

A single detection allows one to set a compelling limit

To prove an effect from QG requires multiple GRBs at different redshifts
Cross correlation between TeV and sub-MeV lightcurves peaks at a lag of 1 s.

Assuming $E_{\text{obs}} = 650$ GeV, $\Delta t = 4$ s and $z=0.1$, we can obtain a constraint on $E_{\text{QG}}$ which is a factor of $\sim 70$ better than previous limits (Biller 1999).

Gus Sinnis Los Alamos National Laboratory
Absorption of TeV Photons

\[ e^- \rightarrow \sim \text{TeV } \gamma \rightarrow e^+ \sim \text{eV } \gamma \]

Gus Sinnis Los Alamos National Laboratory
The First Unidentified TeV Source

HEGRA: Deep observation
113 hours of observation (3 years)
4.6σ significance
30 mCrab strength
Centered on Cygnus OB2 (dense region of young, massive stars)
Possibly an extended source
<table>
<thead>
<tr>
<th>TeV Name</th>
<th>Source</th>
<th>Type</th>
<th>Date/Group</th>
<th>EGRET Catalog</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>TeV 0047−2518</td>
<td>NGC 253</td>
<td>Starburst</td>
<td>2003/Cangaroo</td>
<td>no</td>
<td>B</td>
</tr>
<tr>
<td>TeV 0219+4248</td>
<td>3C66A</td>
<td>Blazar</td>
<td>1998/Crimea</td>
<td>yes</td>
<td>C-</td>
</tr>
<tr>
<td>TeV 0535+2200</td>
<td>Crab Nebula</td>
<td>SNR</td>
<td>1989/Whipple</td>
<td>yes</td>
<td>A (Milagro)</td>
</tr>
<tr>
<td>TeV 0834−4500</td>
<td>Vela</td>
<td>SNR</td>
<td>1997/Cangaroo</td>
<td>no</td>
<td>C</td>
</tr>
<tr>
<td>TeV 1121−6037</td>
<td>Cen X-3</td>
<td>Binary</td>
<td>1999/Durham</td>
<td>yes</td>
<td>C</td>
</tr>
<tr>
<td>TeV 1104+3813</td>
<td>Mrk 421</td>
<td>Blazar</td>
<td>1992/Whipple</td>
<td>yes</td>
<td>A (Milagro)</td>
</tr>
<tr>
<td>TeV 1231+1224</td>
<td>M87</td>
<td>Radio Galaxy</td>
<td>2003/HEGRA</td>
<td>no</td>
<td>C</td>
</tr>
<tr>
<td>TeV 1429+4240</td>
<td>H1426+428</td>
<td>Blazar</td>
<td>2002/Whipple</td>
<td>no</td>
<td>A</td>
</tr>
<tr>
<td>TeV 1503−4157</td>
<td>SN1006</td>
<td>SNR</td>
<td>1997/Cangaroo</td>
<td>no</td>
<td>B</td>
</tr>
<tr>
<td>TeV 1654+3946</td>
<td>Mrk 501</td>
<td>Blazar</td>
<td>1995/Whipple</td>
<td>no</td>
<td>A (Milagro)</td>
</tr>
<tr>
<td>TeV 1710−4429</td>
<td>PSR 1706−44</td>
<td>SNR</td>
<td>1995/Cangaroo</td>
<td>no</td>
<td>A</td>
</tr>
<tr>
<td>TeV 1712−3932</td>
<td>RXJ1713.7−39</td>
<td>SNR</td>
<td>1999/Cangaroo</td>
<td>no</td>
<td>B+</td>
</tr>
<tr>
<td>TeV 2000+6509</td>
<td>1ES1959+650</td>
<td>Blazar</td>
<td>1999/TA</td>
<td>no</td>
<td>A</td>
</tr>
<tr>
<td>TeV 2032+4131</td>
<td>CygOB2</td>
<td>OB assoc.</td>
<td>2002/HEGRA</td>
<td>yes†</td>
<td>B</td>
</tr>
<tr>
<td>TeV 2159−3014</td>
<td>PKS2155−304</td>
<td>Blazar</td>
<td>1999/Durham</td>
<td>yes</td>
<td>A</td>
</tr>
<tr>
<td>TeV 2203+4217</td>
<td>BL Lacertae</td>
<td>Blazar</td>
<td>2001/Crimea</td>
<td>yes</td>
<td>C</td>
</tr>
<tr>
<td>TeV 2323+5849</td>
<td>Cas A</td>
<td>SNR</td>
<td>1999/HEGRA</td>
<td>no</td>
<td>B</td>
</tr>
<tr>
<td>TeV 2347+5142</td>
<td>1ES2344+514</td>
<td>Blazar</td>
<td>1997/Whipple</td>
<td>no</td>
<td>A</td>
</tr>
<tr>
<td>Galactic Plane</td>
<td>Milky Way</td>
<td>Diffuse</td>
<td>2004/Milagro</td>
<td>yes</td>
<td>B (Milagro)</td>
</tr>
</tbody>
</table>

