Exploring the High-Energy Universe

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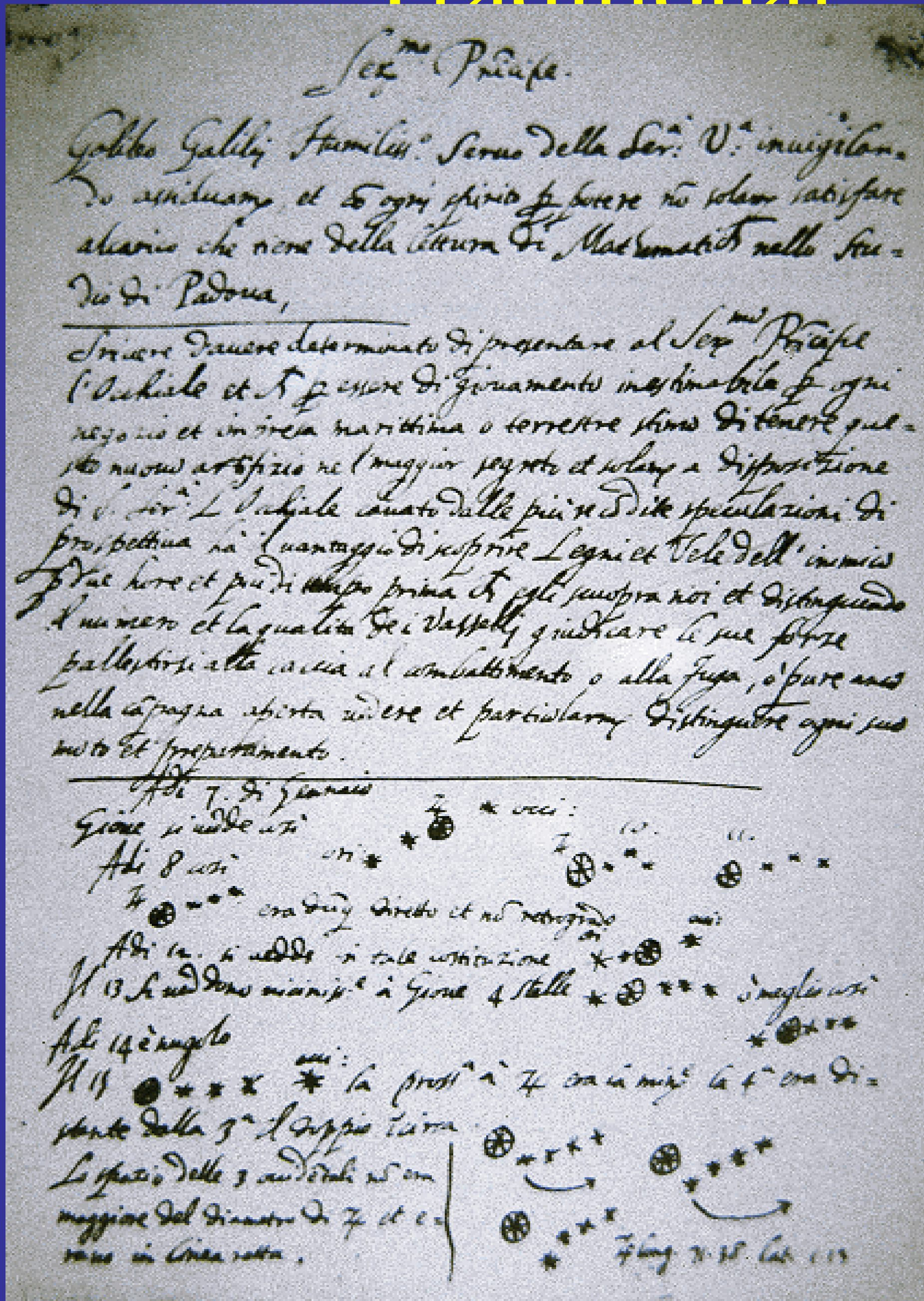
Outline

- Introduction –
  Exploring the universe with γ-ray eyes.
- The science –
  What we know and what we don't (a lot).
- Experimental techniques –
  How the experiments work.
  How we analyze the data from them.

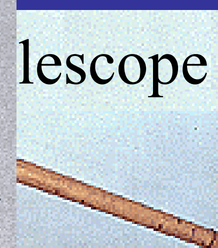
Introduction

“Traditional” Astronomy



to observe the universe.

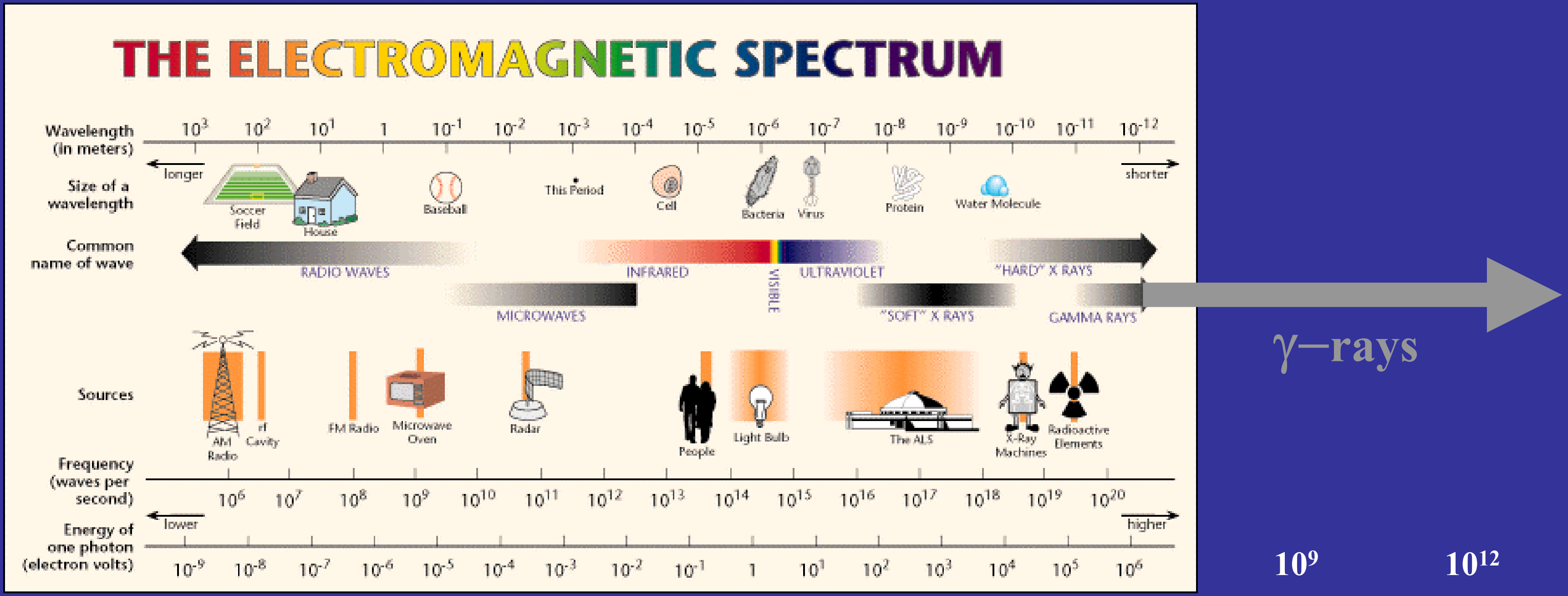
for systematic observations.



Moons of Jupiter

Spectrum of Light

- Before 20th Century – Astronomy used visible light.
- Since 1930 – Other wavebands (radio, X-ray, γ-ray, etc.)



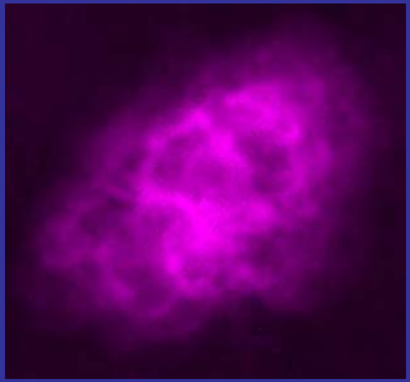
Energy → **1 eV** **keV** **MeV** **GeV** **TeV** **…**

atomic **nuclear** **particle**

Different Energy = Different Physics

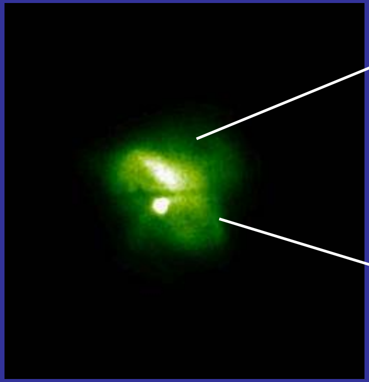
The whole point of using photons of different energies is to probe different physics.

