High-energy Gamma-ray Astrophysics

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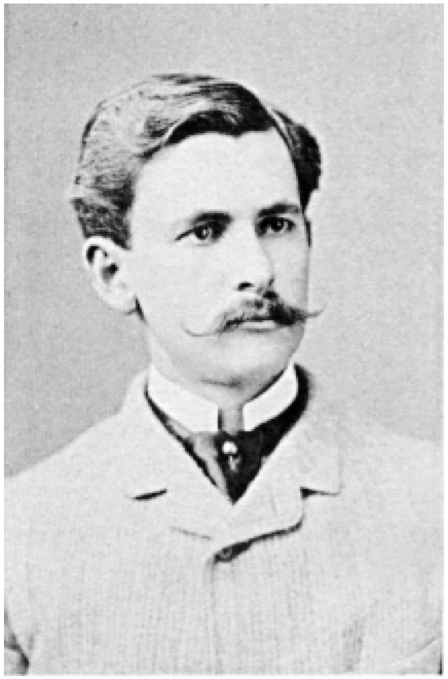
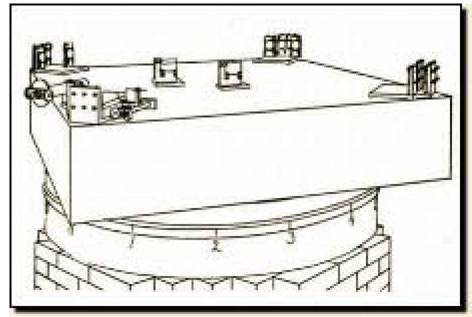
Outline

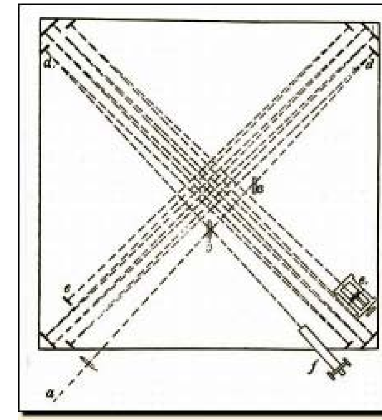
- Preliminaries
  - Why study γ rays?
  - Measurement techniques
- Brief tour of science topics
  - Extragalactic diffuse flux
  - Active Galactic Nuclei (AGN)
  - Unidentified sources
  - Gamma-Ray Bursts (GRB)
  - Supernova remnants and the origin of cosmic rays
  - Dark matter
  - Testing Lorentz invariance
- Instruments and status
  - Ground-based
  - Space-based
- Summary and perspectives

Apologies in advance for omissions in this brief survey!

Historical Connections: Fundamental Physics and Astrophysics







1887: Michelson & Morley publish fundamental results on propagation of light - an experimental cornerstone of relativity.

1920: Michelson makes the first-ever measurement of the diameter of a star (Betelgeuse) by applying interferometry to astronomy. A new field!

Laboratory techniques for fundamental physics investigations have long been successfully and fruitfully applied to astrophysical measurements. These measurements in turn enable us to test and further explore fundamental physics.

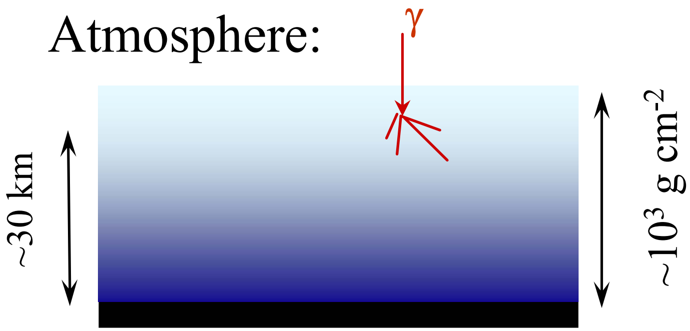
Why study γ's?

Gamma rays carry a wealth of information:

- γ rays do not interact much at their source: they offer a direct view into Nature's largest accelerators.
- similarly, the Universe is mainly transparent to γ rays: can probe cosmological volumes. Any opacity is energy dependent (interesting physics here, too!).
- conversely, γ rays readily interact in detectors, with a clear signature.
- γ rays are neutral: no complications due to magnetic fields. Point directly back to sources, etc.

Cosmic γ-ray Measurement Techniques

Atmosphere:



For E_γ < ~ 100 GeV, must detect above atmosphere (balloons, satellites)

For E_γ > ~100 GeV, information from showers penetrates to the ground (Cerenkov, air showers)

Photon interaction mechanisms:

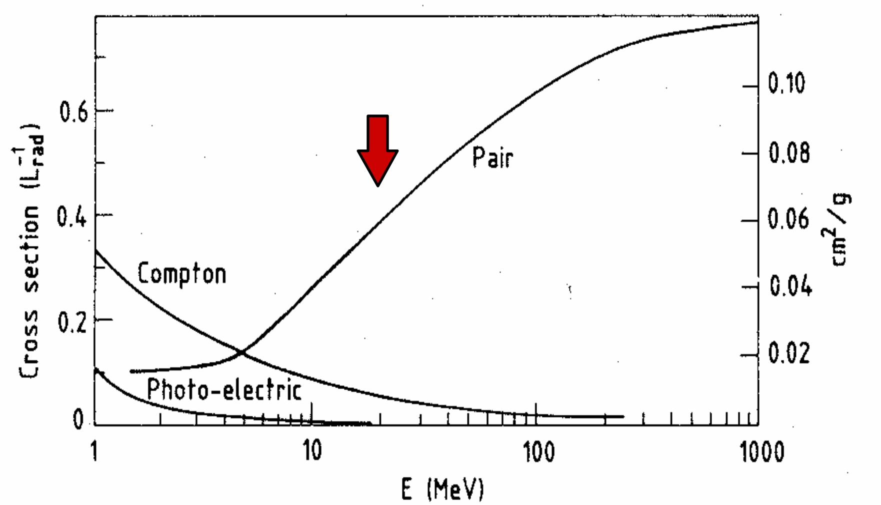
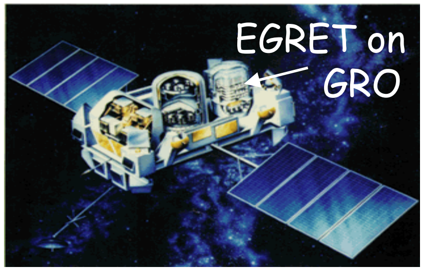


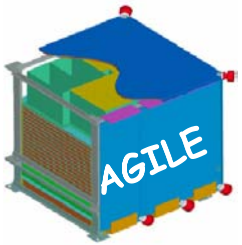
Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

