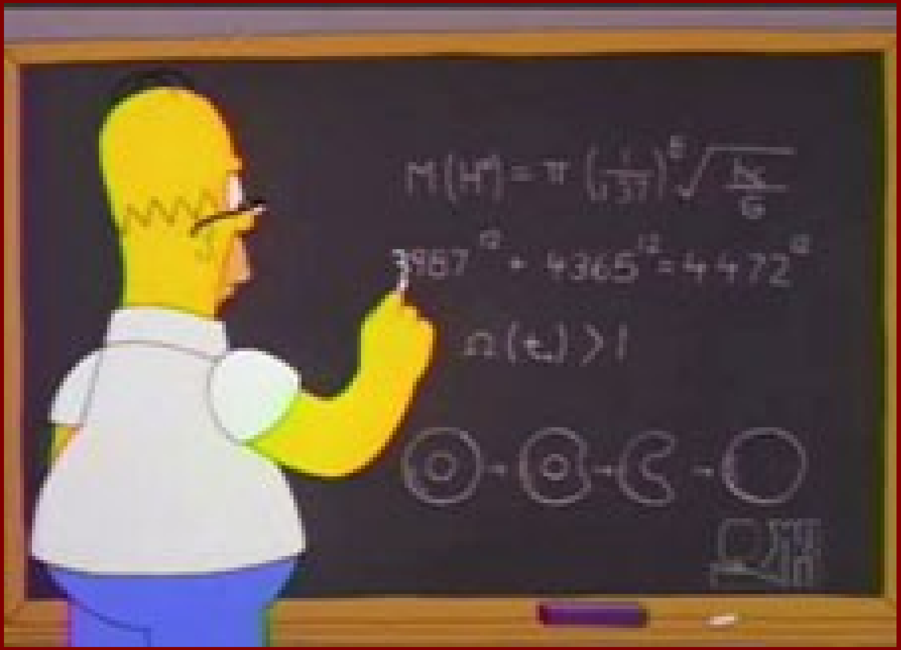
Gamma-ray Astronomy and related projects at McGill



Homer's Physics

2009/03/20

David Hanna

Outline of presentation

introduction to gamma rays

scientific motivation

detection techniques

related projects

People involved:

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Alumini		
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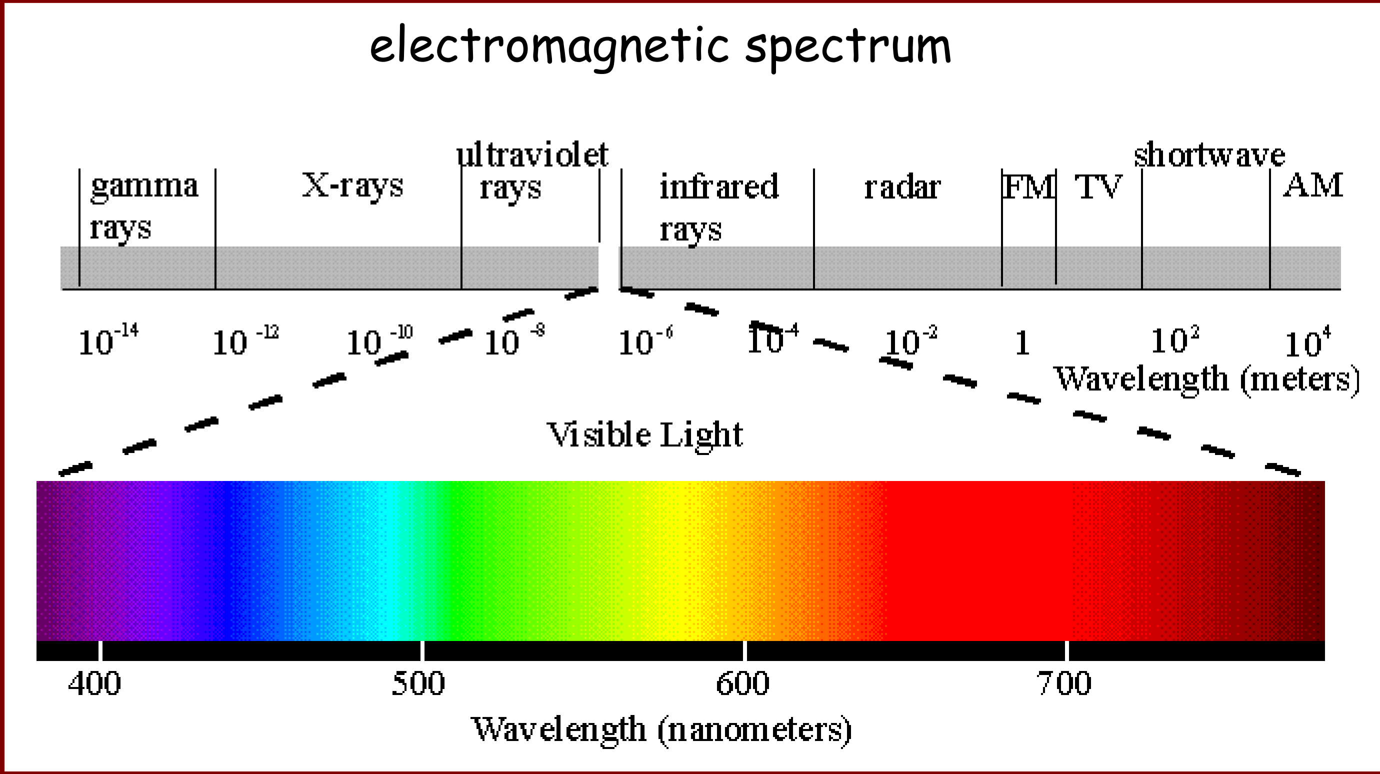
	MSc	Francois Vincent, Theresa Spreitzer, Graham Gauthier, Jean-Philippe Gagnon



What are Gamma Rays?

gamma radiation is a higher energy, shorter wavelength version of the visible light we know so well.

gamma rays are at the opposite end of the Electromagnetic Spectrum from radio waves; their neighbors are the X-rays.

although all electromagnetic radiation can behave as a wave or as a particle (photon), depending on circumstances, gamma-rays are almost always treated as particles; they are detected one by one.

Photon Energies:

visible ~ 1 - 10 electron Volt (eV)

X-ray ~ 1000 – 1000000 eV (1 keV – 1 MeV)

gamma-ray ~ 1000 – 1000000 MeV (1 GeV – 1 TeV)

What is Gamma-ray Astronomy?

all parts of the electromagnetic spectrum are now used for astronomy

different energies reveal different physical processes at work in the Universe

most of the radiation studied arises from molecular, atomic, or nuclear transitions in matter that is in some kind of stable equilibrium (eg a star like our Sun)

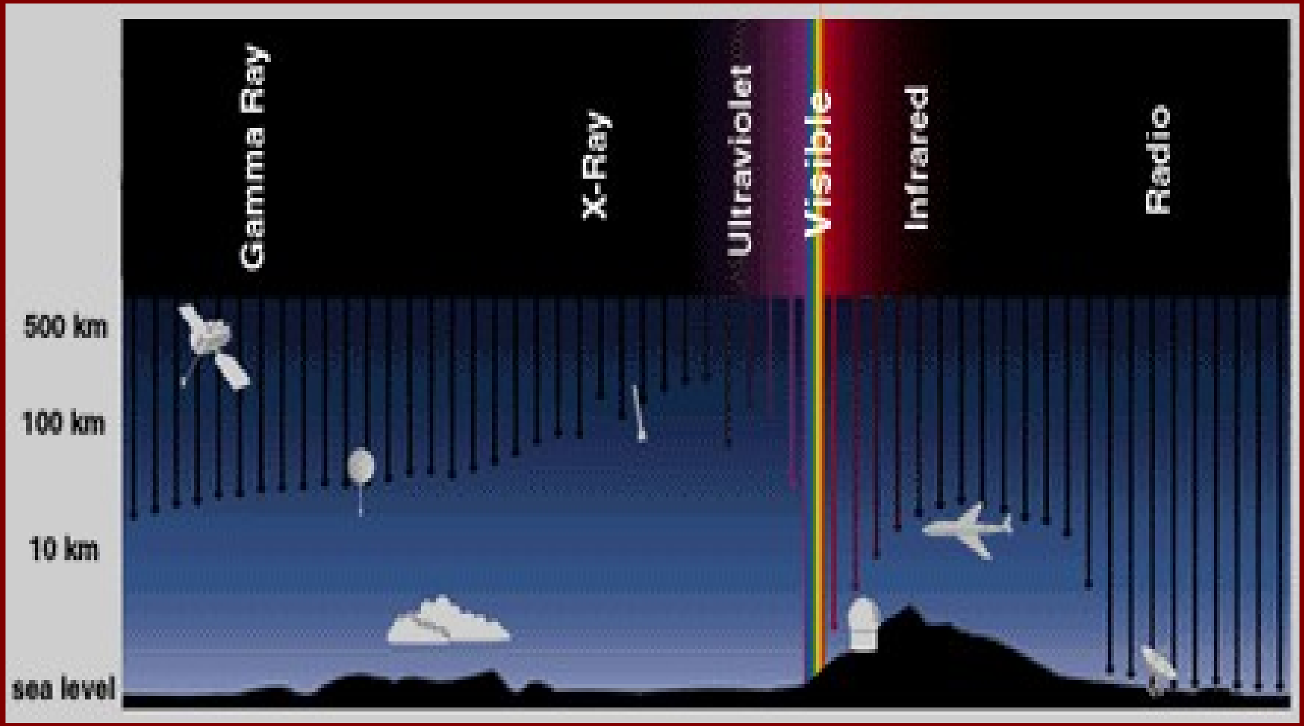
high energy gamma-rays cannot be produced by hot, glowing objects like stars – they come from (and teach us about) more exotic processes

for example:

- a common mechanism for producing high-energy gamma rays is to scatter low energy photons (like visible light) off high energy electrons

- how do those electrons get to such high energies (well beyond what particle physicists can attain with their giant accelerators here on Earth)?

The Crab Nebula, the brightest source of gamma rays in the sky and the source of much of our understanding of high-energy astrophysics



The earth's atmosphere is opaque to much of the electromagnetic spectrum

- classical astronomy only used visible light and our view of the universe was highly constrained and profoundly influenced by that

- the history of modern astronomy has been driven by the opening up of the spectrum to measurements at other energies/wavelengths

- with every new energy range we have discovered new phenomena

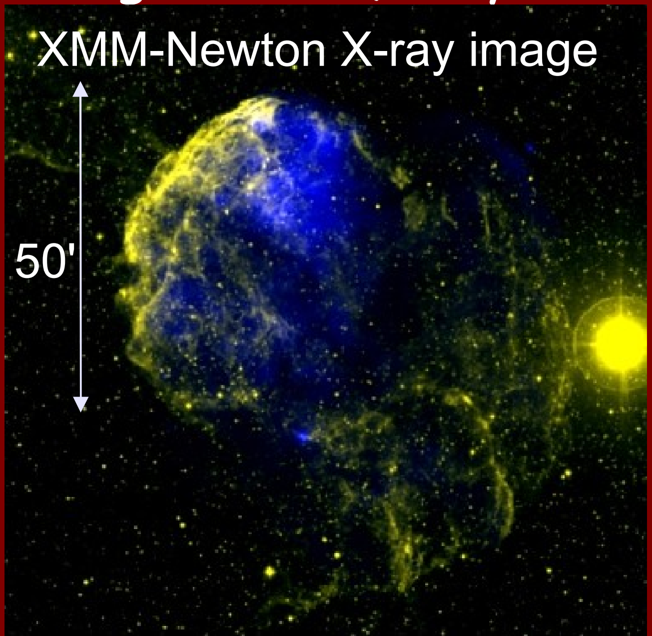
Gamma-ray Astronomy: Sources and Science

galactic (inside the Milky Way - close):

supernova remnants and related phenomena

eg Cas A

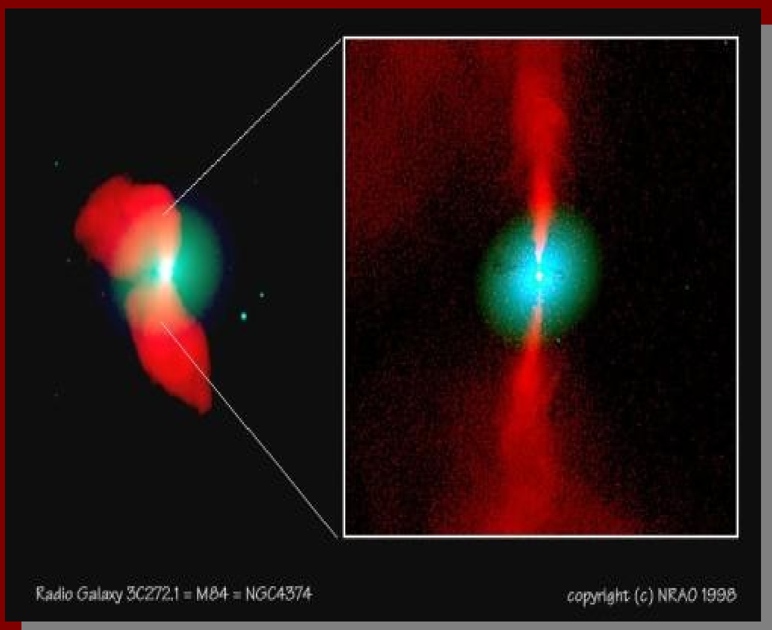
eg IC443 (Jellyfish Nebula)



