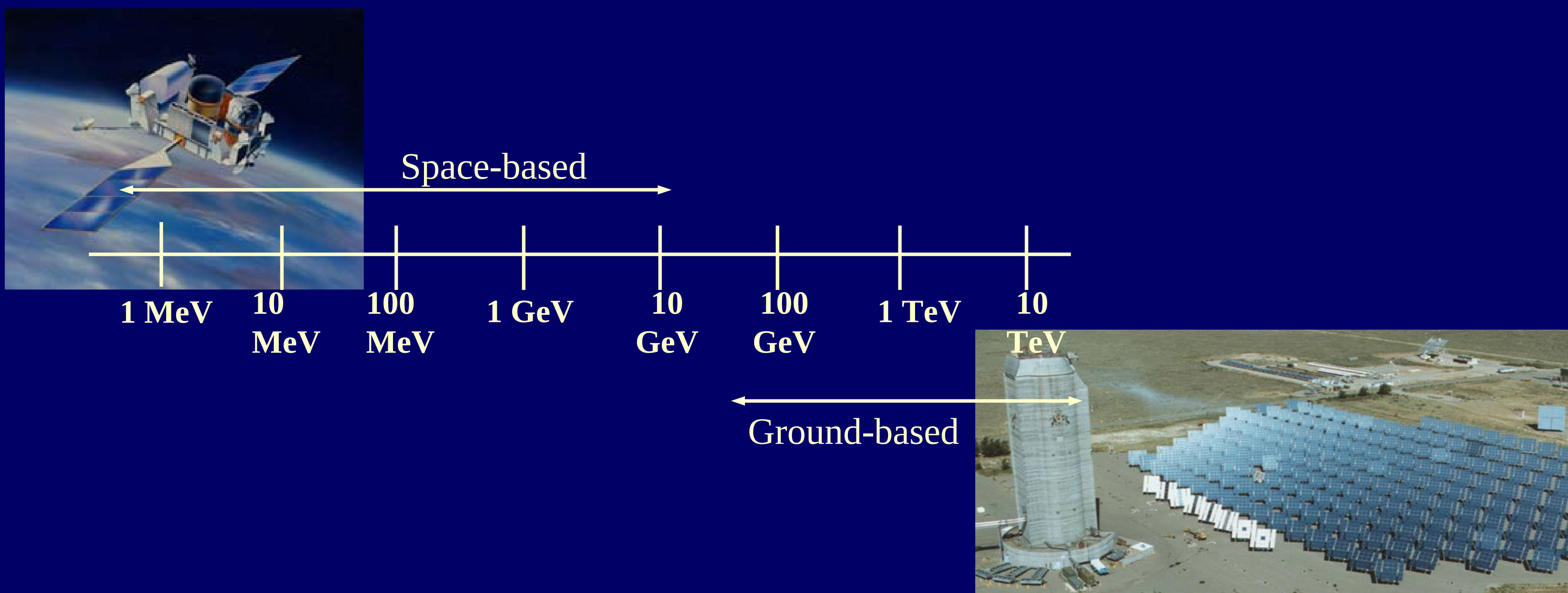
The Spectrum of Markarian 421 Above 100 GeV with STACEE

Jennifer Carson

UCLA / Stanford Linear Accelerator Center

February 2006



Outline

I. Science goal for γ-ray detections from active galaxies
- Understanding particle acceleration

II. Brief overview of VHE gamma-ray astronomy

III. Ground-based detection techniques
- Atmospheric Cherenkov technique
- Imaging vs. wavefront sampling

IV. STACEE

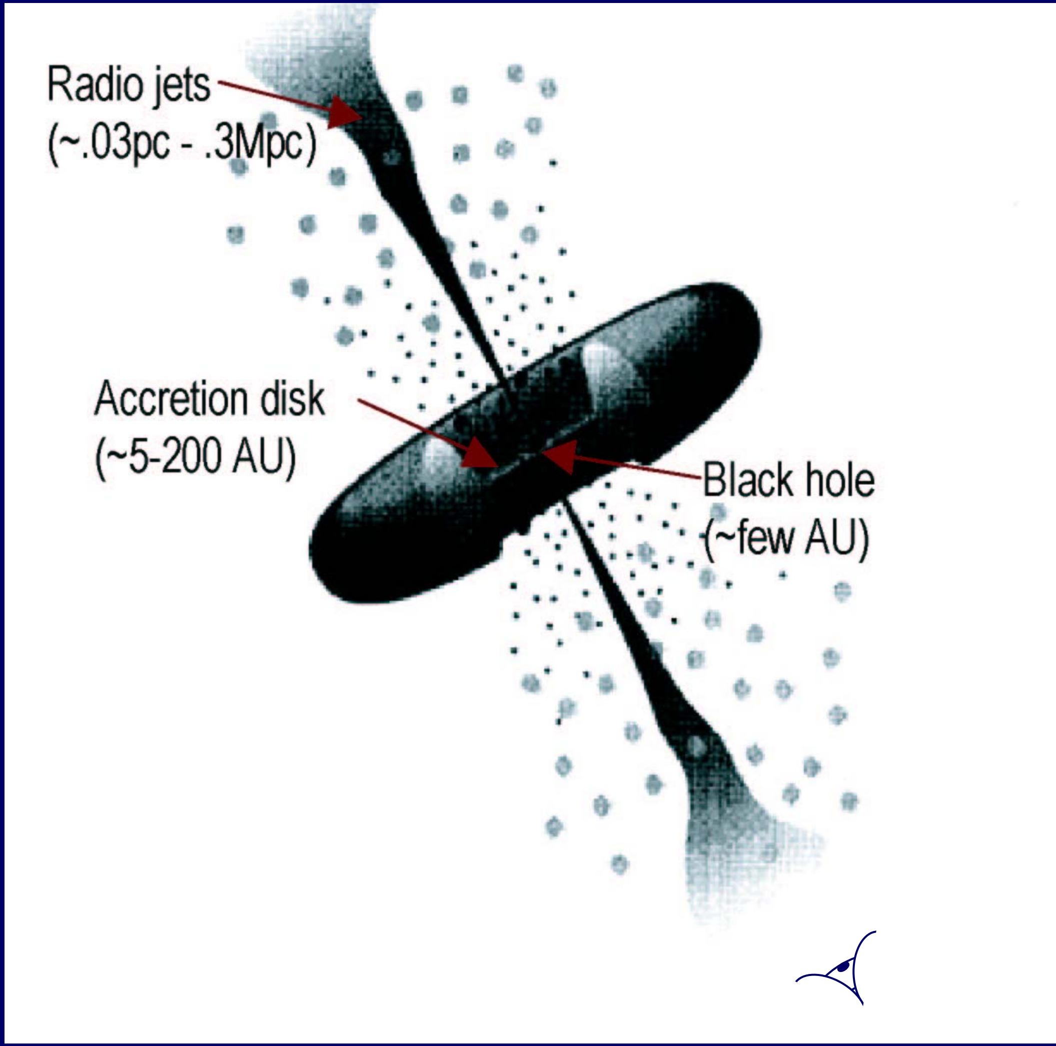
V. Markarian 421
- First STACEE spectrum
- Detection of high-energy peak?

VI. Prospects for the future

Blazars

Radio-loud AGN viewed at small angles to the jet axis

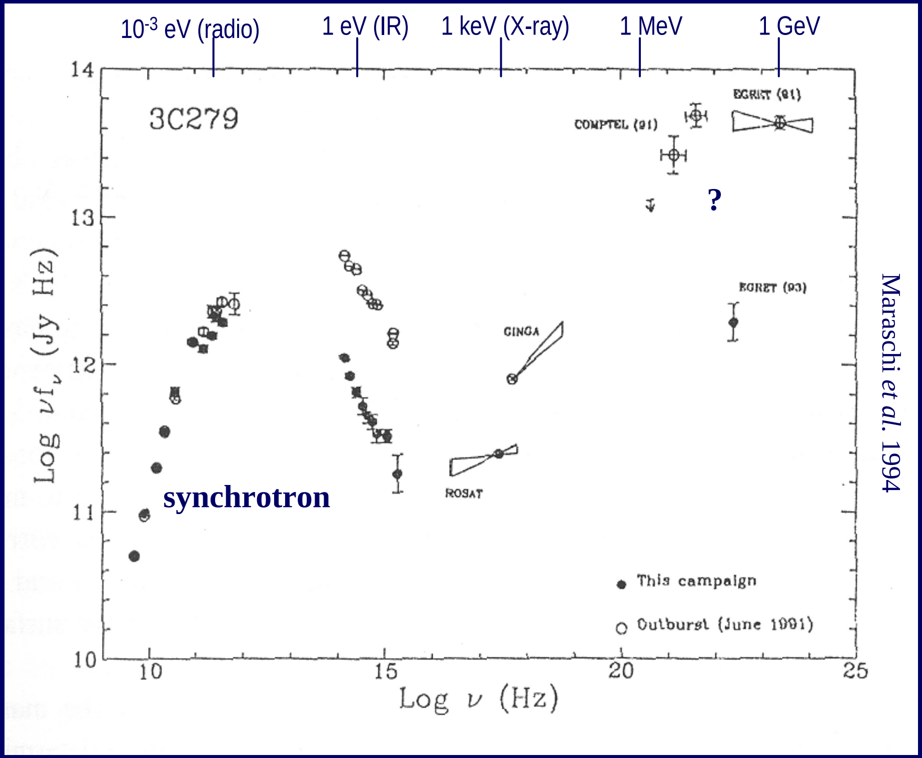
- bright core
- ≥ 3% optical polarization
- strong multi-wavelength variability



Blazars

Radio-loud AGN viewed at small angles to the jet axis

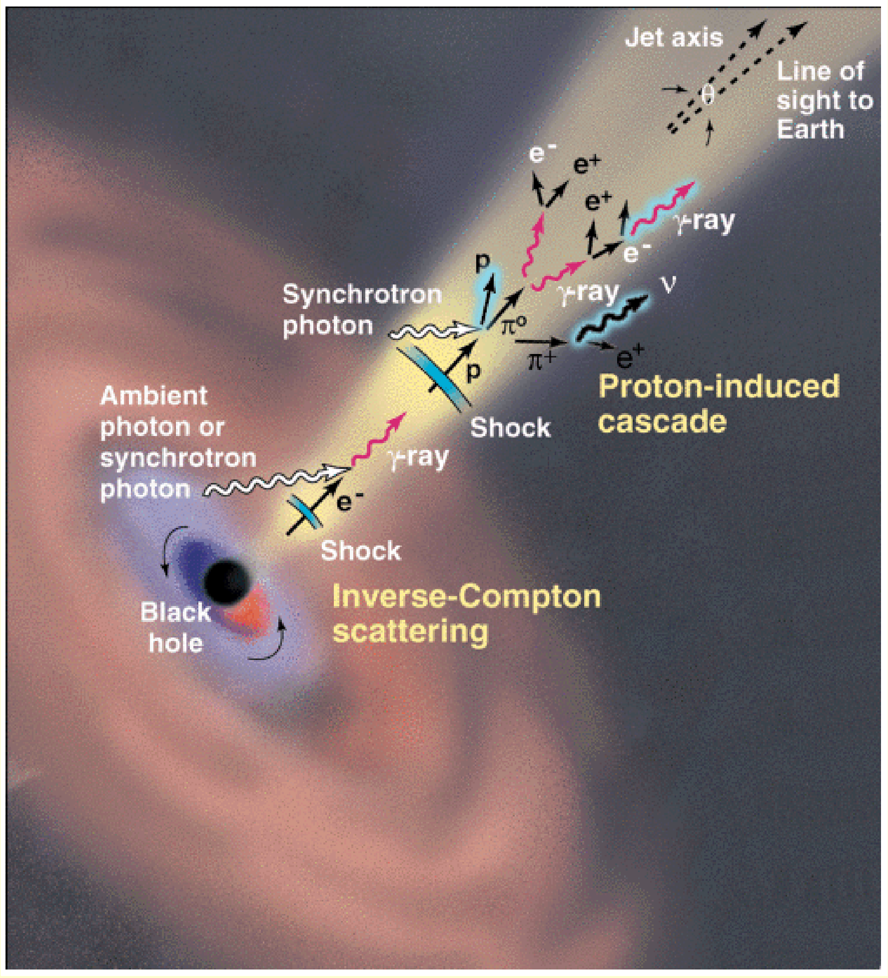
- bright core
- ≥ 3% optical polarization
- strong multi-wavelength variability
- Double-peaked SED: synchrotron emission + ?



What physical processes produce the high-energy emission?

Blazar High-Energy Emission Models

Is the beam particle an e^- or a proton?



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- Inverse-Compton scattering off accelerated electrons
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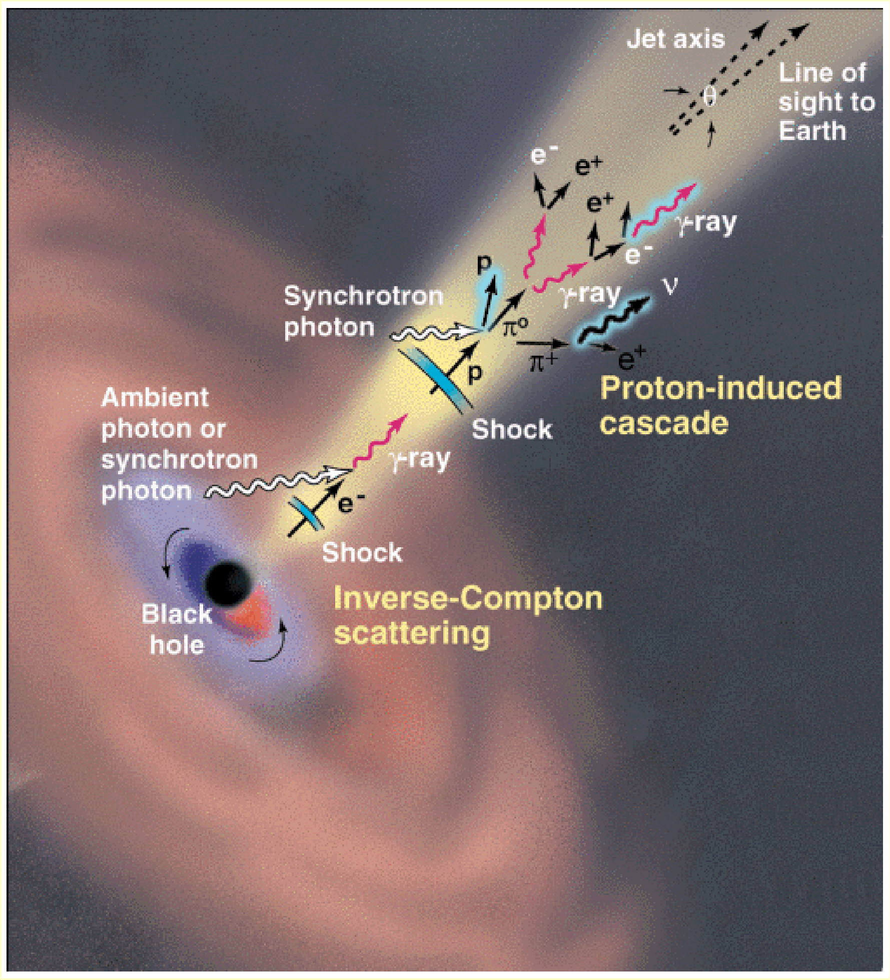

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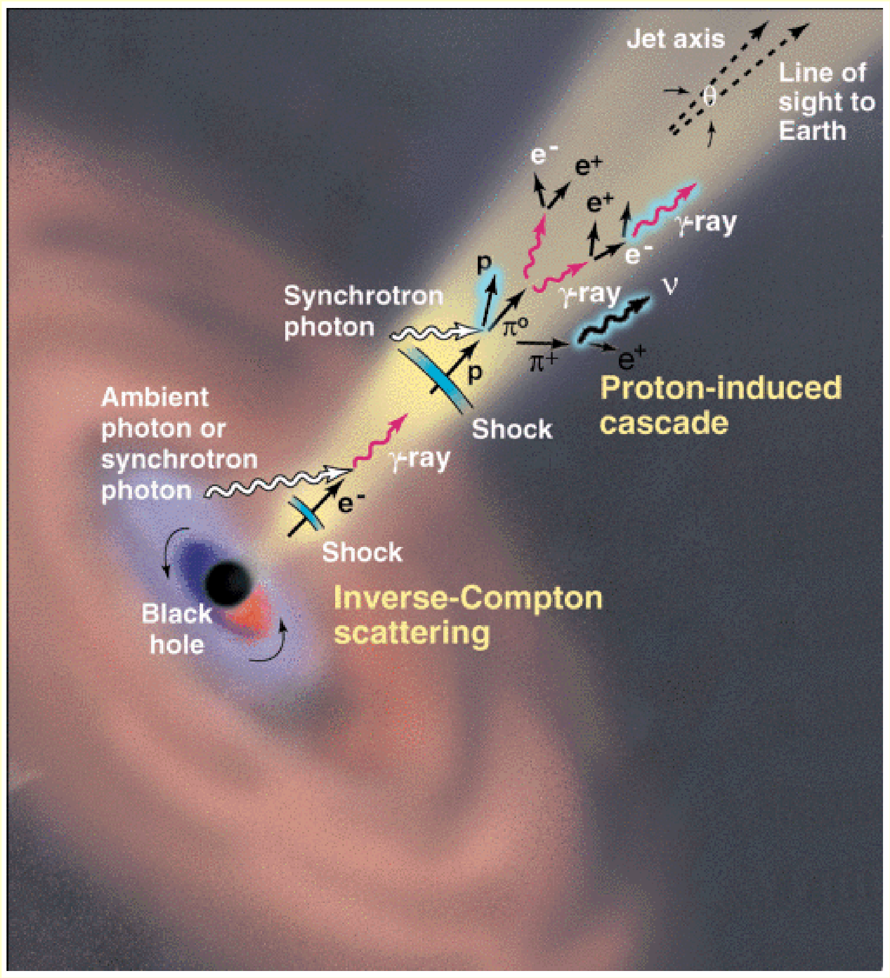
Hadronic models:
- Accelerated protons
- Gamma rays from pion decay or
- Synchroton gamma-ray photons