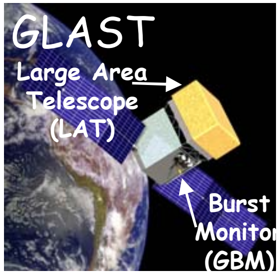
This talk: E_γ >100 MeV

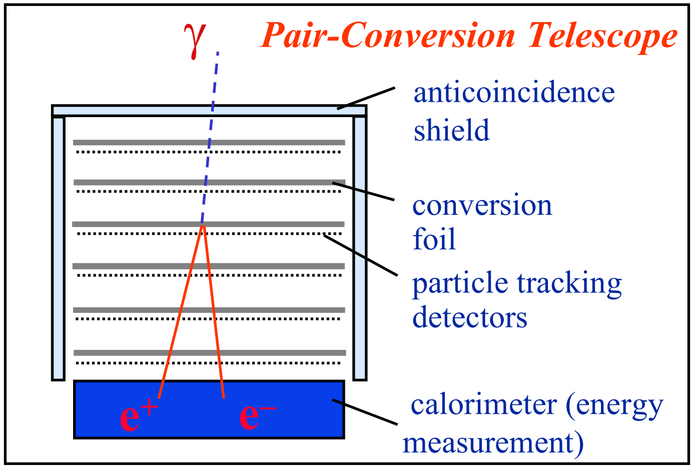
Gamma-ray Experiment Techniques

- **Space-based:**
  - use pair-conversion technique





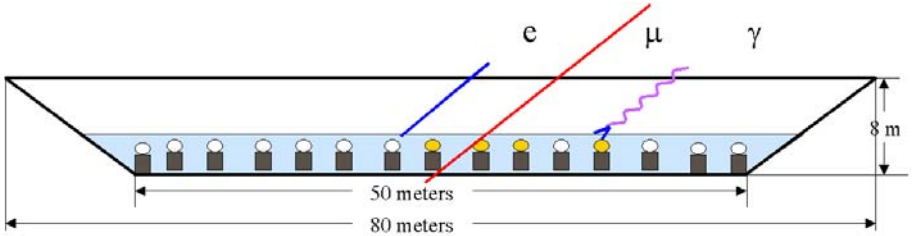




- **Ground-Based:**
  - Airshower Cerenkov Telescopes (ACTs)

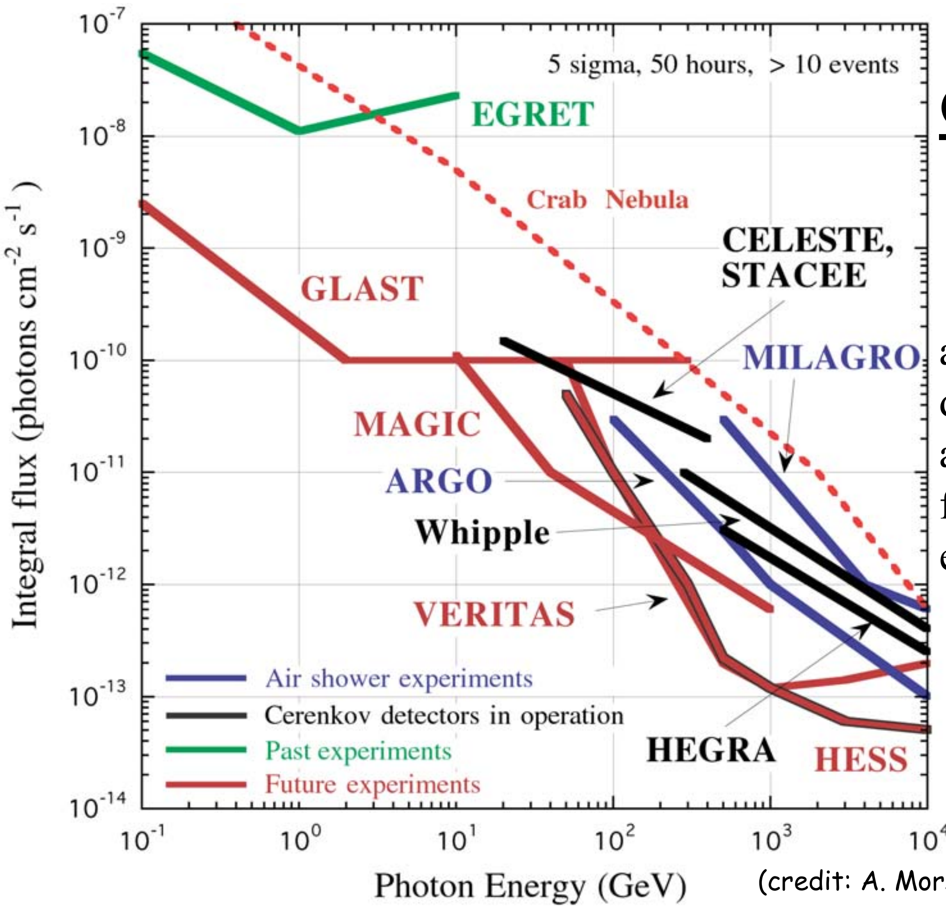
image the Cerenkov light from showers induced in the atmosphere. Examples: Whipple, CANGAROO, HEGRA, STACEE, CELESTE, VERITAS, MAGIC, HESS

  - Extensive Air Shower Arrays (EAS)



Directly detect particles from the showers induced in the atmosphere. Example: MILAGRO