Gamma-ray Astronomy: Sources and Science

extragalactic (outside the Milky Way - far):

active galactic nuclei – supermassive (billion-sun) black hole sucking in the material of the host galaxy and producing jets of fast-moving plasma



eg 3C272.1 (M84)

eg M87

Gamma-ray Astronomy: Sources and Science

- science is a combination of astrophysics and 'fundamental' physics

astrophysics:

- how are very-high-energy gamma-rays made in SNRs and AGNs?
- what is the intergalactic medium like?

fundamental physics:

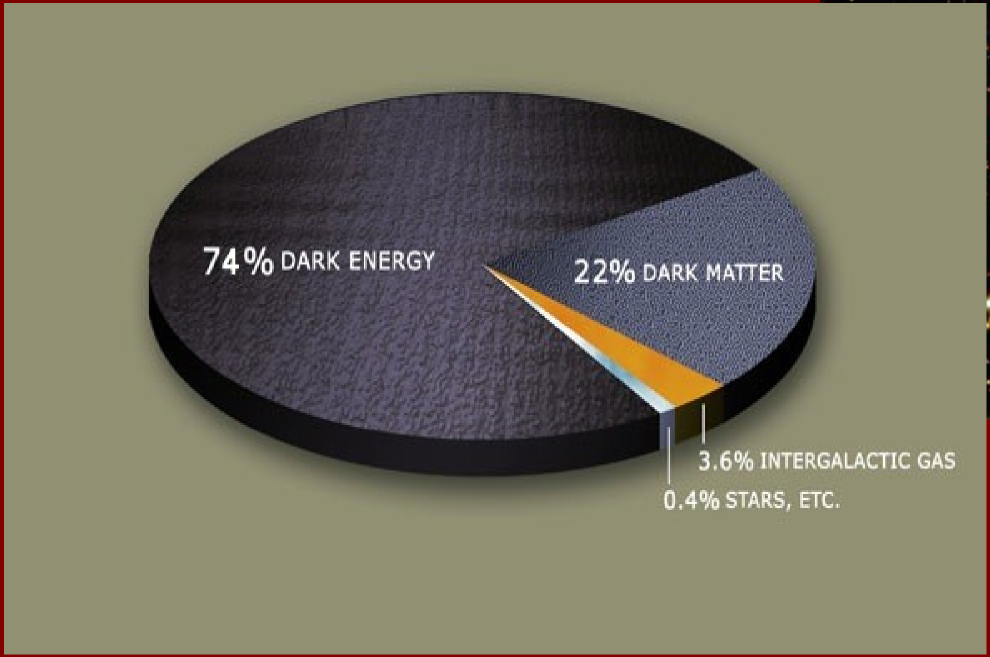
- what is the nature of dark matter?
- does the speed of light depend on the energy of the light?

Dark Matter

- there are many reasons to believe that the matter we know about (atoms etc) makes up only a small (4%) fraction of the mass-energy of the Universe

- dark matter makes up (some of) the rest

- what is it??

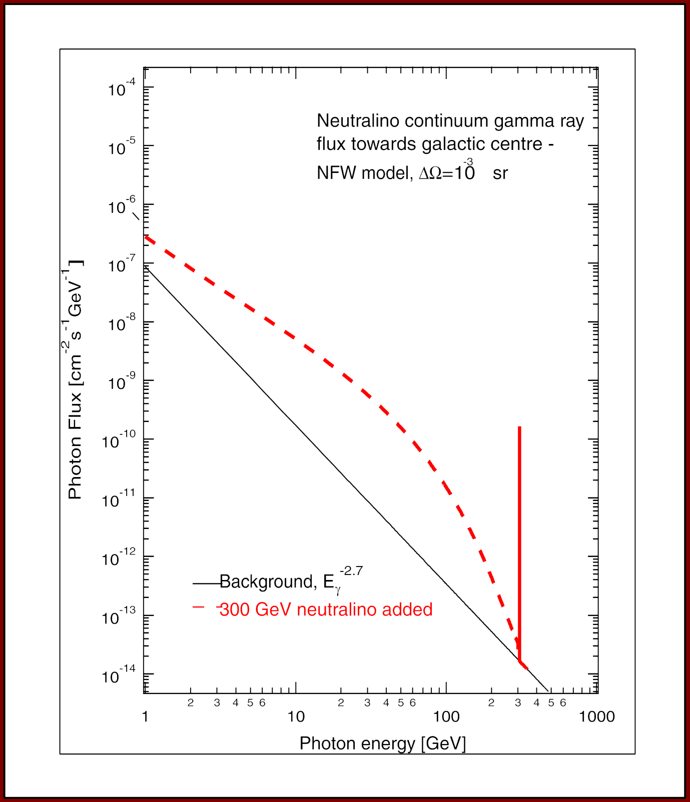


Bullet cluster of galaxies
- red = visible mass
- blue = total mass

Dark Matter

- one favoured scenario is the the dark matter is in the form of weakly interacting massive particles (WIMPs)

- these are being looked for in accelerator experiments and in experiments in underground labs

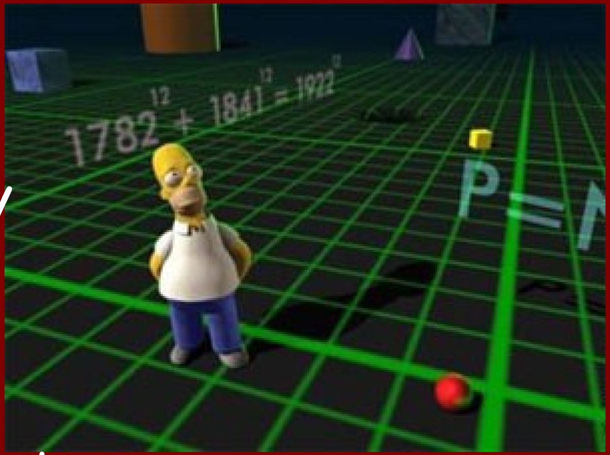


WIMP annihilation at the centre of galaxies can give rise to spectral distortions and/or a 'line' feature

large theoretical uncertainties exist (flux, cross-sections, mass etc) but discovery reach is very large (mass range beyond LHC)

astrophysical connection is direct

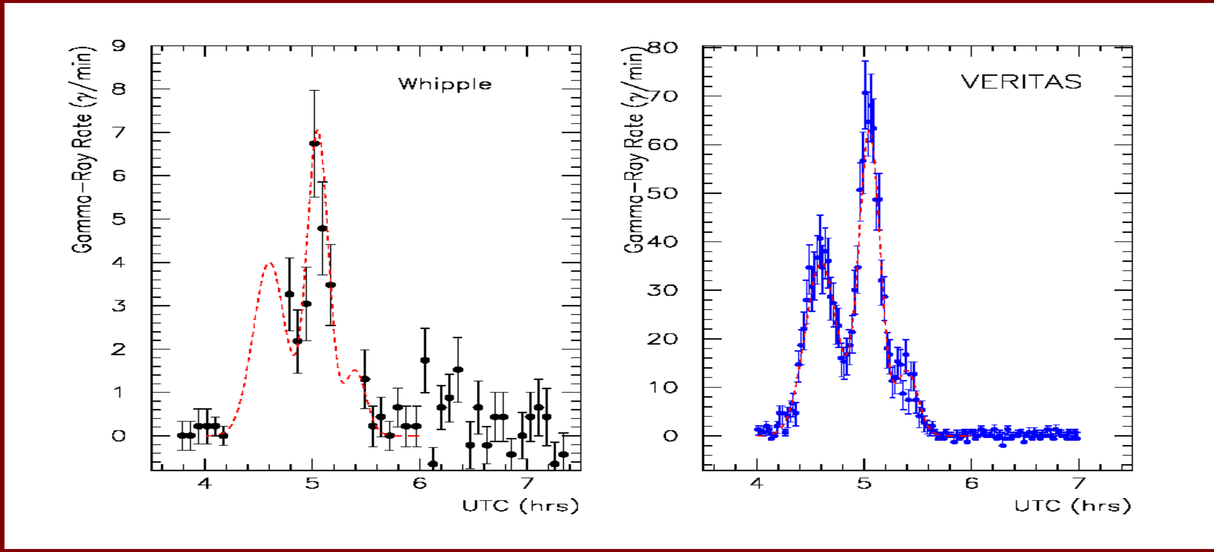
Quantum Gravity



(attempt to bring the theories of gravity and quantum mechanics together)

one consequence that could possibly be observed is that the speed of light depends on the energy of the gamma ray

try to see this using very high energy photons and very long baselines (ie out to AGNs)



use fast flares from distant AGNs to look for effects

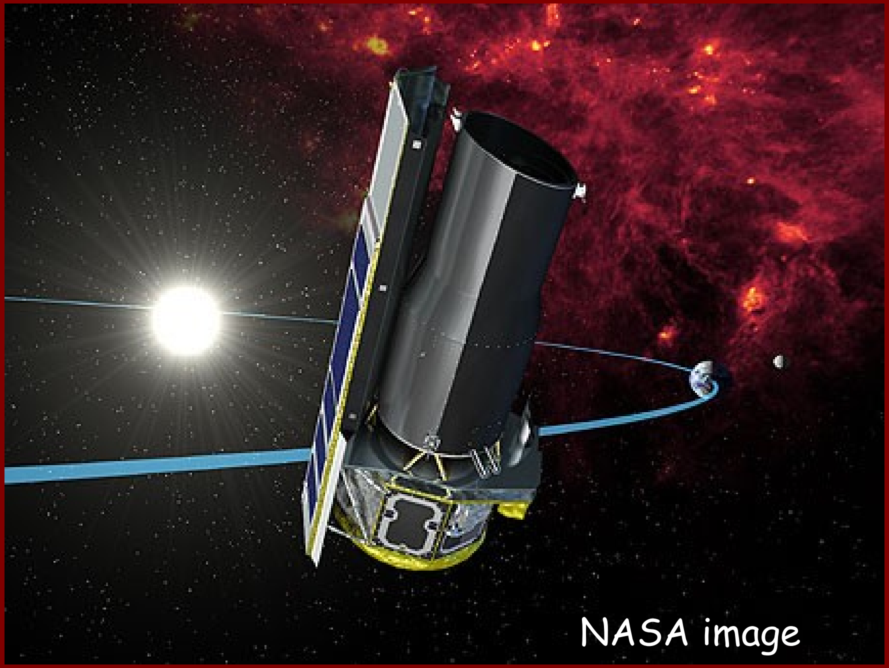
Technology

– how to detect very-high energy gamma rays

Telescopes for different wavelengths: Radio and Infrared

NRAO photo

radio telescopes are large dishes, usually deployed in arrays, like the Very Large Array (VLA) in Socorro, NM

