A Rich Variety of Science at $E > 100$ GeV

- Fundamental physics & cosmology
- Galactic particle acceleration
- Extragalactic particle acceleration

Neutral messengers: $\gamma$, $\nu$ are required to directly observe cosmic accelerators.
Astroparticle Physics, Cosmology & Multimessenger

- Dark matter searches
- Lorentz Invariance Violation (Energy dependent speed of light differences; targets – GRBs, pulse widths of γ-ray pulsars, AGN variability)
- Primordial Black Holes (could evaporate and produce bursts of VHE γs)
- Extragalactic Background Light (γ_{VHE} + γ_{EBL} → e^+ + e^-)
- Intergalactic Magnetic Fields (look for pair cascades/halos)
- Direct Cherenkov emission (produced by the primary particle, CR heavy nuclei)
- Electron-positron measurements (Galactic CR studies)
- Neutrino/ UHECR/ Gravitational Wave Correlations (multimessenger)
VERITAS in Context

Reshmi Mukherjee

ICHEP 2014
The combined sensitivity from 300 MeV to 100 TeV allows complementary studies to probe some particle physics processes.
The Instrument
VERITAS Cherenkov Telescope

Situated at 1280m altitude at Whipple Observatory in Arizona

- 106 m² tessellated
- Recoated every ~2 years
- 499 PMTs
- 500 MSps sampling
- FADCs 3-level trigger
- 3.5°
VERITAS Performance

- Sensitivity improvement: 1% Crab in ~25 hr
- Sensitive energy range: 100 GeV to 30 TeV
- Energy resolution: ~15% - 20%
- Angular resolution: < 0.1° at 1 TeV, 0.14° at 200 GeV (68% values)
- Camera upgraded in 2011 with higher QE phototubes
Increased Observing Time

Observation under moderate moonlight with UV filters

Reduced HV (~81%), gain ~30% nominal

>15% increased exposure
Science
Gamma Rays from Dark Matter

- Dark matter searches motivated by the compelling evidence for the presence of non-baryonic dark matter in various structures of the Universe.

- Weakly Interacting Massive Particle (WIMP) in the mass range of 50 GeV – 10 TeV are well motivated Dark Matter candidates in extensions of the Standard Model of Particle physics (Supersymmetry, Kaluza-Klein).

- Neutralino, the lightest SUSY particle, is the most commonly used candidate: self-annihilates to produces γs.

- Dwarf spheroidals are attractive nearby DM targets; large M/L ~ 200-1000, absence of known VHE backgrounds.

\[
\frac{d\phi}{dE}(\Delta\Omega, E) = \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \left( \frac{dN_\gamma}{dE} \right)_{DM} < J(\Delta\Omega) >
\]

Simulated DM annihilation spectra (Aliu et al. PRD 2012)
VERITAS Dark Matter Targets

- **Galactic Center**: Nearby source, strong DM candidate, but need to measure large astrophysical $\gamma$ ray background.

- **Dwarf Galaxies**: Attractive targets, large mass to light ration ($O(10^3)$ times more DM/visible matter), no $\gamma$ ray background, but DM distribution can be uncertain.

- **Unidentified Fermi-LAT sources**: Fermi-detected gamma-ray sources, Galactic ones are likely local, however nature and distance unknown.

- **Galaxy Clusters**: Largest DM concentration in the Universe, but distance is large, $\gamma$ ray signal weak, sources are extended.
VERITAS Observations of Dwarfs

- 48 hours of data on Segue I (additional observations ongoing), Phys.Rev.D (2012).
- 95% CL ULs from the VERITAS observations of Segue 1 on the WIMP velocity-weighted annihilation cross-section $<\sigma v>$ as a function of the WIMP mass, considering different final state particles.
- Constraints placed on thermally-averaged annihilation cross-section, $<\sigma v>$.

Zitzer et al. arXiv:1307.8367
Smith et al.arXiv:1304.6367
Dwarfs: Segue 1 Results

- Constraints on overall boost factor required to explain the PAMELA positron fraction by a leptophillic dark matter model (e.g. Adriani et al. 2009).