- Medical imaging – ultrasound, NMR, X-ray, PET
- Observations of Crab Nebula

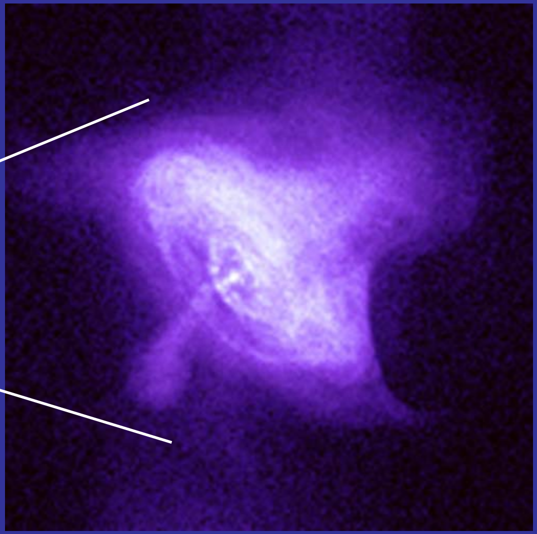


Radio

Visible



X-ray



Crab Pulsar

Thermal versus non-Thermal

In the simplest view:

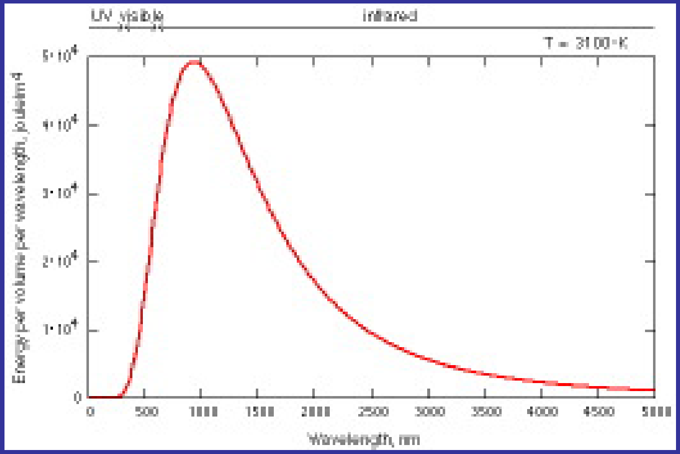
1. <u>Thermal Radiation</u>
   E < 1 keV (low energy)
   Heating or burning.

   1 keV = 2 $\times 10^6$ K

2. <u>Non-Thermal Radiation</u>

   E > 1 keV (high energy)
   Acceleration!

Emission curve for fixed temperature



Fermilab Accelerator

Problem – γ-rays are hard to detect!

Unlike optical light, γ-rays:

- are highly penetrating.
- cannot be easily reflected or imaged.

We can "see" them only by totally absorbing them in a particle detector.

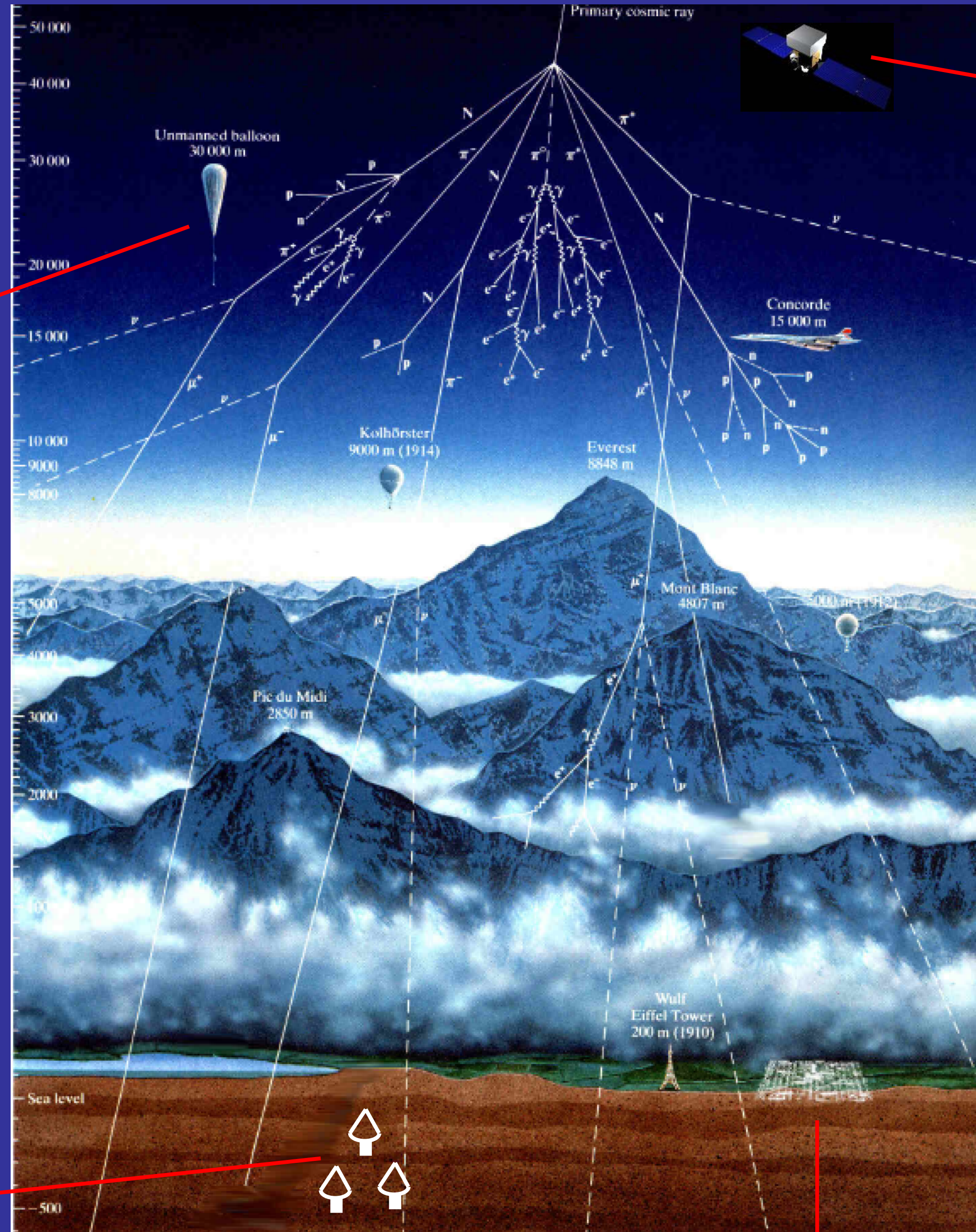
Basic process

$\gamma \rightarrow e^+ e^-$

$\rightarrow$ particle shower or cascade

… or we can use the whole atmosphere to detect them!

Detecting γ-rays



The Science

Do γ-ray sources exist ?

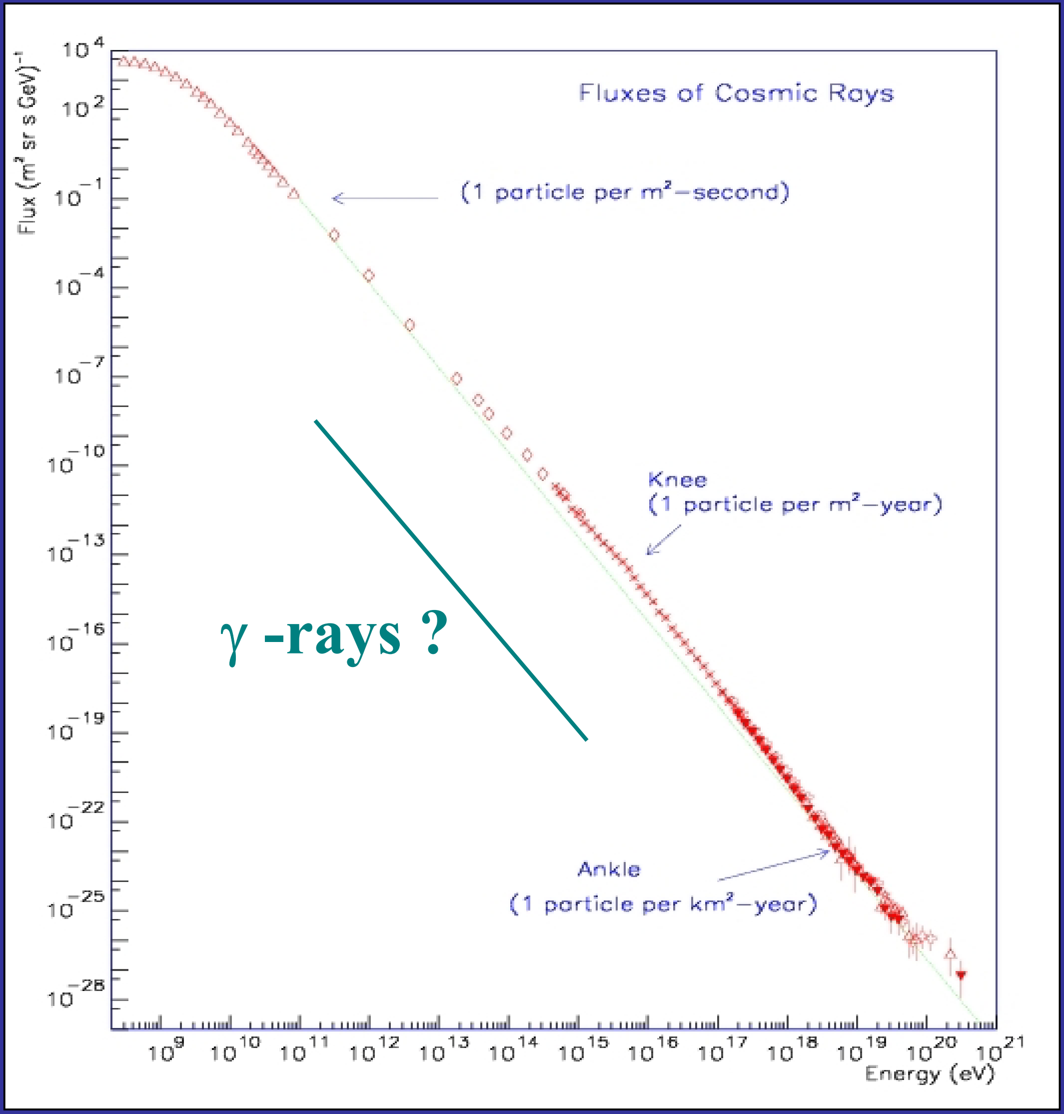
The existence of a penetrating radiation from outer space has been known for 90 years. These are Cosmic Rays.