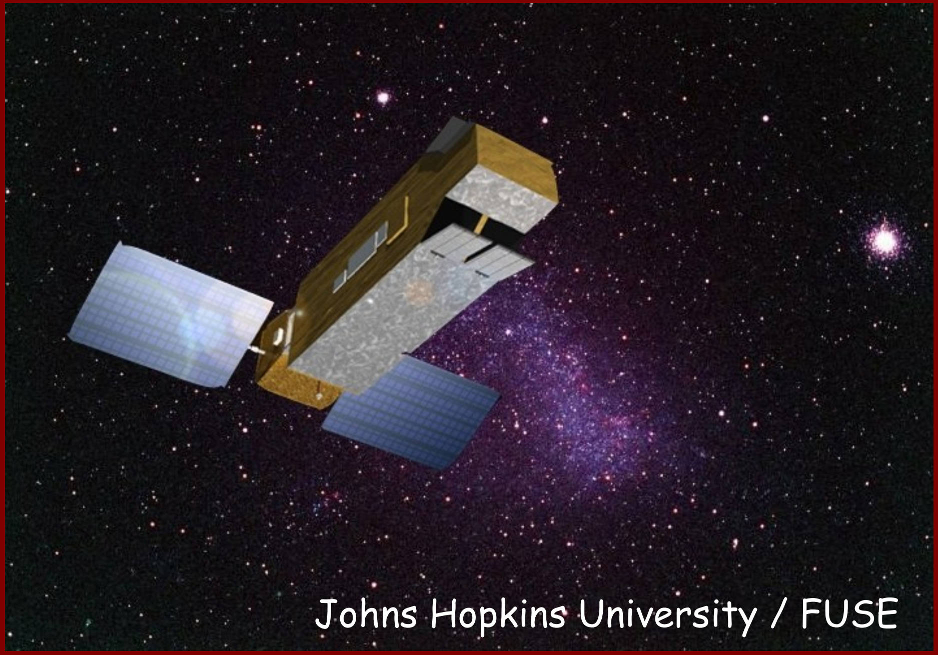


NASA image

far infrared (IR) observations must be performed in space, with orbiting telescopes like Spitzer (launched in 2003)

Telescopes for different wavelengths: Optical and Ultra-violet

optical and near infrared astronomy can be done with Earth-bound observatories like the Gemini telescopes in Hawaii and Chile



ultra-violet (UV) radiation is (mostly) absorbed by the atmosphere so UV telescopes, like the Far Ultraviolet Spectroscopic Explorer (FUSE), need to be on orbiting spacecraft

Telescopes for different wavelengths: X-ray and Gamma-ray

Chandra

X-rays are absorbed by the atmosphere; all astronomy is carried out with orbiting telescopes like the Chandra observatory

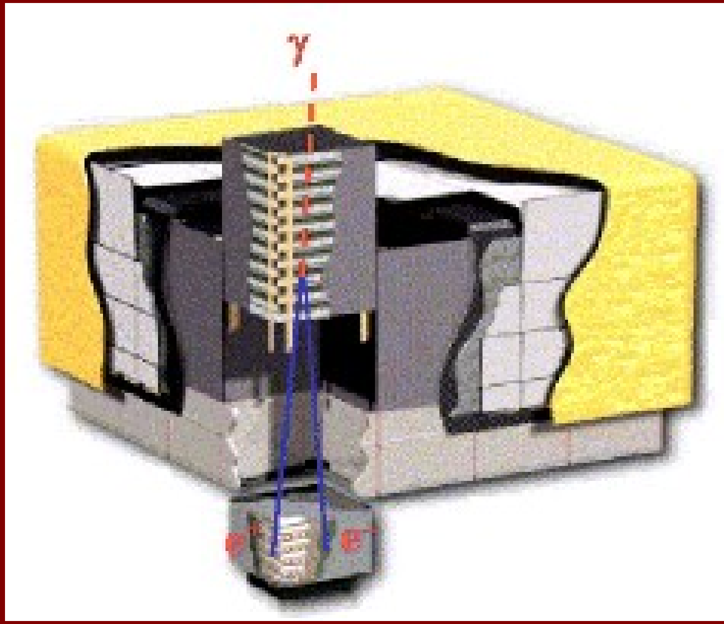
Compton

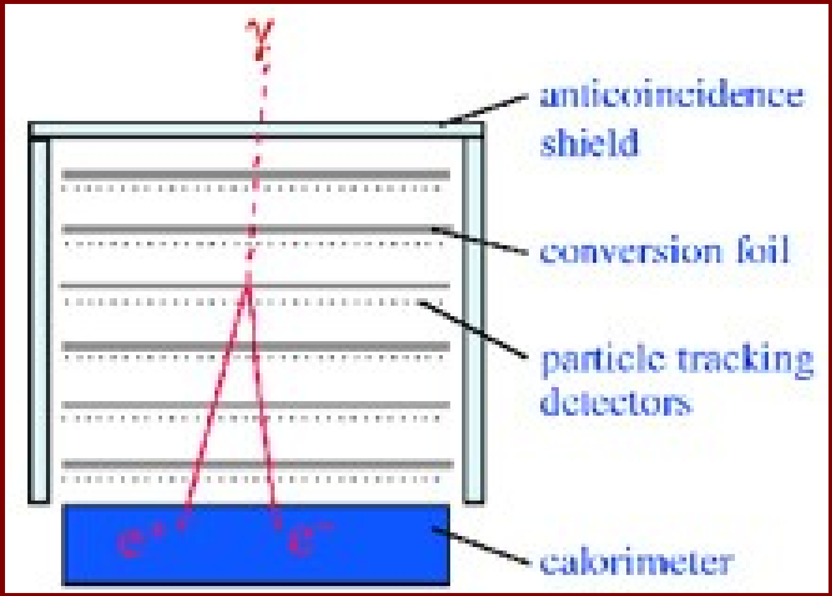
at energies up to about 10 GeV, gamma ray astronomy is done with space-borne detectors like the Compton Gamma-Ray Observatory (1991-2000) and the Fermi Gamma-ray Space Telescope, launched in 2008

Fermi

NASA images

Gamma Rays are different from all other photons
(X-ray, UV, Optical, IR etc) – they can't be focussed



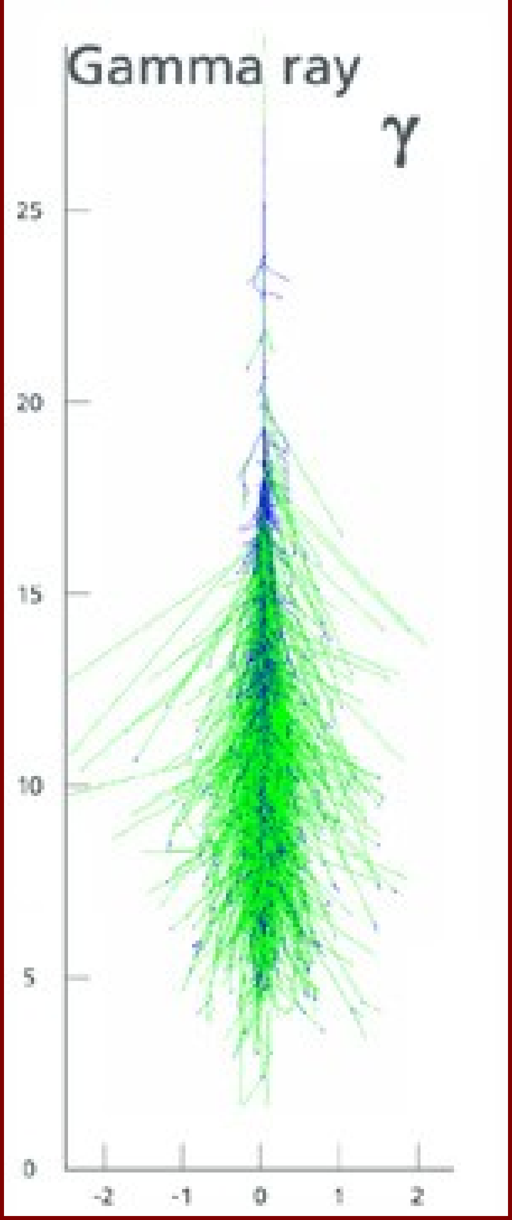


At low energies, convert the gamma ray
into an electron-positron pair

measure the direction and energy of the
electron and positron (easy to do with
techniques developed for particle physics)
to get the direction and energy of the gamma

Telescopes for different wavelengths: Very High Energies

altitude (km) above sea level →



above 50 GeV one can observe
gamma rays from the ground
by using the atmosphere
as part of the detector

the incident photon interacts in
the upper atmosphere and gives
rise to a cascade of particles called
an extensive air shower (EAS)

Telescopes for different wavelengths: very high energy gamma-rays

At energies above 50 GeV or so, Cherenkov radiation generated by charged particles in the air-shower can be detected by arrays of large steerable mirrors and used to reconstruct the energy and direction of the incident gamma ray.

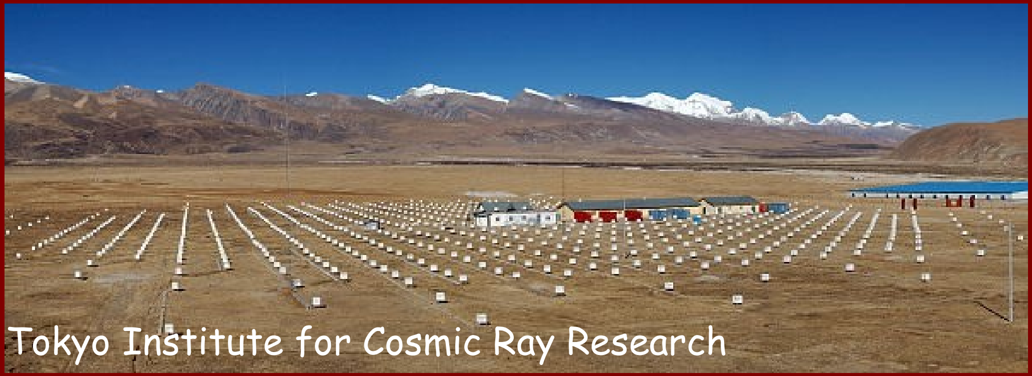
VERITAS is a detector of this type.