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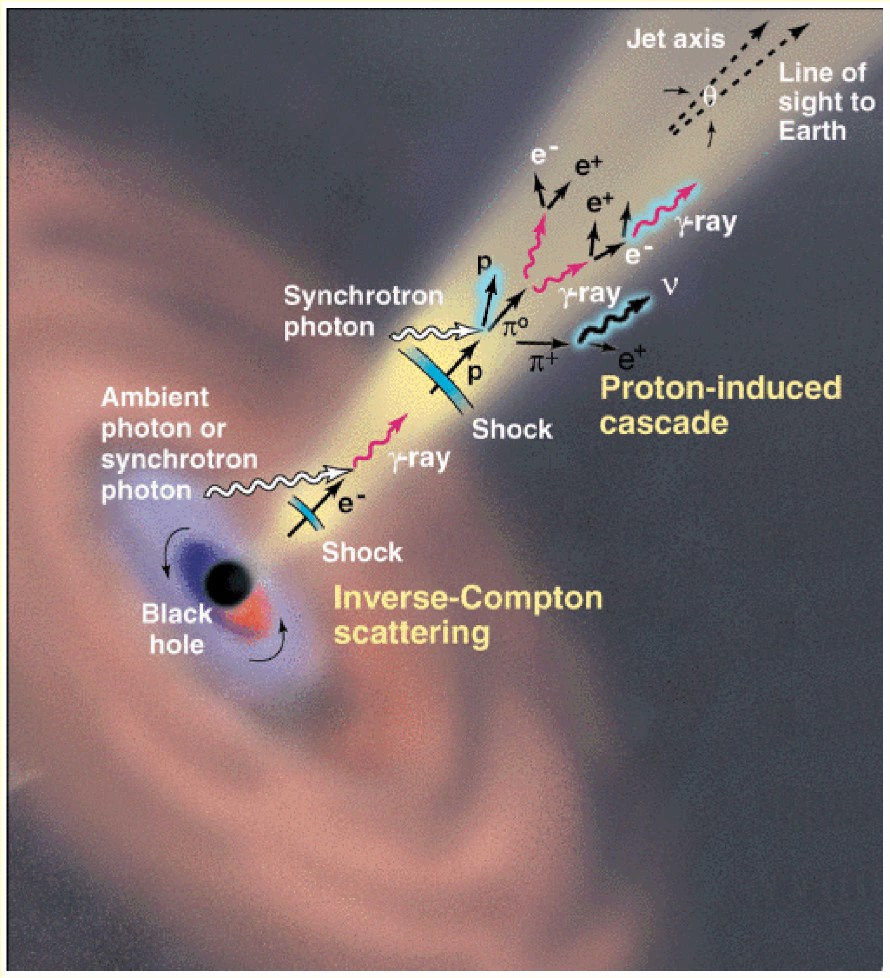
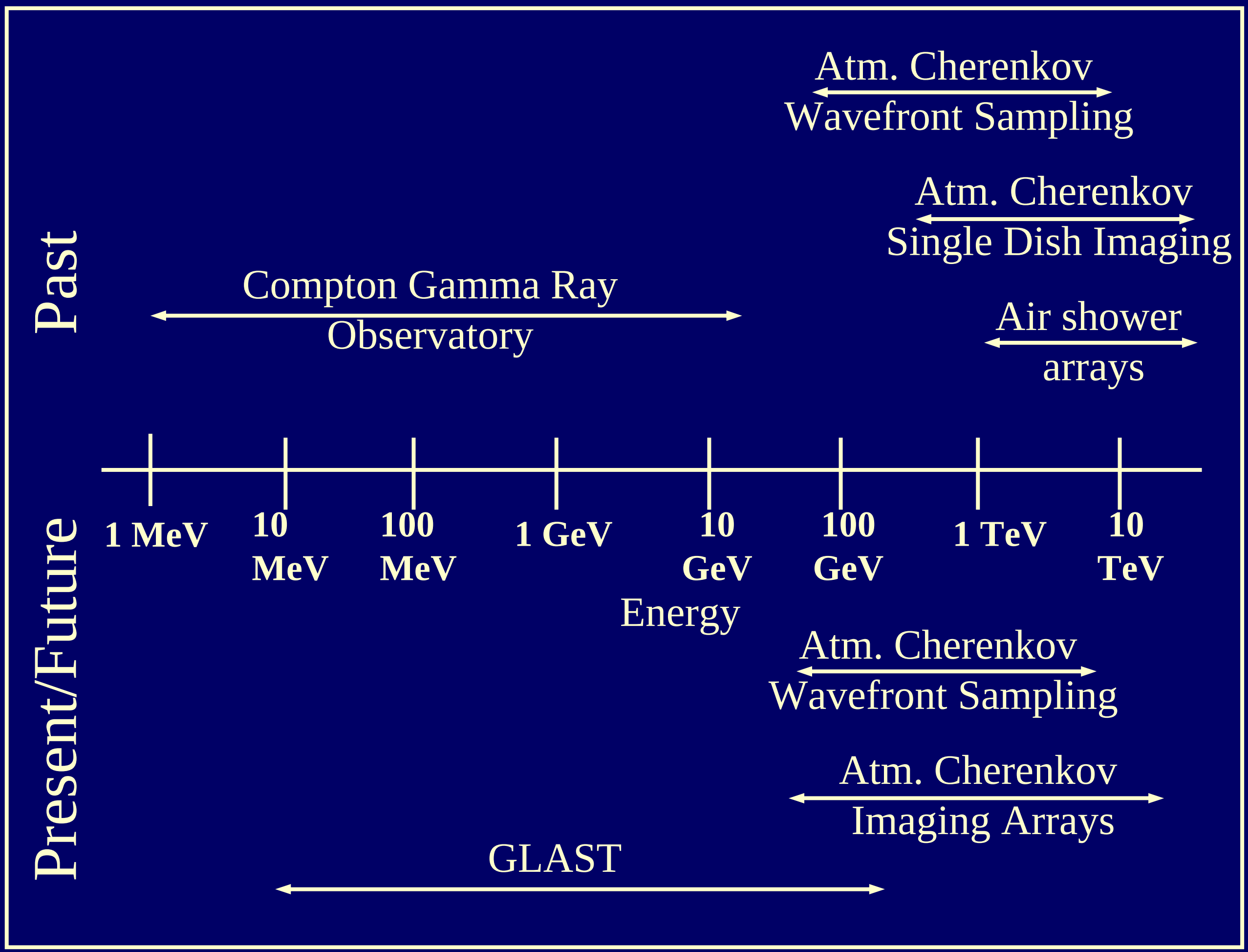
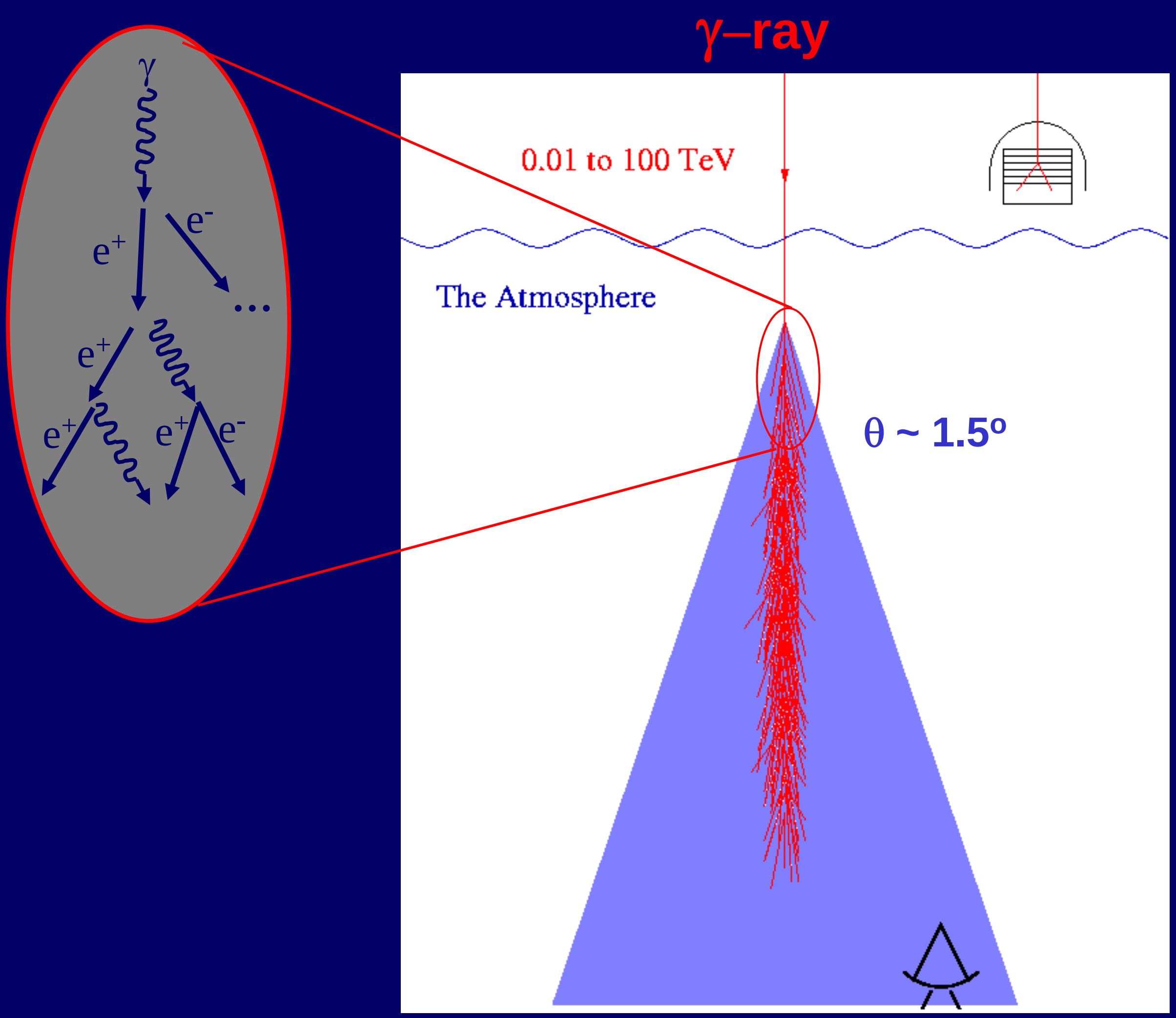
Gamma-ray observations around 100 GeV can distinguish between models



Exploring the Gamma-ray Spectrum



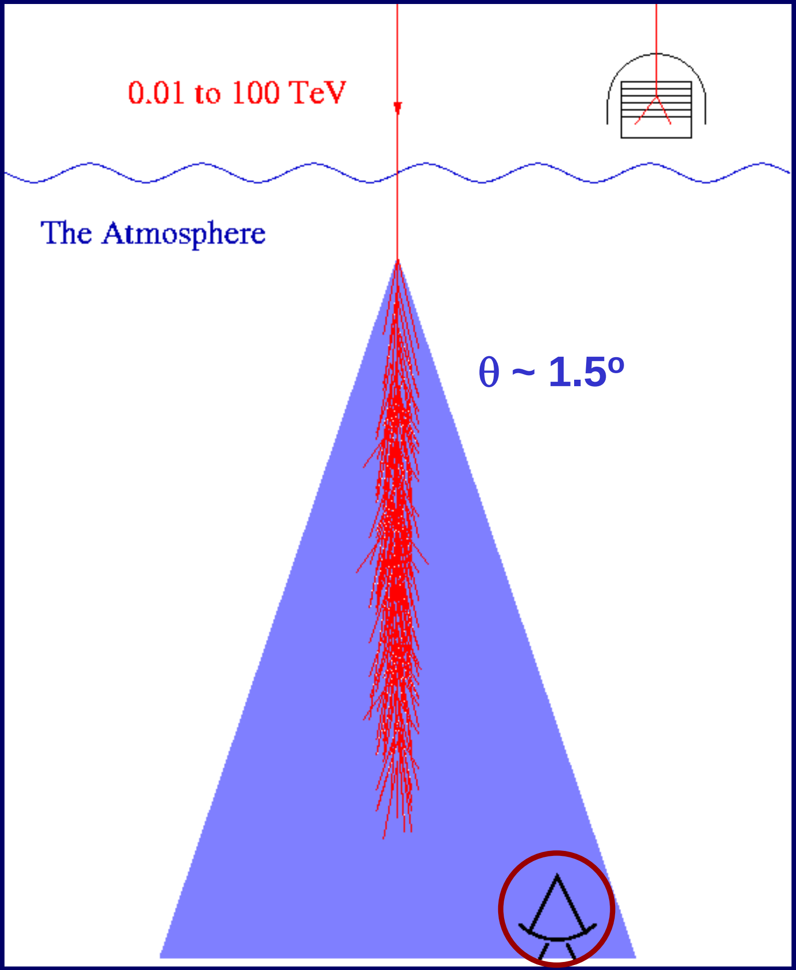
Atmospheric Cherenkov Technique

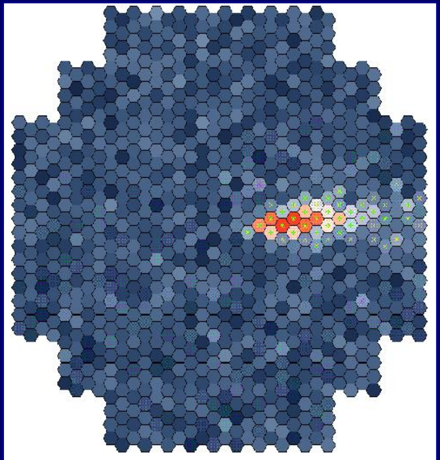


Single-dish Imaging Telescopes

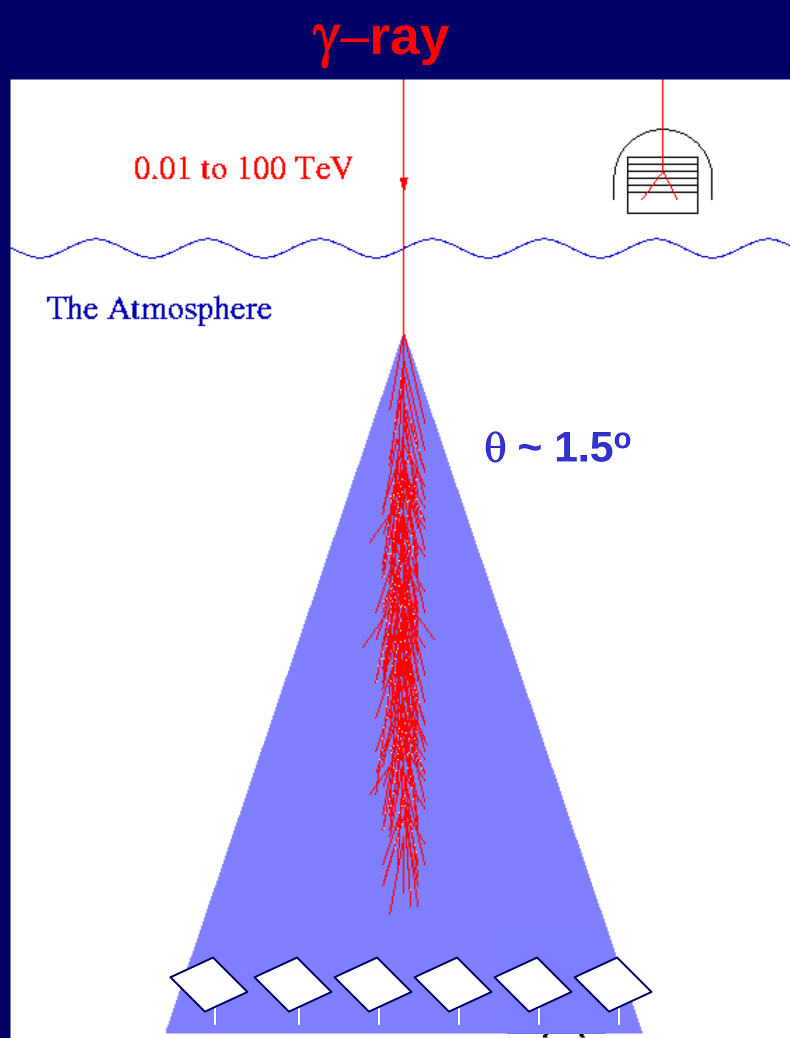
Whipple 10-meter

γ–ray





Wavefront Sampling Technique



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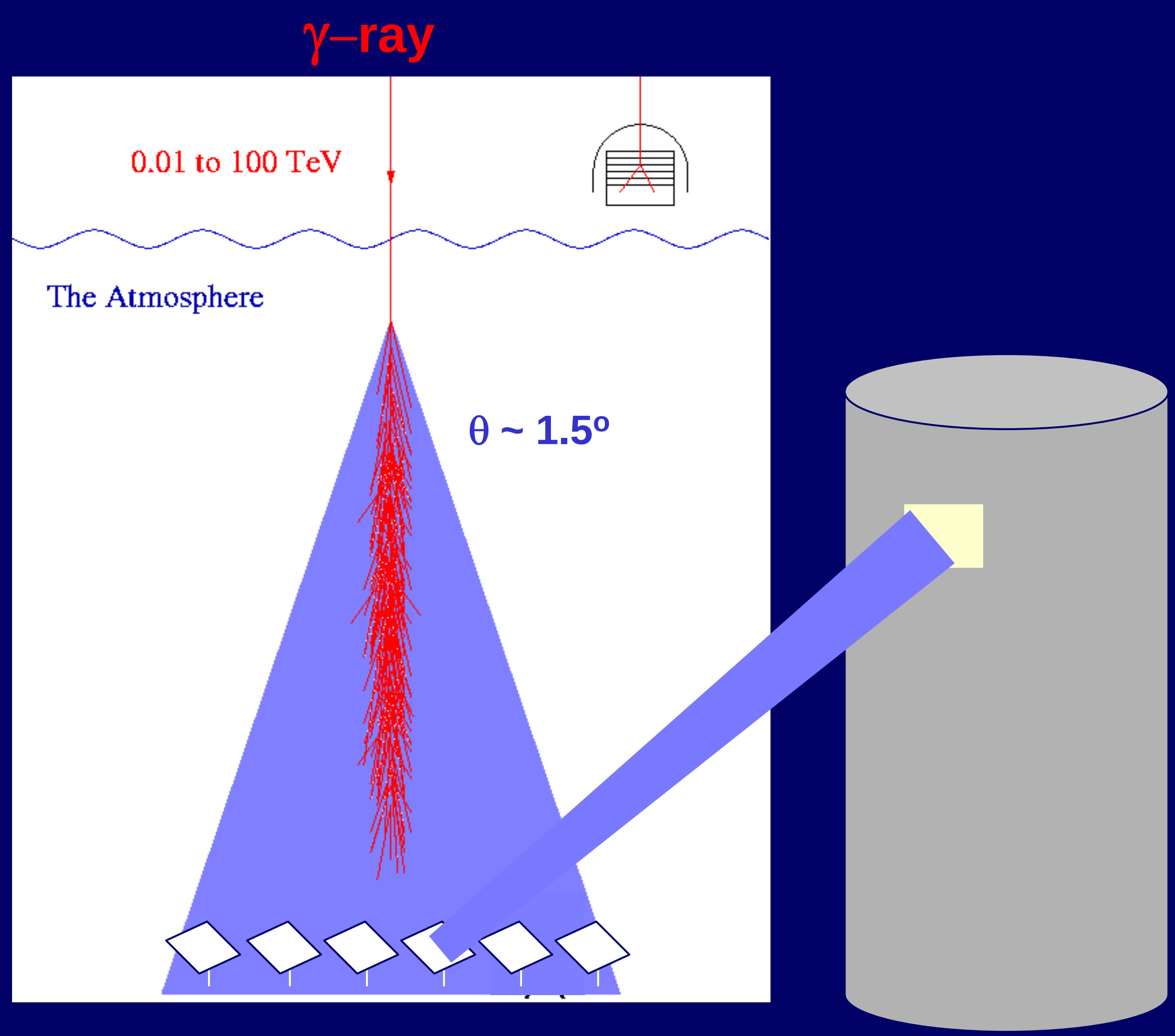

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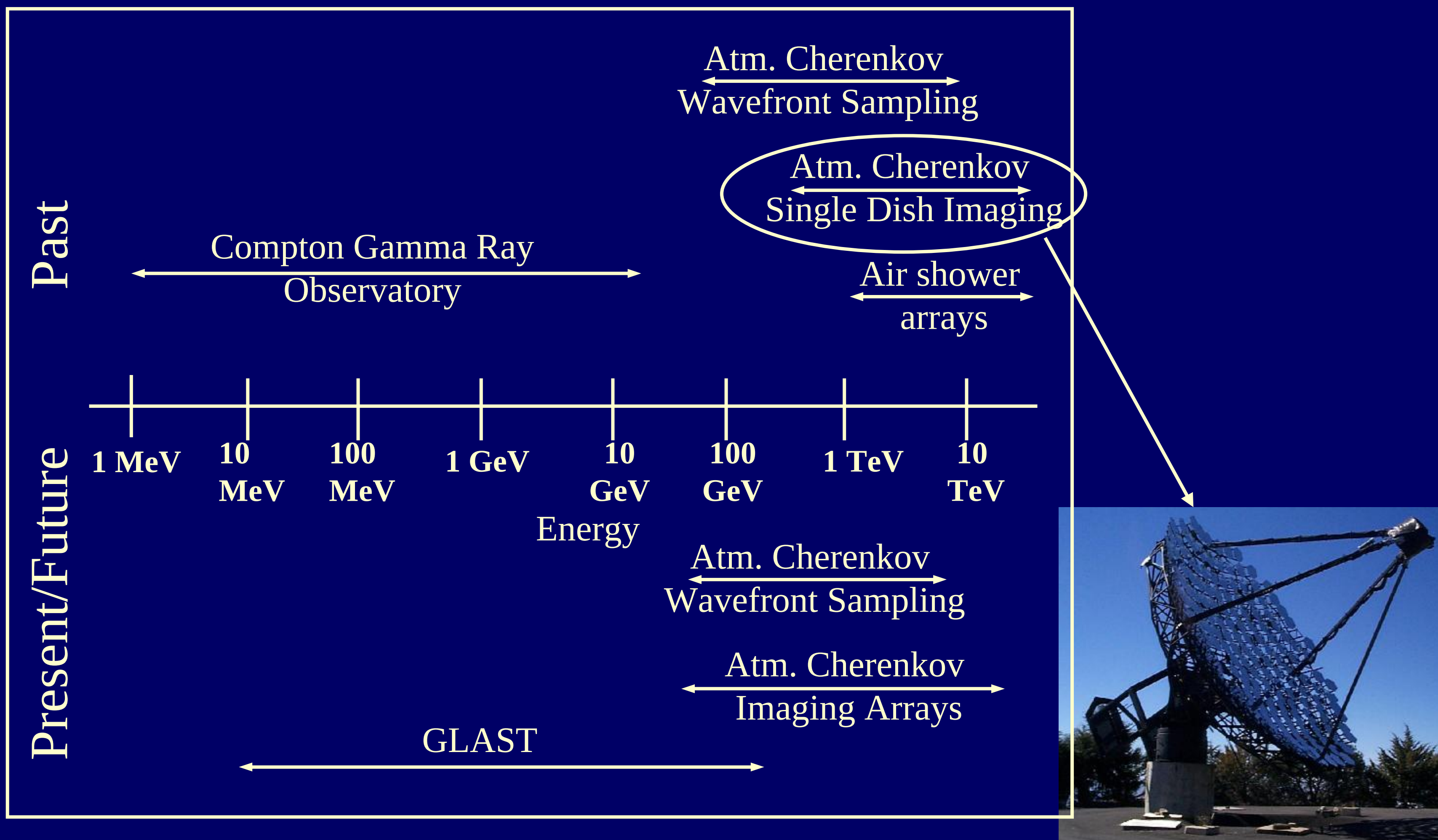

Whipple 10-meter

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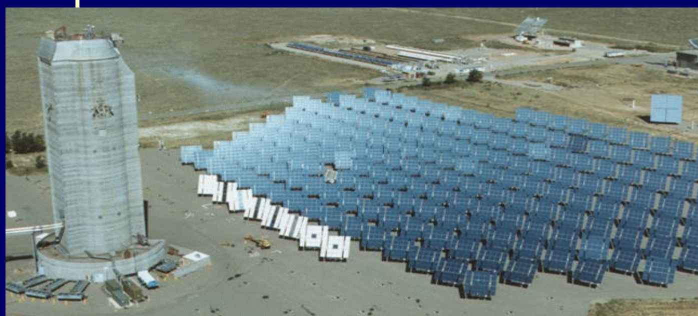


STACEE

Atm. Cherenkov
Wavefront Sampling

Atm. Cherenkov
Single Dish Imaging

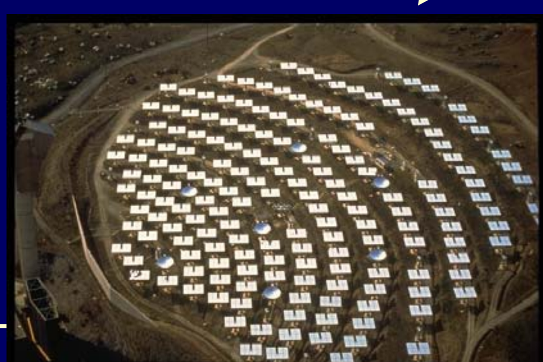
Air shower
arrays

1 MeV | 10 MeV | 100 MeV | 1 GeV | 10 GeV | 100 GeV | 1 TeV | 10 TeV

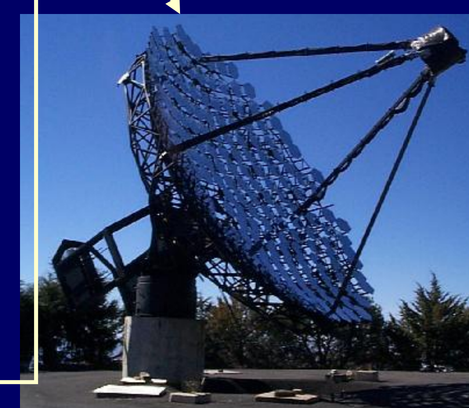
Energy

Atm. Cherenkov
Wavefront Sampling

Atm. Cherenkov
Imaging Arrays



CELESTE



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Exploring the Gamma-ray Spectrum

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Energy

Present/Future

Atm. Cherenkov
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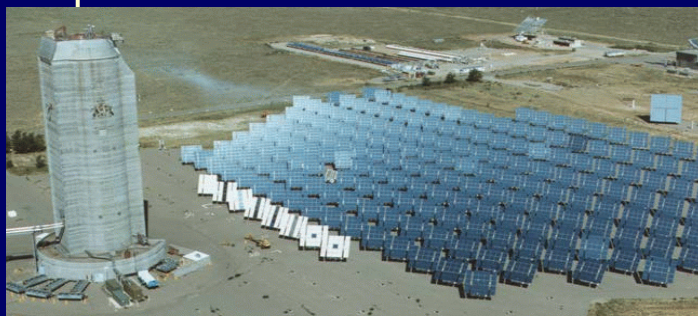
Atm. Cherenkov
Imaging Arrays