Cosmic rays are energetic particles that bombard Earth.

- Discovered in 1919 by Victor Hess.
- Enormous energy range 10^6 eV – 10^{20} eV.
- Charged so trajectories are bent – isotropic arrival.
- Important on Earth for biology, ^{14}C dating, etc.

Clear evidence for high energy accelerators in universe.

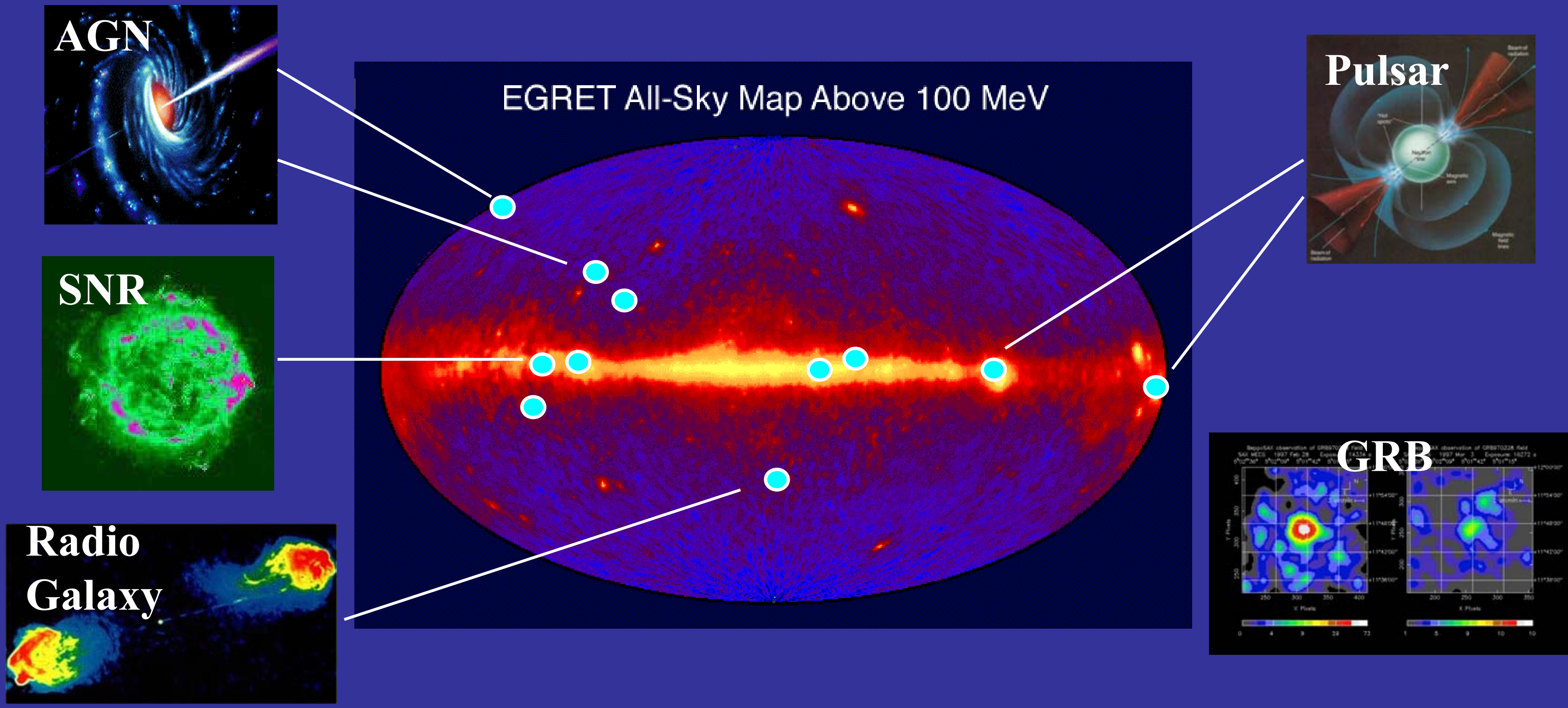
Cosmic Ray Spectrum



Flux of particles

Energy

γ-ray sky



Making a Cosmic Accelerator

POWER SOURCE + **ACCELERATION** + **EMISSION**

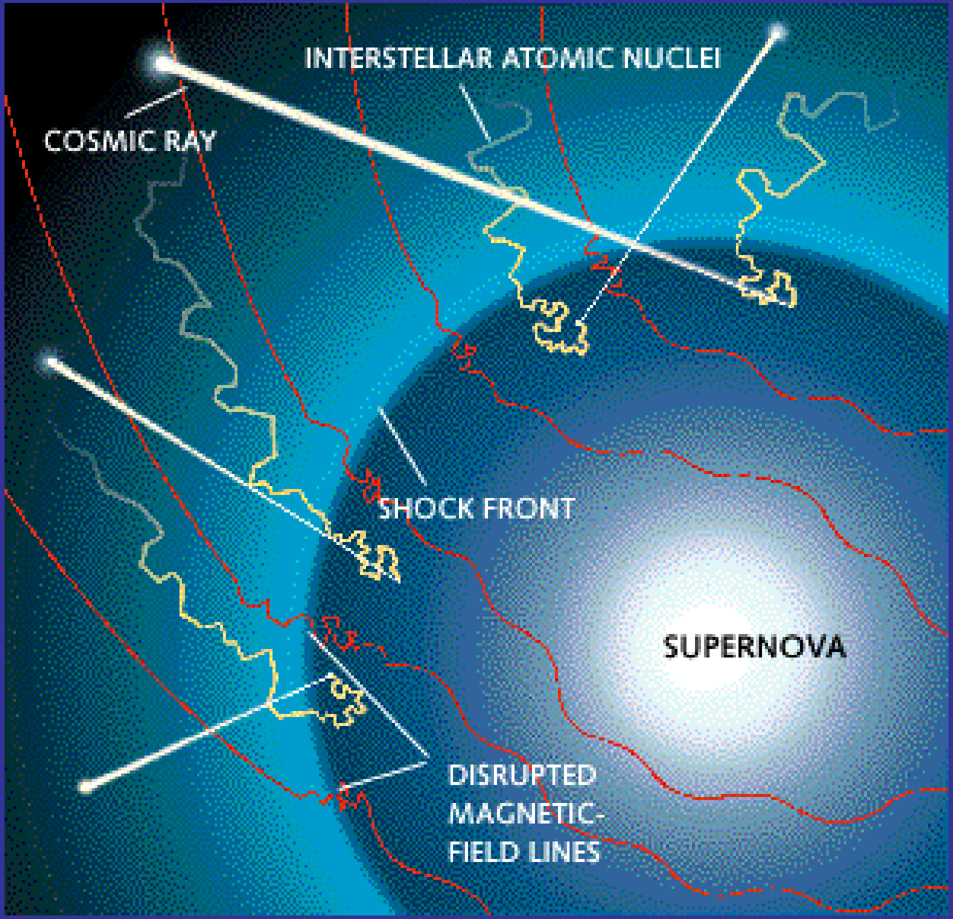
Gravitational, EM Energy

Shocks, turbulence, etc.