Telescopes for different wavelengths: very high energy gamma-rays

Los Alamos National Lab

At photon energies above 1000 GeV or so, the charged particles in the air-shower can penetrate to detectors on the ground

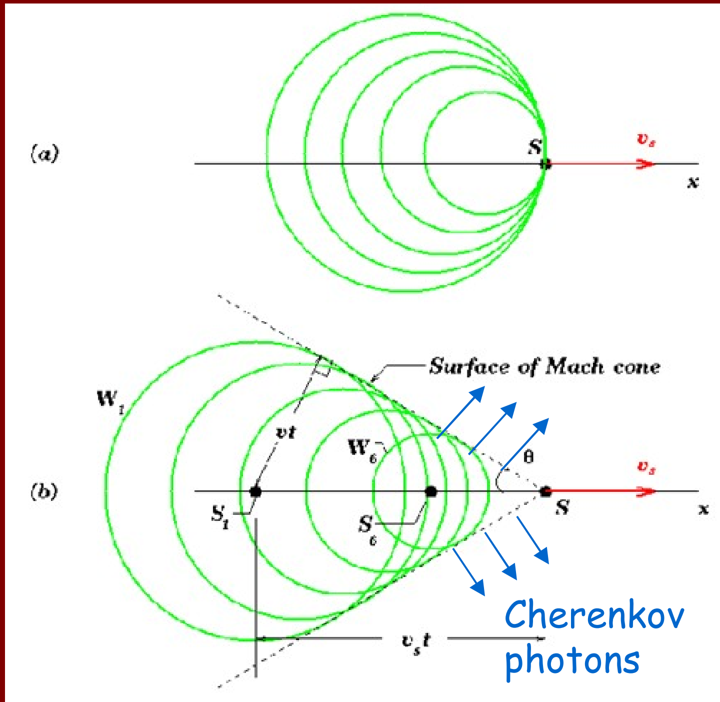
In the MILAGRO detector the particles generate Cherenkov light in a large pool of pure water viewed by photomultiplier tubes



Tokyo Institute for Cosmic Ray Research

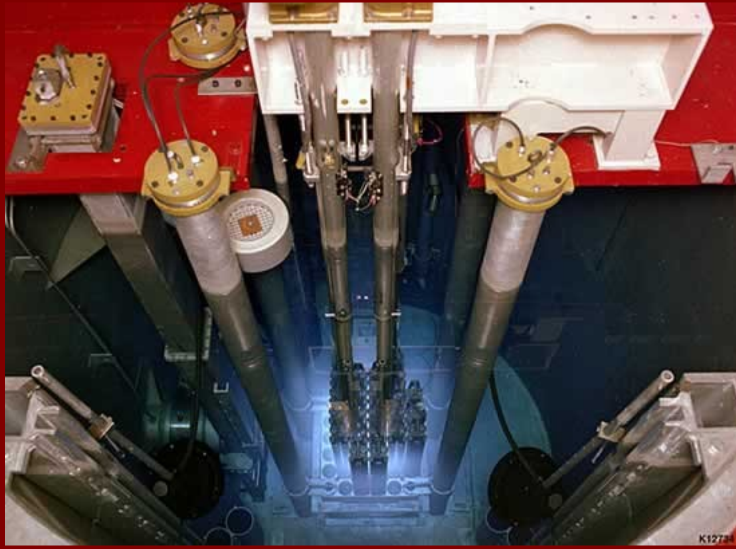
In the Tibet Air Shower gamma detector the particles are detected using scintillation counters

What is Cherenkov Radiation ?



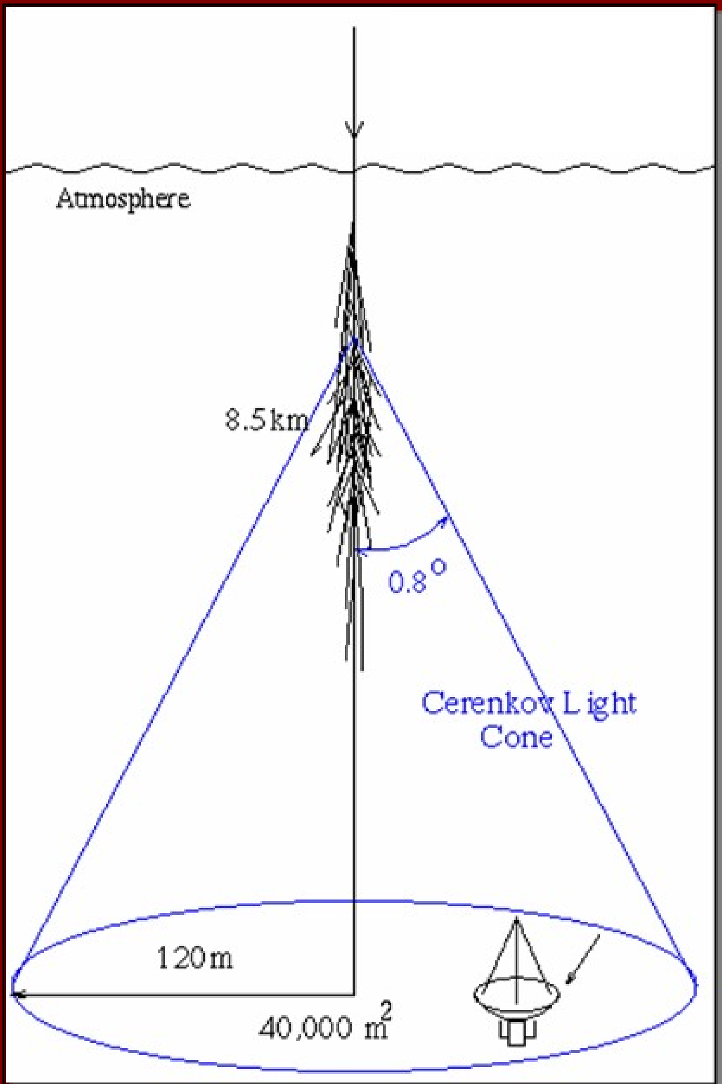
when a charged particle travels faster than the local speed of light, it is super-luminal and sets up a shock front which results in the optical equivalent of a sonic boom

this 'lumic boom' is manifest as a stream of ultraviolet and blue photons emitted in a cone about the particle track



the light is very faint but if there are enough charged particles around (like in a swimming pool reactor) the blue glow can be seen with the naked eye

Gamma-ray Astronomy Using Atmospheric Cherenkov Telescopes



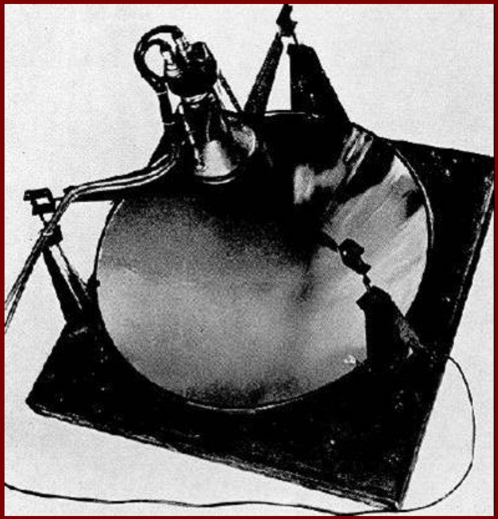
the Cherenkov photons generated by the particles in the air shower easily penetrate to the ground even if the charged particles are absorbed

one can detect showers from gamma rays with energies down to about 50 GeV

the light pool is large (40,000 m^2) and, since a detector placed anywhere within it can register the arrival of a gamma ray, the effective area of the detector is also that large

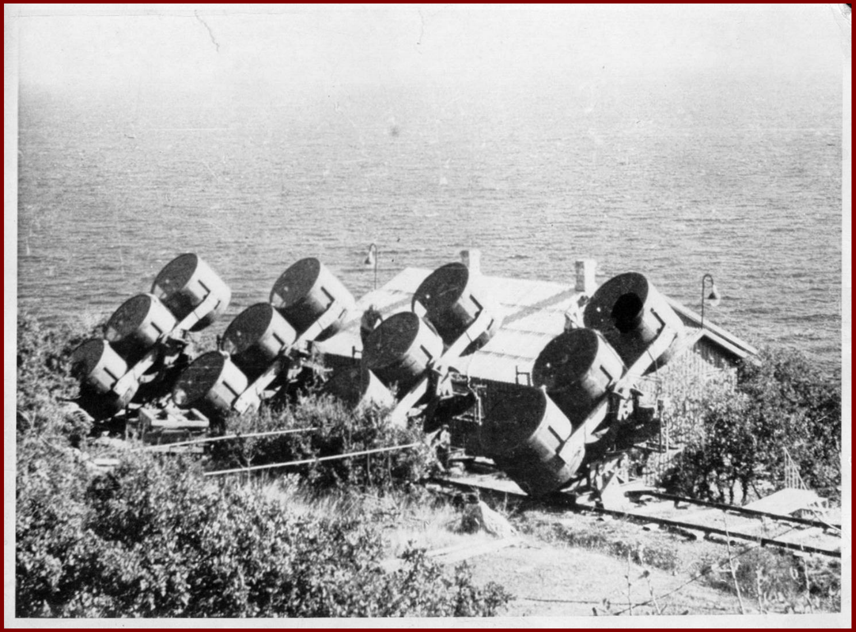
this makes the technique especially valuable since the fluxes of such high energy gamma rays are very low and a huge detector is the only way to catch a significant number of them

Development of the Atmospheric Cherenkov Technique



1953 – Proof of Concept:

Galbraith and Jelley (UK) demonstrate the existence of atmospheric Cherenkov radiation using a 25 cm diameter mirror as collector and a 5 cm diameter photo-multiplier tube as light sensor



1960 – First Gamma-ray Telescope:

Chudakov and collaborators (USSR) construct the first dedicated instrument for TeV astronomy using twelve 1.5 m searchlight mirrors

Development of the Atmospheric Cherenkov Technique

1968 – First Gamma-ray Telescope on Mt Hopkins:

Weekes and collaborators construct the first large-scale instrument, based on a 10 meter diameter reflector
– it is still running almost 40 years later!

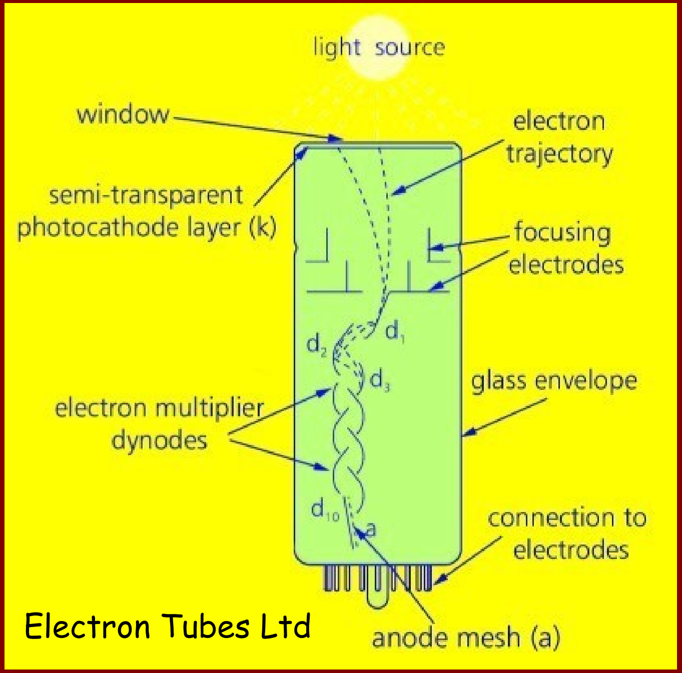
Trevor Weekes and George Rieke at the Whipple Base Camp (present site of the VERITAS array)

Imaging – the key to success

gamma-rays can be detected but they also need to be distinguished from a potentially overwhelming background of charged cosmic rays that also produce air-showers and therefore Cherenkov light – there are 10000 cosmic rays for every gamma-ray!

to separate gamma rays from cosmic rays we need to take a picture of the blue streak in the sky that is the Cherenkov signal – differences in the shape of the image can be used to reject cosmic rays

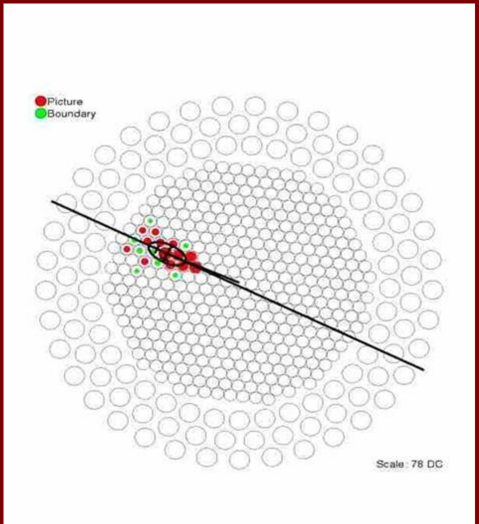
photograph of the camera installed at the focus of the Whipple telescope
- each pixel of the camera is a photomultiplier tube – a highly sensitive device which can detect the faint Cherenkov light
– even one or two photons will give a detectable pulse