† CygOB2 lies within the 95% error ellipse of the EGRET source 3EG J0233+4118
8 verified (A) sources, 5 B sources, 5 C sources
10 extragalactic source, 8 galactic

Gus Sinnis Los Alamos National Laboratory
EGRET Sky Map

EGRET All-Sky Gamma Ray Survey Above 100 MeV

270 sources (150 unidentified)

Gus Sinnis Los Alamos National Laboratory
Milagro TeV Sky Map

Gus Sinnis Los Alamos National Laboratory
Current Status of VHE Astronomy

- Only 8 confirmed sources (89, 92, 2x95, 97, 2x99, 2002)
- Lack of sources due to:
  - Small field of view of ACTs
  - Low sensitivity of all-sky instruments
  - Transient nature of sources (GRBs and AGN)
- Small source counts lead to poor understanding of VHE sources
- VHE GRBs inconclusive (Milagrito)
- HAWC – high sensitivity over entire sky
  - Detect many sources
  - Monitor transient sources
  - Discover VHE emission from GRBs
  - Limit/Measure effects of quantum gravity
The Need for HAWC

- **GLAST**
  - Will discover 1000’s of sources
  - Many variable
  - ACTs can monitor ~15/year at stated sensitivity
- **GRBs**
  - Detect highest energy photons in prompt phase
- **AGNs**
  - Detect/Monitor AGN at redshift < 0.3
  - Study AGN transients in VHE regime
  - Populations studies
- **Fundamental Physics**
  - Lorentz violation at high energies (quantum gravity?)
  - Dark matter
- **VHE sky surveyed to 40% of Crab flux**
  - Sensitive Sky Survey < 1% of Crab flux
- **Time Domain Astrophysics in the VHE Regime**
  - Extreme states of extreme systems
HAWC: High Altitude Water Cherenkov Telescope
HAWC Performance Requirements

• Energy Threshold ~20 GeV
  • GRBs visible to redshift ~1
  • Near known GRB energy
  • AGN to redshift ~0.3

• Large fov (~2 sr) / High duty cycle (~100%)
  • GRBs prompt emission
  • AGN transients
  • Time domain astrophysics in VHE regime

• Large Area / Good Background Rejection
  – High signal rate
  – Ability to detect Crab Nebula in single transit

• Moderate Energy Resolution (~40%)
  – Measure GRB spectra
  – Measure AGN flaring spectra
Effect of Altitude

Approximation B

Low Energy Threshold Requires High Altitude

Gus Sinnis Los Alamos National Laboratory
EAS Particle Content

Low Energy Threshold Requires Detection of Gamma Rays in EAS

Gus Sinnis Los Alamos National Laboratory
Detecting Extensive Air Showers

**Air Cherenkov Telescope**
- Low energy threshold (300 GeV)
- Good background rejection (99.7%)
- Small field of view (2 msr)
- Small duty cycle (< 10 %)

**Extensive Air Shower Array**
- High energy threshold (100 TeV)
- Moderate background rejection (50%)
- Large field of view (~2 sr)
- High duty cycle (>90%)

Gus Sinnis Los Alamos National Laboratory
HAWC Strawman Design

- 200m x 200m water Cherenkov detector
- Two layers of 8” PMTs on a 2.7 meter grid
  - Top layer under 1.5m water (trigger & angle)
  - Bottom layer under 6m water (energy & particle ID)
  - ~10,000 PMTs total (5,000 top and 5000 bottom)
  - Trigger: >50 PMTs in top layer
- Two altitudes investigated
  - 4500 m (~Tibet, China)
  - 5200 m (Atacama desert Chile)
Effective Area vs. Energy

Gus Sinnis Los Alamos National Laboratory
Event Reconstruction

Gus Sinnis Los Alamos National Laboratory
Angular Resolution

Gus Sinnis Los Alamos National Laboratory
Energy Distribution of Fit Events

Median Energy 180 GeV
(Milagro ~3 TeV)

Gus Sinnis Los Alamos National Laboratory
Background Rejection Bottom Layer

Gammas
- 30 GeV
- 20 GeV

Protons
- 70 GeV
- 270 GeV

Gus Sinnis Los Alamos National Laboratory
Background Rejection

Uniformity Parameter
nTop/cxPE > 4.3
Reject 70% of protons
Accept 87% of gammas
1.6x improvement in sensitivity