Gamma-ray Observatories



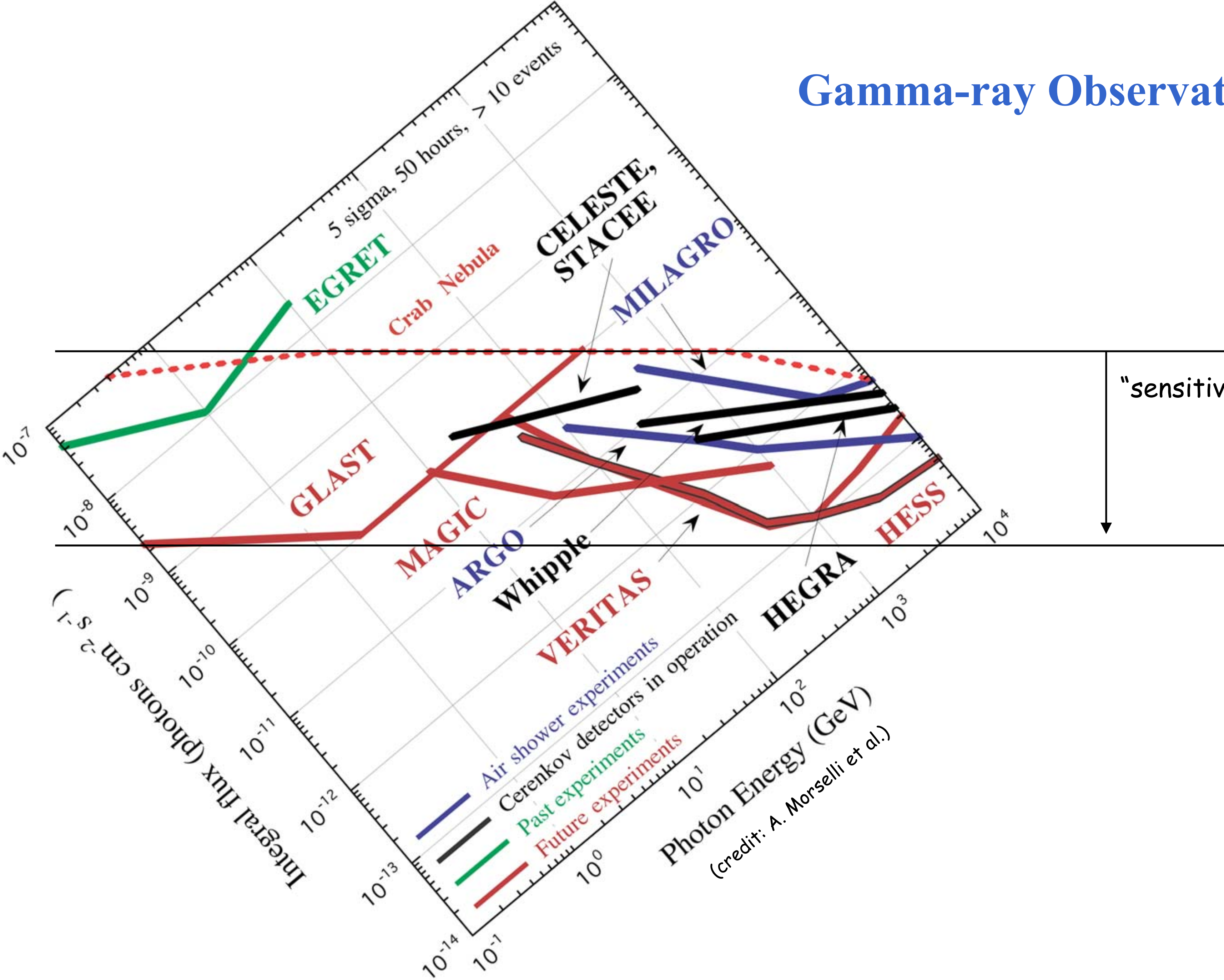
(credit: A. Morselli et al.)

Complementary capabilities

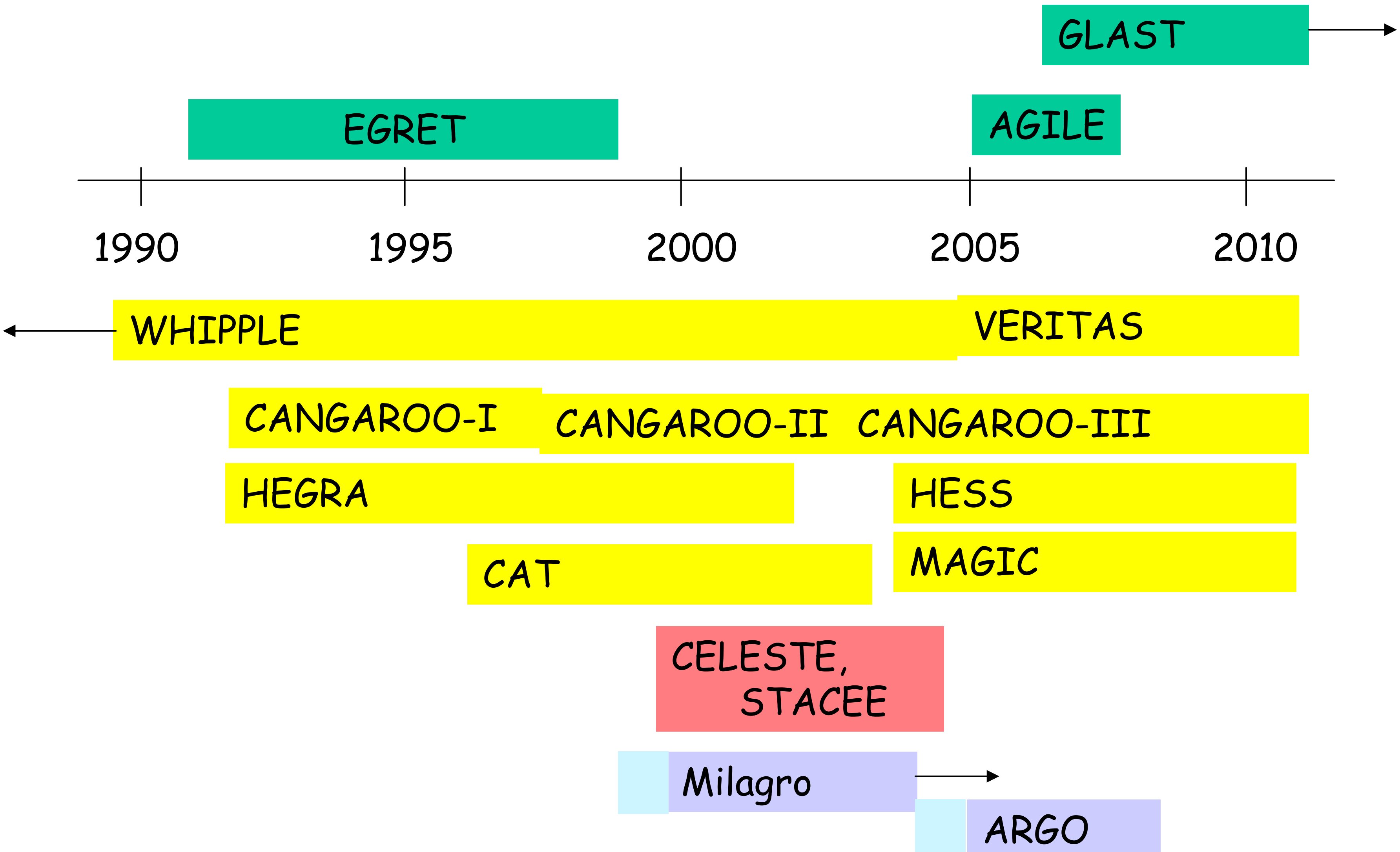
	ground-based		space-based
	ACT	EAS	Pair
angular resolution	good	fair	good
duty cycle	low	high	high
area	large	large	small
field of view	small	large	large+can reorient
energy resolution	good	fair	good, w/ smaller systematic uncertainties

The next-generation ground-based and space-based experiments are well matched.