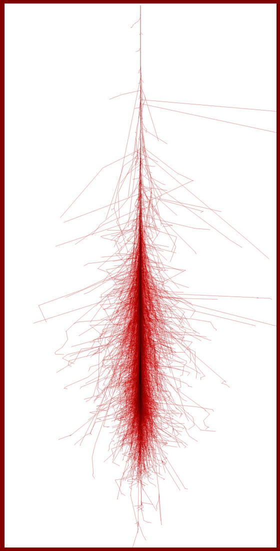


A gamma-ray image:

the pattern of pixels forms a smooth elliptical shape which points to the center of the camera

this is the result of the smooth nature of the gamma-induced shower itself

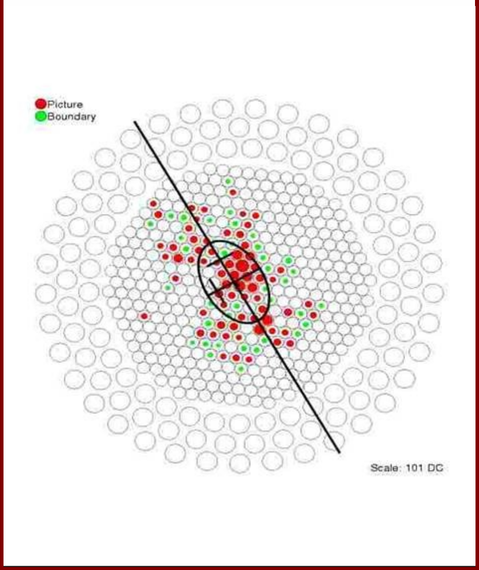


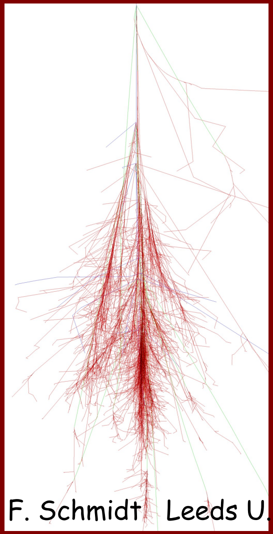


A cosmic-ray image:

the pattern of pixels is chaotic and non-elliptical

this is the result of the clumpier nature of showers resulting from cosmic rays, which are protons and light nuclei and have more complicated physics



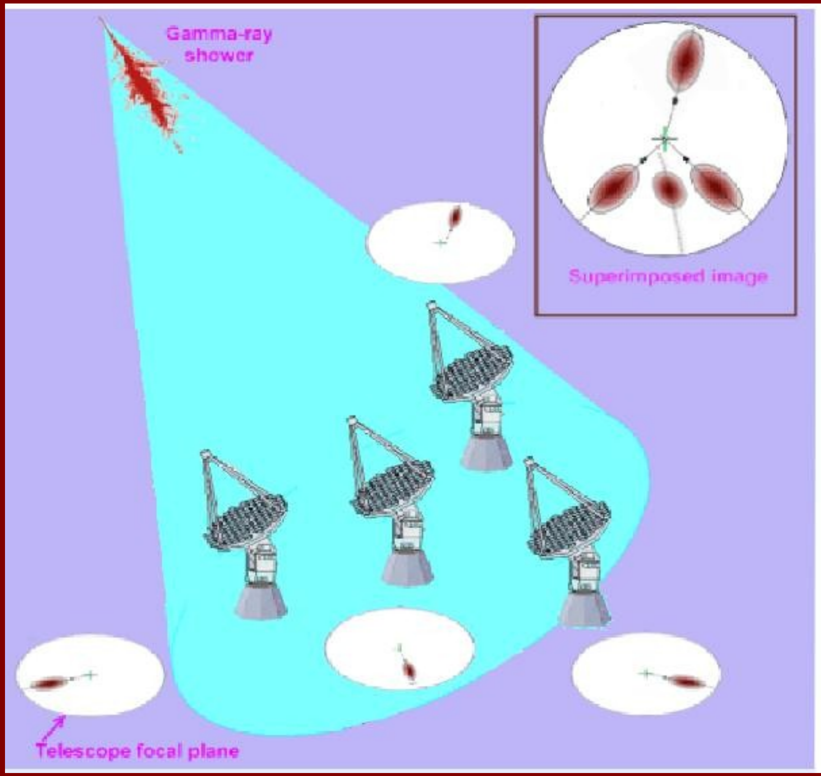


Using the imaging technique, the Whipple collaboration was able to detect:
- the Crab Nebula (1989) – (the first galactic source to be detected at high energy)
- Markarian 421 (1991) – (the first extra-galactic source to be detected at high energy)

The next step: arrays of telescopes

- during the 1990's the HEGRA collaboration built and operated an array of 5 small (8.5 m^2) imaging telescopes on the Canary Island of la Palma

- they showed that multiple views of the same shower can give
    - better angular resolution
    - better background rejection
    - better energy resolution
    - better sensitivity



Cangaroo collaboration adapted by P Cogan

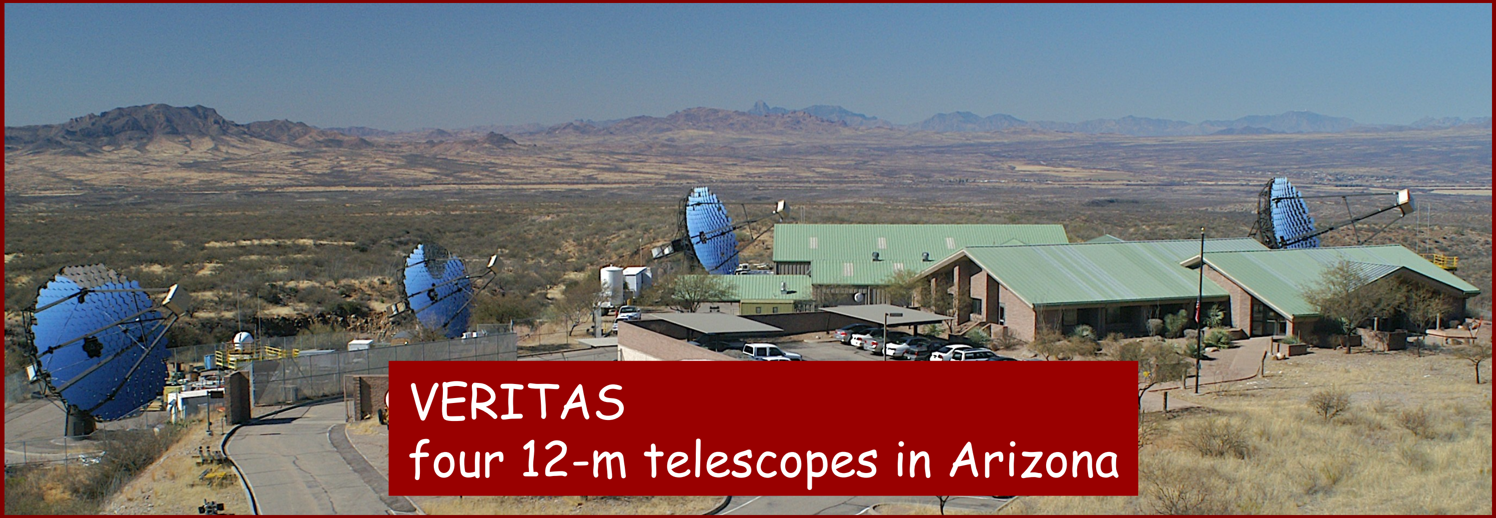
It was clear that arrays of large telescopes would enable significant gains to be made

The third generation

there are now four instruments for the 50 GeV – 10 TeV energy range

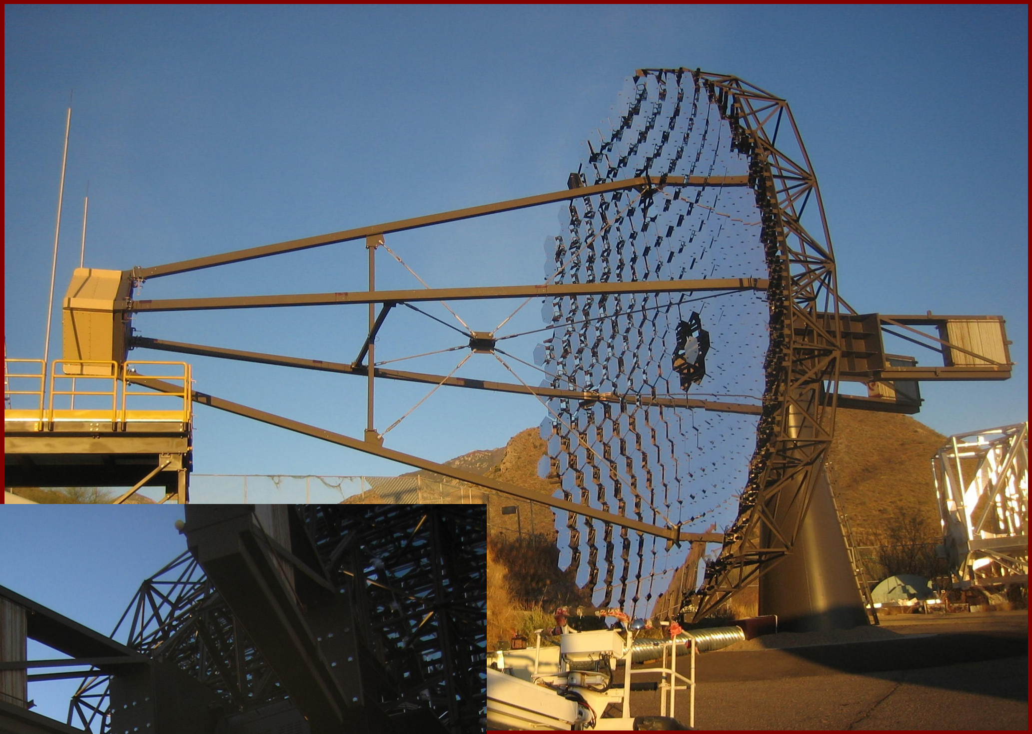
2 view the southern skies
2 view the northern skies

since they are at different latitudes they complement each other when viewing transient phenomena, since they can only operate at night



VERITAS: some details

the array comprises four 12 m diameter telescopes



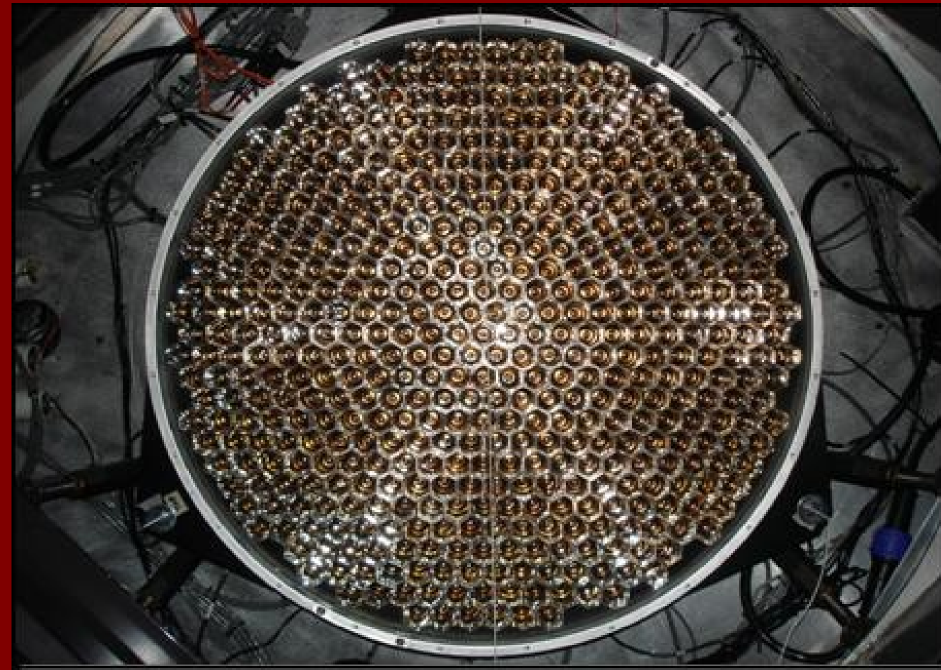
each has 350 mirror facets made from glass surfaced with anodized aluminum

they are mounted on a steel frame to make a Davies-Cotton reflector with a 12 m focal length and a point-spread function with a width of 0.07 °

the reflector is pointed by an altitude-azimuth mount which can slew at 1° per second and point with an accuracy of 0.015 °