GLAST

Exploring the Gamma-ray Spectrum

Present/Future



STACEE

HESS

1 MeV | **10 MeV** | **100 MeV** | **1 GeV** | **10 GeV** | **100 GeV** | **1 TeV** | **10 TeV**

Energy

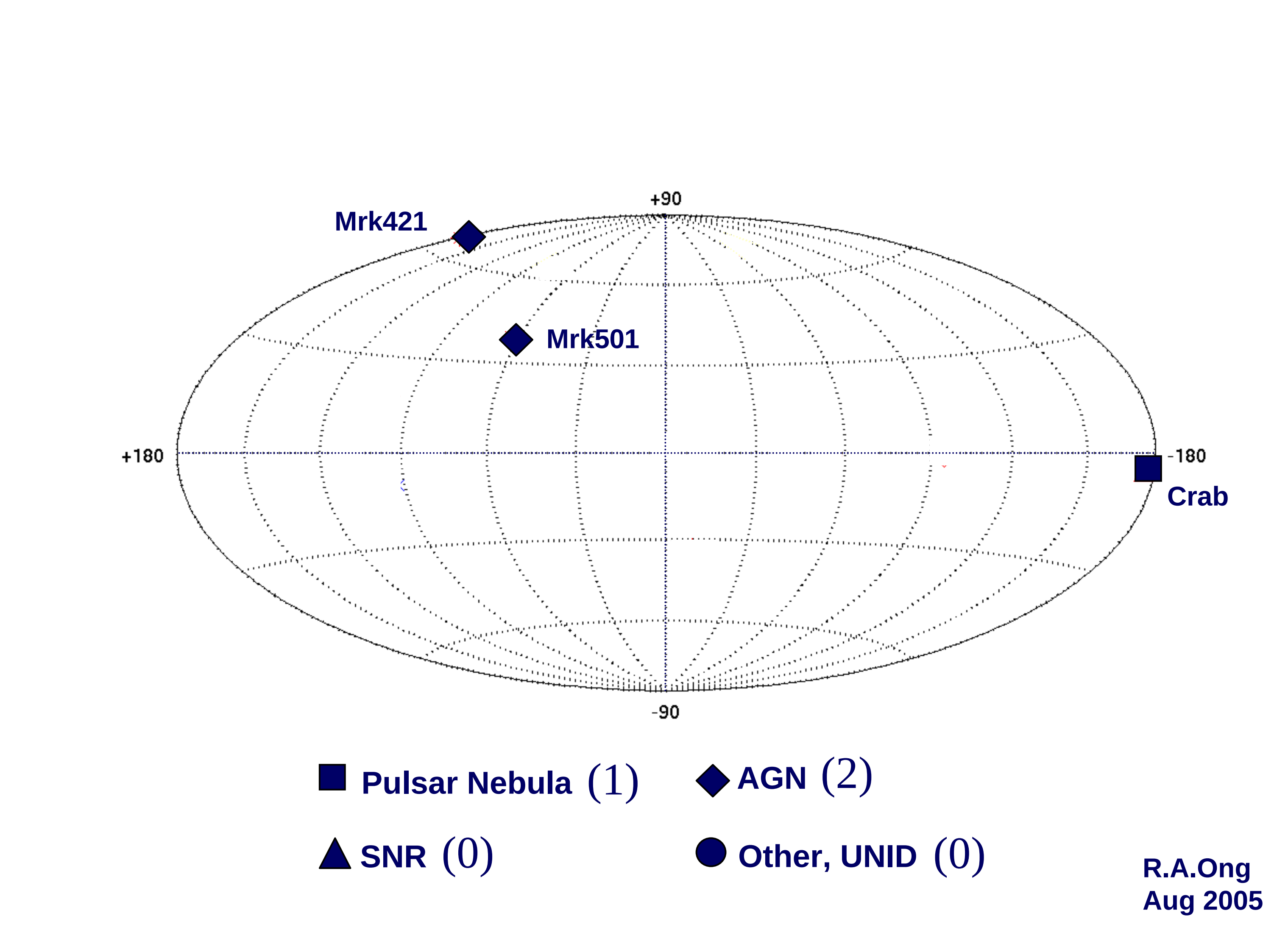
Atm. Cherenkov
Wavefront Sampling

Atm. Cherenkov
Imaging Arrays

VERITAS

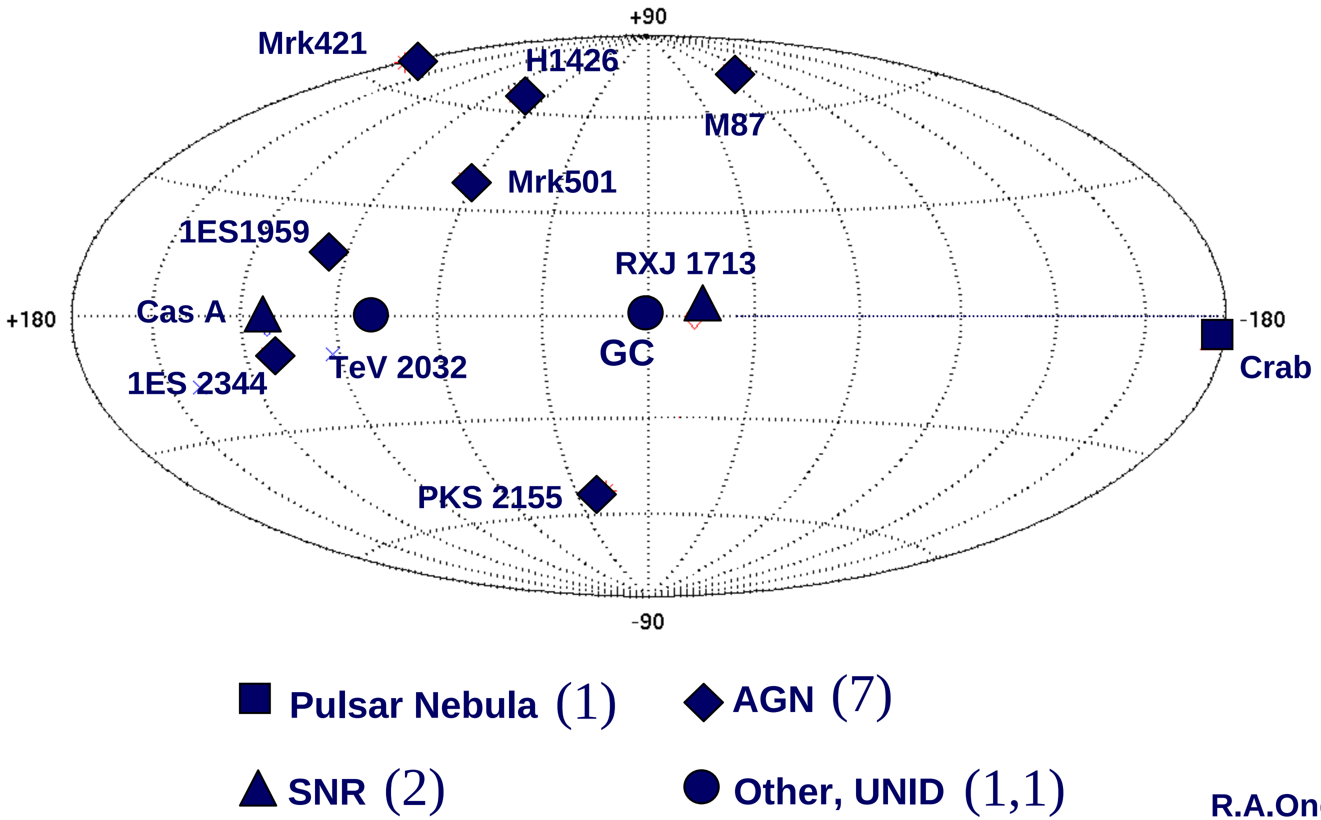
The High-Energy Gamma Ray Sky

1995 – 3 sources



The High-Energy Gamma Ray Sky

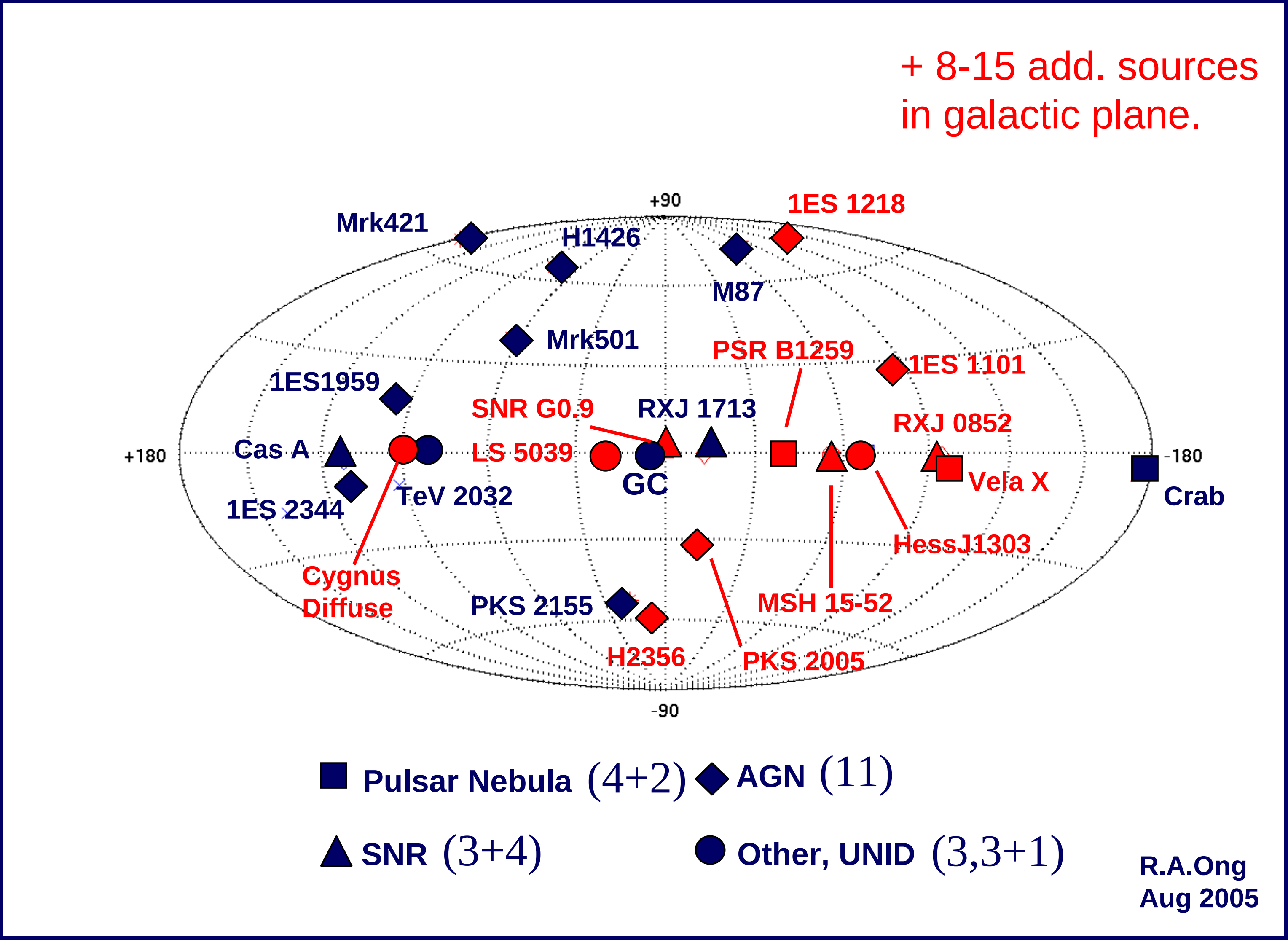
2004 – 12 sources



R.A.Ong
Aug 2005

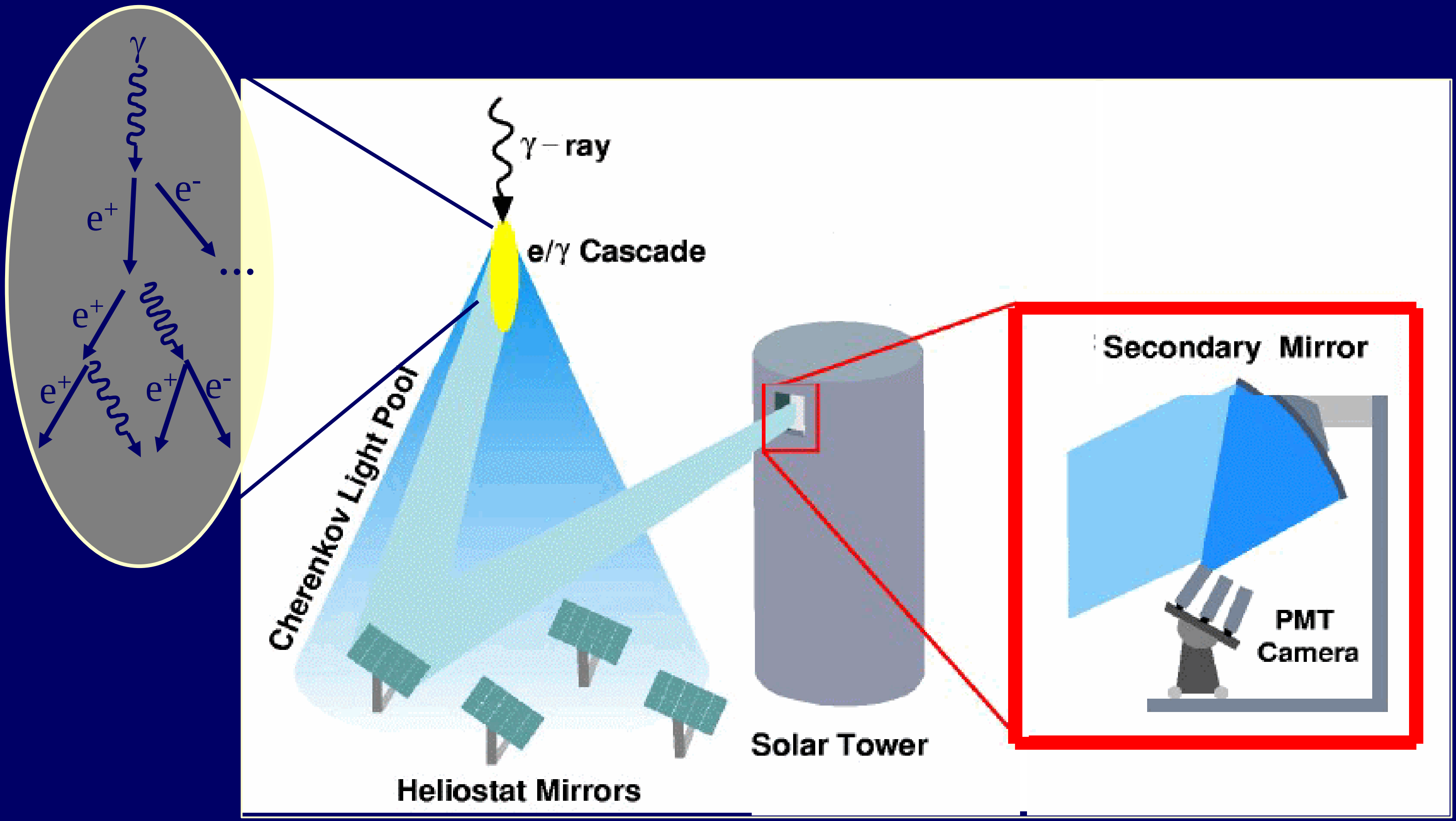
The High-Energy Gamma Ray Sky

2005 – 31 sources!



Wavefront Sampling Detectors

STACEE & CELESTE

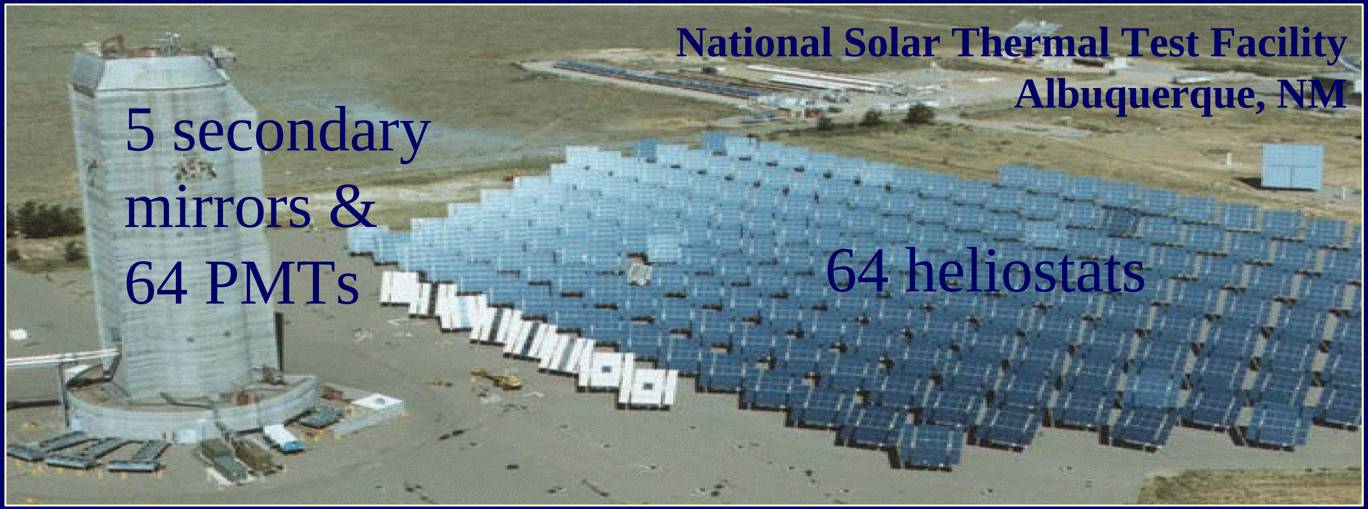


Cherenkov light intensity on ground → energy of gamma ray

Cherenkov pulse arrival times at heliostats → direction of source

STACEE

Solar Tower Atmospheric Cherenkov Effect Experiment



STACEE

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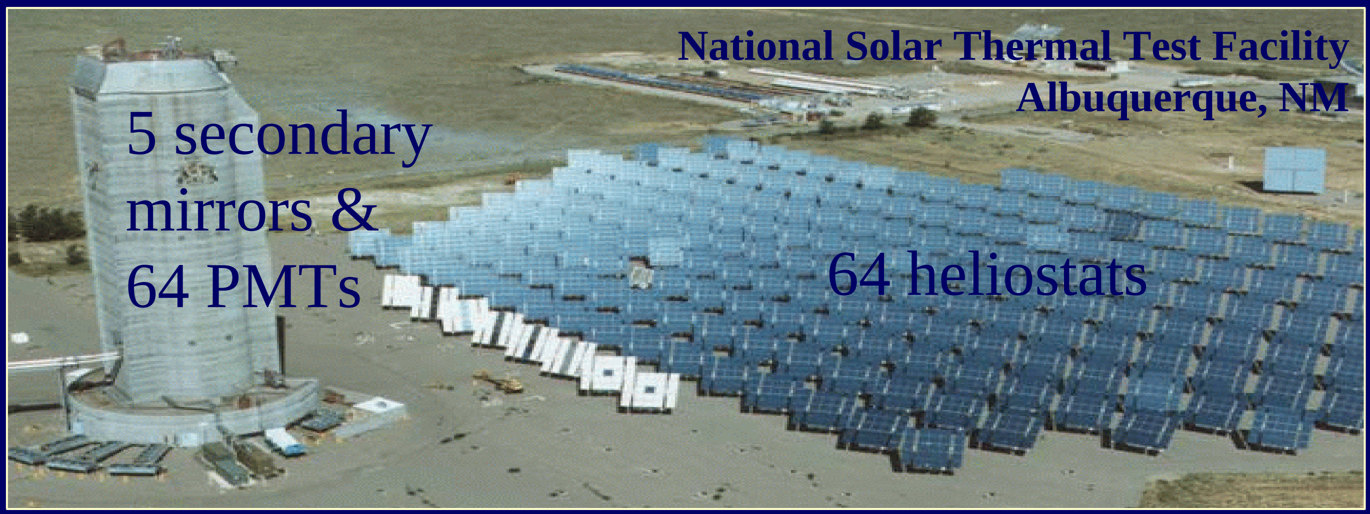
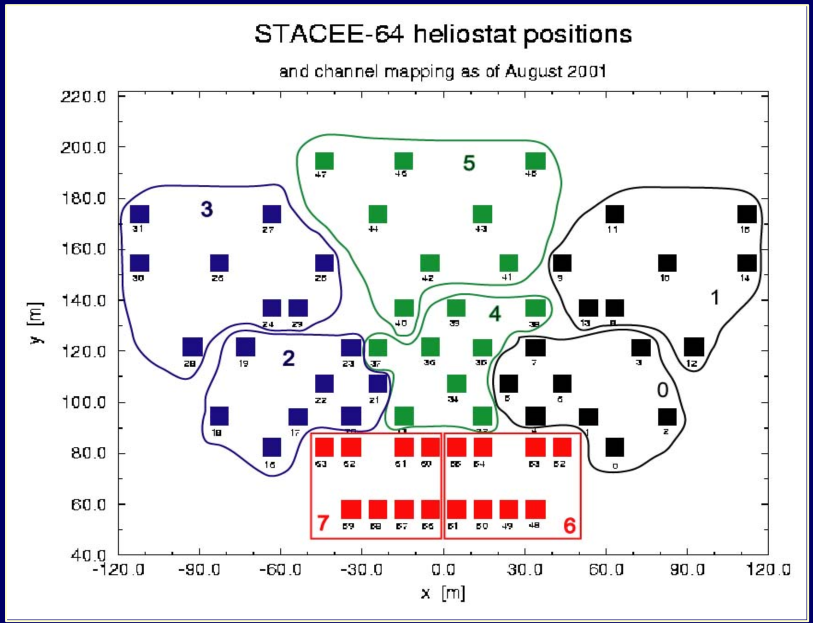
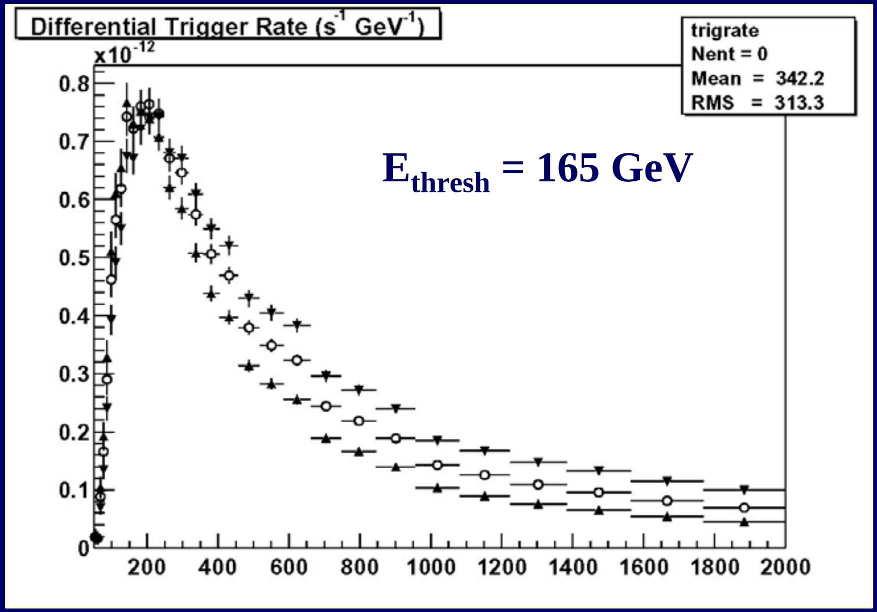