Radiation Process

Two Examples of Cosmic Accelerators

Supernova Remnant



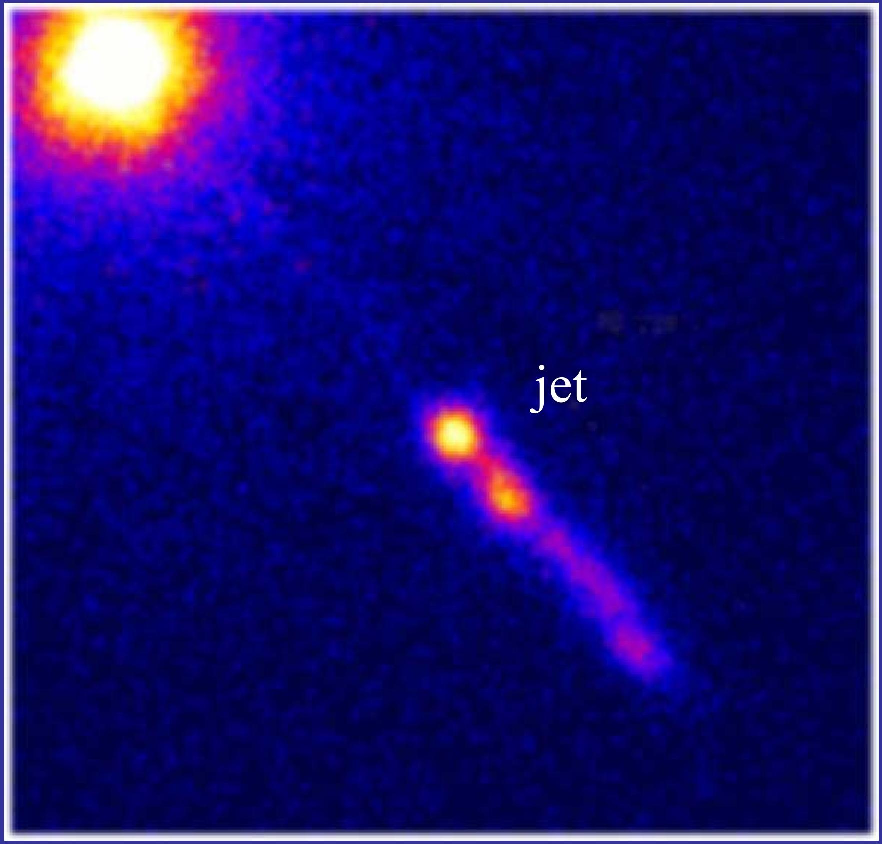
- Collapse of massive star
- Remnant expansion powers shock wave
- Particle acceleration in shock

Statistical process by which particles randomly scatter and gain energy.

Build computer models of particle acceleration.

Active Galaxies (Quasars)

Quasar 3C273



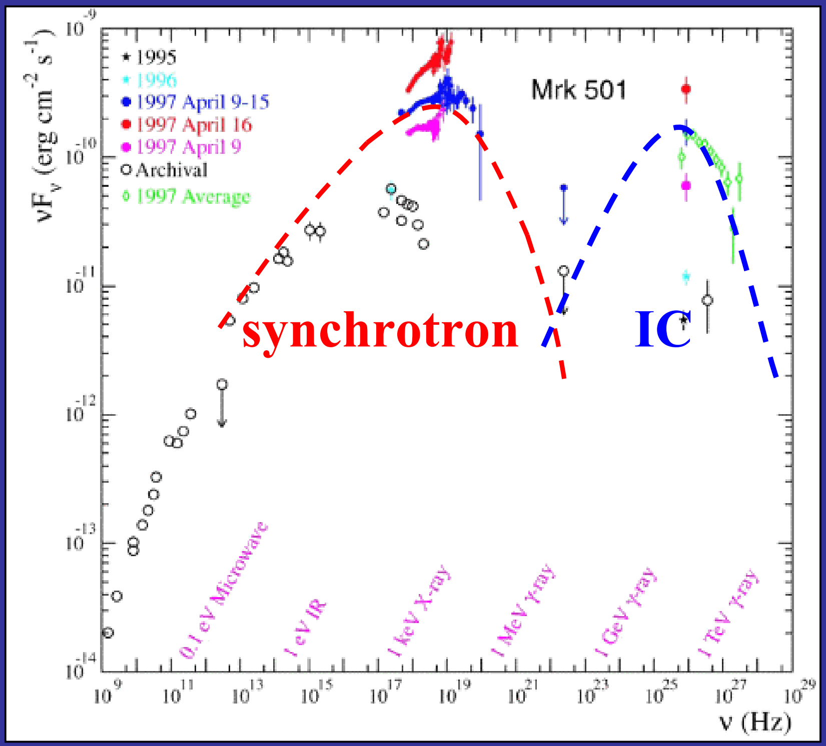
X-ray image

Active galaxies have:

- Enormous luminosities.
- Central nucleus of activity.
- Relativistic beams or jets.

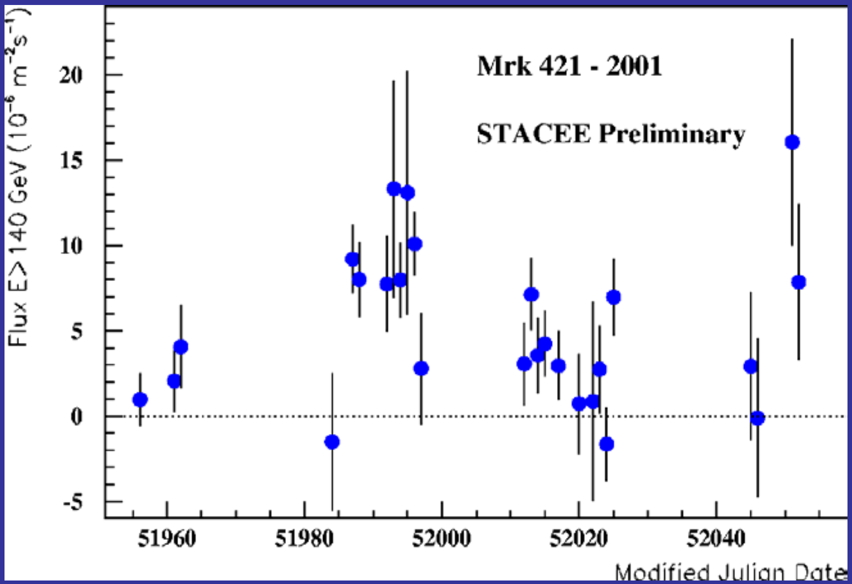
Spectra and Variability

Energy Spectrum



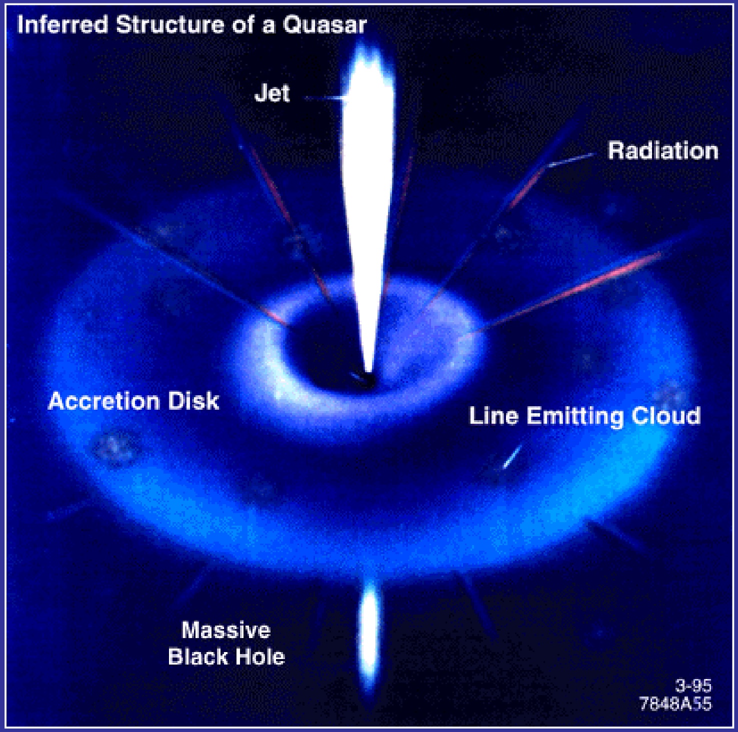
- Power peaks at high energies.
- X-rays & γ-rays highly correlated.

Time Variability

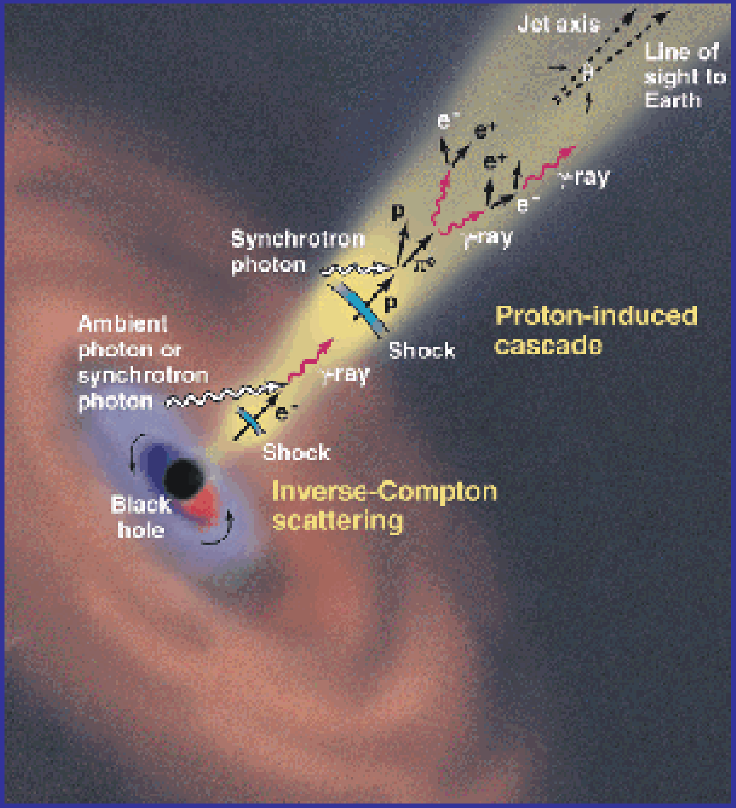


- Dramatic variability.
- 10^{11} γ-rays per sec hit Earth.