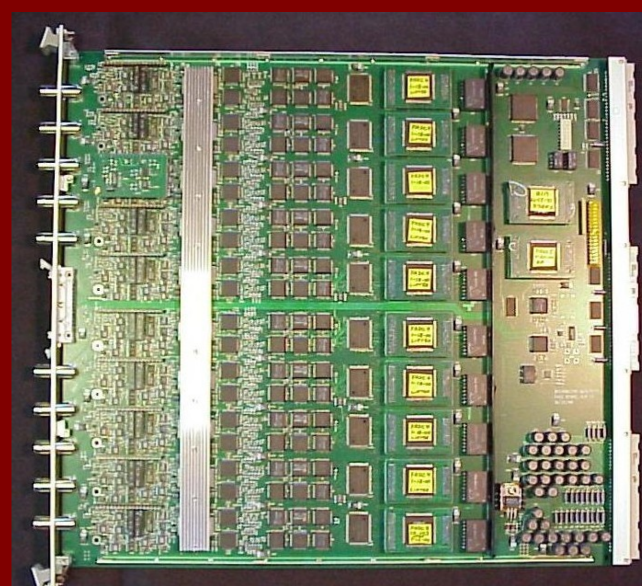
at the focus of each telescope is a camera made with 499 25 mm diameter photomultiplier tubes (PMTs)

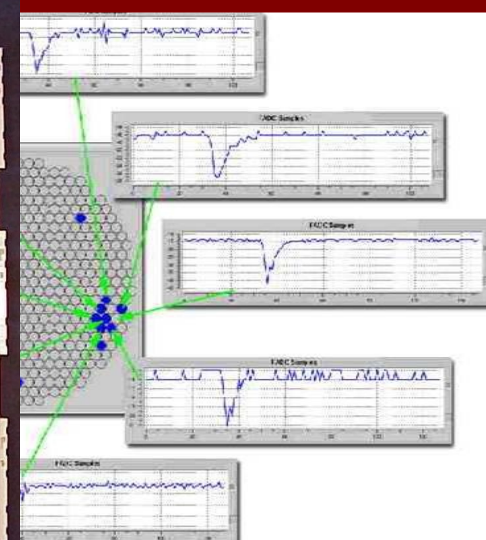
each PMT views a patch of sky 0.15° in diameter



the PMTs are read out using custom designed flash analog to digital converters (FADCs) which continuously measure the signal every 2 nanoseconds - like a digital oscilloscope on every PMT

one can use the information to measure how many Cherenkov photons hit the PMT and when they arrived

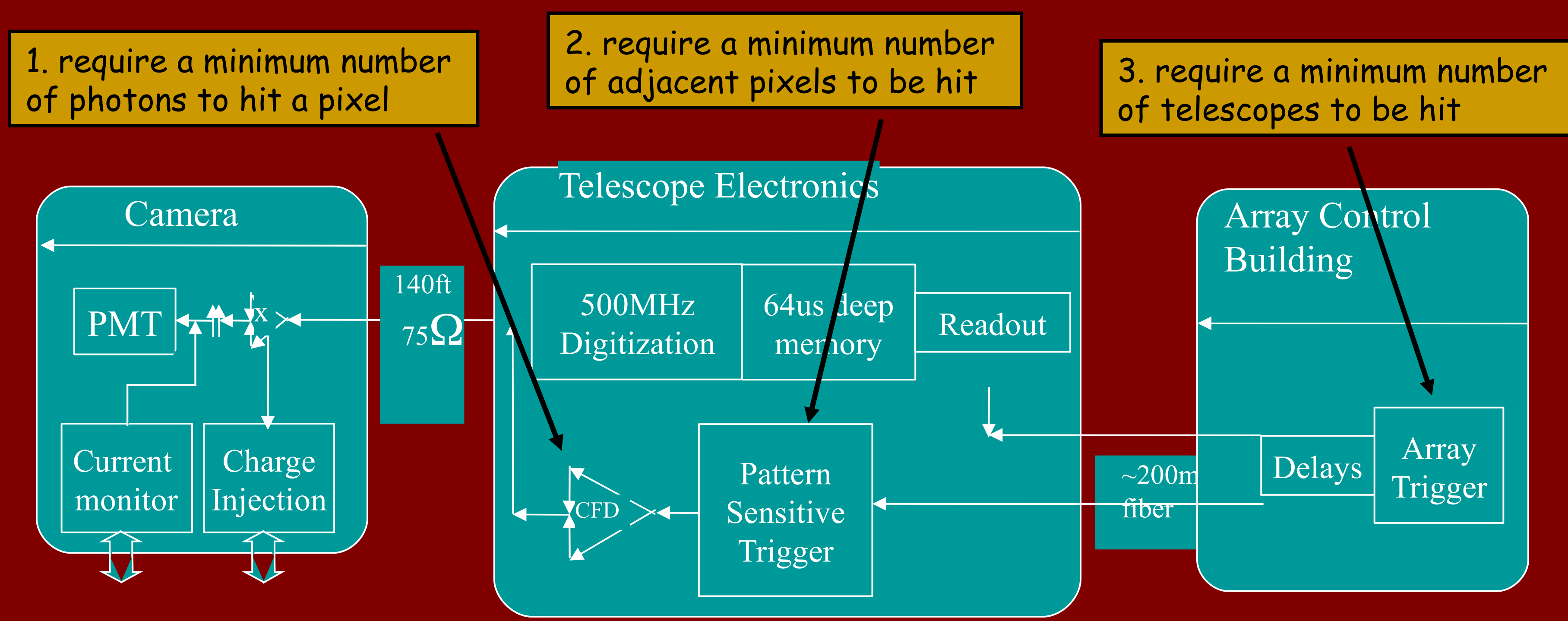




VERITAS Trigger

One can think of the VERITAS cameras and FADC system as a very grainy but very fast movie camera – only 499 pixels (a cheap camcorder has more than a million) but a frame speed of 500,000,000 per second!

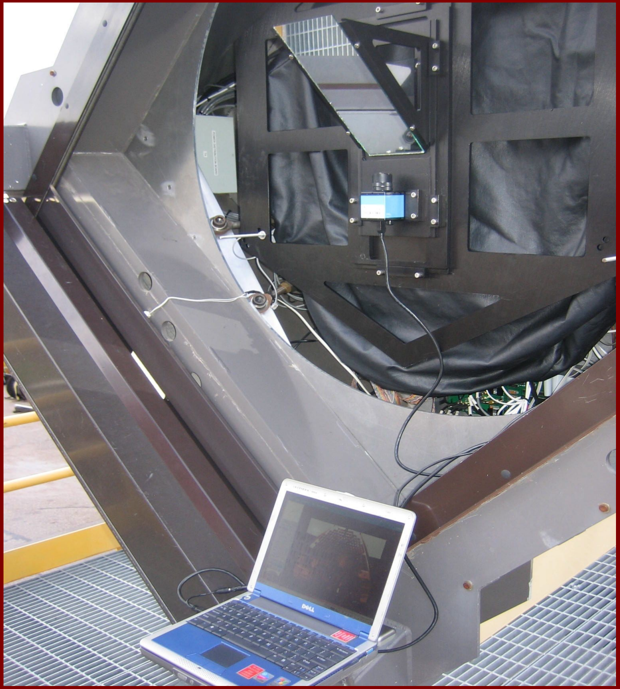
We can't store all those data (equivalent to all the books in print every half-second) so we select interesting 'video clips' that are about 50 nanoseconds long. This selection is done by a 3-stagetrigger :



VERITAS Components

Mirror Mounts

Trigger Electronics



Mirror Alignment Tool

designed and built by

The VERITAS Collaboration

Four Countries, Six Funding Agencies,
Twenty Institutions, Eighty members

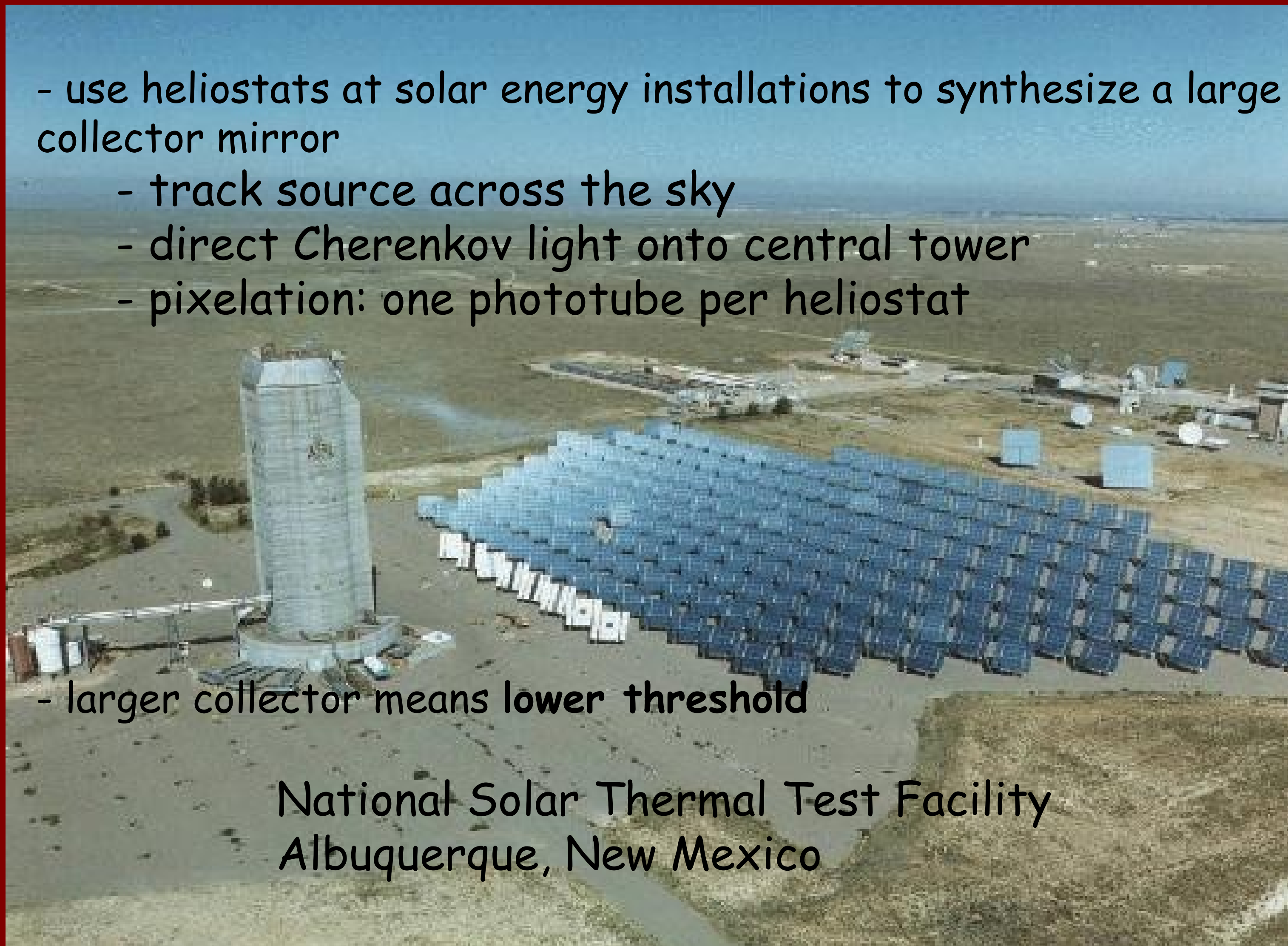
Smithsonian Astrophysical Observatory *
Adler Planetarium
Purdue University *
Barnard College, NY
Iowa State University *
DePauw University, IN
Washington University, St. Louis *
Grinnell College, IA
University of Chicago *
University of California, Santa Cruz

University of Utah *
University of Massachussetts
University of California, Los Angeles *
Cork Institute of Technology
McGill University, Montreal *
Galway-Mayo Institute of Technology
National University of Ireland, Dublin *
National University of Ireland, Galway
University of Leeds *
Argonne National Lab
Associate Members