- PMT rate @ 4 PEs: ~10 MHz
- Two-level trigger system (24 ns window):
  - cluster: ~10 kHz
  - array: ~7 Hz
- 1-GHz FADCs digitize each Cherenkov pulse



STACEE Advantages / Disadvantages

- 2-level trigger system ⇒ good hardware rejection of hadrons
- GHz FADCs ⇒ pulse shape information
- Large mirror area ($64 \times 37 m^2$) ⇒ **low energy threshold**



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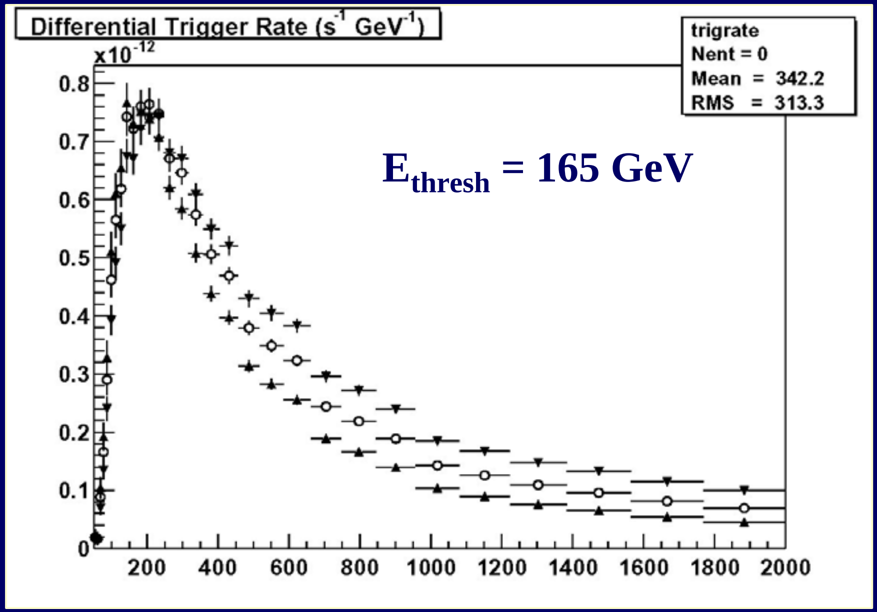


But…

- Limited off-line cosmic ray rejection
  ⇒ **limited sensitivity**: 1.4σ/hour on the Crab Nebula
- Compare to Whipple sensitivity: 3σ/hour above 300 GeV

STACEE Data

Observing Strategy: Equal-time background observations for every source observation (1-hour “pairs”)

Analysis:

Cuts for data quality

↓

Correction for unequal NSB levels

↓

Cosmic ray background rejection

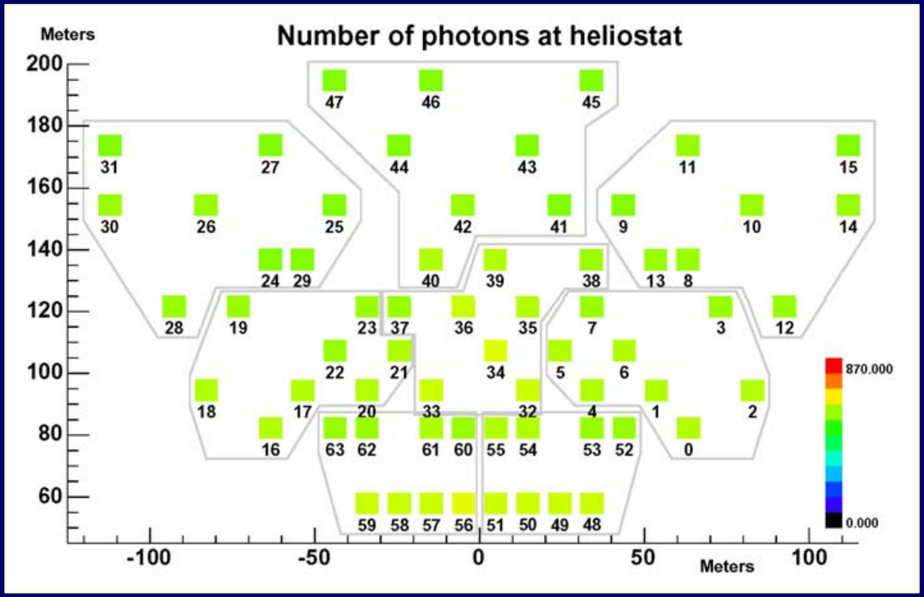
↓

Significance/flux determination

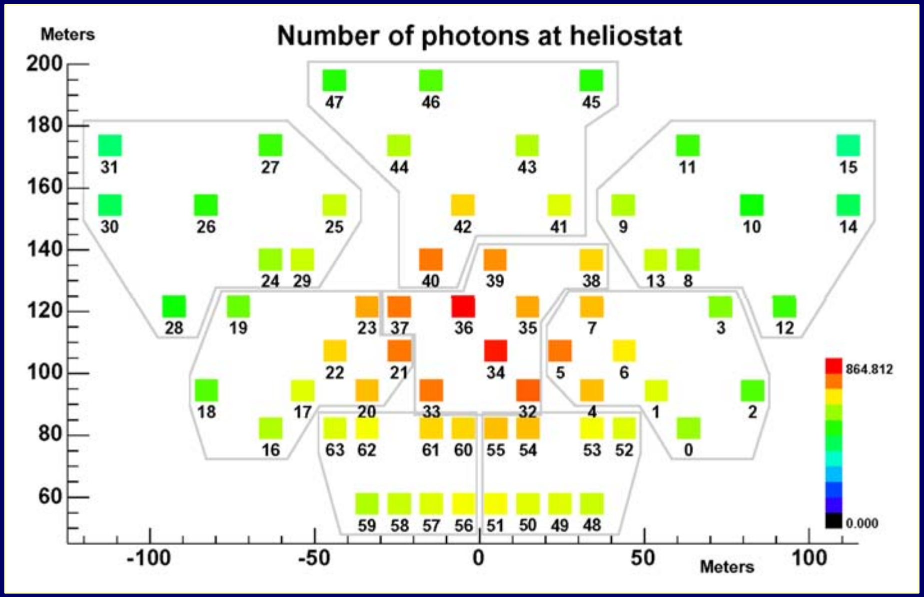
Energy Reconstruction Idea

Utilize two properties of gamma-ray showers:

1. Linear correlation: Cherenkov intensity and gamma-ray energy
2. Uniform intensity over shower area



200 GeV gamma ray



500 GeV proton

Energy Reconstruction Method

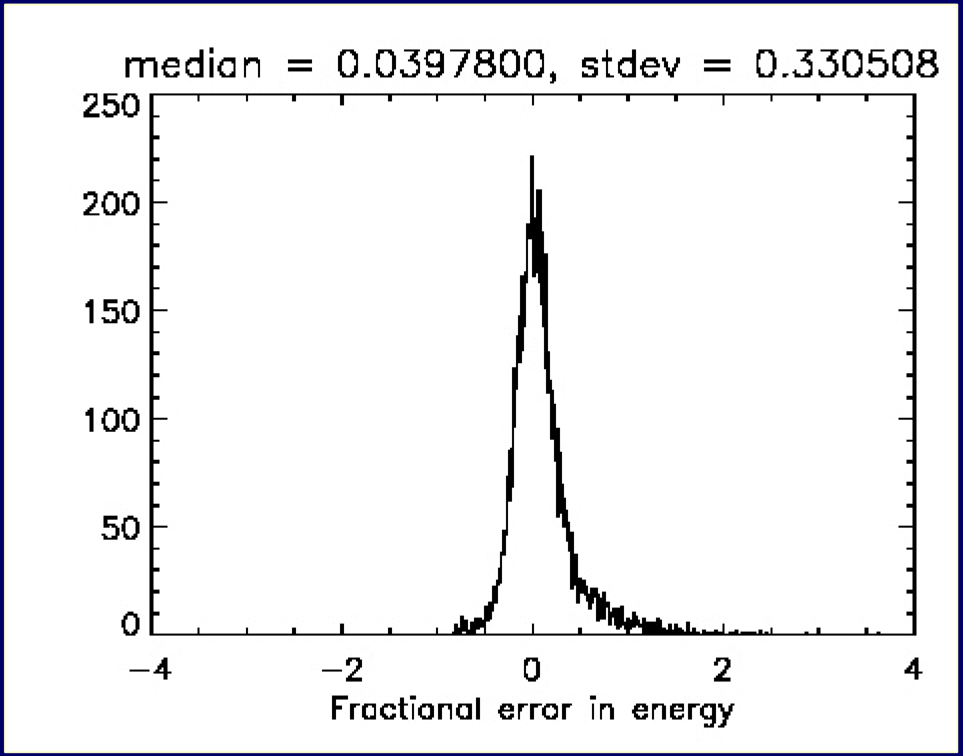
New method to find energies of gamma rays from STACEE data:

1. Reconstruct Cherenkov light distribution on the ground from PMT charges
2. Reconstruct energy from spatial distribution of light

Results:

fractional errors < 10%

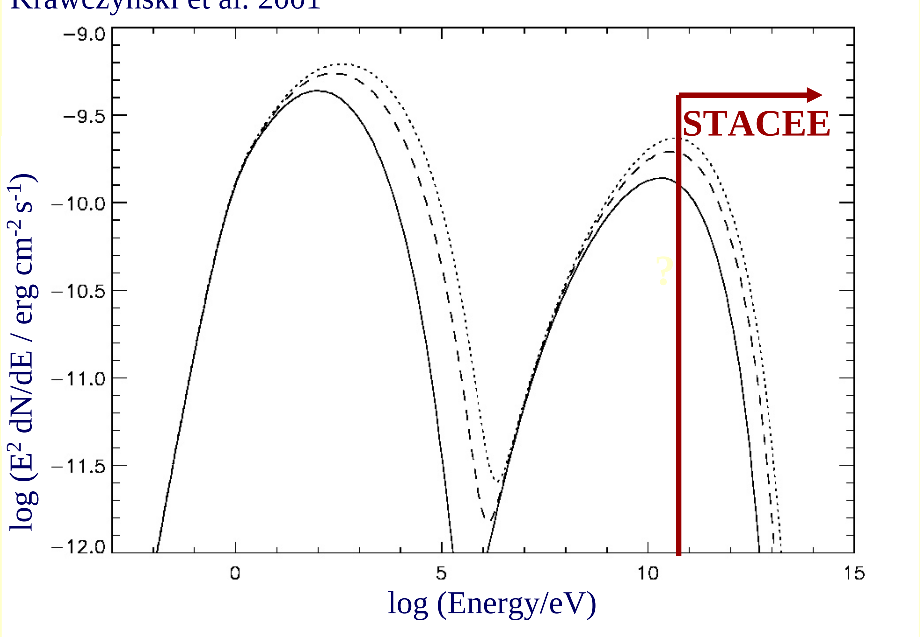
energy resolution ~25-35%



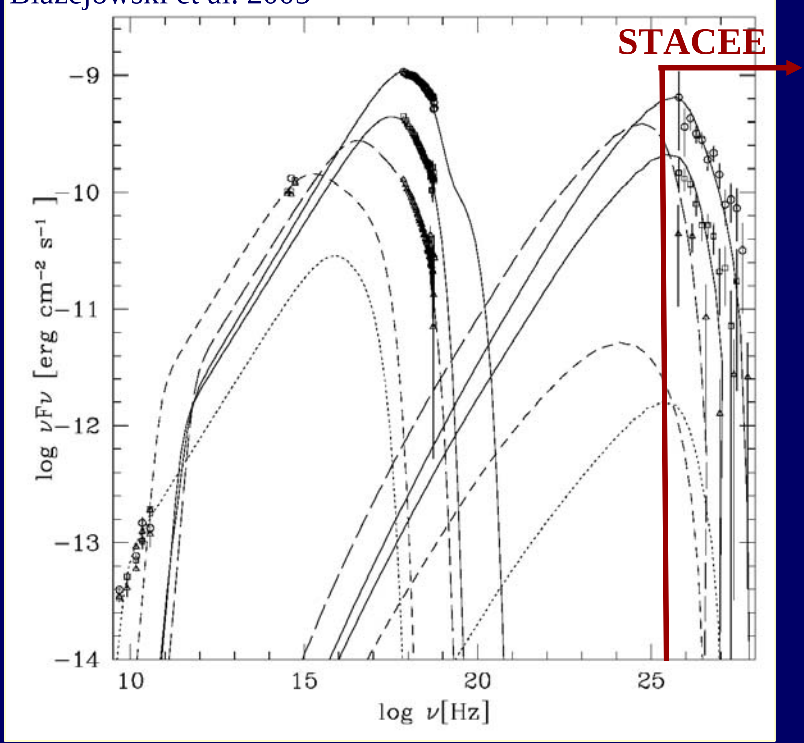
Markarian 421

- Nearby: z = 0.03
- First TeV extragalactic source detected (Punch et al. 1992)
- Well-studied at all wavelengths except 50-300 GeV
- Inverse-Compton scattering is favored
- High-energy peak expected around 100 GeV
- Only one previous spectral measurement at ~100 GeV (Piron *et al.* 2003)

Krawczynski et al. 2001

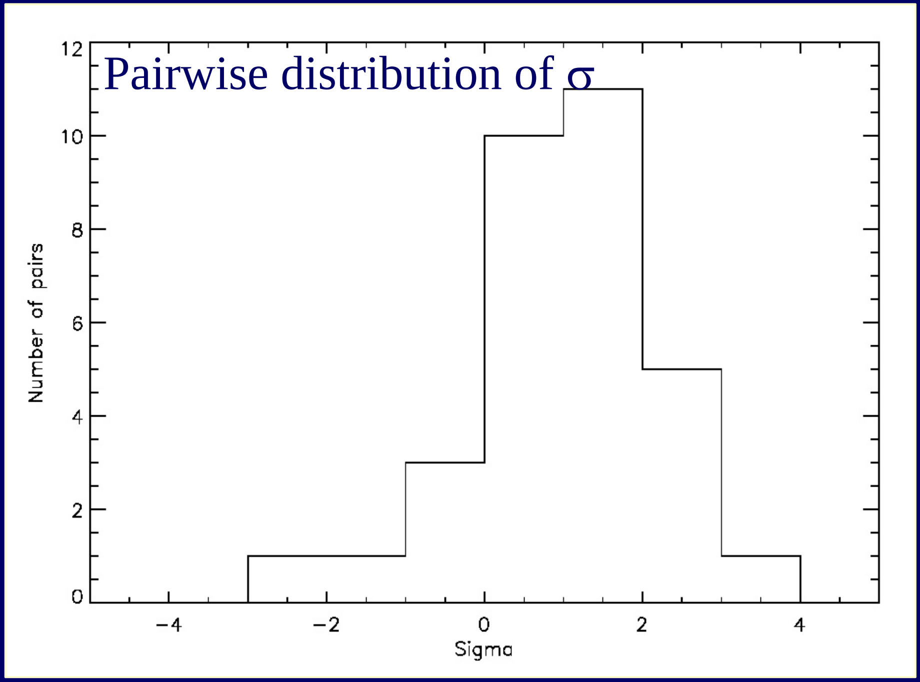


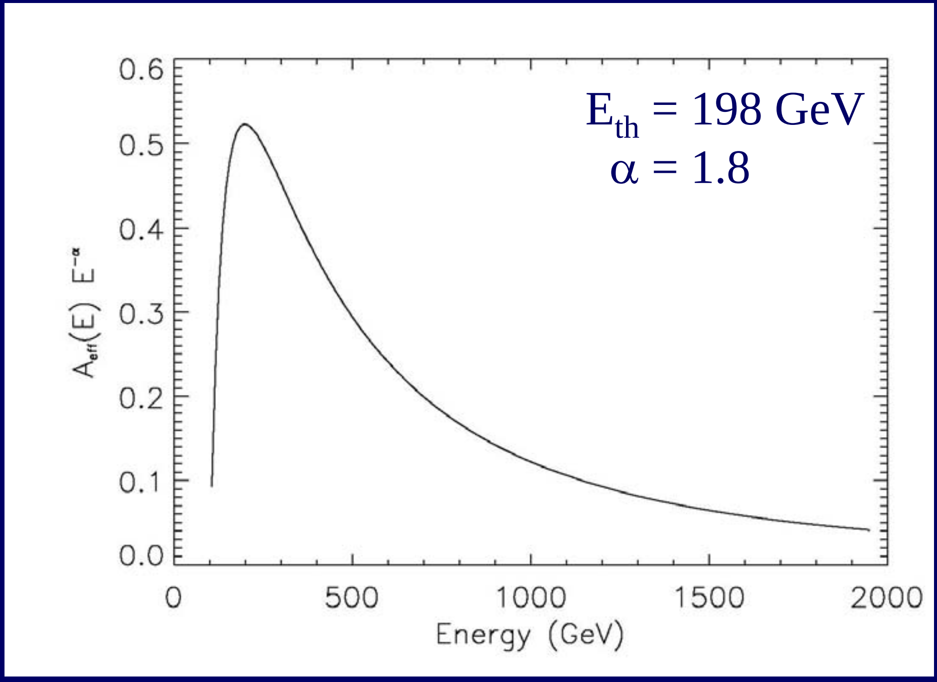
Blazejowski et al. 2005



STACEE Detection of Mkn 421

- Observed by STACEE January – May 2004
- 9.1 hours on-source + equal time in background observations
- $N_{on} - N_{off} = 2843$ gamma-ray events
- 5.8σ detection
- 5.52 ± 0.95 gamma rays per minute
- Energy threshold ~198 GeV for $\alpha = 1.8$

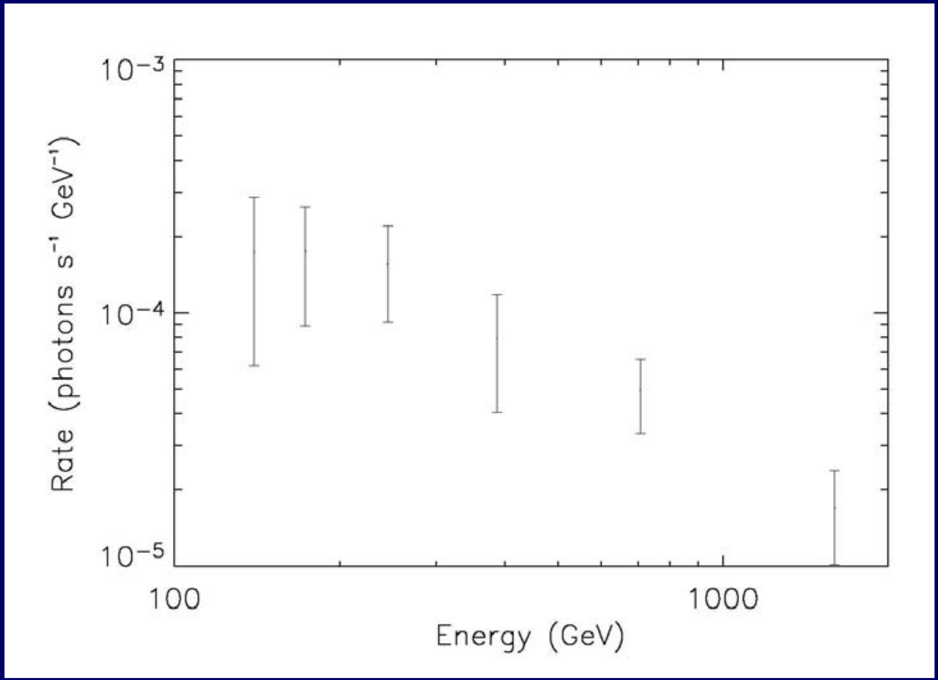




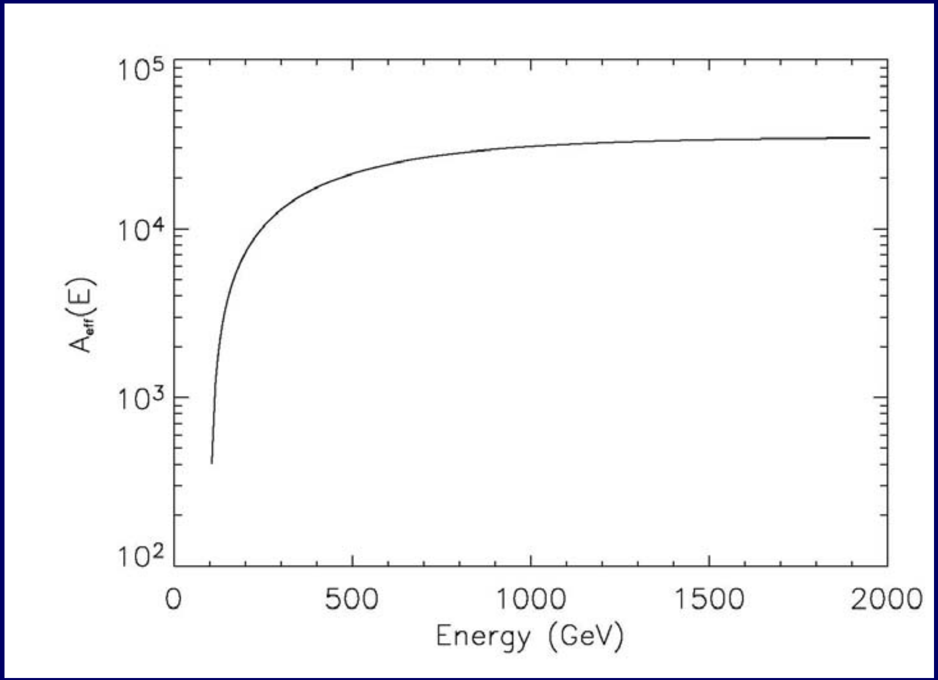
Spectral Analysis of Mkn 421

- Six energy bins between 130 GeV and 2 TeV
- Find gamma-ray excess in each bin
- Convert to differential flux with effective area curve

Gamma-ray rate (photons s^{-1} GeV^{-1})