Models for Active Galaxies



Conceptual picture



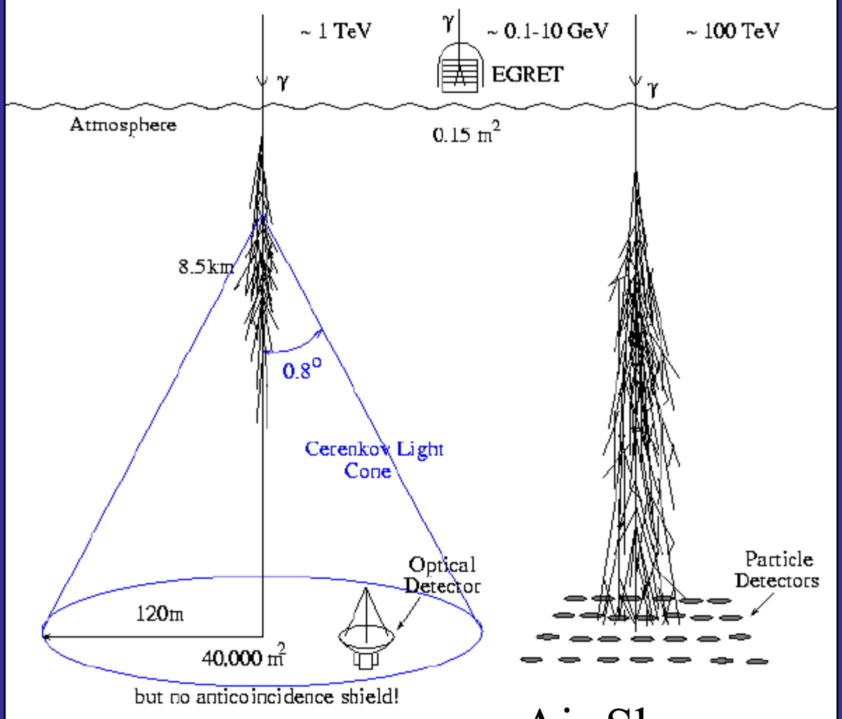
Develop models that explain the observed emission.

γ-rays probe shortest distances.

Experimental Techniques

Detecting HE Particles

Satellite
(small)



Atmospheric
Cherenkov

Air Shower
Array

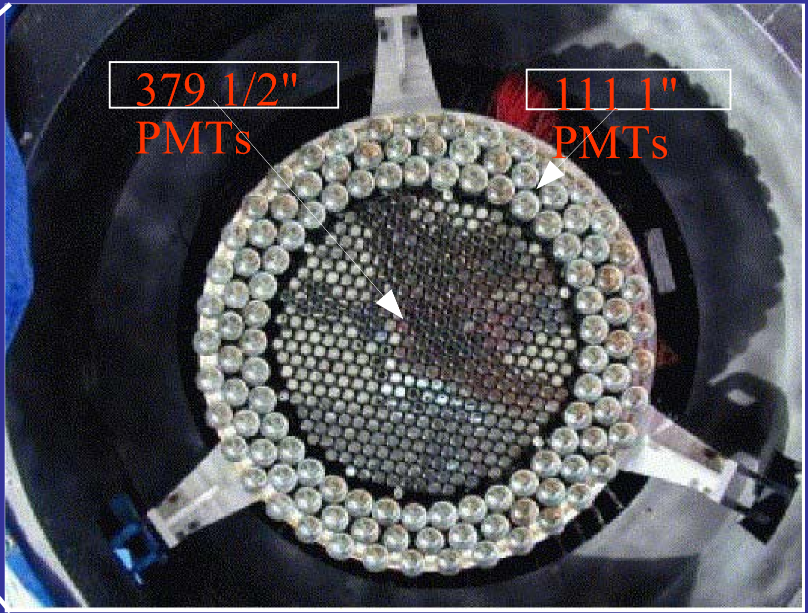
Next
page

EGRET (NASA)

CASA-MIA (Utah)

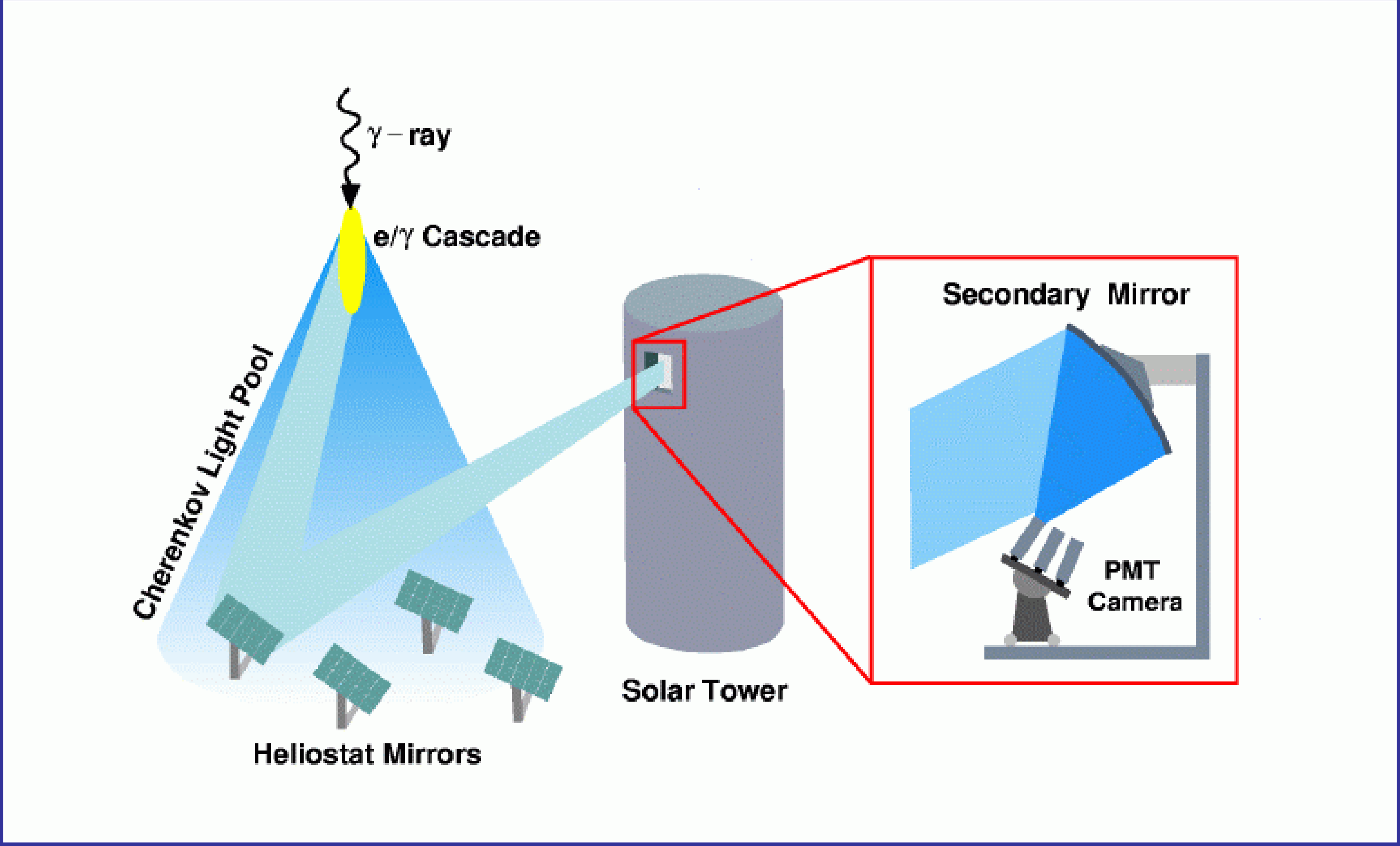
Atmospheric Cherenkov Telescope

Whipple 10m Reflector
(Mt Hopkins, AZ)