Project office: F.L. Whipple Observatory, SAO

Funding from NSF/DOE/Smithsonian/PPARC/SFI/NSERC

The STACEE Detector and OSETI

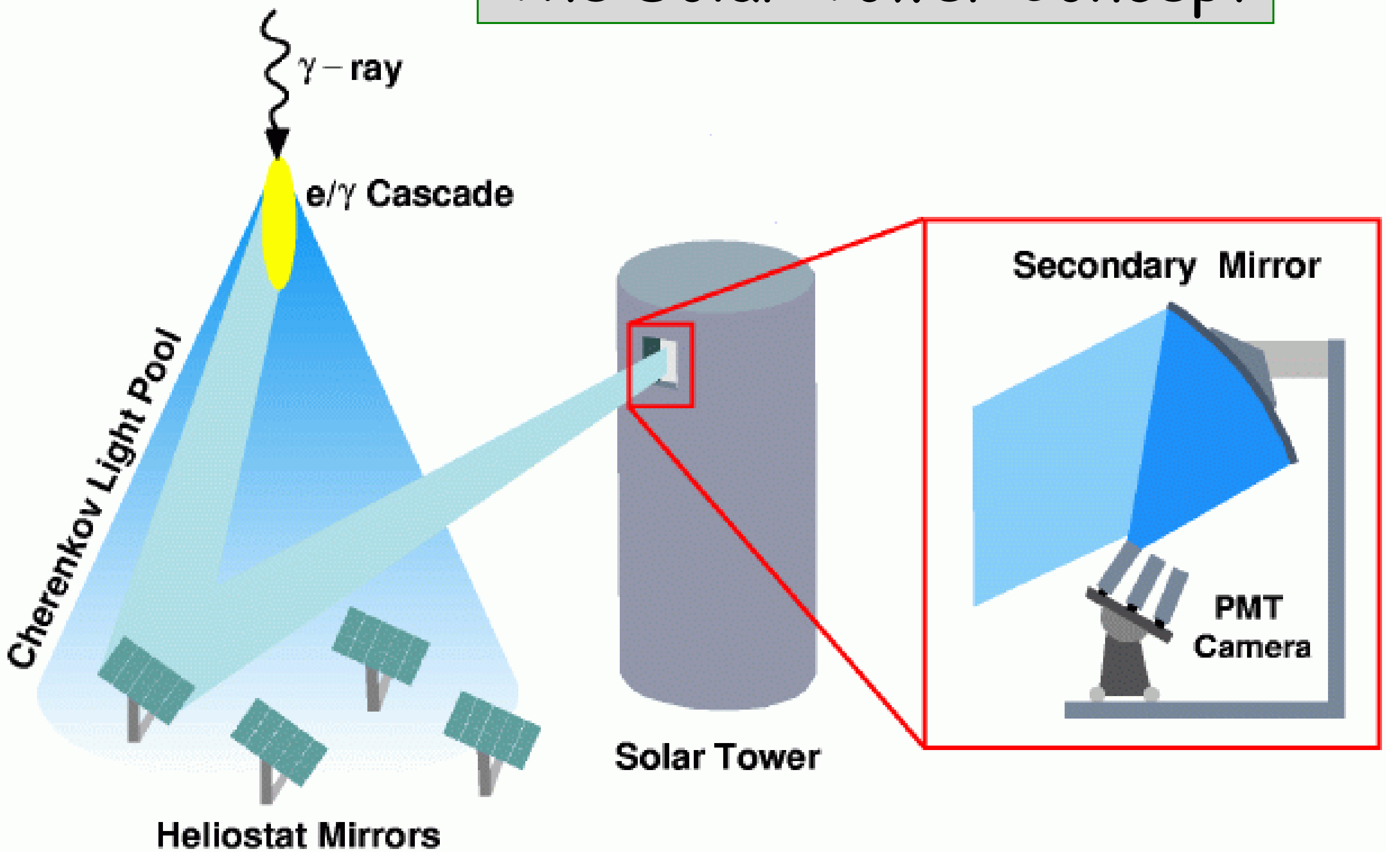


- use heliostats at solar energy installations to synthesize a large collector mirror
    - track source across the sky
    - direct Cherenkov light onto central tower
    - pixelation: one phototube per heliostat

- larger collector means **lower threshold**

National Solar Thermal Test Facility
Albuquerque, New Mexico

The Solar Tower Concept



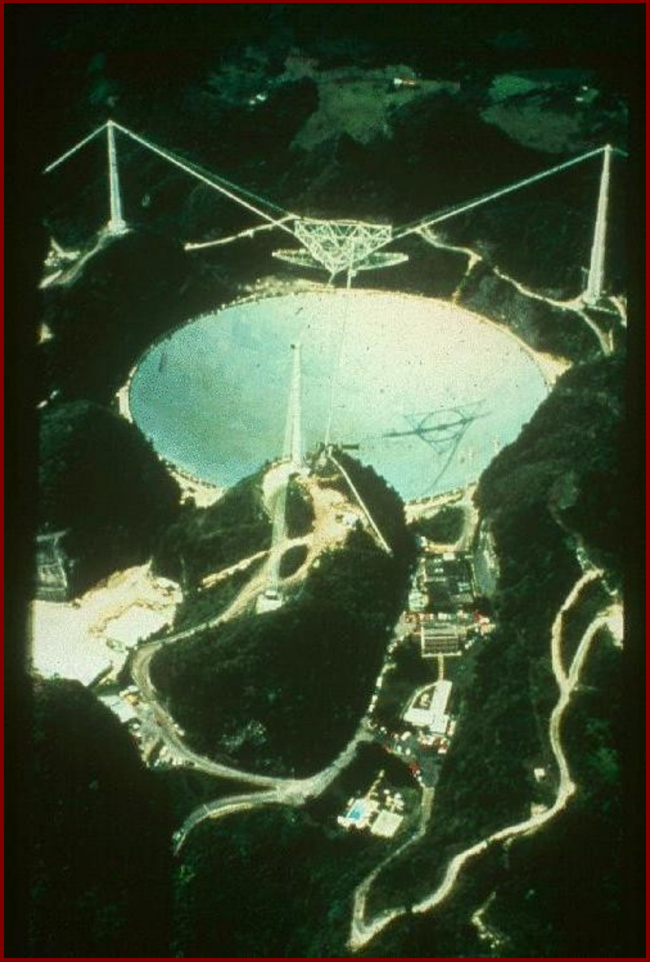
The essential idea:

use the enormous area of heliostats at a central-tower solar power facility to collect the Cherenkov photons

Search for Extra-Terrestrial Intelligence (SETI)

- look for some kind of signal that cannot arise from natural (astrophysical) phenomenon

- usually carried out at radio wavelengths (hydrogen 21 cm line)



Paul Allen Array

ARECIBO

Search for Extra-Terrestrial Intelligence (SETI)

- radio searches going on since 1960's

- no discoveries – parameter space is really big
    - frequency
    - direction
    - dispersion effects
    - .....

- efforts concentrate on electronics/computing to sift the data

- maybe looking for a simple 'Morse code' signal is wrong (look at the electromagnetic stuff in our cities – really complicated)

Paul Horowitz

Optical Search for Extra-Terrestrial Intelligence (OSETI)

- a "new" approach – first proposed in 1960's by Charles Townes (inventor of the laser)

- radio detection methods are handicapped when photon flux is low (ie faint sources)

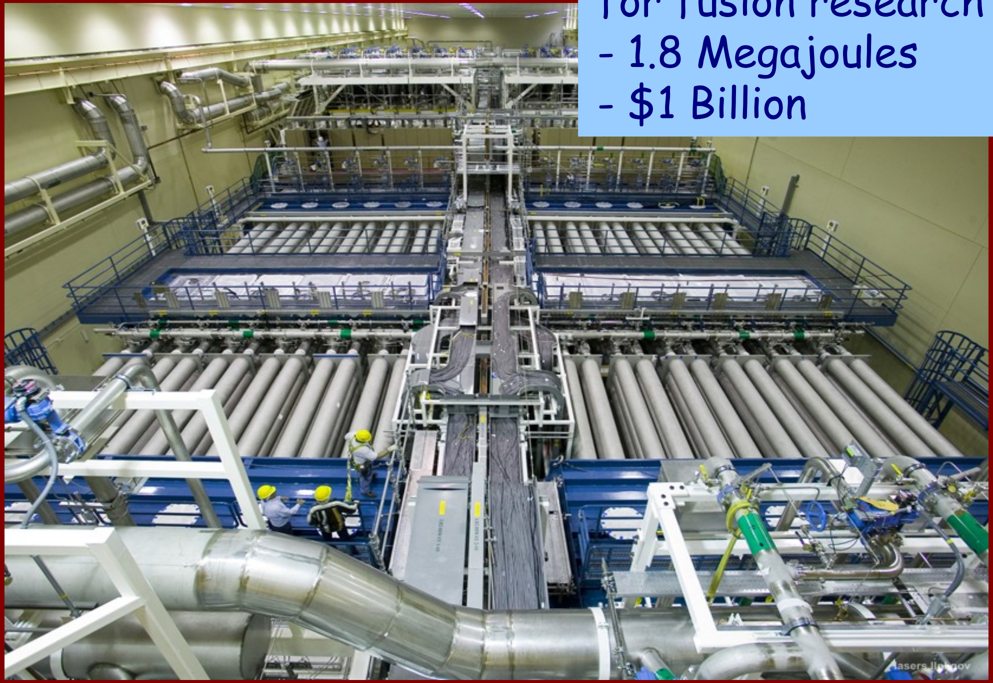
- dispersion (due to inter-stellar electrons) also a problem at radio wavelengths

- try simple photon counting at shorter wavelengths

- "Moore's Law" progress in laser technology over 40 years

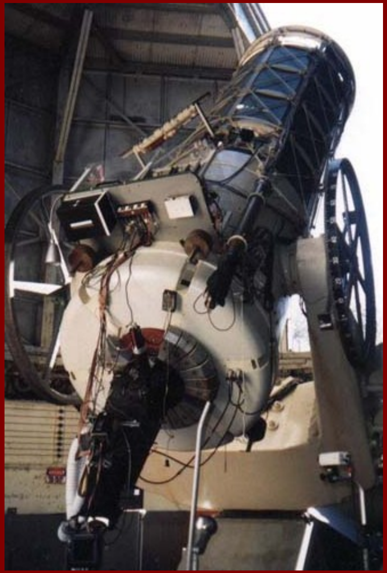
- possible to make lasers that are brighter than the sun

Livermore Laser for fusion research
- 1.8 Megajoules
- $1 Billion



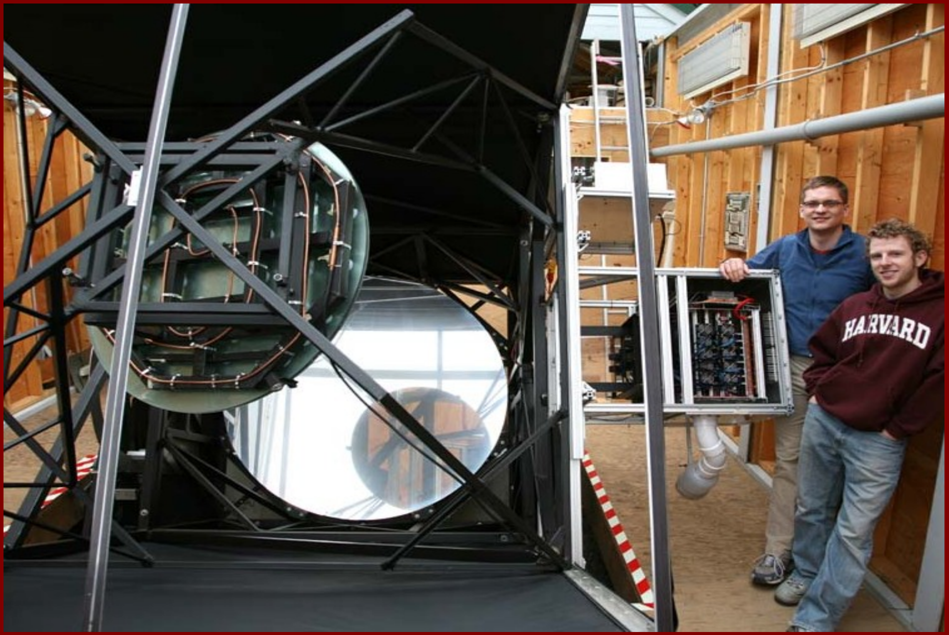
Optical Search for Extra-Terrestrial Intelligence (OSETI)

initial work done on small telescopes at Harvard, Princeton and UC Berkeley and Santa Cruz