Gamma-ray Observatories



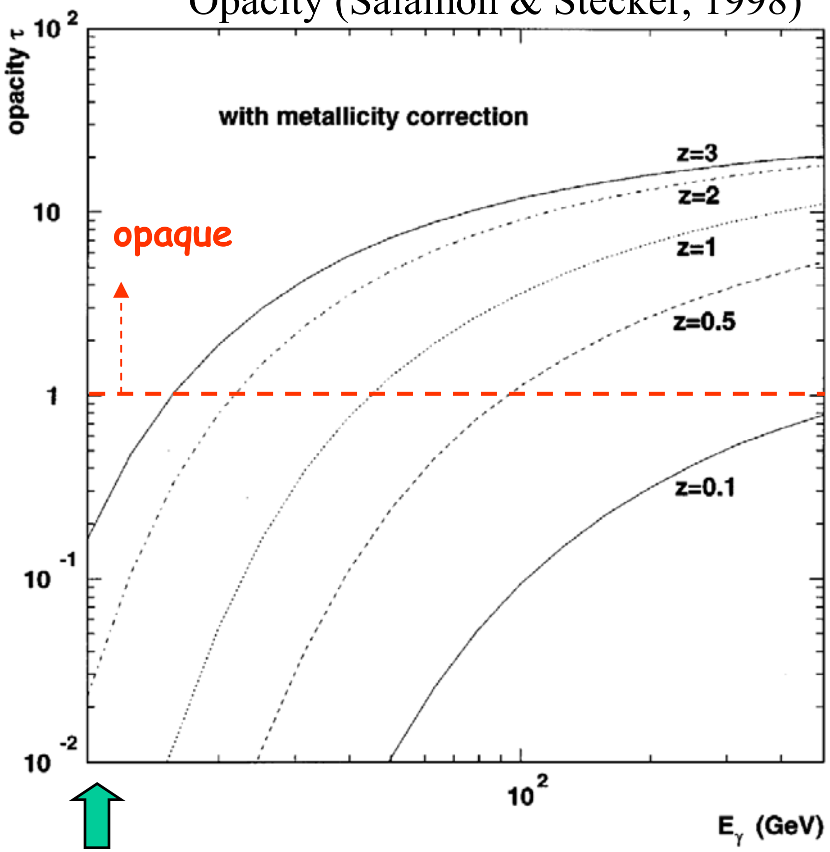
Experiment Timeline



Important Observational Boundary Condition

Photons with E>10 GeV are attenuated by the diffuse field of UV-Optical-IR extragalactic background light (EBL)

Opacity (Salamon & Stecker, 1998)



No significant attenuation below ~10 GeV.

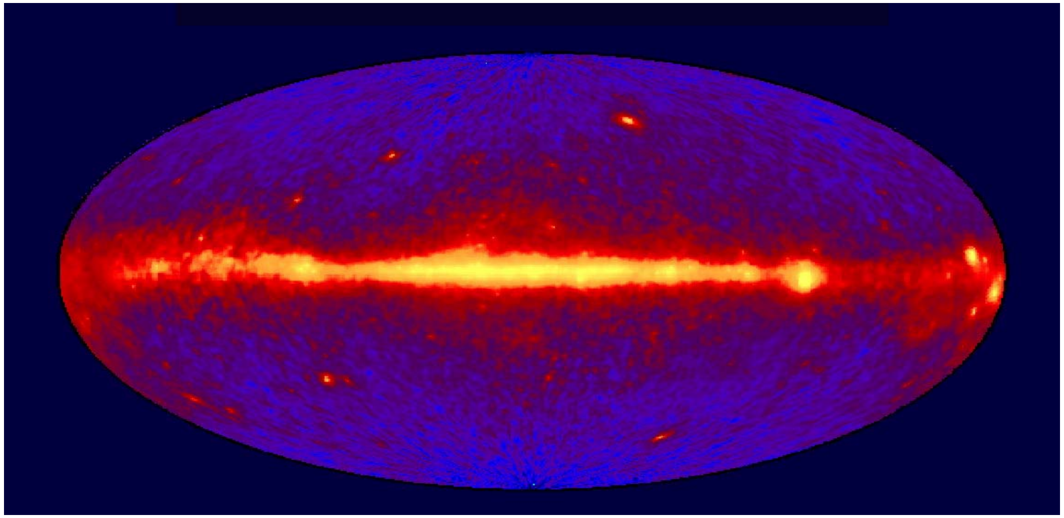
only $e^{-\tau}$ of the original source flux reaches us

EBL over cosmological distances is probed by gammas in the 10-100 GeV range. <u>Important science!</u>

In contrast, the TeV-IR attenuation results in a flux that may be limited to more local (or much brighter) sources.

A dominant factor in EBL models is the time of galaxy formation -- <u>attenuation measurements can help distinguish models</u>.

Features of the gamma-ray sky



EGRET all-sky survey (galactic coordinates) E>100 MeV

diffuse extra-galactic background (flux ~ 1.5×10^{-5} $cm^{-2}s^{-1}sr^{-1}$)

galactic diffuse (flux ~O(100) times larger)

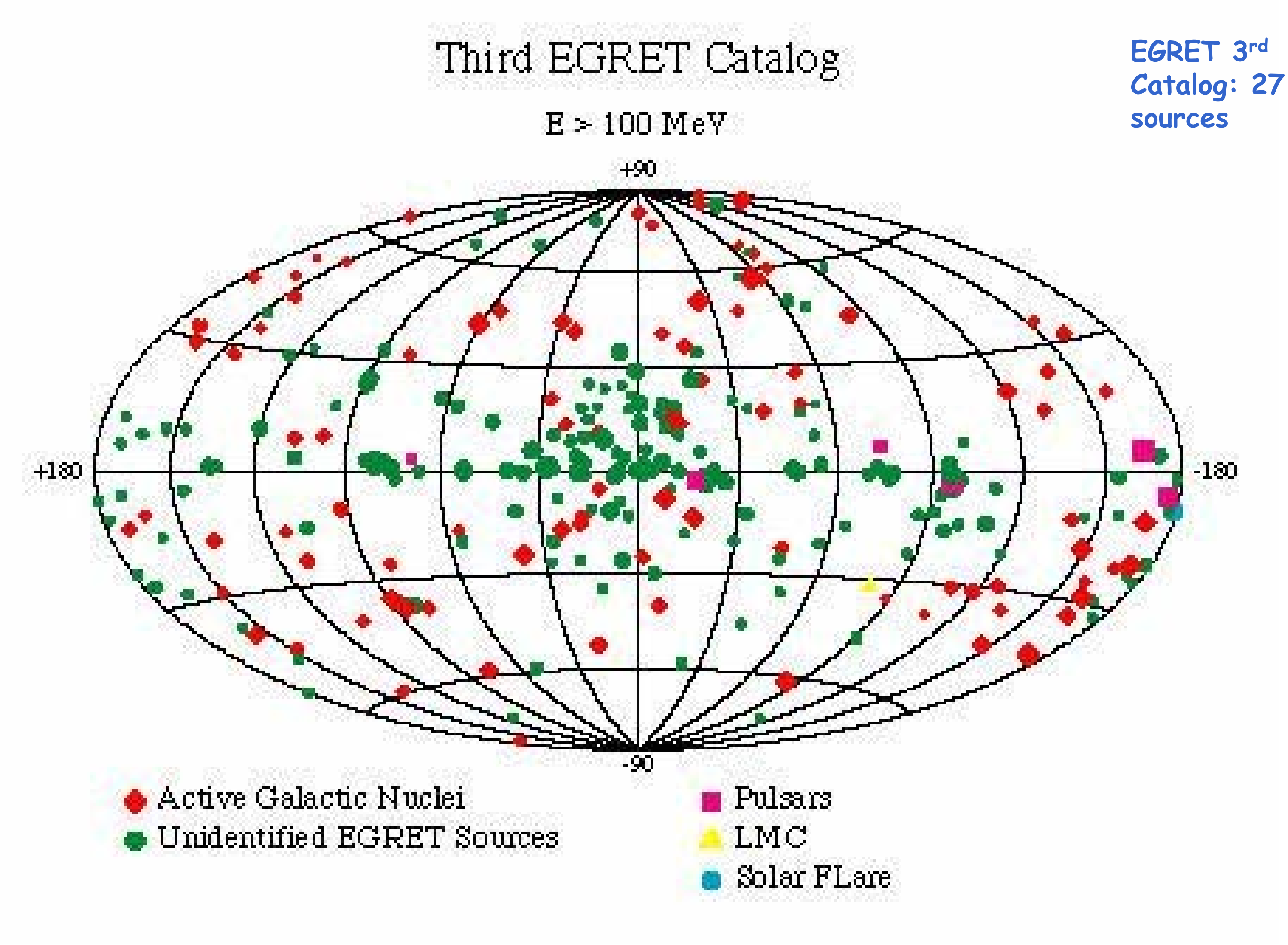
high latitude (extra-galactic) point sources (typical flux from EGRET sources O(10^{-7} - 10^{-6}) $cm^{-2}s^{-1}$