- VERITAS 95% limits constrain some models which predict large boosts, both astrophysical in nature or from particle physics processes (i.e. Sommerfeld enhancements).
Dwarf Galaxy Projections

- Future Plans: Significant observing time dedicated to dark matter targets.
- > 100 hrs on Segue 1 collected.

Stacking analysis allows for a single constraint to be made from multiple observations.
The Galactic Center is at large zenith angles for VERITAS, >50°.
- Energy threshold ~2 TeV
- ~46 hours of good data.
- GC (Sgr A*) spectrum consistent with archival data.
LIV Tests with Pulsars

- Probe physics at Planck energy ($10^{19}$ GeV)
- Use astrophysics observations in the VHE gamma-ray band constrain LIV.
- Peaks at 100 MeV (Fermi) and 120 GeV (VERITAS) line up
- $\Delta t_{95\%} < 1.65 \cdot \delta \cdot P/2^{1/2} < 100\mu$s
- Linear: $E_{LIV} > 3 \times 10^{17}$ GeV
- Quadratic: $E_{LIV} > 7 \times 10^9$ GeV

Detection of the Crab pulsar above 100 GeV with VERITAS

Otte: arXiv:1305.0264)
Neutrino Correlations

- Neutrino/ UHECR/ gravitational wave follow ups and correlations.
- IceCube: Select events which have muon tracks (location error ~1 degree), and tracks starting within the instrumented volume.
- Rapid follow-up program in place -- searches for neutrino-like events coincident with known TeV sources.

3.5 hours on Event ID 5, UL ~ 1.2% Crab.
2.5 hours on Event ID 13 UL ~ 1.6% Crab.
99% UL, > 300 GeV.

Holder, 2013, IceCube Meeting, Banff
Astrophysics Results

- Pevatrons & Tevatrons in the outer Galaxy
- Relativistic Jets
Galactic Sources: Pevatrons & Tevatrons

Cygnus
A rich area of the γ-ray sky:
MeV to multi-TeV data from EGRET, Fermi, MAGIC, VERITAS, ARGO, Tibet, Milagro – and upcoming HAWC.
Resolving the mysterious Milagro sources in the Cygnus-X region with VERITAS

- Milagro discovery of diffuse TeV emission from the direction of Cygnus X (2001-2007).
- Strong VERITAS excess consistent with large Milagro source.

VERITAS $\gamma$-ray excess maps of the MGRO J2019+37 region in two different energy bands.

- 1 TeV (red)
- 0.6-1 TeV (green).
Investigating the TeV Morphology of MGRO J1908+06

- Powerful extended VHE γ-ray source discovered by Milagro
- VERITAS results suggest a complex region. TeV emission could be due to interaction between the energetic particles emitted by the pulsar and either the SNR or molecular clouds.
The Extragalactic VERITAS Sky

Starburst Galaxies
- Increased star formation leads to high cosmic ray density.
- 100x Milky Way CR density

Radio Galaxies
- Close, with misaligned jets

Blazars
- Active Galaxies, with jets orientated towards our line of sight

Reshmi Mukherjee

ICHEP 2014
Extragalactic Science

Understanding the nature of black Holes
- How do SMBHs launch relativistic jets? How do AGN jets accelerate particles?

Cosmic ray origin
- Particle acceleration to extreme energies - origin of UHE cosmic rays ($E>10^{18}$ eV)?
- Study of cosmic rays in starburst galaxies & ultra-luminous infrared galaxies.

Blazars as probes for cosmology
- $\gamma$-ray opacity measurements, star formation history of the Universe ($\gamma_{\text{TeV}} + \gamma_{\text{EBL}} \rightarrow e^+ + e^-$).
- IGMF: Were intergalactic magnetic fields seeded by primordial magnetic fields?
- Test the validity of the Lorentz Invariance (LIV) principle at high energies.
Flare on June 28, 2011 detected by VERITAS; 125% Crab flux (> 200 GeV); $\Gamma = 3.8 \pm 0.3$;