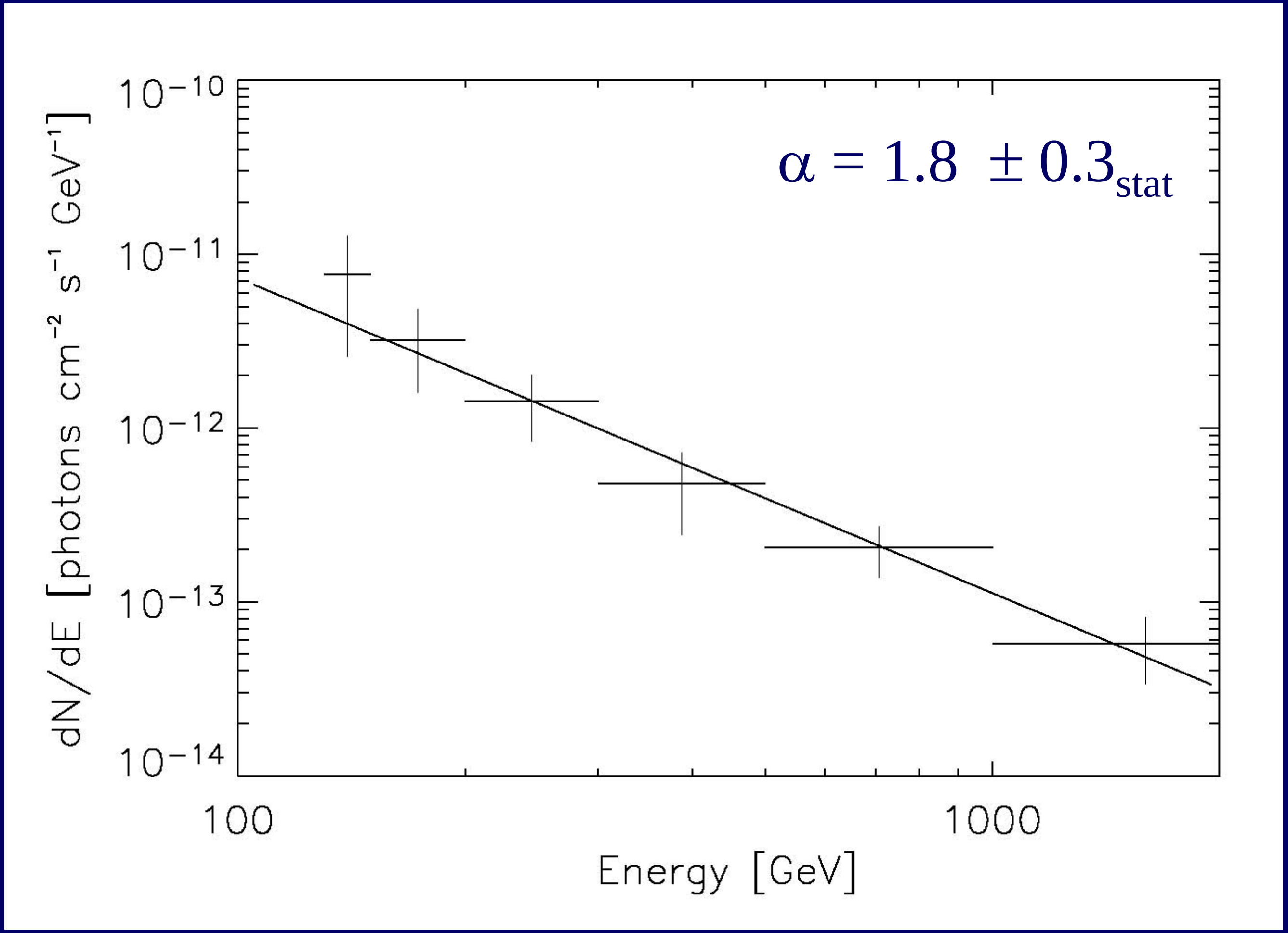


Effective area (m^2)



Spectral Analysis of Mkn 421

First STACEE spectrum



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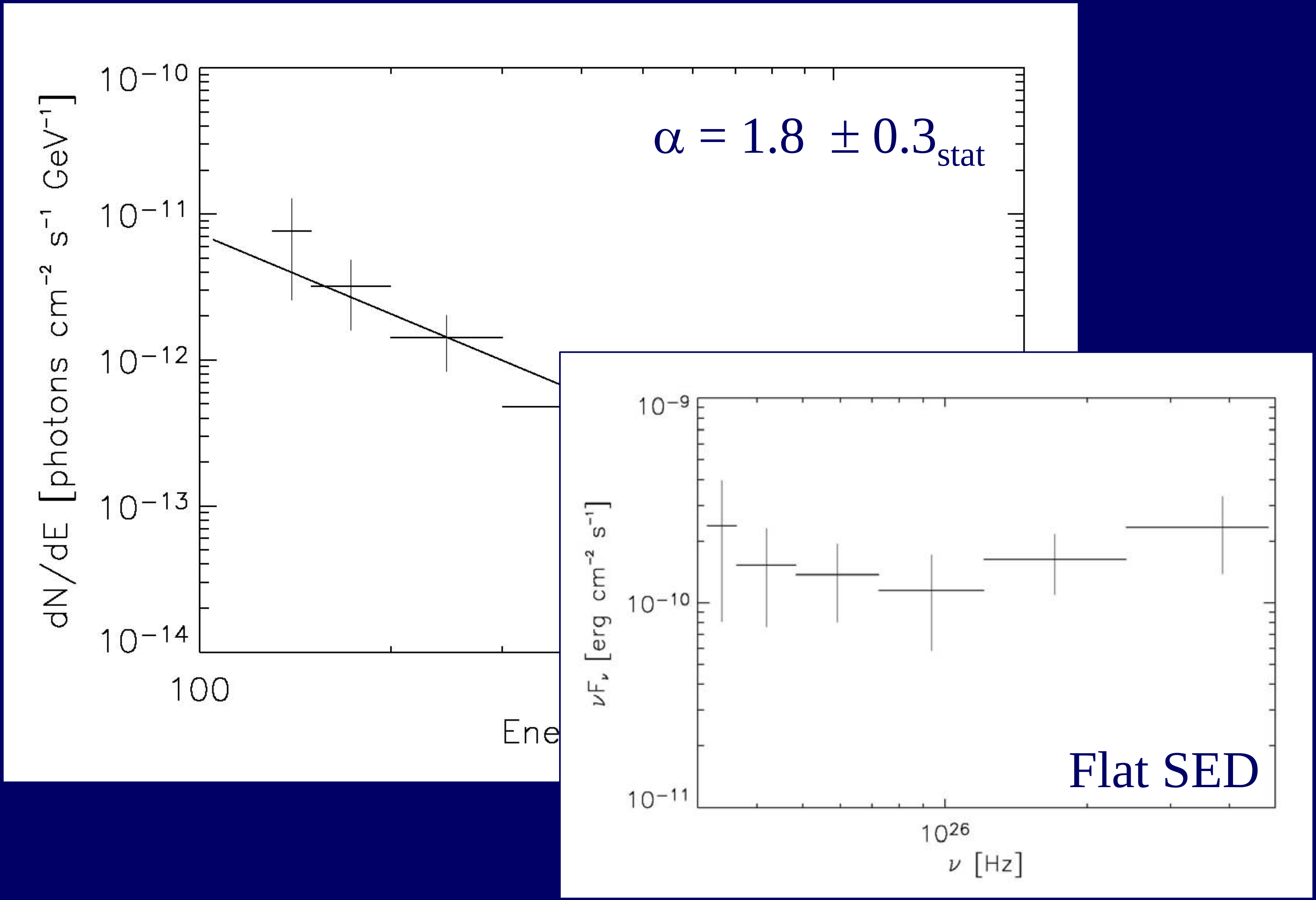
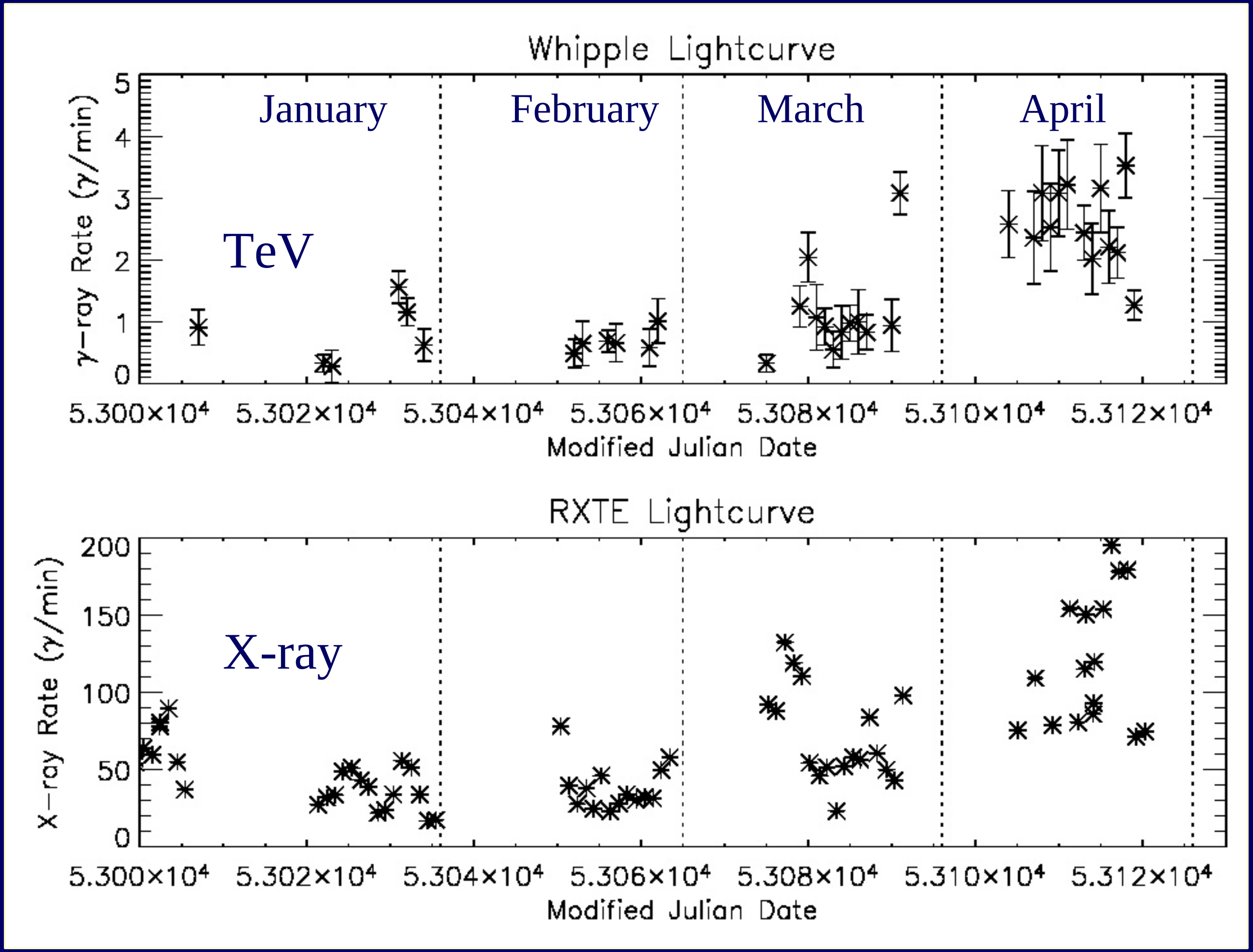


2004 Multiwavelength Campaign



PCA data courtesy of W. Cui, Blazejowski *et al.* 2005

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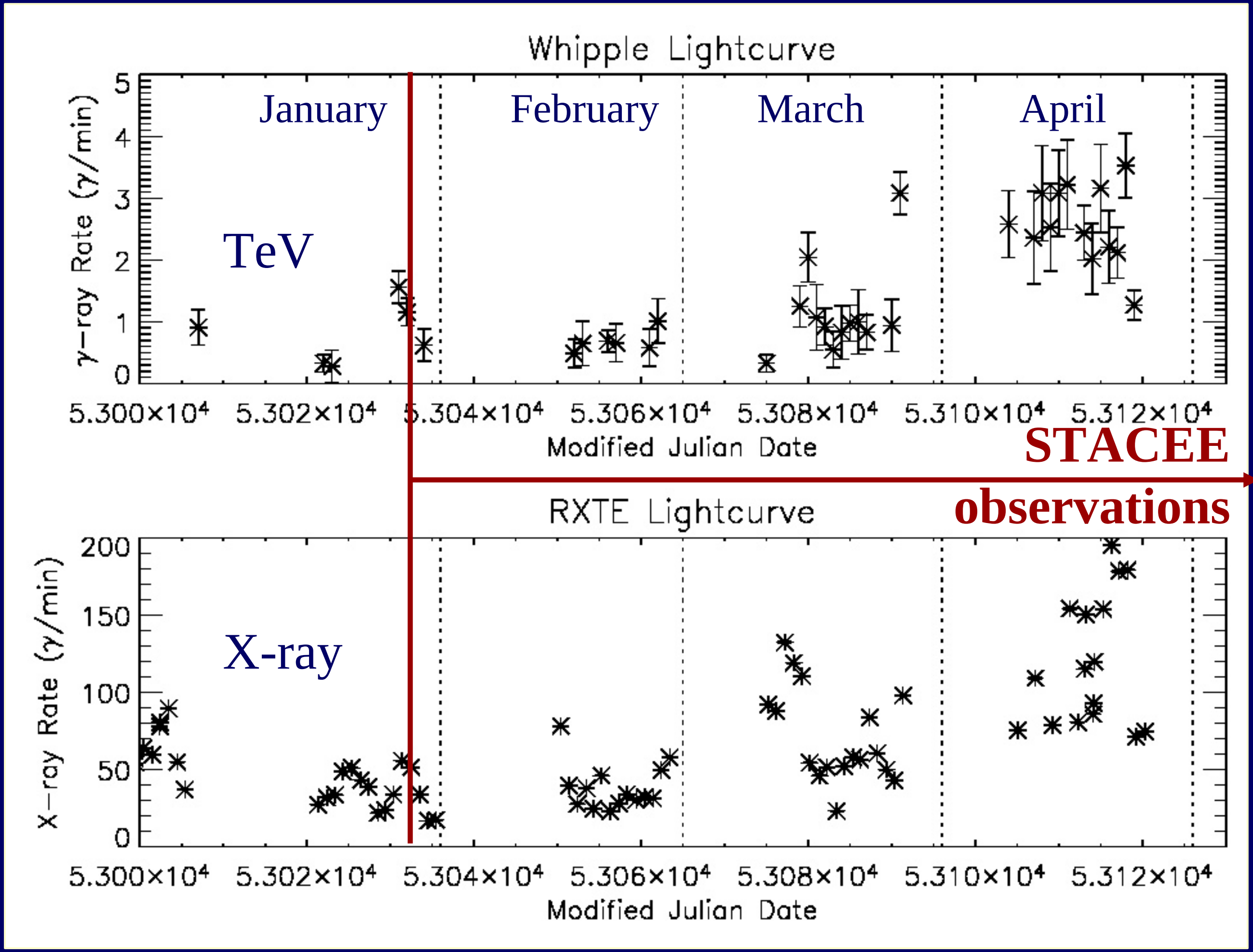
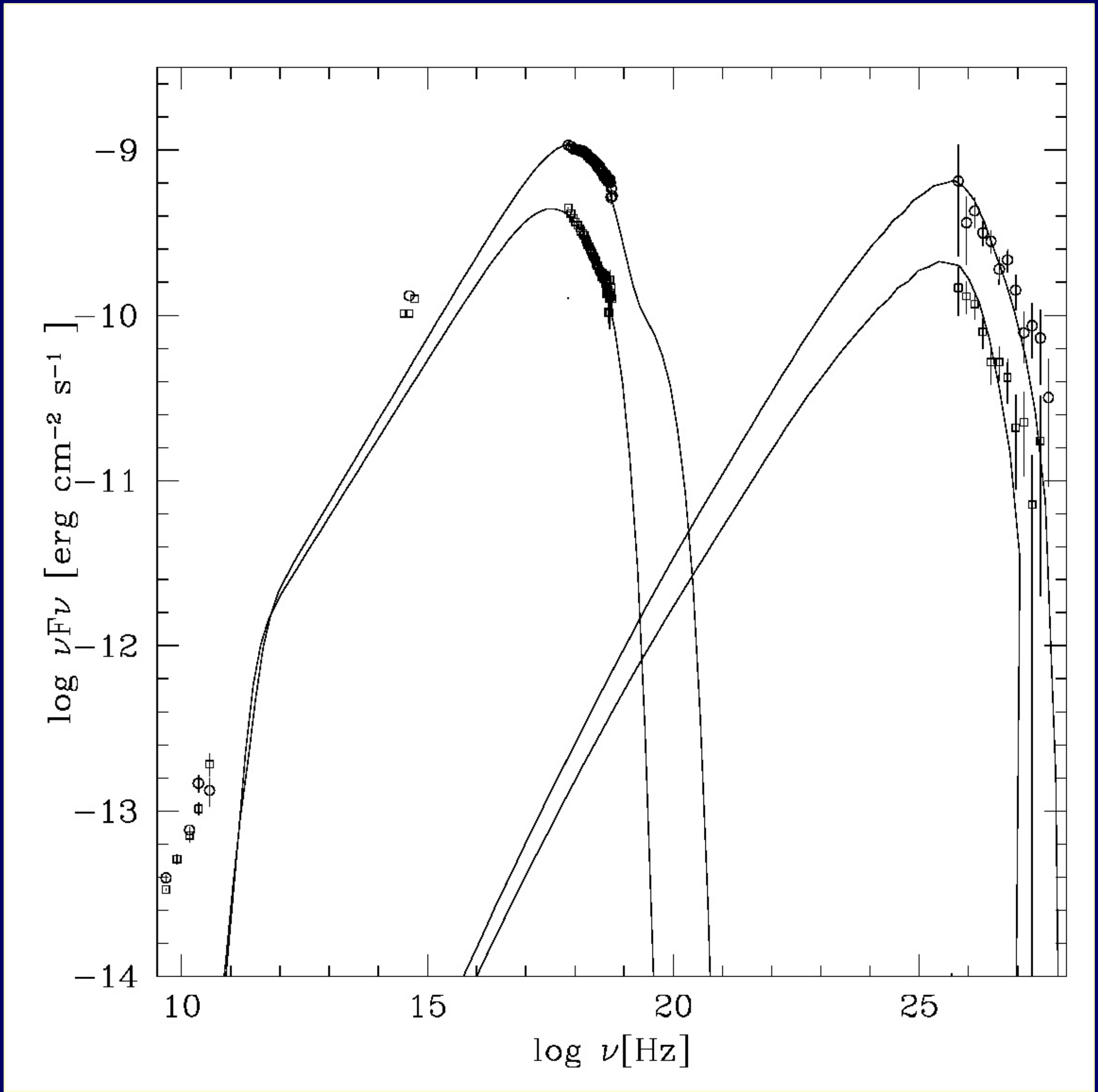


PCA data courtesy of W. Cui, Blazejowski *et al.* 2005

- STACEE coverage: 40% of MW nights
- ~90% of STACEE data taken during MW nights
- STACEE combines low and high flux states

Multiwavelength Results



Blazejowski *et al.* 2005

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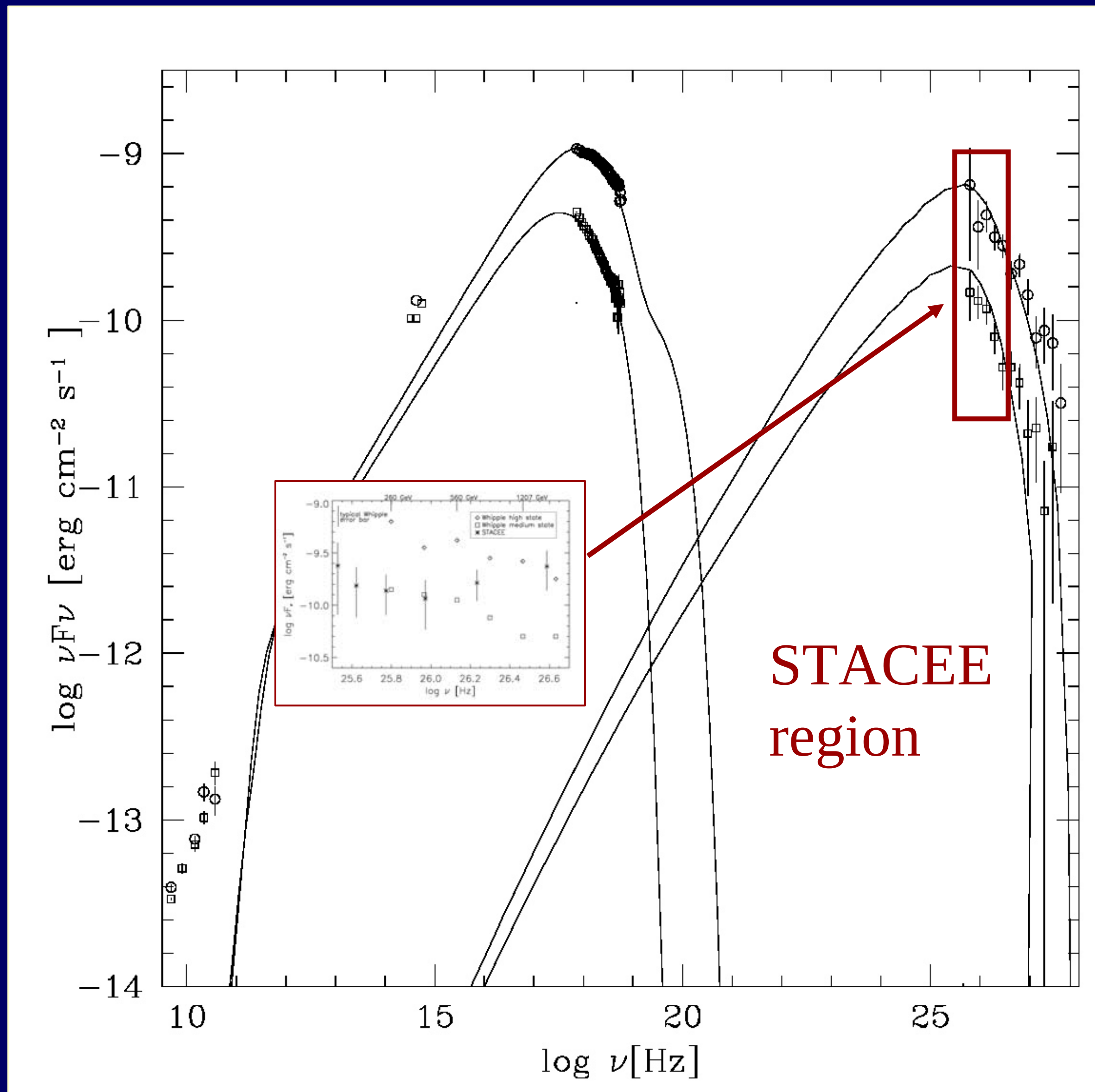
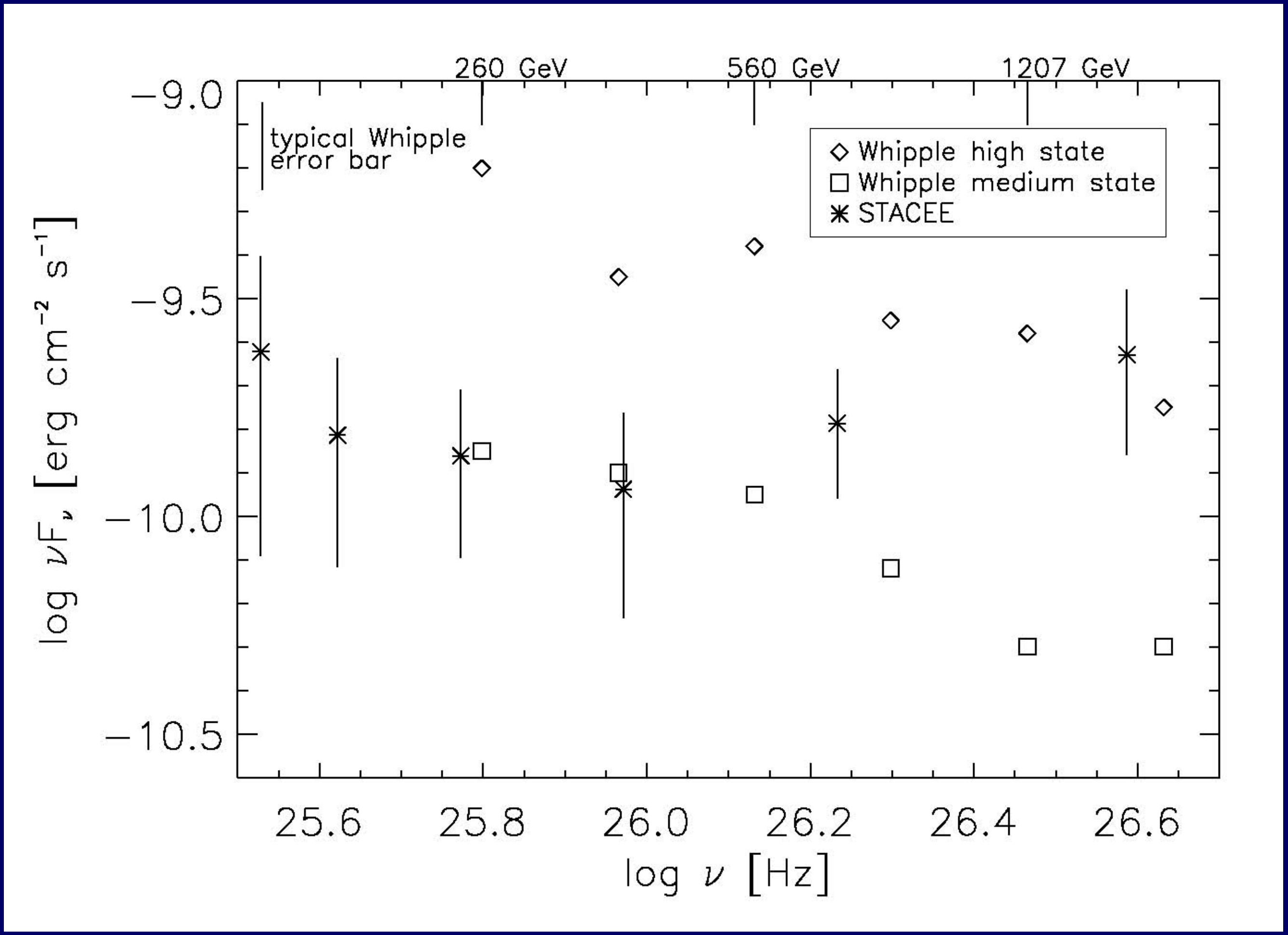