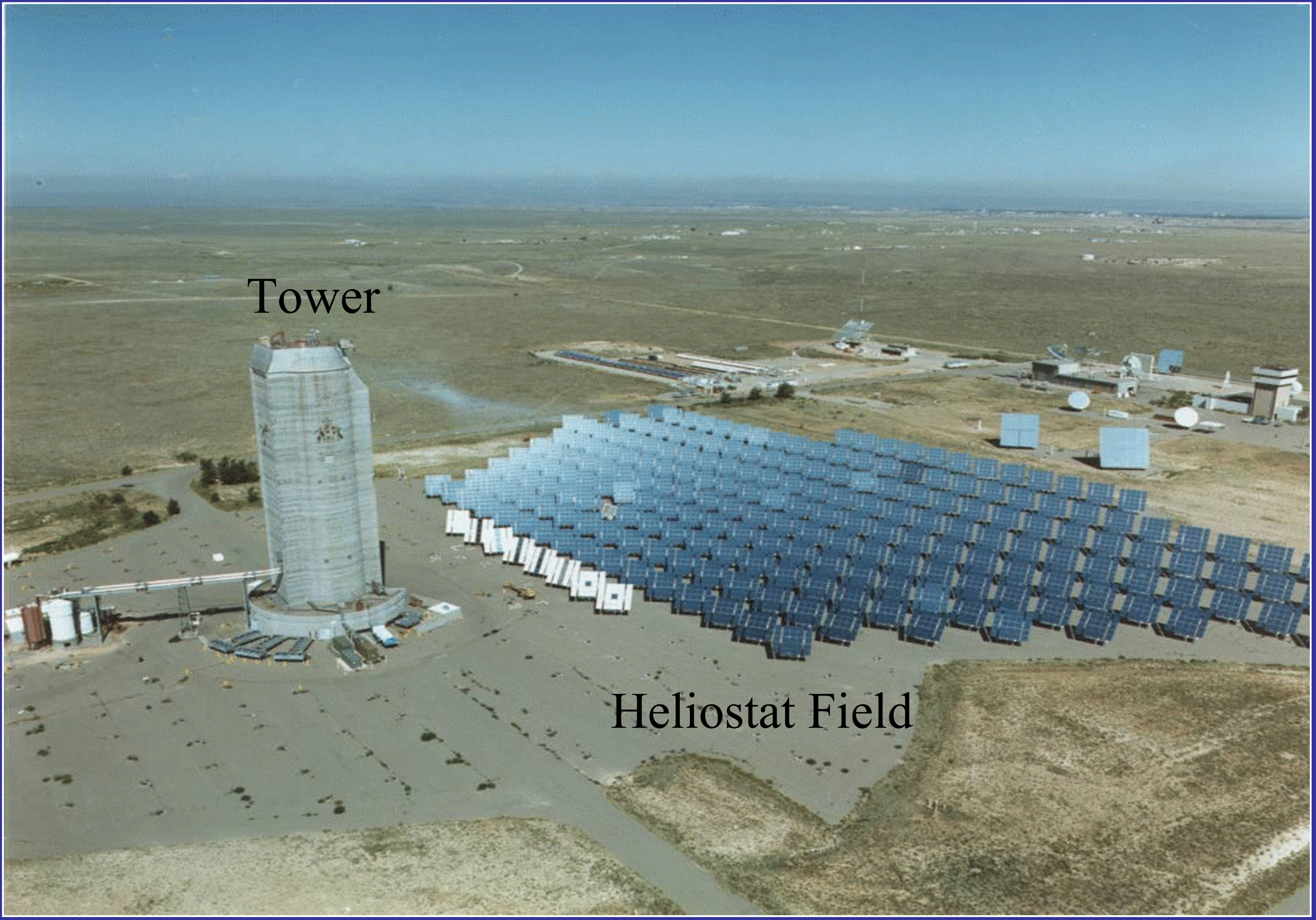


Imaging PMT Camera
500 Elements

Solar Tower Atmospheric Cherenkov Effect Expt. (STACEE)