galactic sources (pulsars, un-ID'd)

An essential characteristic: VARIABILITY in time!

⇨ Field of view, and the ability to repoint, important for study of transients.

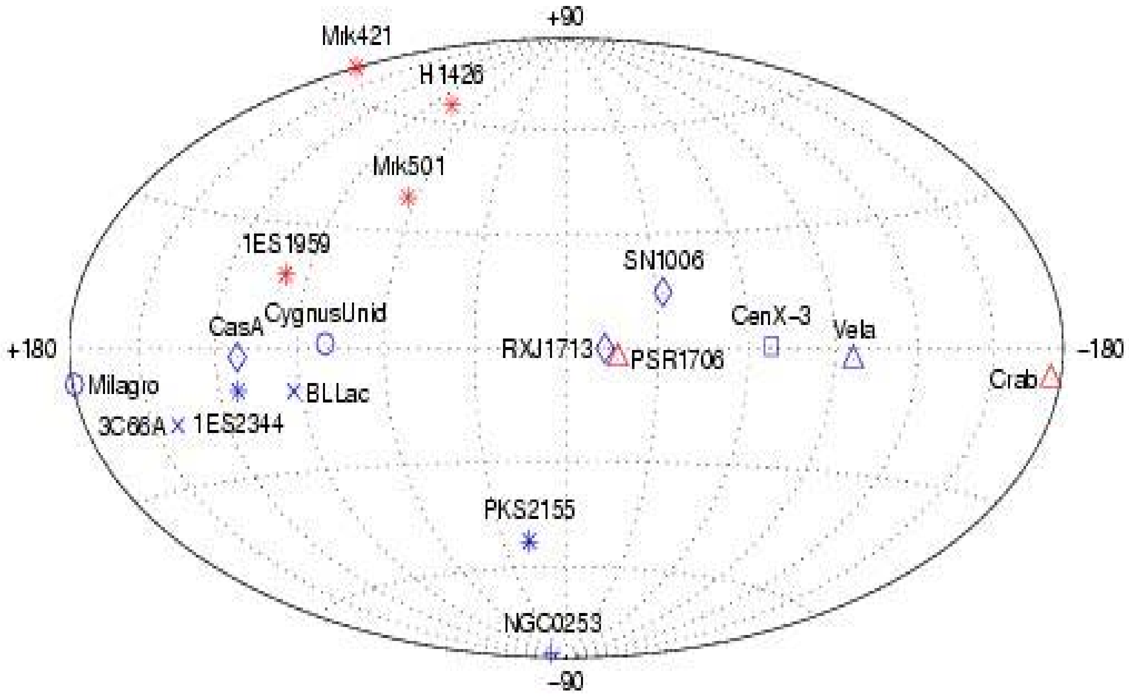
Sources (E>100 MeV)



EGRET 3rd Catalog: 271 sources

The TeV Sky (thus far)

- TeV sky and GeV sky are different!



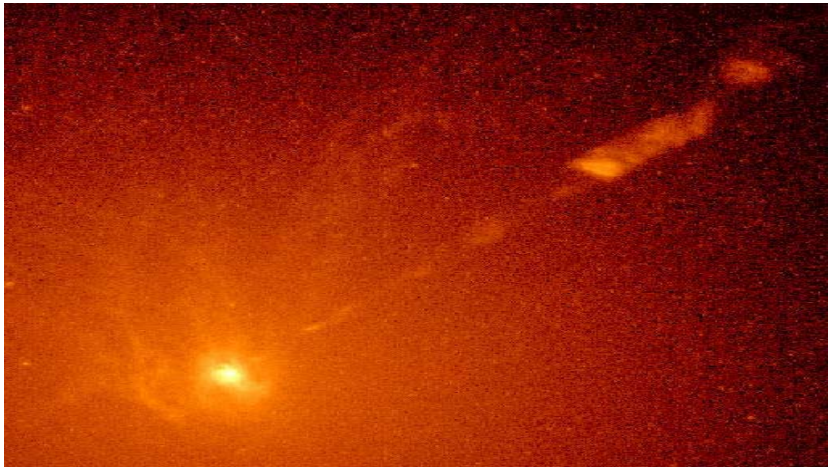
- 4 new detections since Gamma2001 Conference (April, 2001):
  (1 starburst galaxy (NGC253), 1 radio galaxy (M87), 1 blazar (H1426), 1 UNID – CygOB2 association?)
- fair sampling? only a small fraction of the TeV sky observed thus far!