Blazejowski *et al.* 2005

STACEE + Whipple Results



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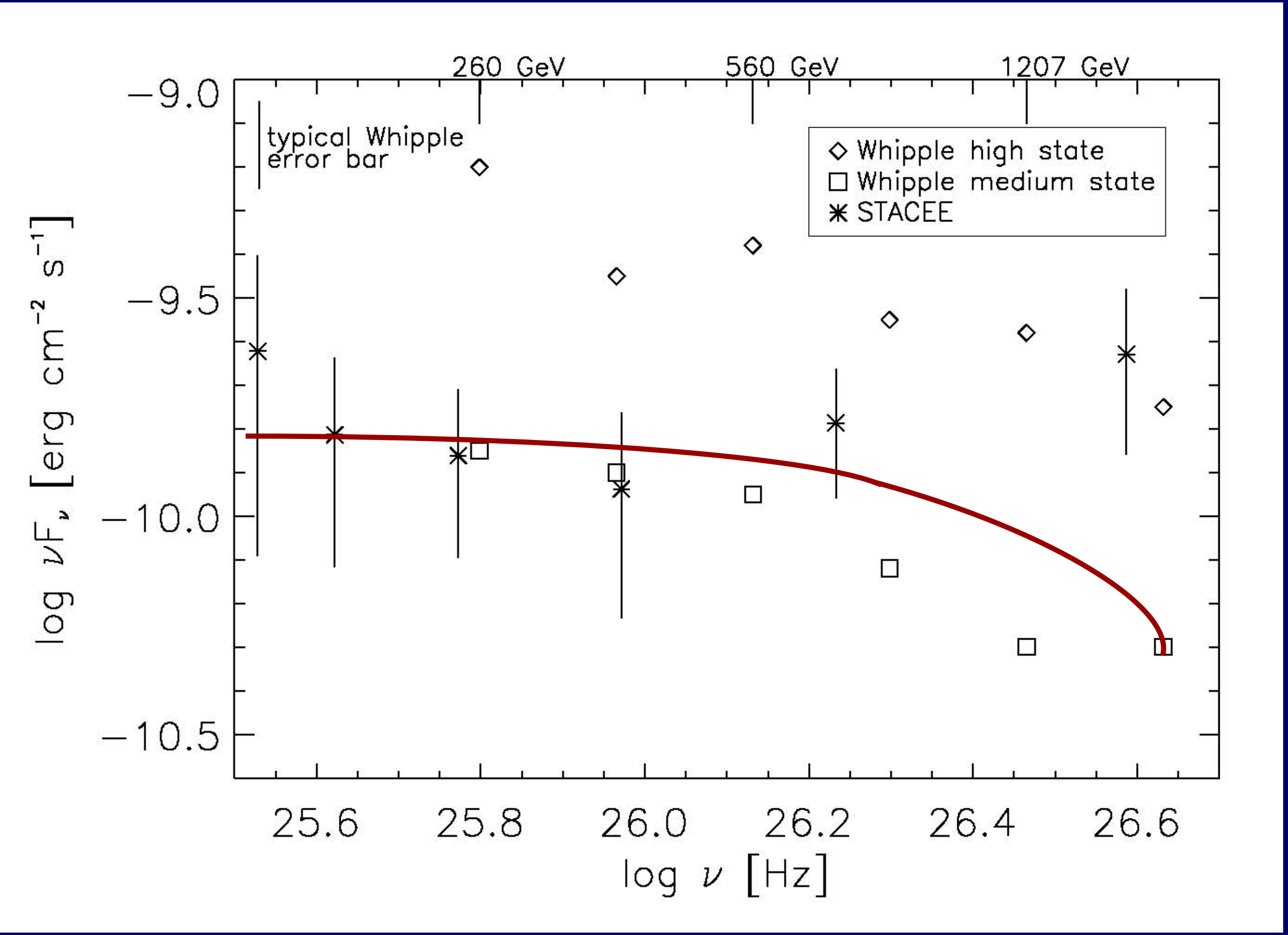


Science Interpretation

• STACEE's first energy bin is ~90 GeV below Whipple's.

• STACEE result:

→ is consistent with a flat or rising SED.

→ suggests that the high-energy peak is above ~200 GeV.

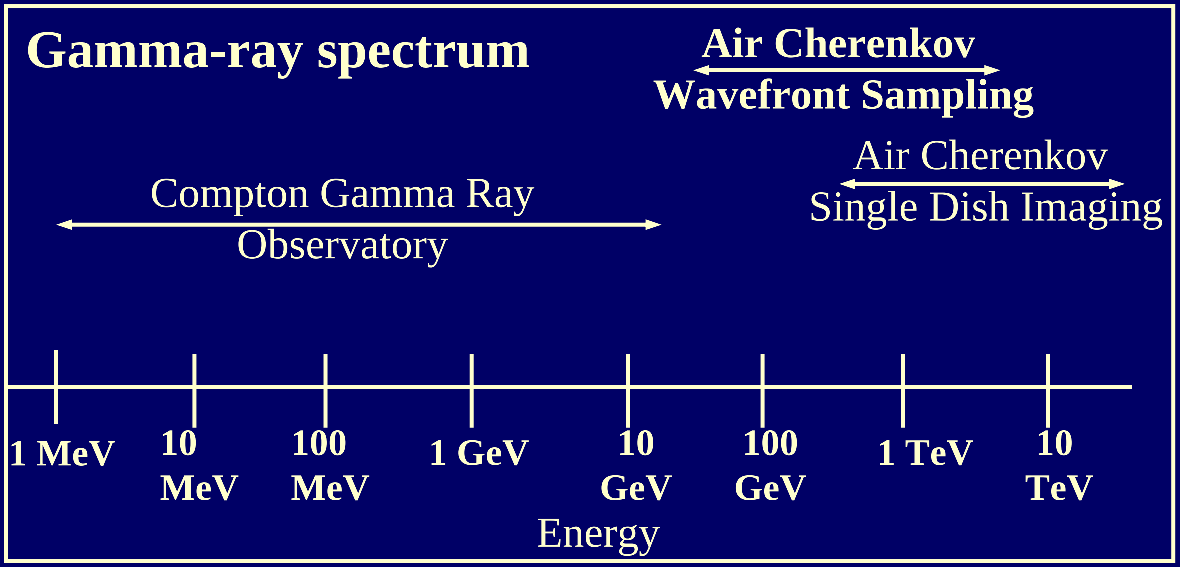
→ slghtly is inconsistent with most past IC modeling.

• Combined STACEE/Whipple data suggest that the peak is around 200-500 GeV.

• SED peak reflects peak of electron energy distribution.

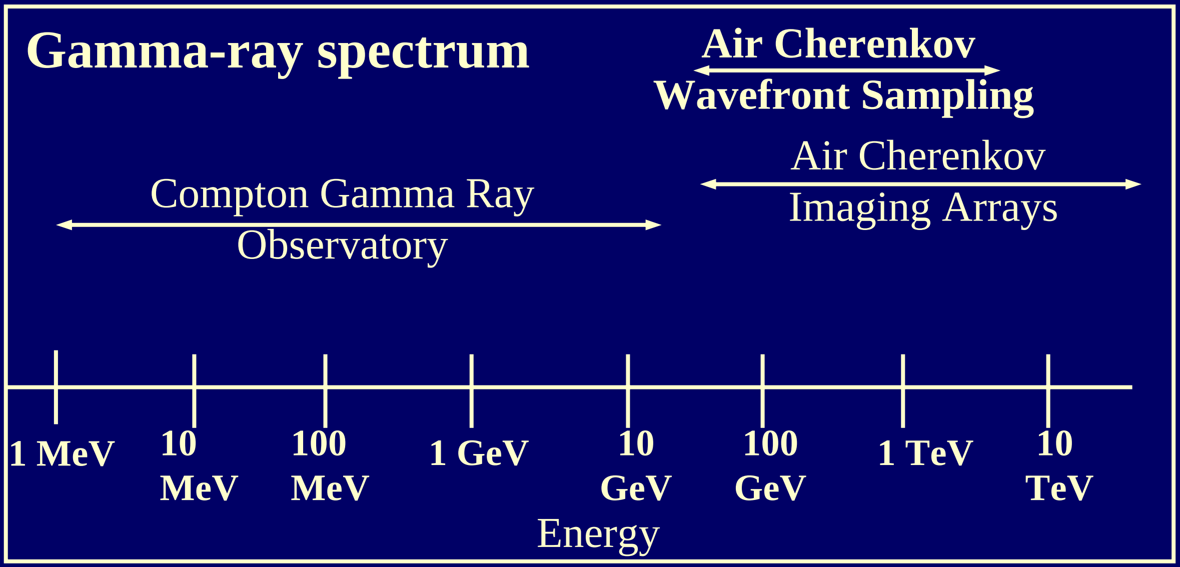
Prospects for the Future

- STACEE will operate for another year



Prospects for the Future

- STACEE will operate for another year
- Imaging arrays coming online, $E_{threshold} \approx 150$ GeV
  - HESS: 5σ Crab detection in 30 seconds!
  - VERITAS: 2 (of 4) dishes completed



VHE Experimental World

Prospects for the Future

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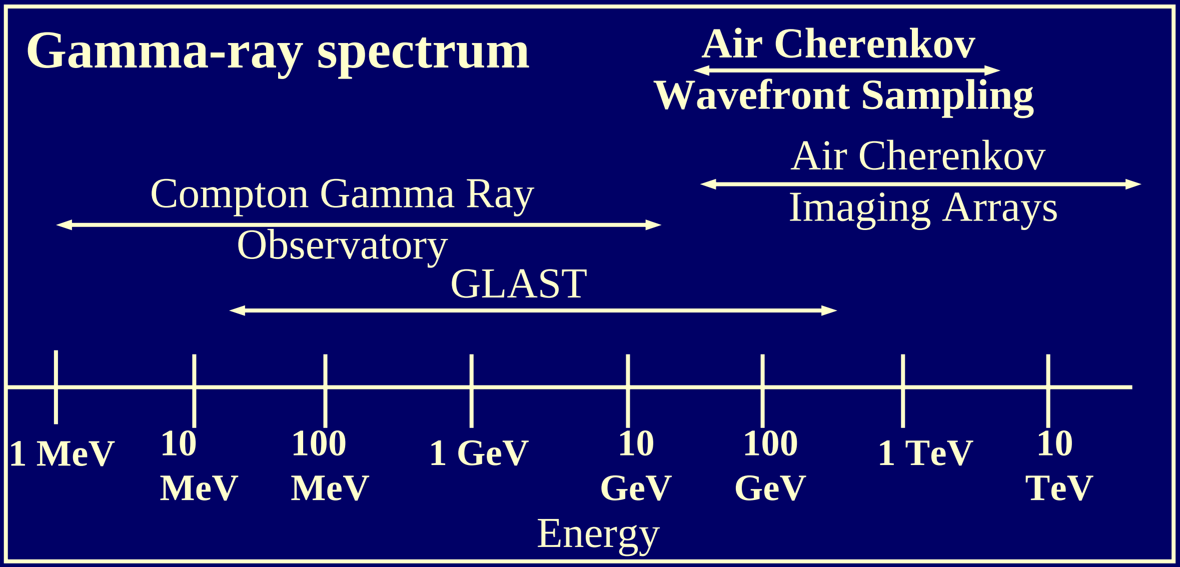
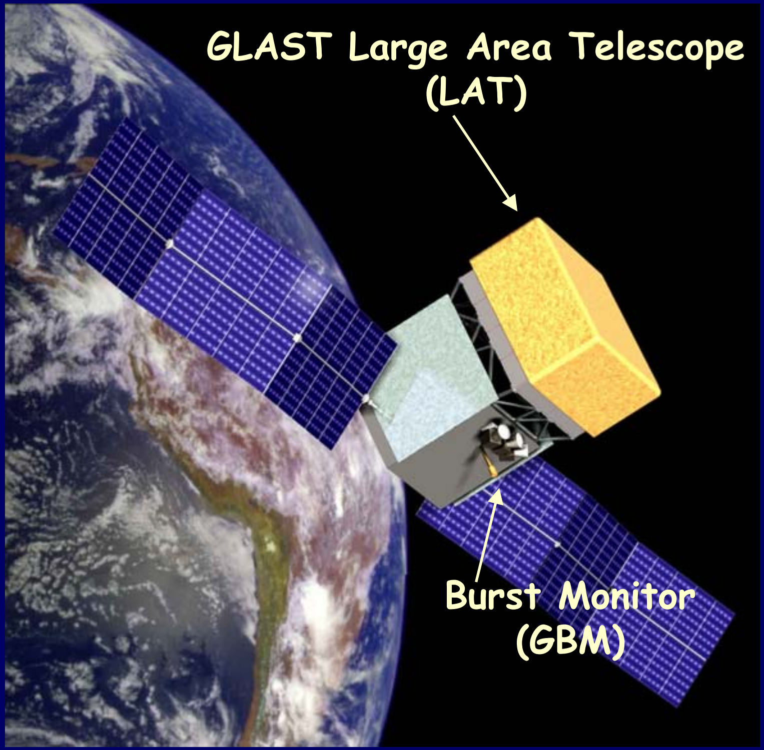
  - VERITAS: 2 (of 4) dishes completed
- GLAST launch in 2007!

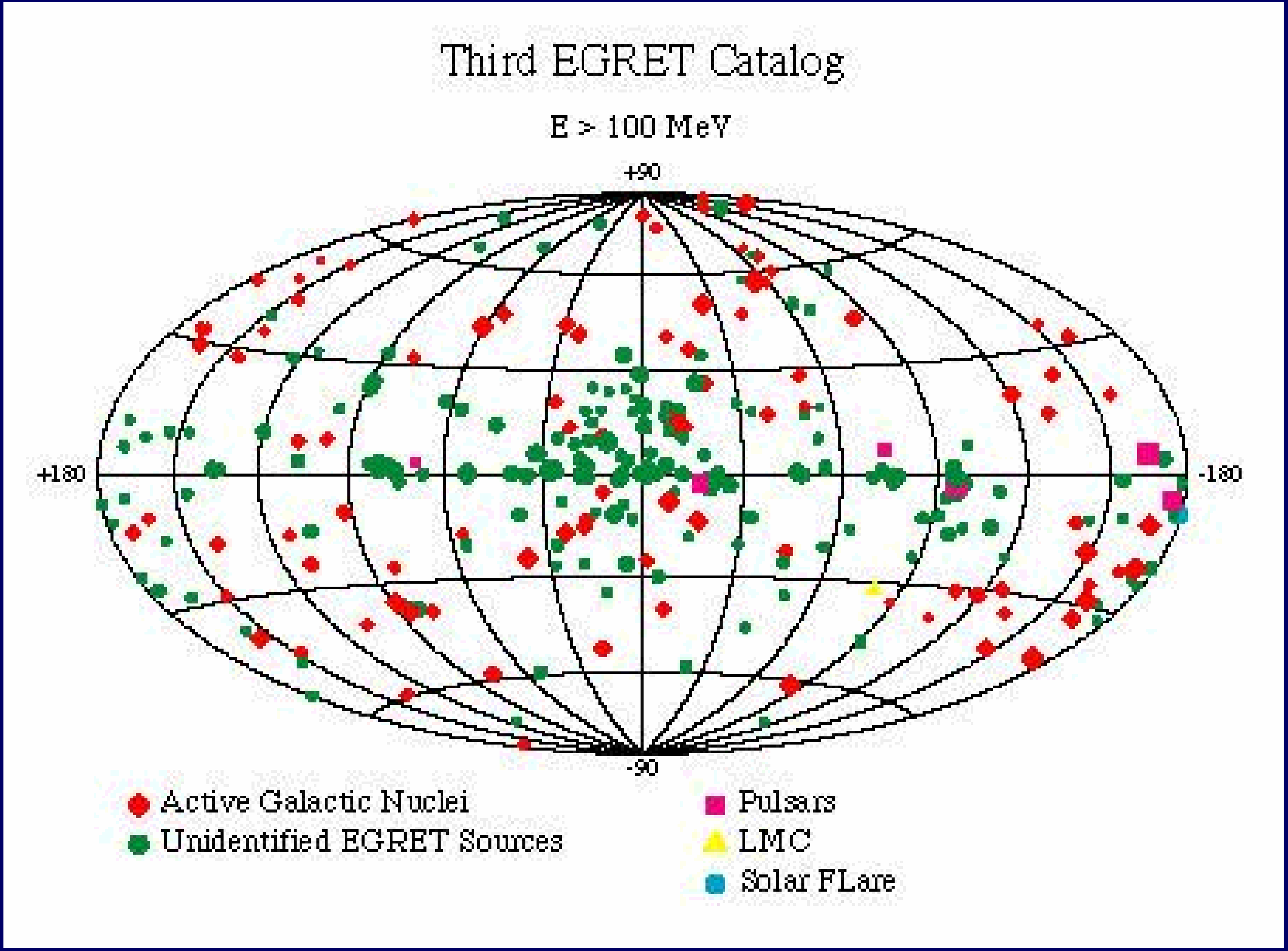


GLAST

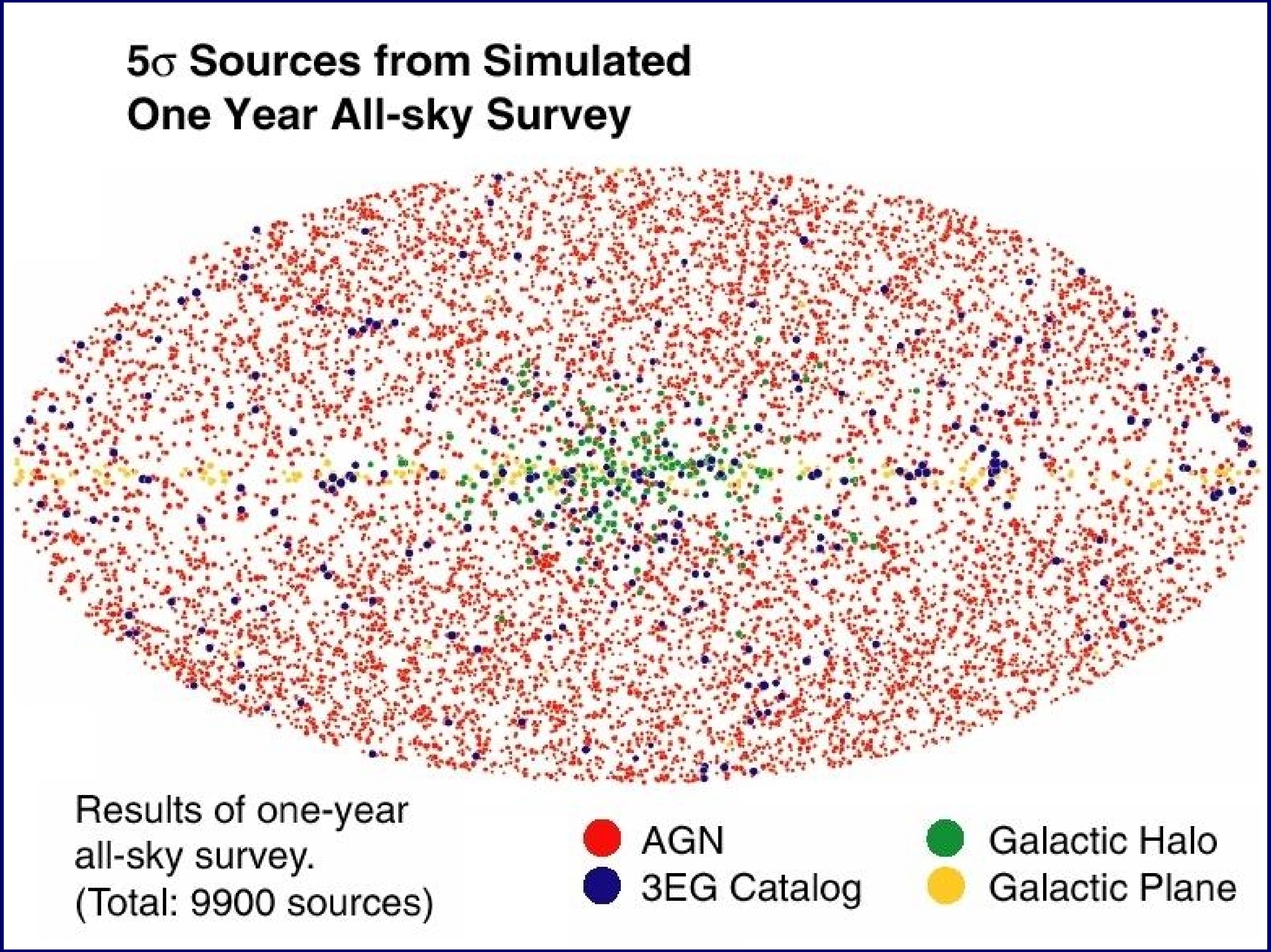
- Two instruments:
  - $\rightarrow$ LAT: 20 MeV – >300 GeV
  - $\rightarrow$ GBM: 10 keV – 25 MeV
- LAT energy resolution ~ 10%
- LAT source localization < 0.5'