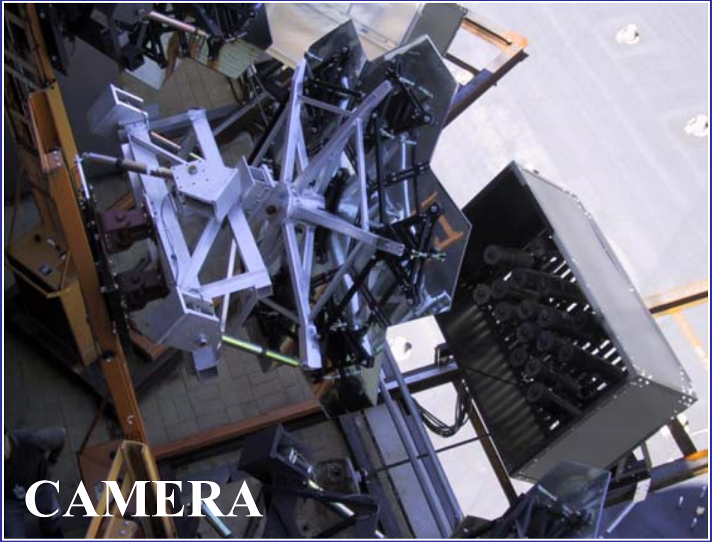


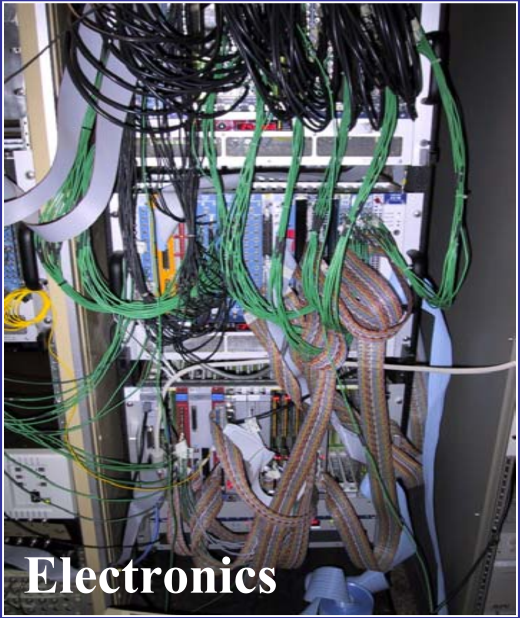
STACEE



National Solar Thermal Test Facility
Sandia National Labs – Albuquerque, NM

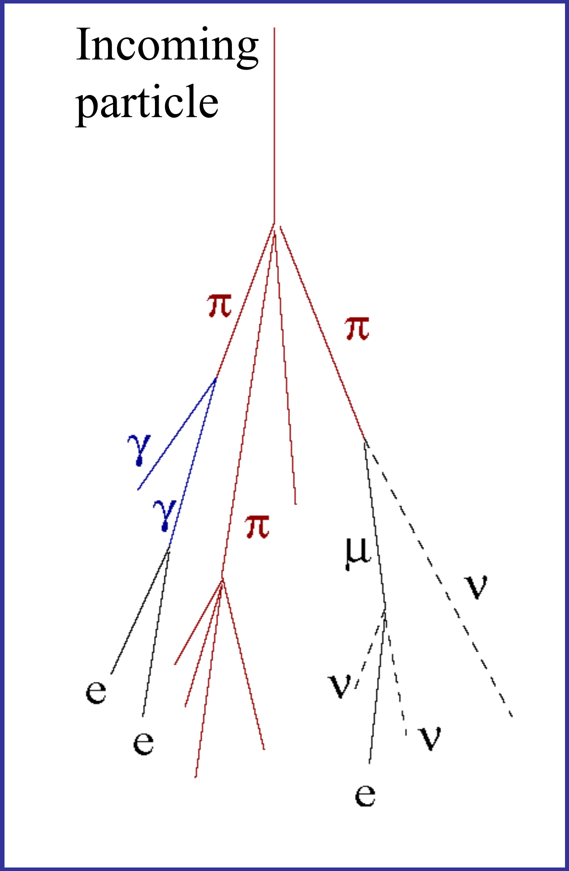
STACEE





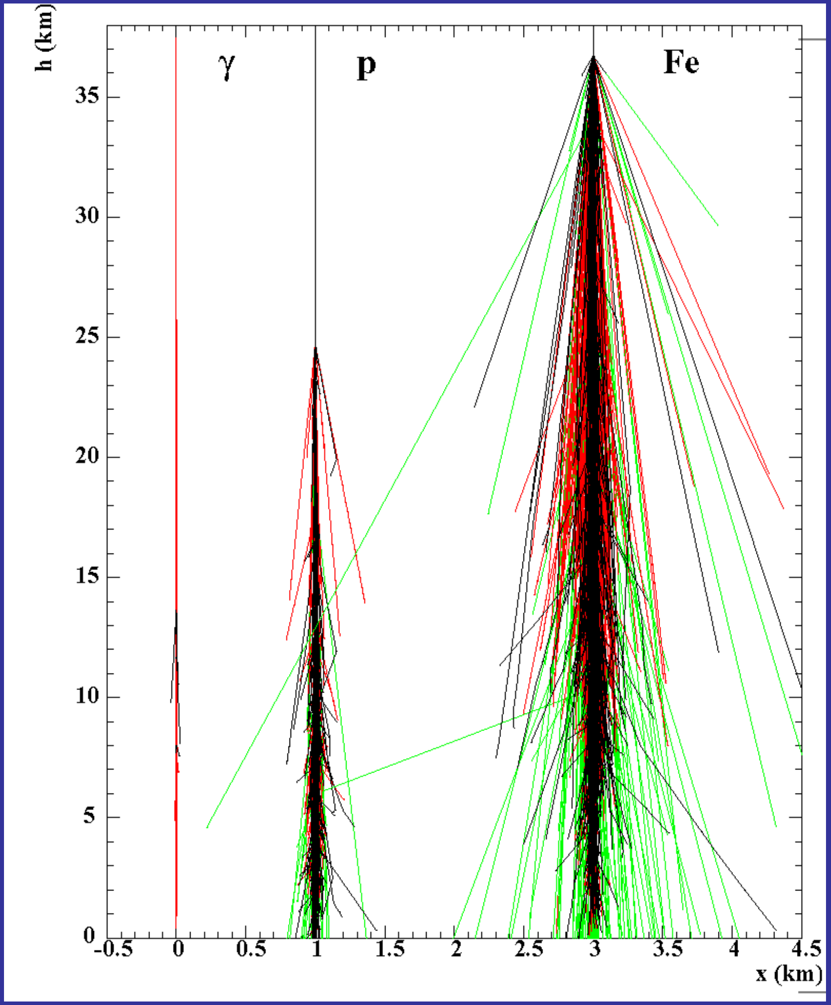
Simulation
&
Data Analysis

Modeling Showers I



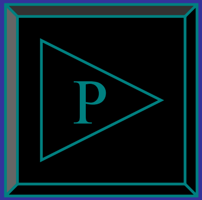
Statistical treatment of particle:

- interaction
- decay
- propagation

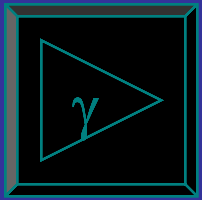


Results from detailed Monte Carlo simulation.

Modeling Showers II



Proton shower movie

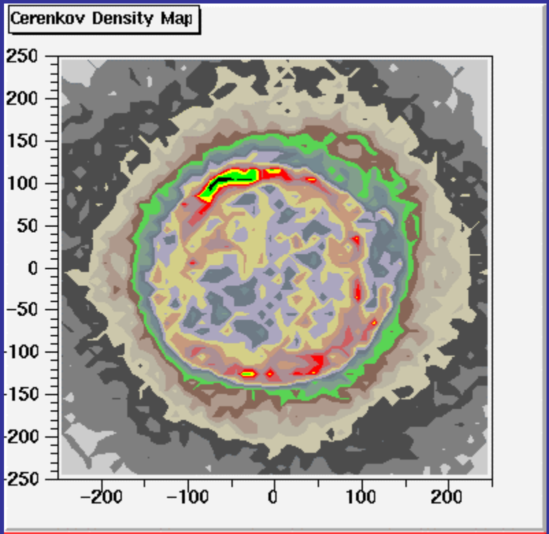


γ-ray shower movie

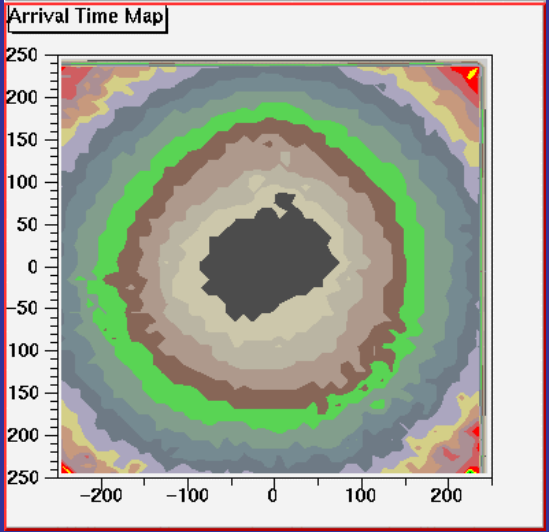
Each shower is a single statistical "event".

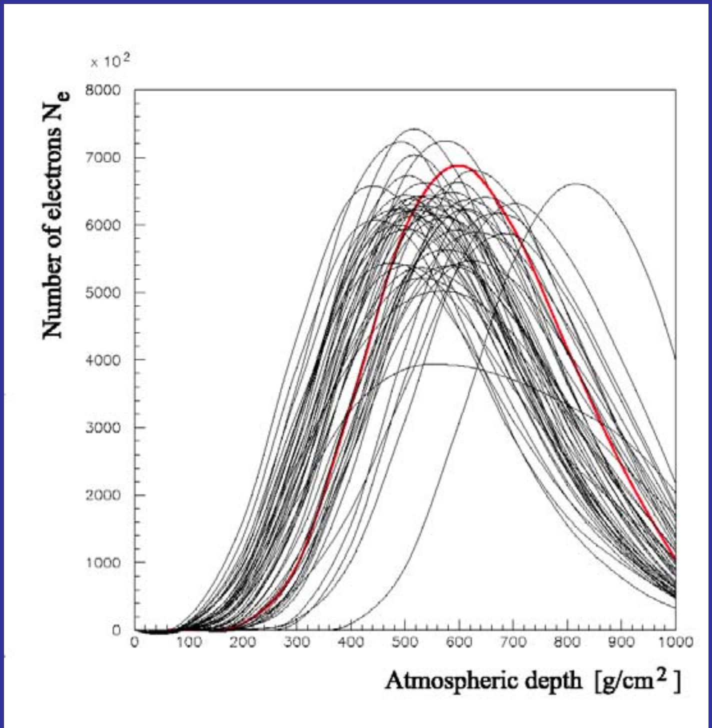
Modeling Showers III

Density of light on the ground.



Time of arrival on the ground.





Fluctuations are important.

Data Analysis

- Each Cherenkov flash corresponds to a single event.
- For each event, we record the arrival times and amplitudes of the pulses recorded by each detector.
- We use this information to reconstruct the event – i.e. to determine the most likely value for event direction, energy.

Maximum Likelihood fit using data & simulation.

The Background Problem

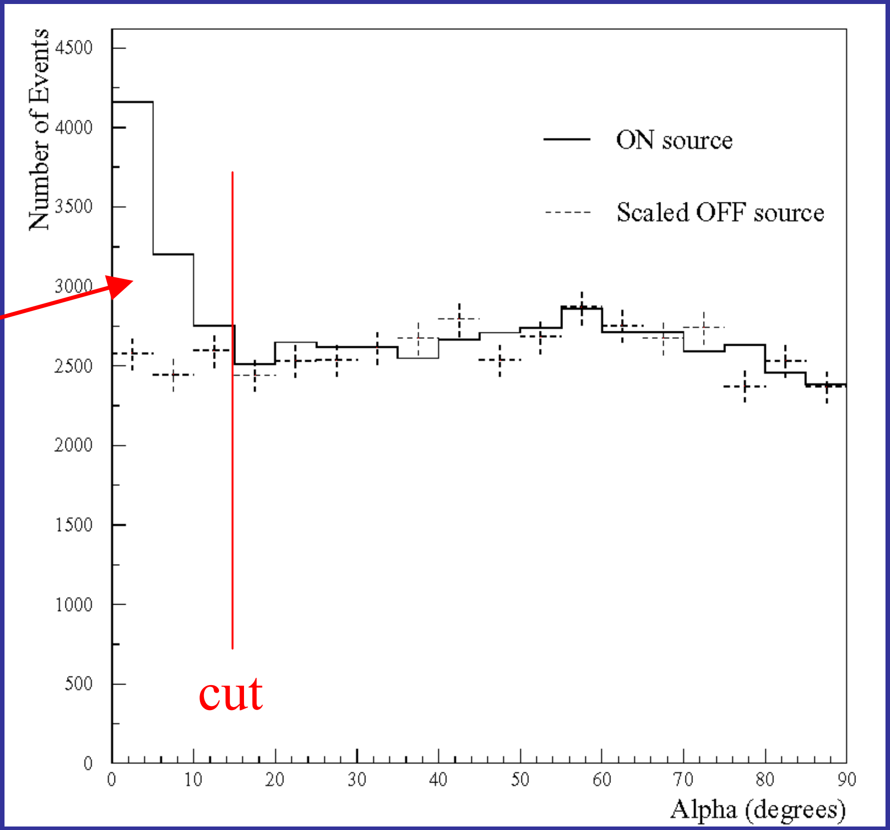
Ideally, we would record the arrival time, direction, and energy of each g-ray we detect … but …

We can't do this because the signal/background is low. Most showers we record are charged cosmic ray particles.

1. We take data ON source and OFF source.
2. Analysis is based on a statistical extraction of the relevant quantities..

Statistical Separation

Histogram of reconstruction angle.



S/B ~ 1/3

To detect a <u>new</u> source, we must use prior knowledge of distributions like these from simulation or earlier detections.

Energies & Variability

Energies:

- Reconstruct energy spectrum for ON and OFF.
- Calculate ON – OFF, point by point.