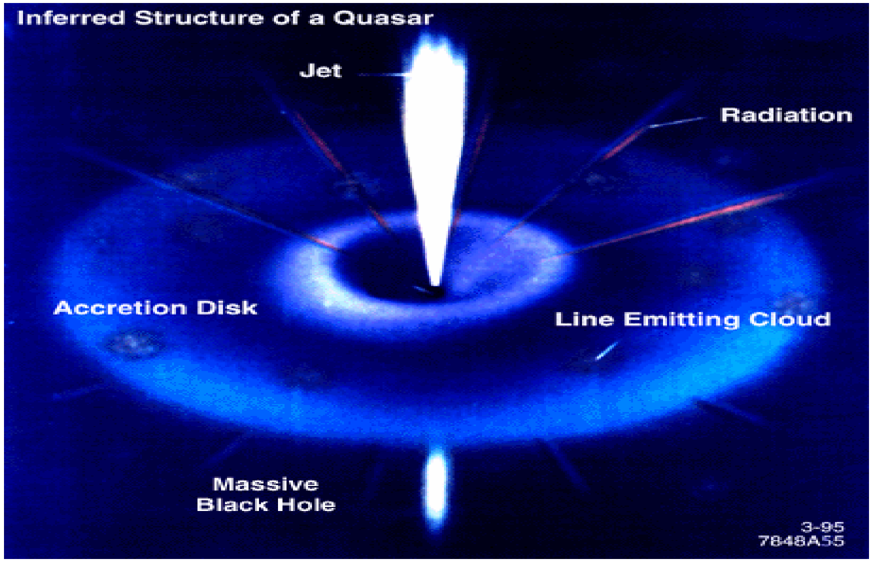
Active Galactic Nuclei (AGN)

Active galaxies produce vast amounts of energy from a very compact central volume.

Prevailing idea: powered by accretion onto super-massive black holes (10^6 - 10^{10} solar masses). Different phenomenology primarily due to the orientation with respect to us.

HST Image of M87 (1994)



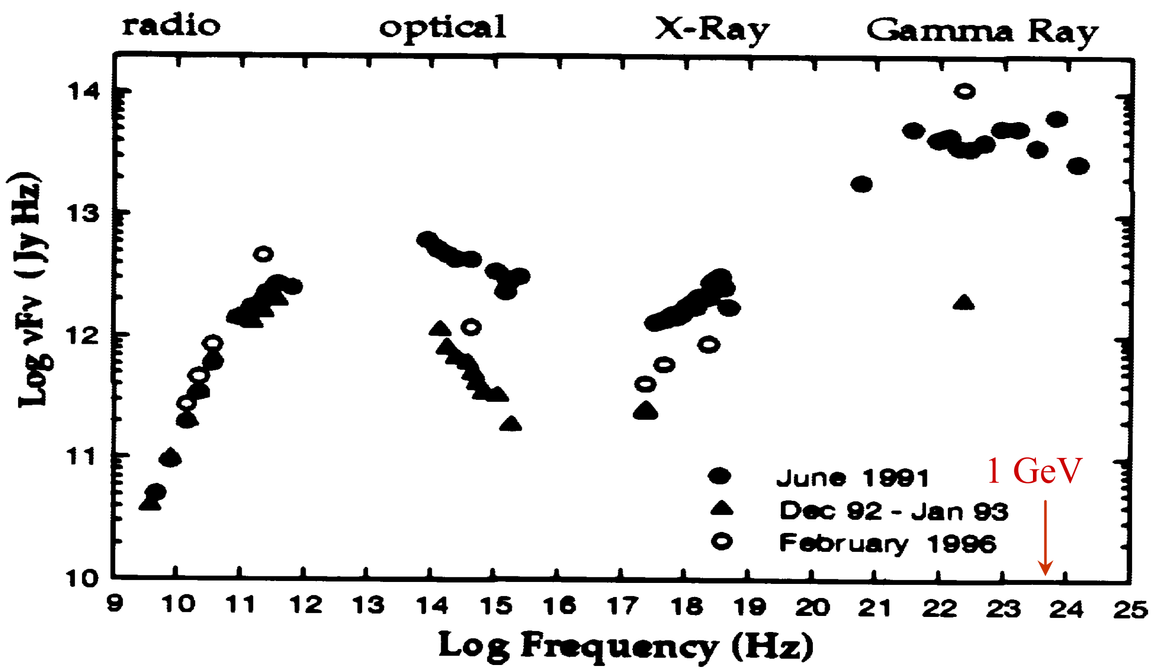


Models include energetic (multi-TeV), highly-collimated, relativistic particle jets. High energy γ-rays emitted within a few degrees of jet axis. Mechanisms are speculative; γ-rays offer a direct probe.

AGN Shine Brightly in Gammas

Power output of AG

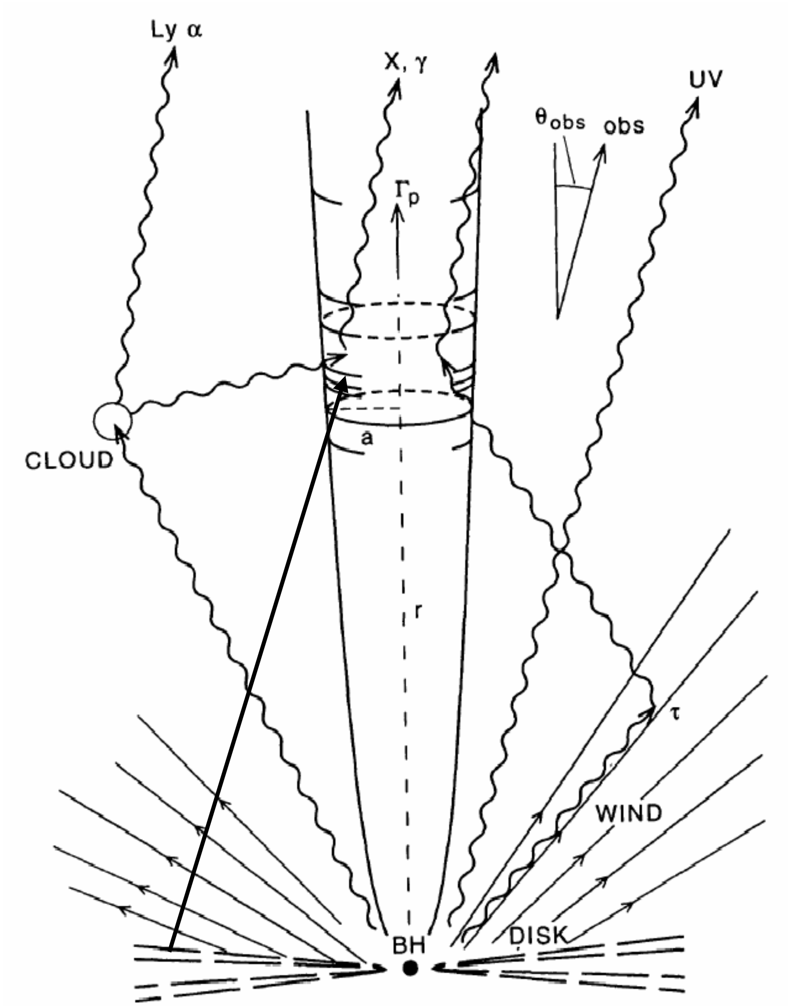
Estimated luminosity of 3C 279:
 ~ 10^{45} erg/s
corresponds to 10^{11} times total solar luminosity
just in γ-rays. Large variability within day