EGRET Sources



GLAST Potential



Conclusions

- Gamma-ray observations of AGN are key to understanding particle acceleration in the inner jets
- Many new VHE gamma-ray detectors & detections
- STACEE
  - "1st-generation" instrument sensitive to ~100 GeV gamma rays
  - Energy reconstruction is successful
  - 5.8σ detection of Markarian 421
  - Preliminary spectrum between 130 GeV and 2 TeV
  - Second spectrum of Mkn 421 at 100-300 GeV
  - High-energy peak is above ~200 GeV
- Bright future for gamma-ray astronomy

Cosmic Ray Background Rejection

What we have:

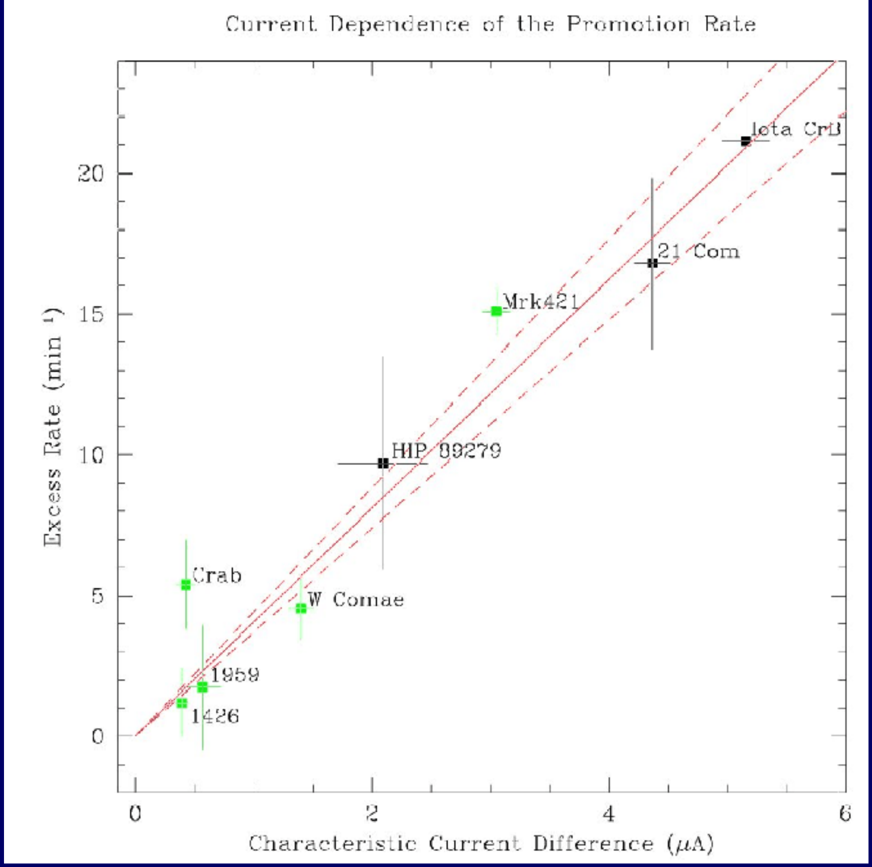
- Hardware hadron rejection ($\sim 10^3$)
- Off-source observations for subtraction
- χ^2 from shower core reconstruction ('templates')
- Timing information & χ^2 from wavefront fit
- RMS on average # photons at a heliostat
- Limited directional information
  - reconstruction precision ~0.2°, FOV ~0.6°

Some initial success with the Crab nebula…

- 5.4 hours on-source after data quality cuts
- 3.0σ before hadron rejection
- Cut on core fit χ^2 + wavefront fit χ^2 + direction: **5.7σ!**

Field Brightness Correction

Extra light in FOV from stars will increase trigger rate due to promotions of sub-threshold cosmic rays



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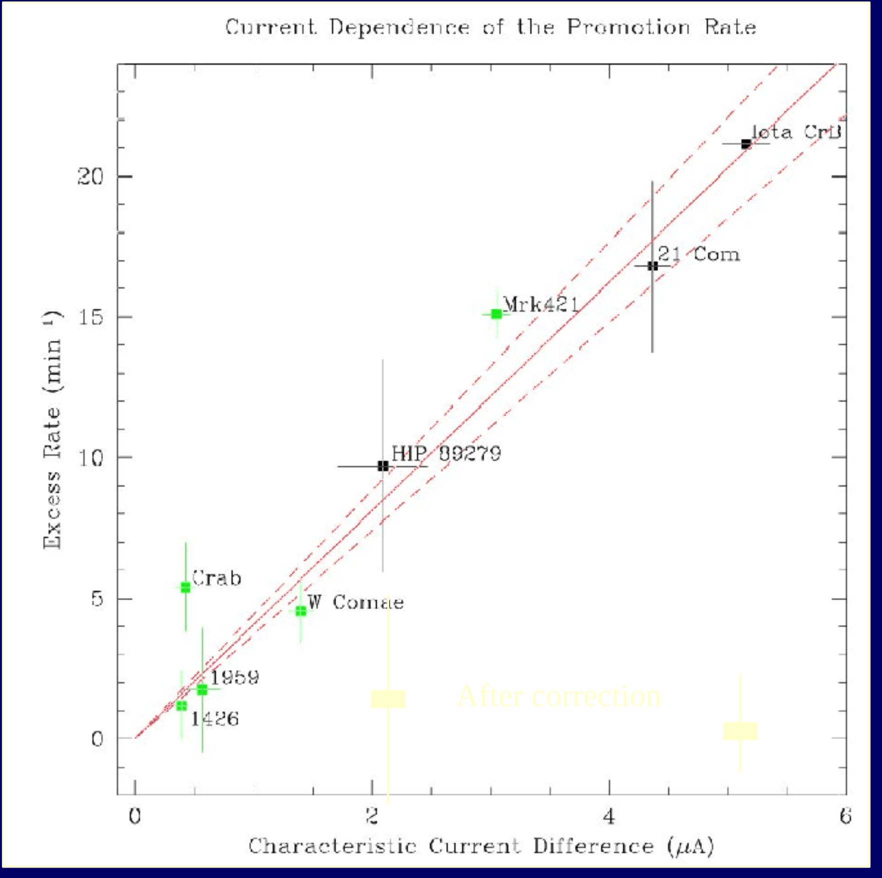
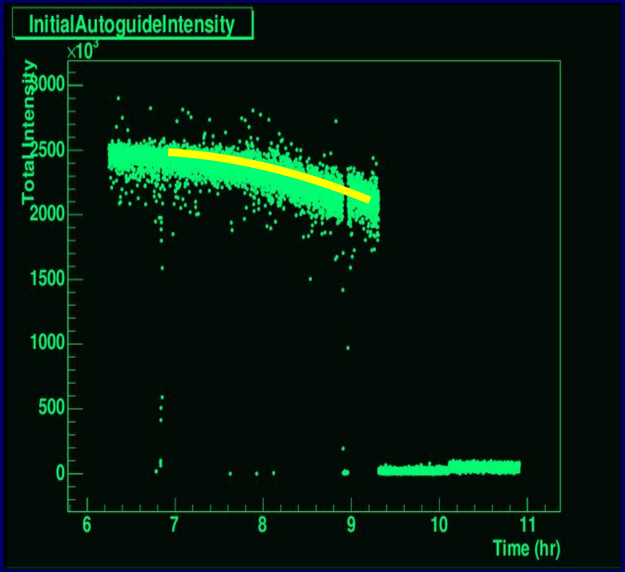
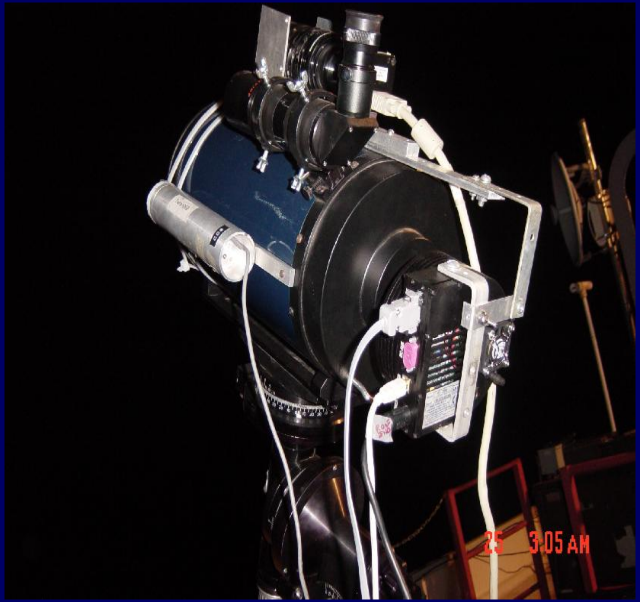


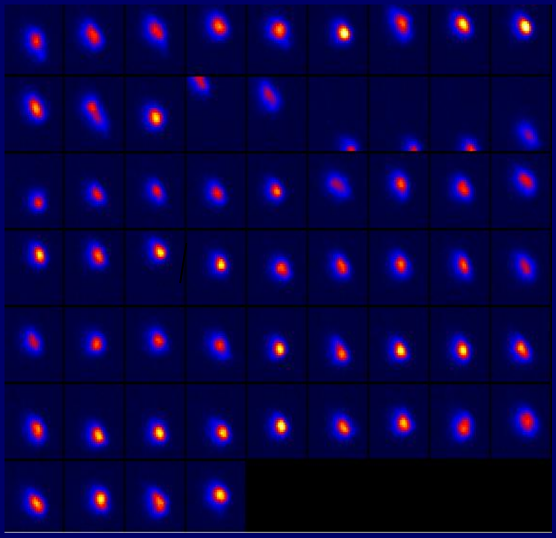
Correct using information from FADCs to equalize light levels

STACEE Atmospheric Monitor

- Goal: measure atmospheric transmission and detect clouds.
- Meade 8" S-C scope, Losmandy equatorial mount with PC-controlled “goto” pointing/tracking, SBIG CCD camera for pointing and photometry.
- Two IR radiometers (cloud detectors).
- Full Weather station.







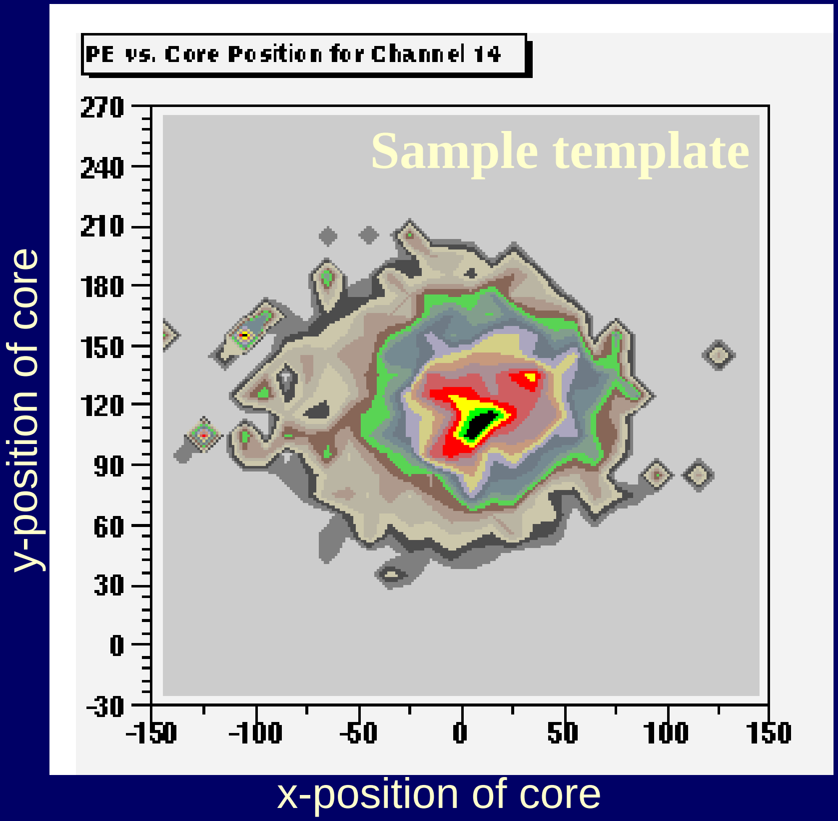
Methods for Finding the Shower Core

1. Finding the centroid

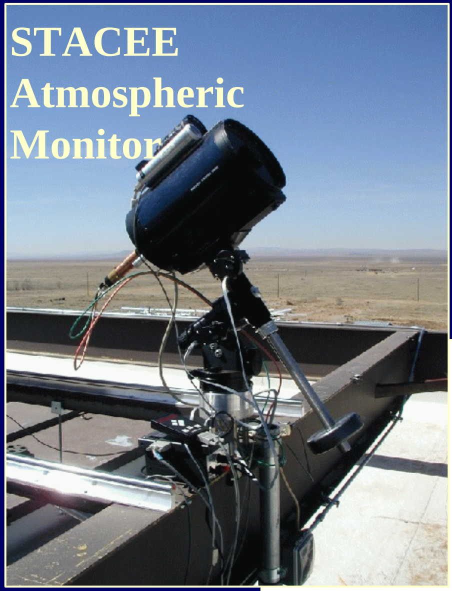
- If we sampled the entire shower, we could find its centroid.
- The *early* part of the shower is contained within the array.
- Use the first few nanoseconds of the shower to find the centroid.

2. 'Template' method

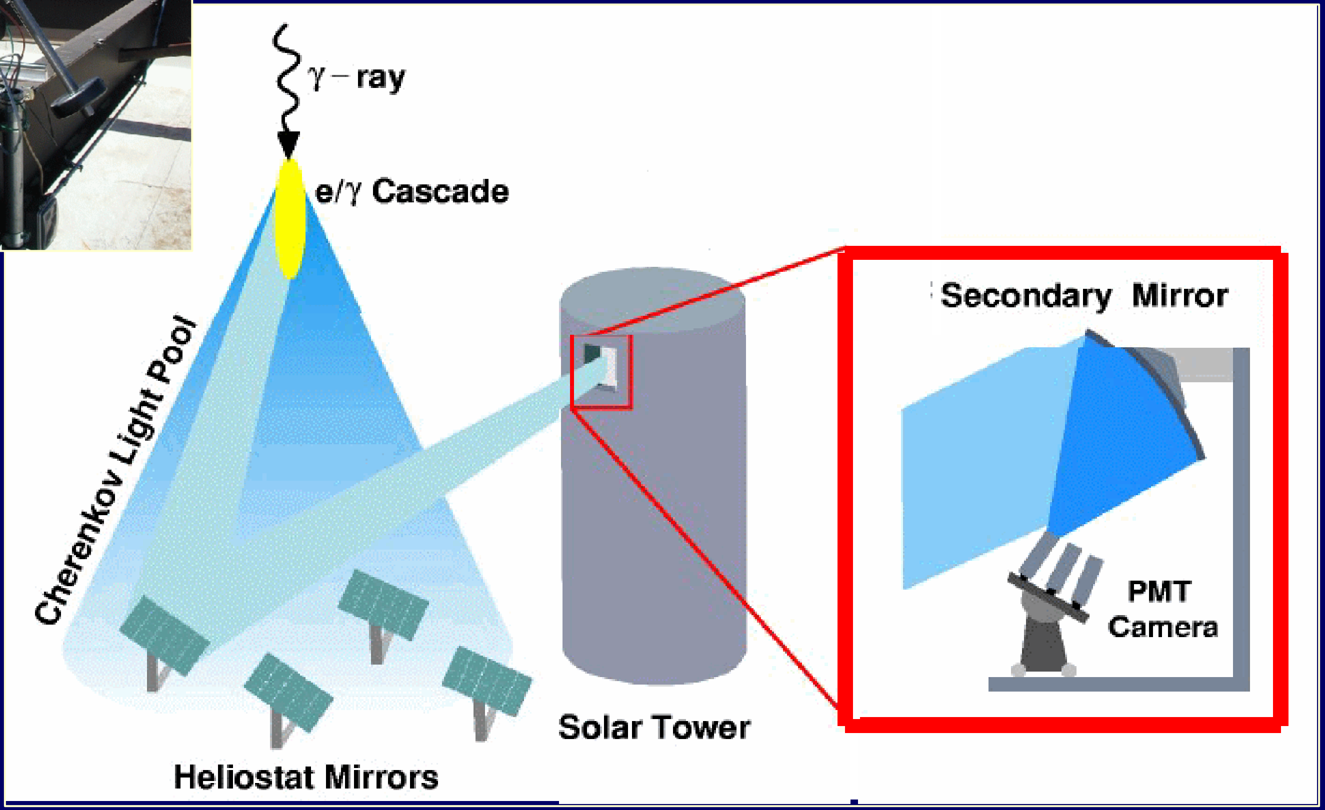
- # PEs vs. shower core position
- One template per PMT and energy
- Fit core and energy with maximum likelihood estimator
- Pros:
  - precise
  - χ^2 for hadron rejection
- Con: 'black box'



Calibrating the Detector

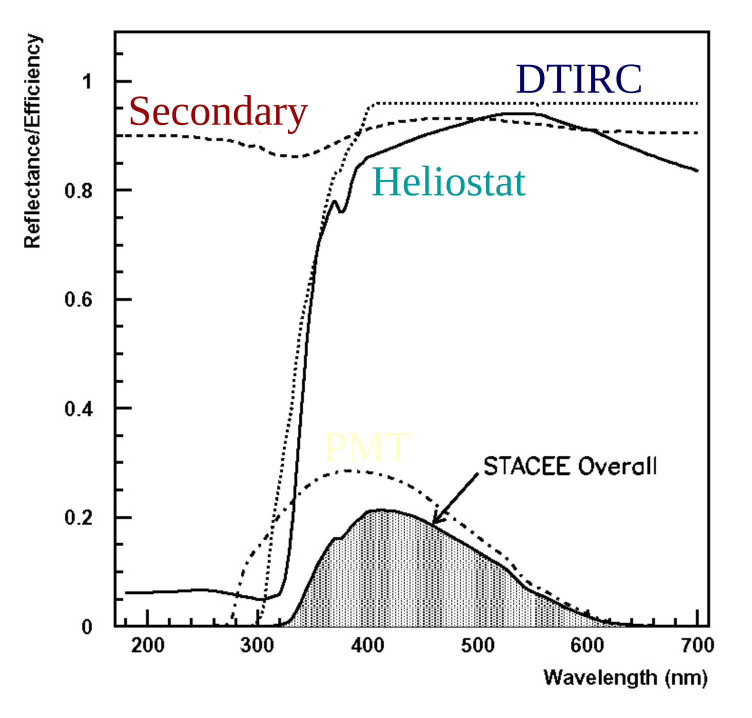


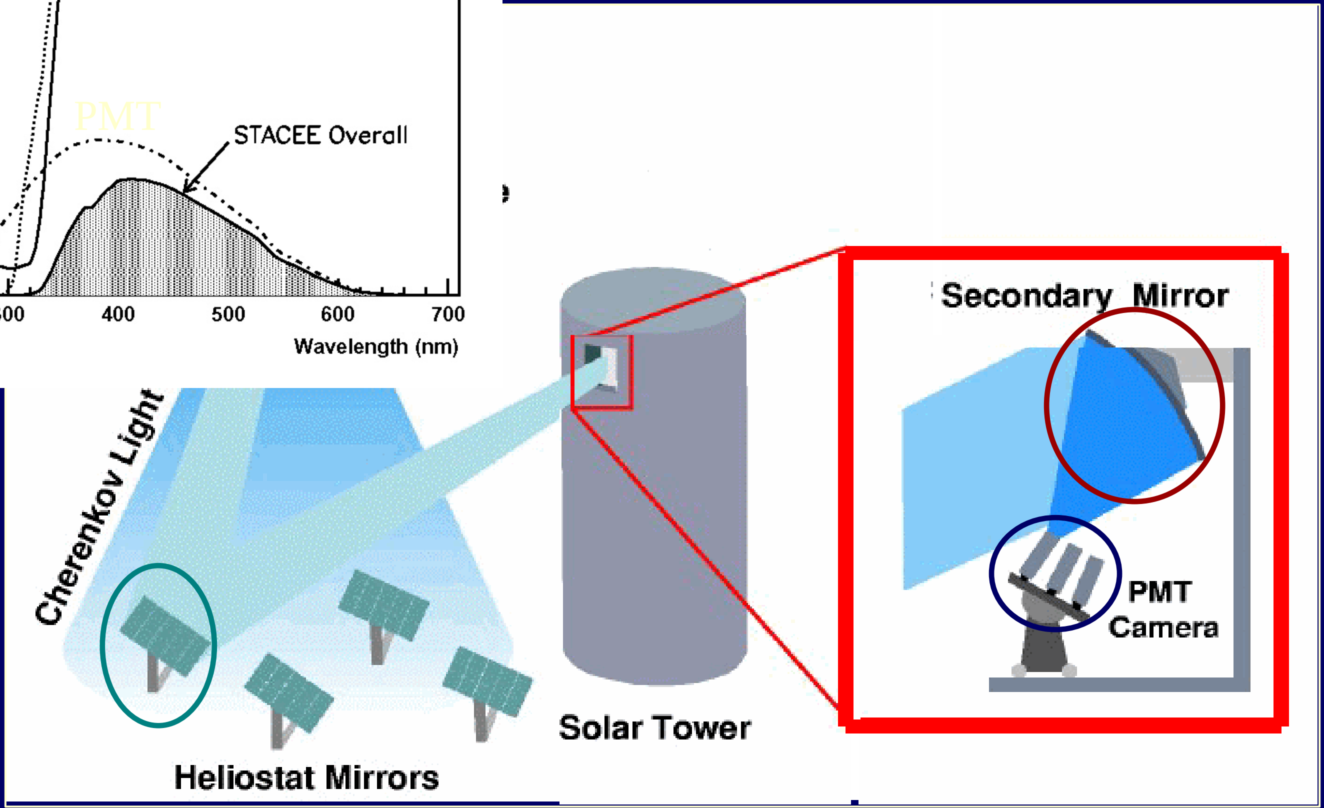
Air shower simulations &
Atmospheric monitoring