Gus Sinnis Los Alamos National Laboratory
D.C. Sensitivity: Galactic Sources

- Crab Spectrum: $dN/dE = 3.2 \times 10^{-7} \ E^{-2.49}$
  - Milagro 0.002 (0.001) Hz raw (cut) rate
  - HAWC 0.220 (0.19) Hz raw (cut) rate
  - Whipple 0.025 Hz
  - Veritas 0.5 (.12) Hz raw (cut) rate
- Background rate 80 (24) Hz raw (cut)
- $4 \sigma/\sqrt{\text{day}}$ raw data
- $6 \sigma/\sqrt{\text{day}}$ cut data
  - $120 \sigma/\sqrt{\text{year}}$
- 40 mCrab sensitivity (all sky) in one year
  - Whipple: 140 mCrab per source
  - VERITAS: 7 mCrab per source (15 sources/year)
Transient Sensitivity

Mrk flares

Gus Sinnis Los Alamos National Laboratory
Effect of EBL on Distant Sources

Gus Sinnis Los Alamos National Laboratory
Energy Distribution After EBL

Gus Sinnis Los Alamos National Laboratory
AGN Sensitivity

![Graph showing AGN sensitivity over time and flux.](Image)

1 Year

Gus Sinnis Los Alamos National Laboratory
Gamma Ray Burst Sensitivity

- BATSE (50 keV)
- GLAST (100 MeV)
- EGRET (100 MeV)
- New Array (400 GeV, no cutoff)
- New Array (300 GeV, cutoff at 300 GeV)
- New Array (100 GeV, cutoff at 100 GeV)
- New Array (50 GeV, cutoff at 50 GeV)

---

50 events

Gus Sinnis Los Alamos National Laboratory
Point Source Sensitivity

Flux Sensitivity of Gamma-Ray Telescopes

- **VERITAS**
- Whipple
- Milagro
- STACEE-64
- EGRET
- GLAST
- HAWC
- Crab Nebula - $E^{-2.49}$

Flux($E>E_{\text{min}}$) (cm$^{-2}$ sec$^{-1}$)

E$_{\text{min}}$ (GeV)
Time Domain Sensitivity

![Solid Angle/Sensitivity](chart.png)

Gus Sinnis Los Alamos National Laboratory
Conclusions

• A large area, high altitude all-sky VHE detector will:
  – Detect the Crab in a single transit
  – Detect AGN to z = 0.3
  – Observe 15 minute flaring from AGN
  – Detect GRB emission at ~50 GeV / redshift ~1
  – Detect 6-10 GRBs/year (EGRET 6 in 9 years)
  – Monitor GLAST sources at VHE energies
  – Begin field of VHE time-domain astrophysics
Conclusions

• Continuing work
  – Improve background rejection & event reconstruction
    • Increase sensitivity by ~50% - 100%?
    • Develop energy estimator
  – Detailed detector design (electronics, DAQ, infrastructure)
  – Reliable cost estimate needed (~$30M???)
  – Site selection (Chile, Tibet, White Mountain)

• Time Line
  – 2004 R&D proposal to NSF
  – 2006 full proposal to NSF
  – 2007-2010 construction
Site Visit: YBG 4/1-6

- Excellent location
  - Land available
    - many km² available at 4300m
    - Room at ~4800m
  - Power available (3 MWatts generated in YBJ)
  - Water available
  - Dormitories (“Western rooms”)
- Existing gamma ray detectors
  - ASγ array
  - ARGO detector
Site Visit: IHEP Beijing

- Scientists excited by project (IHEP and Tibet University)
  - Would like full-scale collaboration
  - Have experience with AS\gamma and ARGO
- IHEP Director Hesheng Chen enthusiastic about project
  - Committed to provide land, power, water, and people
    - Will provide letter to NSF on request
  - Funds for infrastructure (building, etc) can not be promised at this time
    - They paid ~$2M for ARGO building/infrastructure
CORSIKA: Energy Resolution

Gus Sinnis Los Alamos National Laboratory
CORSIKA: Energy Resolution

Delta E/E vs Primary Energy (GeV)

Energy Resolution: Particle Counting

Gus Sinnis Los Alamos National Laboratory
CORSIKA: Energy Resolution

**Delta E/E (>50 GeV)**

- **ede50**
  - Entries: 5098
  - Mean: 0.006835
  - RMS: 0.4522
  - \( \chi^2 / \text{ndf} \): 139.9 / 26
  - Constant: 3862 ± 79.5
  - MPV: -0.2811 ± 0.0042
  - Sigma: 0.137 ± 0.002

**Delta E/E (>300 GeV)**

- **ede300**
  - Entries: 343
  - Mean: -0.04854
  - RMS: 0.2725
  - \( \chi^2 / \text{ndf} \): 36.03 / 14
  - Constant: 349.1 ± 27.0
  - MPV: -0.2289 ± 0.0123
  - Sigma: 0.09641 ± 0.00565

Gus Sinnis Los Alamos National Laboratory
Background Rejection

Gus Sinnis Los Alamos National Laboratory