Flux decayed by factor of 10 in $\tau = 13 \pm 4$ min => Strongly constrains size of emission region ($R < c\tau\delta/(1+z) \sim 2.2 \times 10^{13}\delta$ cm).
Probing the EBL for large optical depths

\[ \gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^- , \]
\[ \gamma_{VHE} \gamma_{EBL} > (m_e c^2)^2 \]
\[ F_{\text{obs}}(E) = e^{-\tau(E, z)}F_{\text{emitted}} \]

E > 0.1 TeV gamma-ray measured for blazar PKS 1424+240 out to a distance of at least 7.4 billion light-years (red shift > 0.6035) (Furniss 2013).
Discovery of a new TeV source

- Arrival directions of all photons events with zenith angle < 105° recorded by Fermi -LAT between 2008 Aug 4 and 2009 Aug 25 with reconstructed energies greater than 30 GeV.

Archambault et al. 2014; arXiv: 1308.5017
Summary & Future Outlook

- The scientific reach of VERITAS covers the study of both Extragalactic and Galactic objects as well as the search for astrophysical Dark Matter.

- Some highlights from VERITAS presented at this meeting.

- DM studies continue to be a high priority for VERITAS. Ongoing observations of dark matter targets -- significant portion of VERITAS observing time.

VERITAS measurements will greatly compliment lower energy constraints by Fermi-LAT. IACTs probe a unique and model-independent parameter space.

Future prospects: Ongoing world-wide effort CTA to construct the next-generation Cherenkov Observatory. One of the strongest motivations for CTA is the discovery potential for identifying and studying dark matter.
The VERITAS Collaboration

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Iowa St. Univ
Purdue
SAO
Washington Univ.
University of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Utah
Canada
McGill Univ.
U.K.
Leeds Univ.

Ireland
Cork Inst. Tech
Galway-Mayo
N.U.I. Galway
UCD
Extra Slides
VERITAS Observations of Segue 1

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- Place constraints on thermally-averaged annihilation cross-section, $\langle \sigma v \rangle$. 

![Graphs showing $\langle \sigma v \rangle$ as a function of WIMP mass for different final states.](image)
Most extreme active galactic nuclei:
- Almost all AGN seen at high energies are blazars – radio loud AGN viewed directly along the jet axis. – (The small viewing angle of the jet makes it possible to observe strong relativistic effects).

- Accreting SMBH, oppositely directed plasma jets at superluminal speeds

- Jets propelled by magnetic fields twisted by differential rotation by the BH’s accretion disk (e.g. Blandford & Znajek 1977; Meier et al. 2001)

- Particle acceleration outward along the jet in an acceleration and collimation zone containing a coiled magnetic field (e.g. Vlahakis & Konigl 2004). Energy transported as bulk motion of electrons, protons & magnetic field.
The Atmospheric Cherenkov Technique

Area = $10^4 - 10^5$ m$^2$ ~60 optical ph/m$^2$/TeV
Camera Upgrade

Main criteria: Quantum Efficiency

- 2200 new PMTs: Hamamatsu R10560-100-20 MOD. Higher QE: ~32%
- Improved photo-detection efficiency, increased effective area, lower $E_{th}$, narrower pulse ~40%
- Trigger rate 2.5 times higher

See Otte et al. arXiv:1110.4702
Tycho Supernova Remnant

- VERITAS detection of Tycho SNR: Young, Type-Ia SNR
- Possible interaction with Molecular Cloud
- Spectrum favors hadronic models
Relativistic Jets in the Universe

Jets are ubiquitous in nature. Relativistic jets are extremely powerful outflows of collimated plasma that occur in a variety of objects of different mass scales.

- Key outstanding issues: acceleration, collimation and stability/propagation of observed jets.

Jet of M 87, one of the closest AGN (20 Mpc), resolved in radio, optical & X-ray. The jet is oriented at ~ 20°. VERITAS detects a variable, point source of TeV γ rays.
DM Constraints from Galactic Center

- VERITAS uses an ON and OFF observation technique to better characterize the background.
- LZA ➔ higher array threshold for VERITAS (relatively high Higgs mass measured by LHC could imply larger natural mass of neutralinos, closer to the TeV scale e.g. Olive 2013).
Galactic Center