Harvard 61" telescope

A dedicated 1.5 m telescope for doing 'all-sky' surveys has been built by Horowitz' group at Harvard



Optical Search for Extra-Terrestrial Intelligence (OSETI)

- need to look for nanosecond (billionth of a second) optical flash in the presence of night sky background (ie starlight)

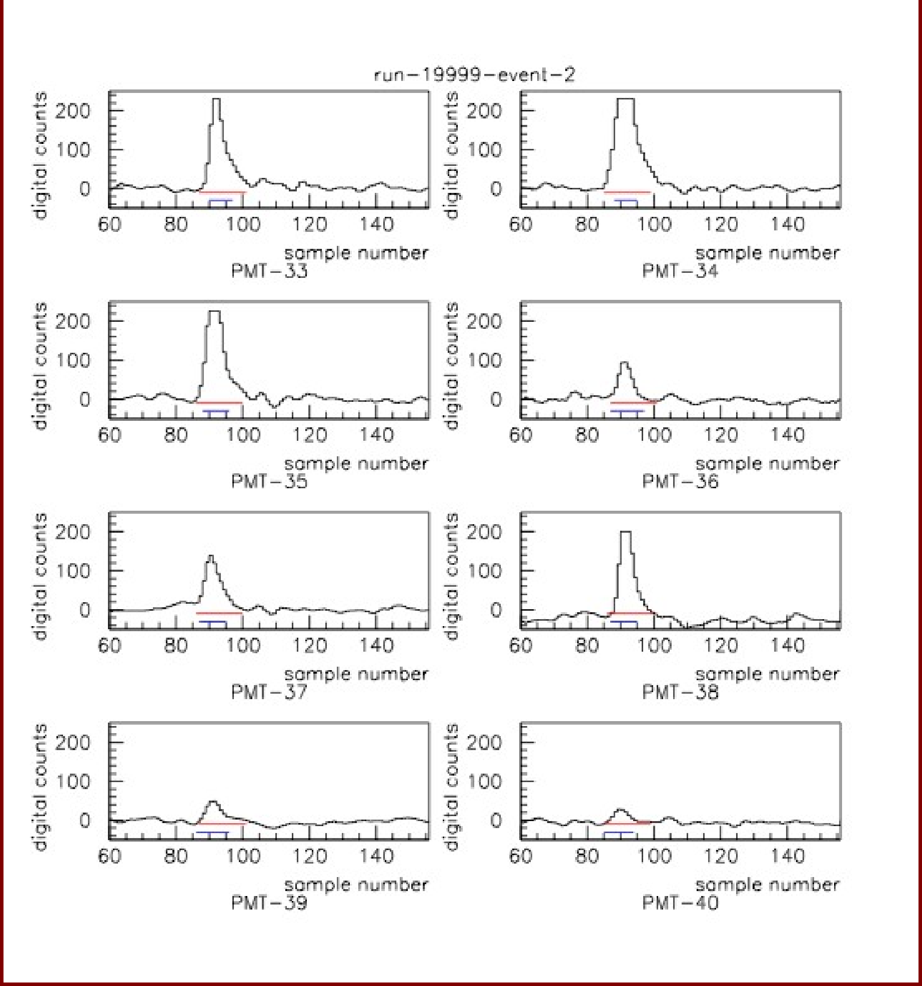
- Cherenkov gamma-ray telescopes can do that!

- plus they have HUGE mirror areas (STACEE: 64 x 37m2) can look for fainter signals

- background is from air-showers

- strategy is to require a signal from <u>all</u> 64 channels and that it be the same in all channels (same time and same size)

- search carried out in 2007 during final season of STACEE
    - 182 nearby sun-like stars
    - 10 minutes on each
    - no signal (or background)
    - flux sensitivity 10 photons/m2



Gamma-ray Telescopes for security applications

national governments are funding R&D relevant to counter-terrorism

in Canada this is done by CRTI (launched in May 2002)

C = CRBNE(chemical, radiological, biological, nuclear, explosive)

RTI – research and technology initiative

promotes partnerships between universities and federal labs (eg NRC)

Gamma-ray Telescopes for security applications

CRTI-07-0193RD

A COMPTON GAMMA IMAGER FOR CRIMINAL AND NATIONAL SECURITY INVESTIGATION

Lead: Natural Resources Canada

Partners:
- National Research Council
- McGill University
- Royal Canadian Mounted Police
- Public Safety Canada
- Canada Border Services Agency

Start-End: 2008-2013

Funds: $1,425,258

Objectives:

To aid in intelligence gathering prior to or following a radiological or nuclear incident, a Compton gamma imager will be developed.

This instrument will be able to display the location of radioactive material, overlaid on a photograph of the surroundings.

Technologies:

The Compton gamma imaging technique relies on tracking a gamma ray as it deposits energy within a pixellated detector. Design studies will be conducted using both Monte Carlo simulations and experimental techniques. The performance at large stand-off distances will be optimized, respecting the operational constraints of ruggedness and portability.

Outputs:

- optimized gamma imager design
- prototype Compton gamma imager
- image reconstruction algorithms
- demonstrations under challenging scenarios
- deployment procedures documentation

Impact:

A compact and efficient gamma imager will expedite both surveillance and response operations.

This will ultimately improve safety for investigators, responders, and the Canadian public.

Gamma-ray Telescopes for security applications

physicists involved:

Laurel Sinclair (NRCan)
Henry Seyward (NRCan)
Patrick Saull(NRC)
David Hanna (McGill)
Audrey Macleod (McGill)
Jojo Boyle (McGill)

aim:

build a rugged portable instrument that can make images of radioactive material from a “dirty” bomb (radiological dispersion device) either before or after it is deployed

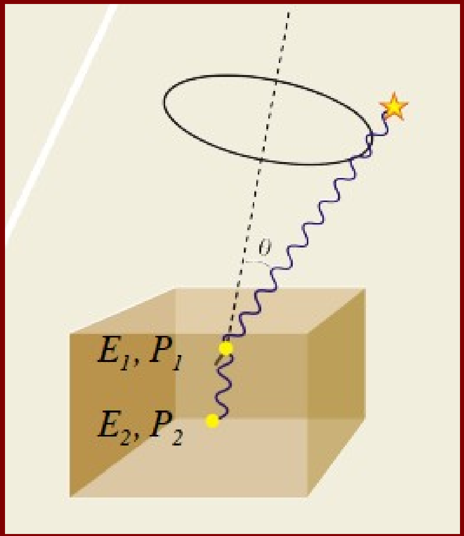
Gamma-ray Telescopes for security applications

technology

- to detect gamma-rays from threat isotopes one needs capability in the 100 keV to 2 MeV energy range

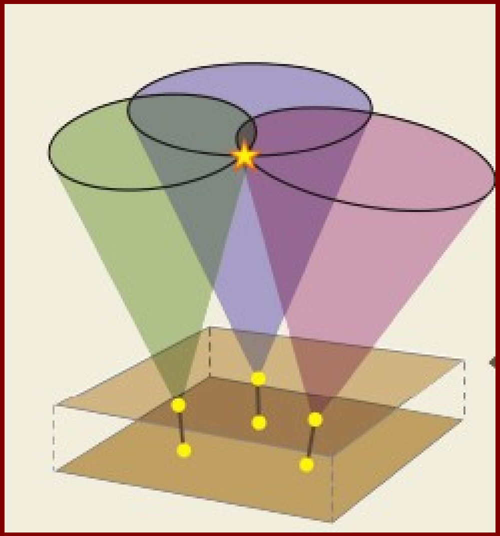
- this is the hardest range technologically

- technique of choice is Compton scattering

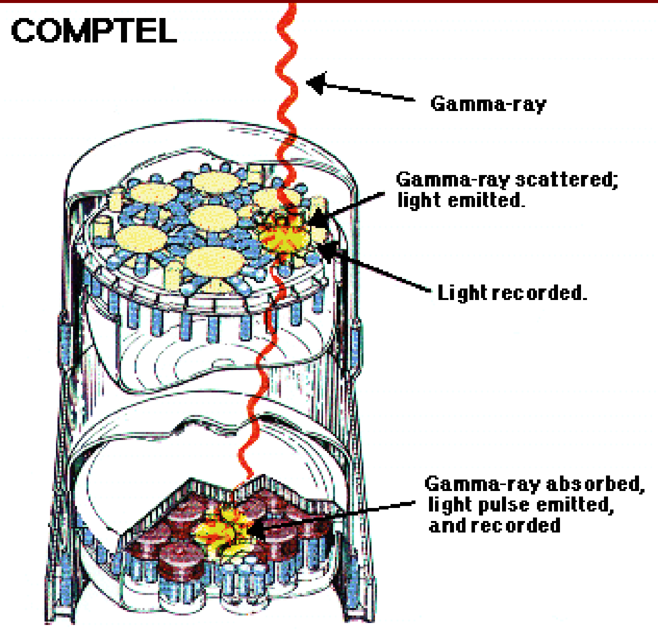


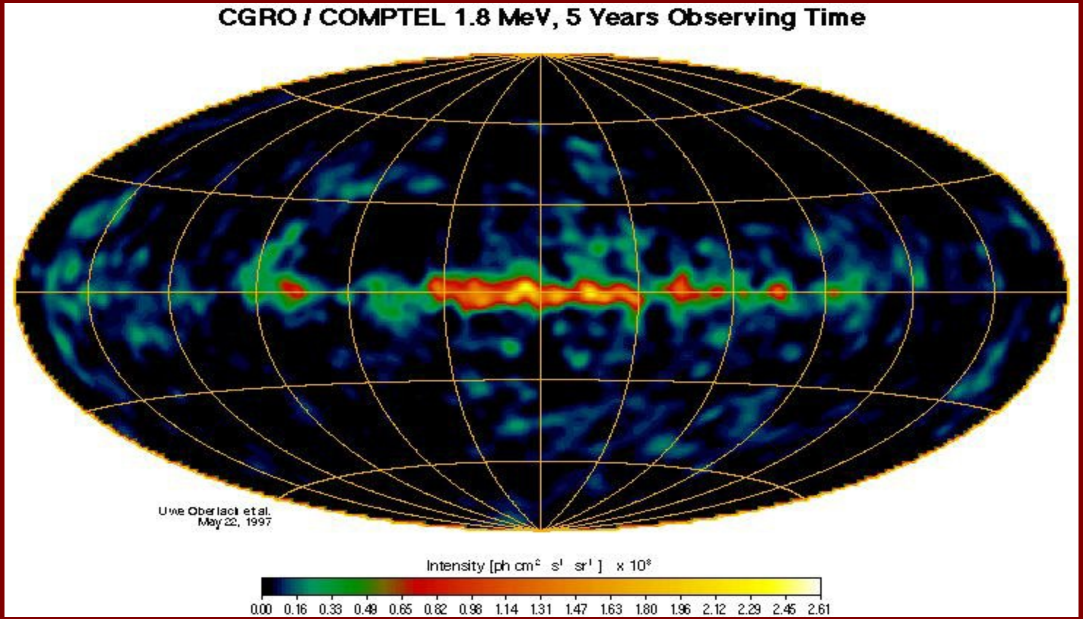
- single photon gives a circle

- multiple photons resolve ambiguities



Compton Telescopes have been used in gamma-ray astronomy (eg Comptel on the CGRO)





McGill research is focussed on modern technology (multichannel phototubes, new scintillators (LYSO))

many cross-links with next-generation Cherenkov telescopes

Future Possibilities for Research . . . .

DOCTOR FUN

3 Apr 98

Despite funding cuts, research into the origin of gamma-ray bursts continues as best it can.