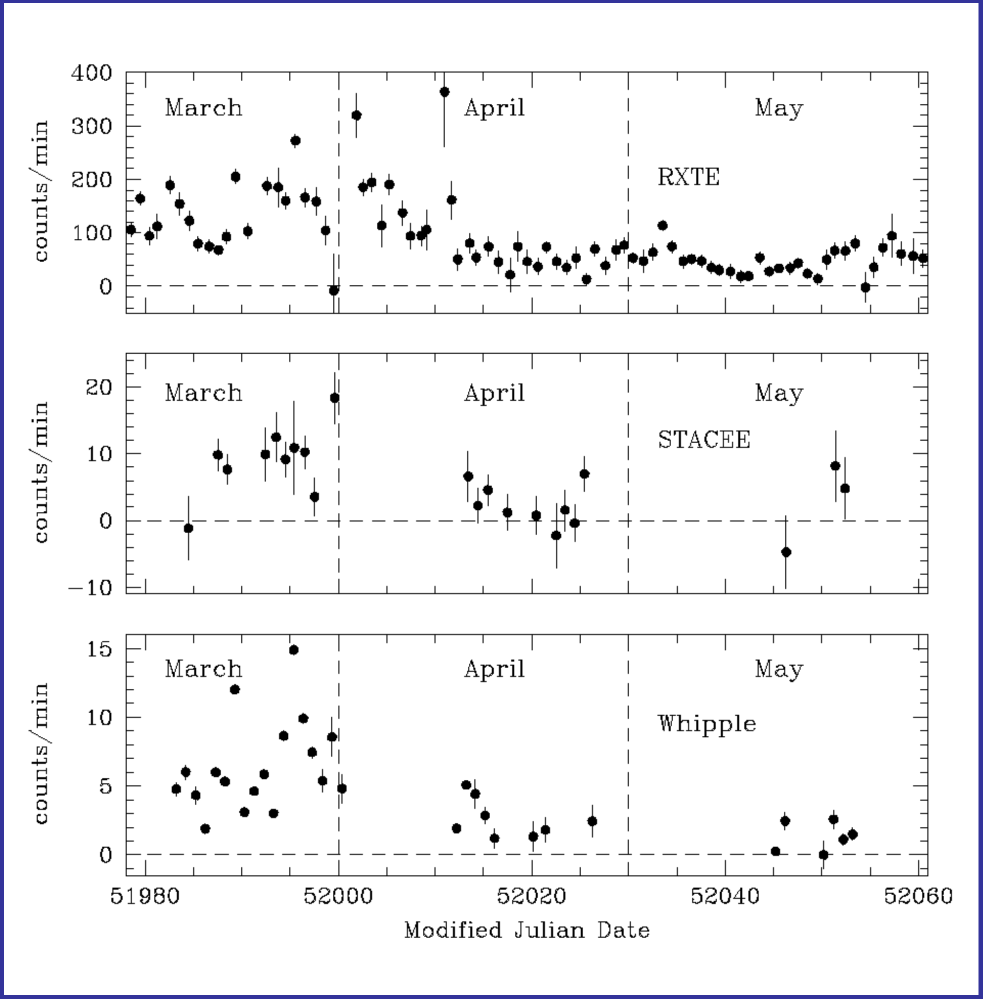
Variability:

- Difficult because data is sparsely sampled. Source is only detectable when high in the sky, on clear nights, with no Moon.

- To compare data sets between experiments is even more difficult.

Example: Flare of Active Galaxy

Count Rate



RXTE Satellite

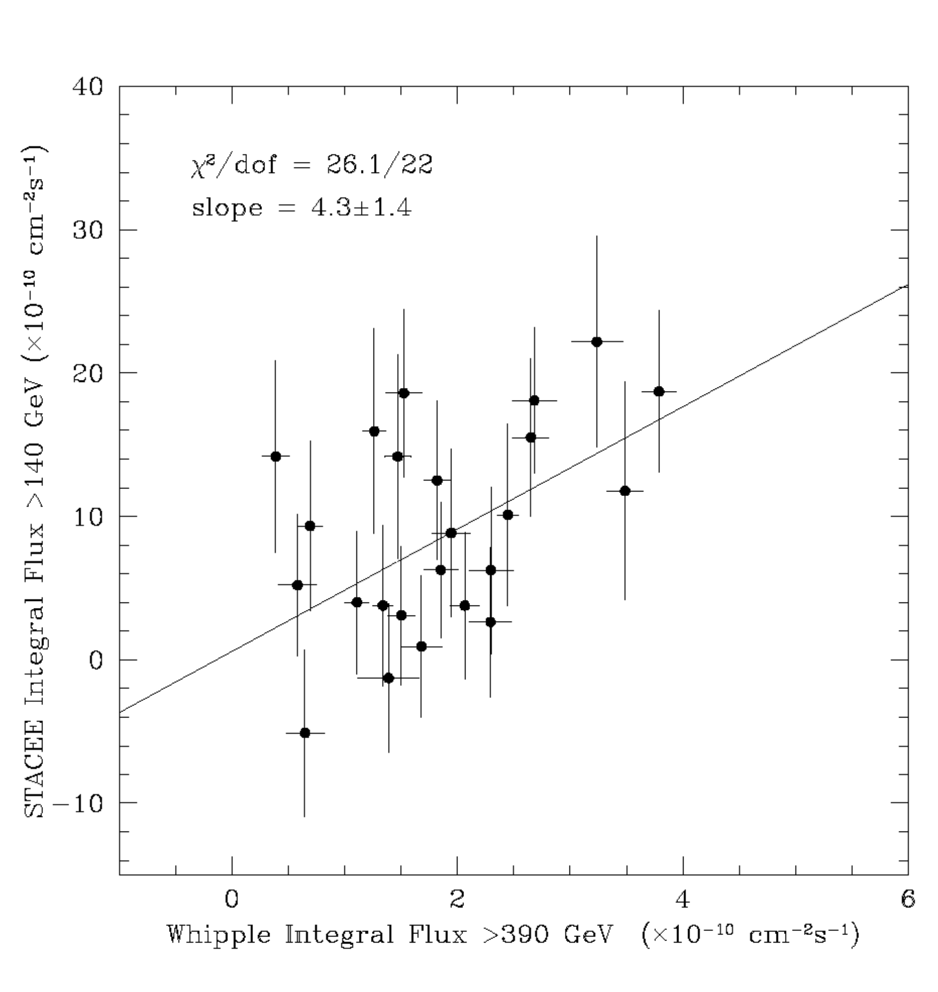
STACEE

WHIPPLE

Date

Simplest Analysis

Binned scatter plot



Possibly correlated.

Better ?

<u>Discrete correlation function (DCF)</u>

Two data trains: a, b
Calculate for all pairs:

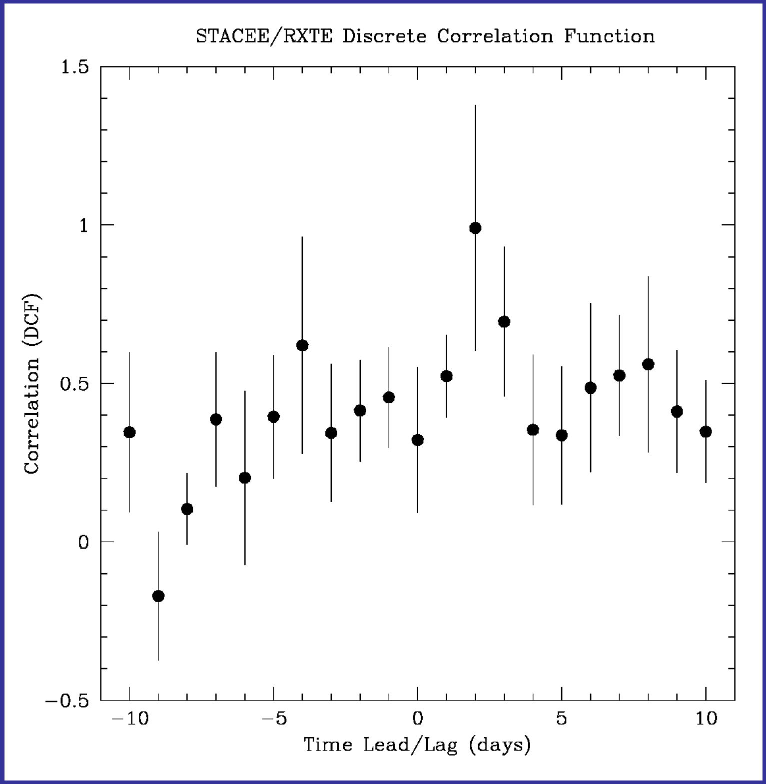
$$UCDF_{jk} = \frac{(a_j - \bar{a})(b_k - \bar{b})}{\mathrm{sqrt}\,[\,(\sigma_a^2 - e_a^2)(\sigma_b^2 - e_b^2)\,]}$$

where time lag $\Delta t_{jk} = t_j - t_k$

Then determine the DCF by

- binning in time
- averaging over the N pairs

DCF Plot



No strong evidence for correlation.

Would be interested in getting viewpoint of a statistician.

Summary

- Gamma-ray astronomy is a frontier field that probes the highest energy processes in the universe.

- Telescopes use the entire atmosphere as detecting volume – instruments are in their early stages.

- Interpretation of data is challenging. We are working on ways to substantially improve the S/B.

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes."

Marcel Proust (1871-1922)