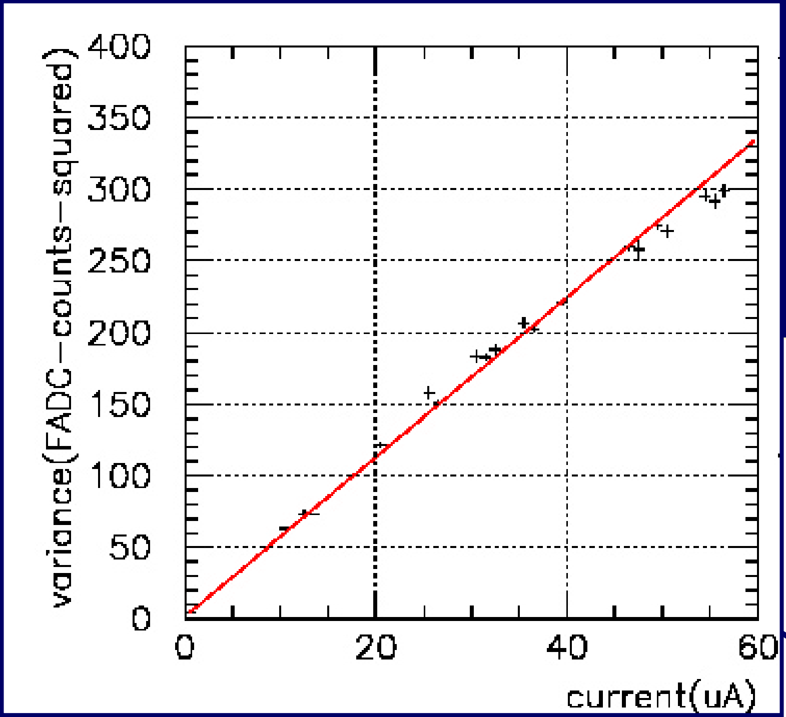
Calibrating the Detector

Trasmission measurements

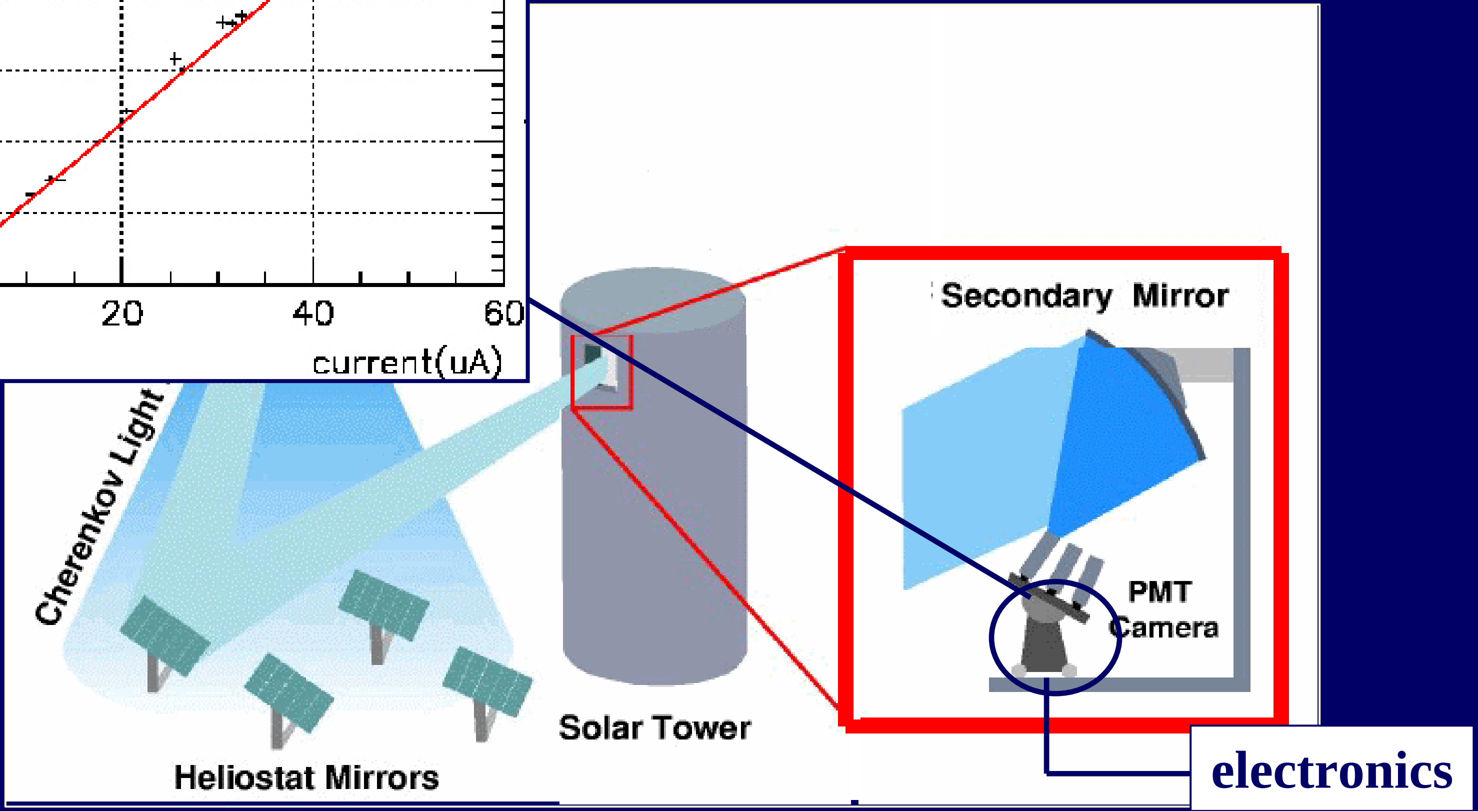




Calibrating the Detector



PMT Gain Calibration

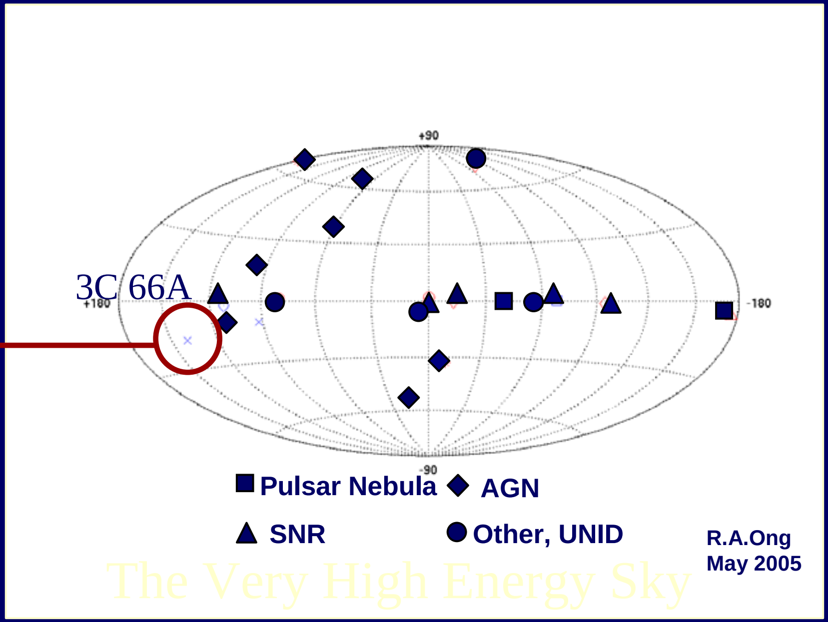


STACEE AGN Targets

Which objects are most scientifically promising?

3C 66A

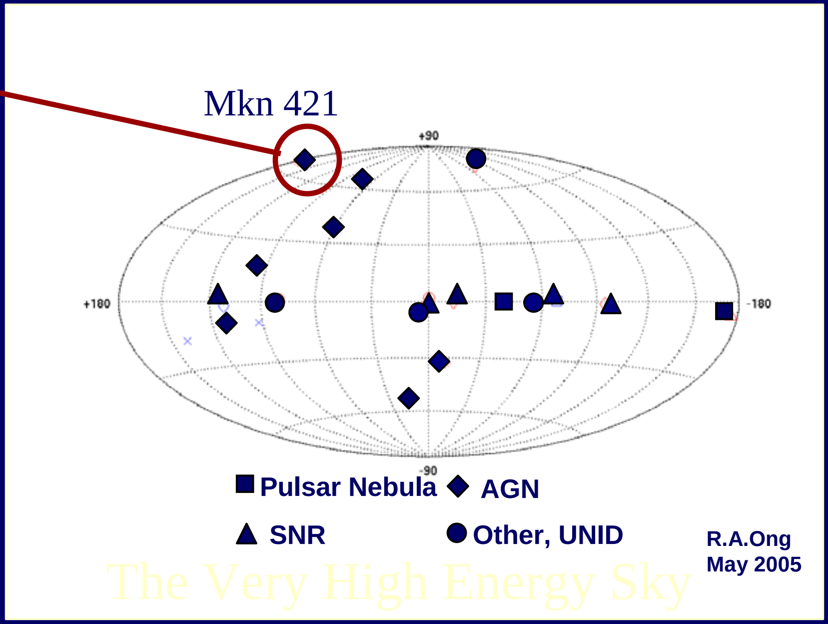
- z = 0.444
- Strong source at energies < 10 GeV
- One questionable measurement at TeV energies
- High redshift $\Rightarrow$ heavy absorption
- STACEE flux limit (Bramel *et al.* 2005)



STACEE AGN Targets

Which objects are most scientifically promising?

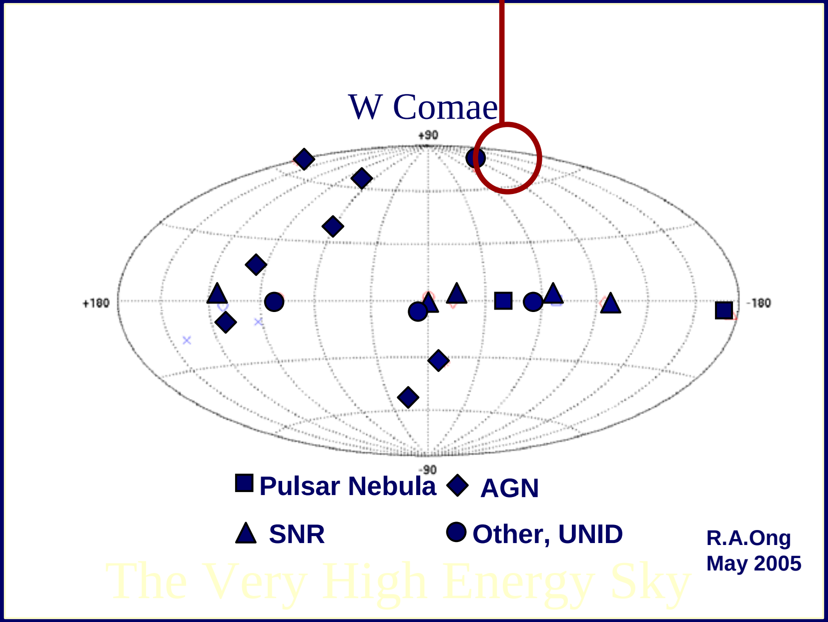
Mkn 421
- z = 0.031
- Well-studied at TeV energies
- Target of multi-λ variability studies
- One previous measurement at 50-300 GeV
- High-energy peak is at ~100 GeV
- Potential to constrain the optical EBL
- STACEE detection (Carson 2005)



STACEE AGN Targets

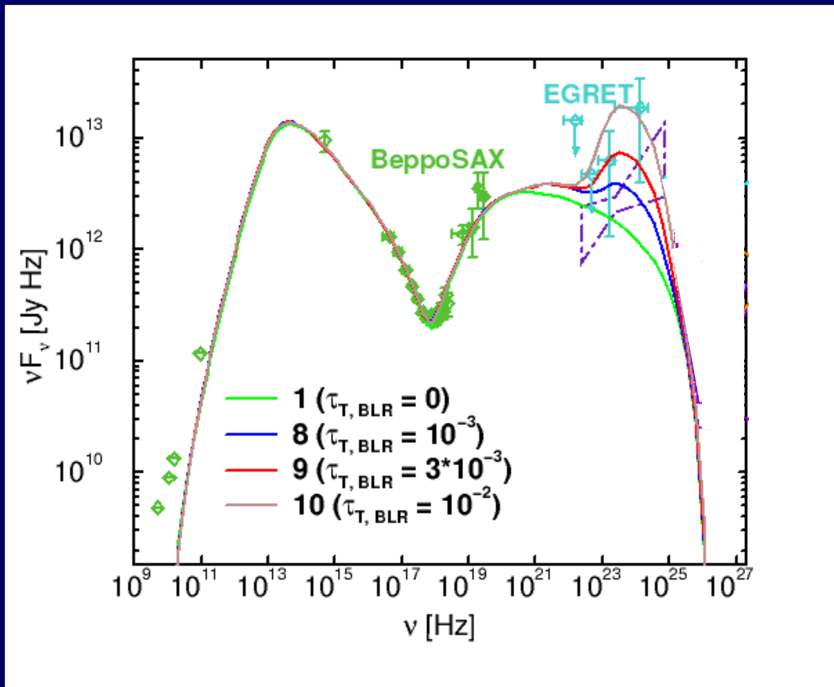
Which objects are most scientifically promising?

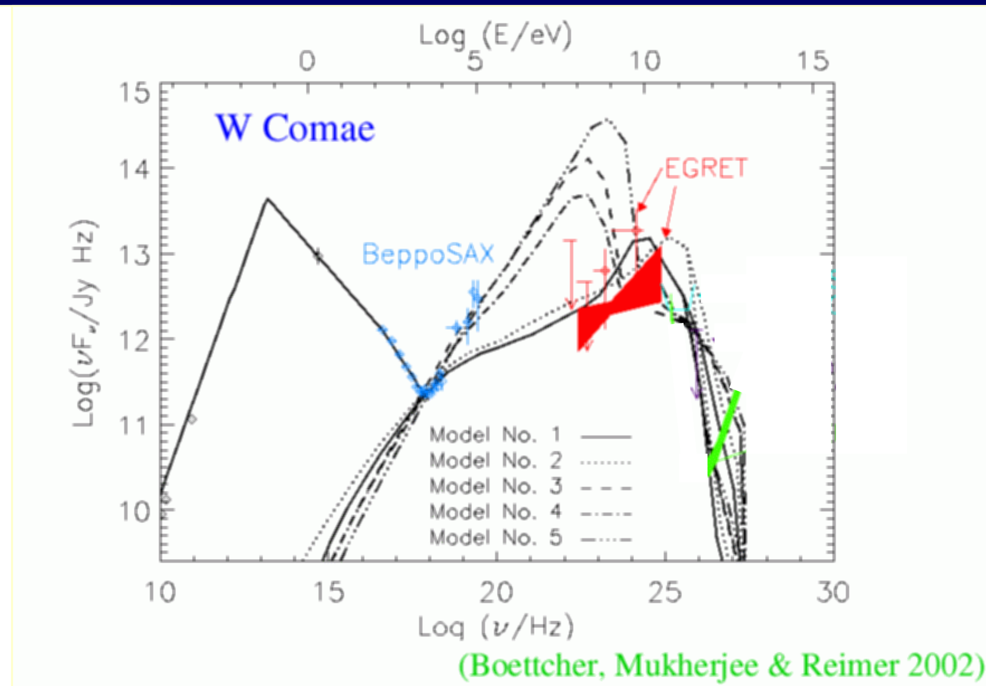
W Comae
- z = 0.102
- Hard EGRET spectrum: $\alpha = 1.73$
- Limits only at TeV energies
- STACEE observations can test model predictions
- STACEE flux limit (Scalzo *et al.* 2004)



Models of W Comae

Predicted differences around 100 GeV





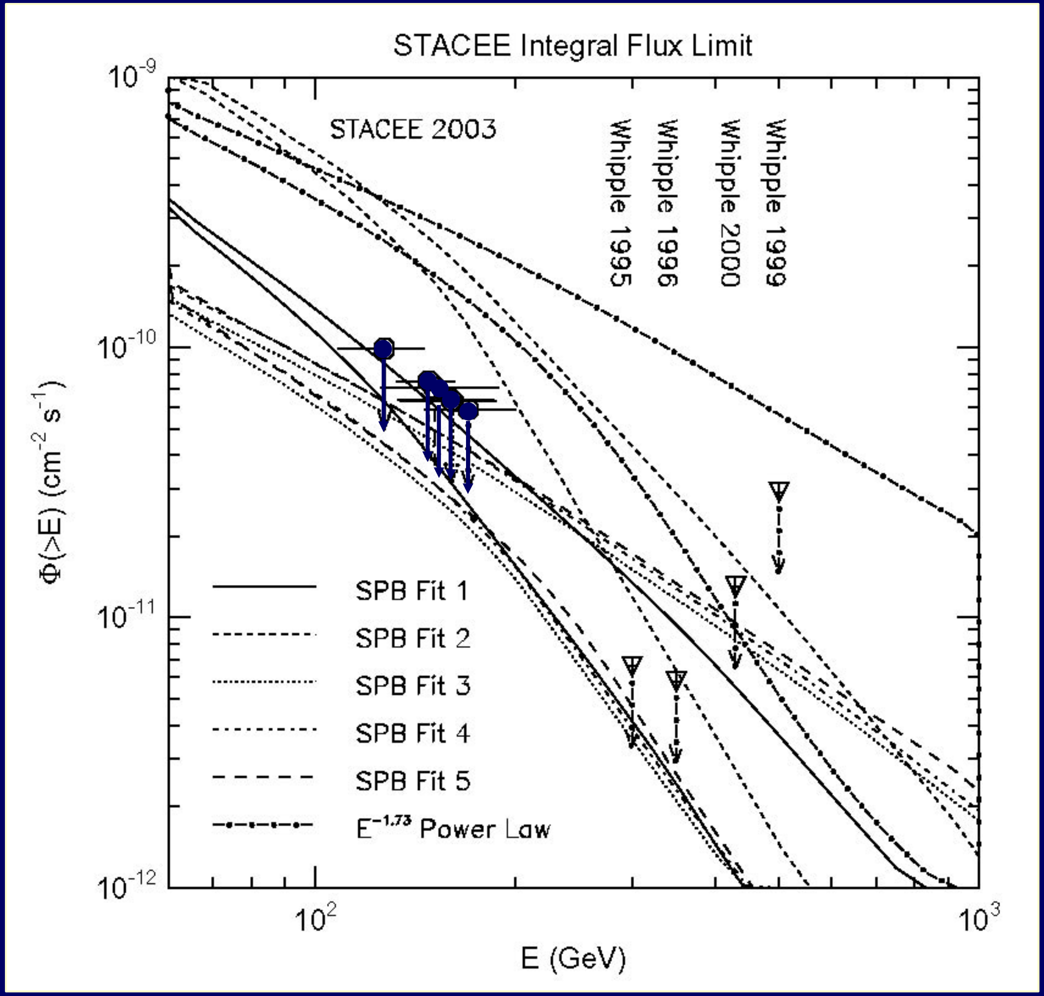
Leptonic models
no emission predicted above 100 GeV

Hadronic models
significant emission above 100 GeV

STACEE Measurement of W Comae

STACEE flux limit constrains hadronic emission models

$\Phi < \sim 2.5 \times 10^{-10}$ cm^{-2} s^{-1} for hadronic models above 165 GeV



Scalzo et al. 2004

STACEE Measurement of W Comae

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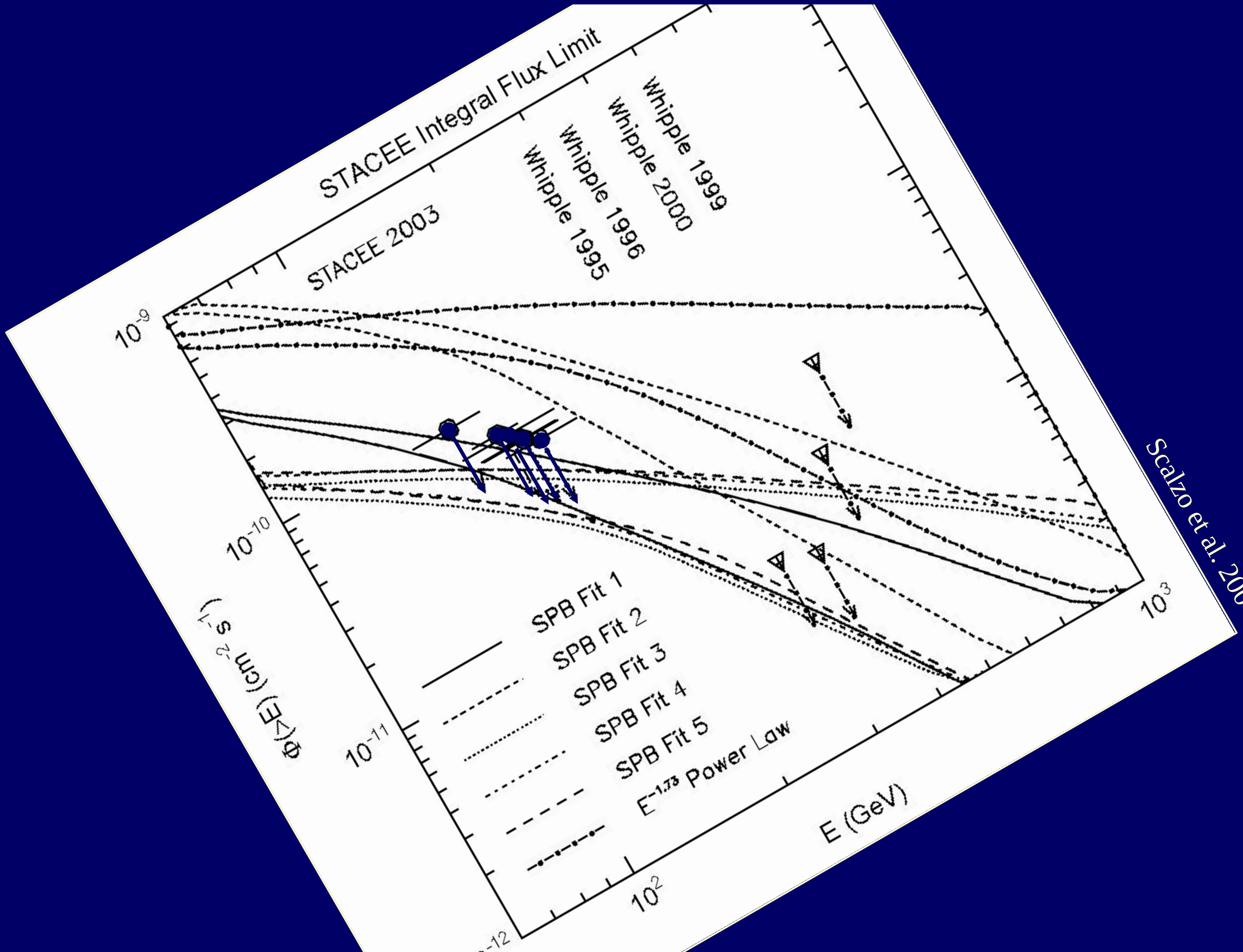

Scalzo et al. 2004