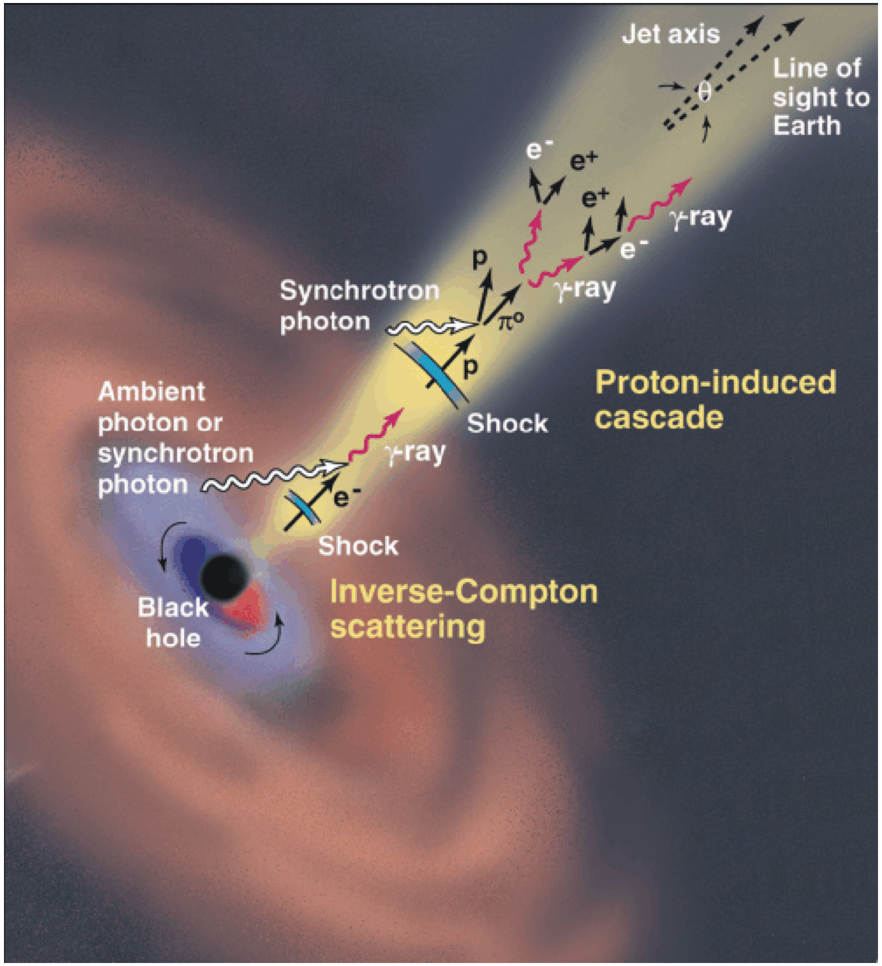
Multiwavelength Spectrum of 3C 279

Sum all the power over the whole electromagnetic spectrum from all the stars of a stars of a typical galaxy: an AGN emits this amount of power in JUST γ rays from rays from a very small volume!

Models of AGN Gamma-ray Production



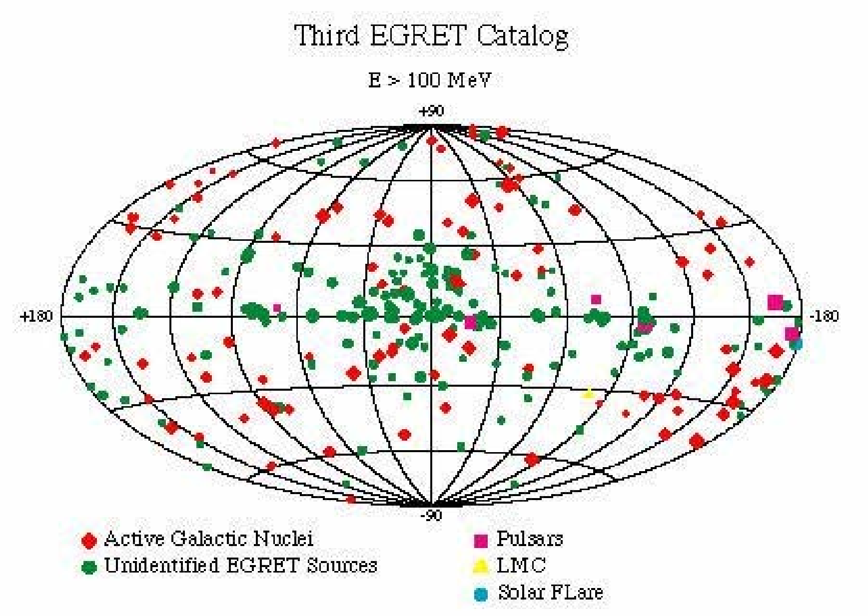
(from Sikora, Begelman, and Rees (1994))



(credit:J. Buckley)

A surprise from EGRET:

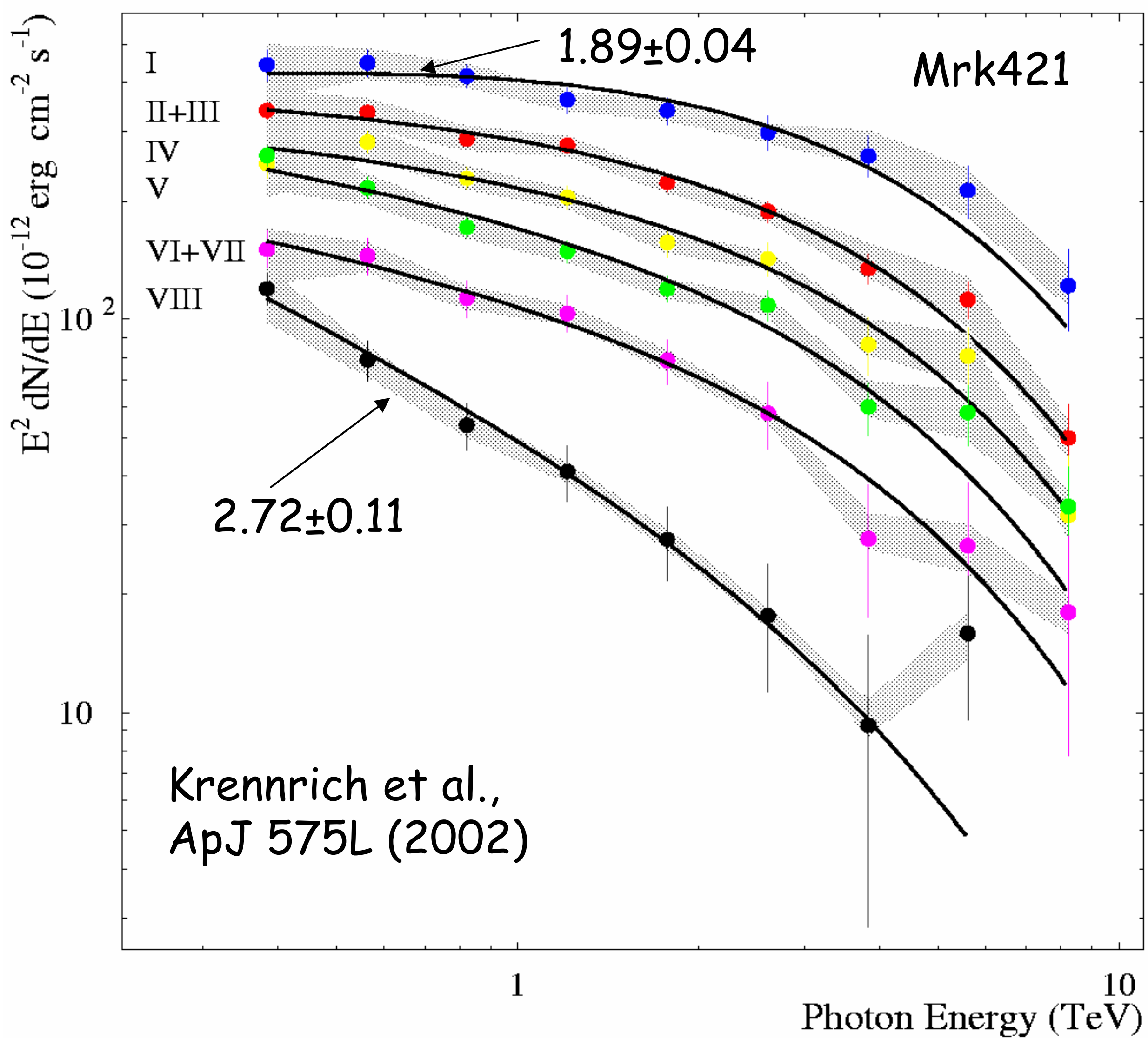
detection of >70 AGN shining brightly in γ-rays -- Blazars



- a key to solving the longstanding puzzle of the extragalactic diffuse gamma flux -- is this integrated emission from a large number of unresolved sources?
- blazars provide a source of high energy γ-rays at cosmological distances. The Universe is largely transparent to γ-rays (any opacity is energy-dependent), so they probe cosmological volumes.

TeV Spectral Variability with Intensity

- Whipple found evidence for spectral variability [exponent a function of total luminosity] in flares of Mrk 421.
- ~same cutoff in the region 3-6 TeV.
- CAT found similar effects in Mrk501 (Djannati-Atai et al.)

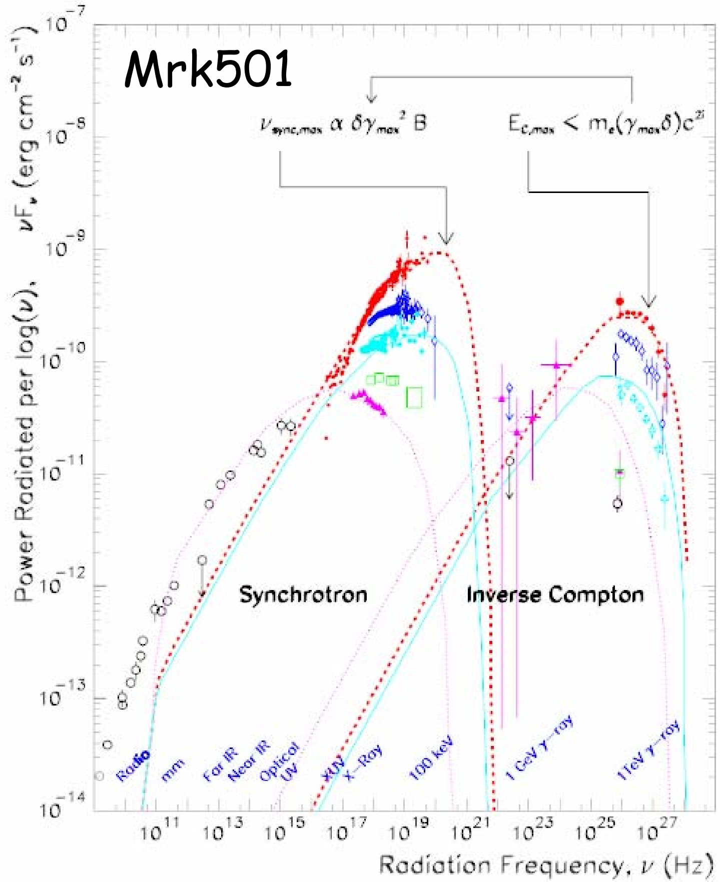


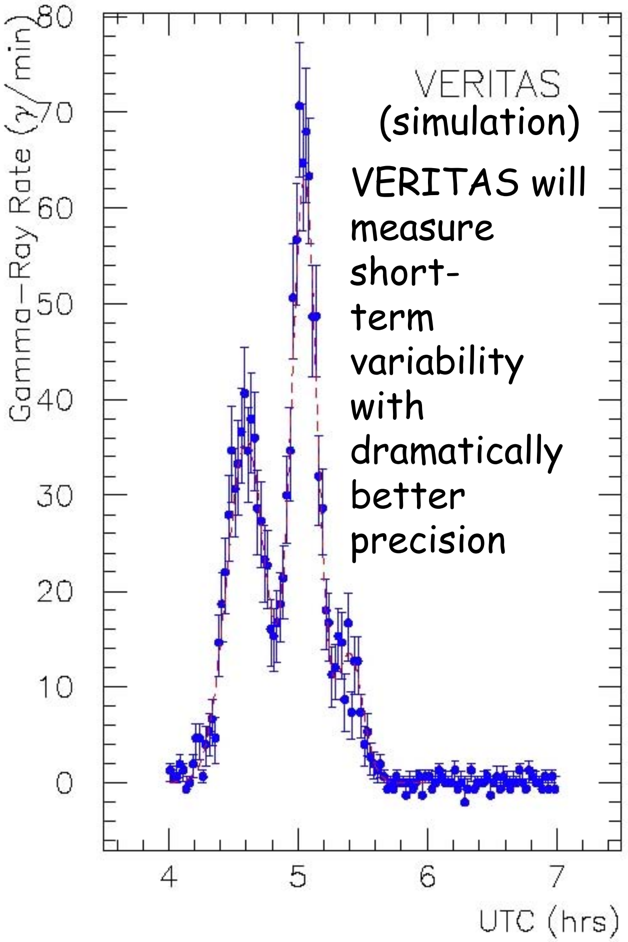
AGN: Future Prospects

- **Multiwavelength studies will continue to be the key to understanding how the engines work**

- **Next generation of observatories will provide a wealth of new data.**

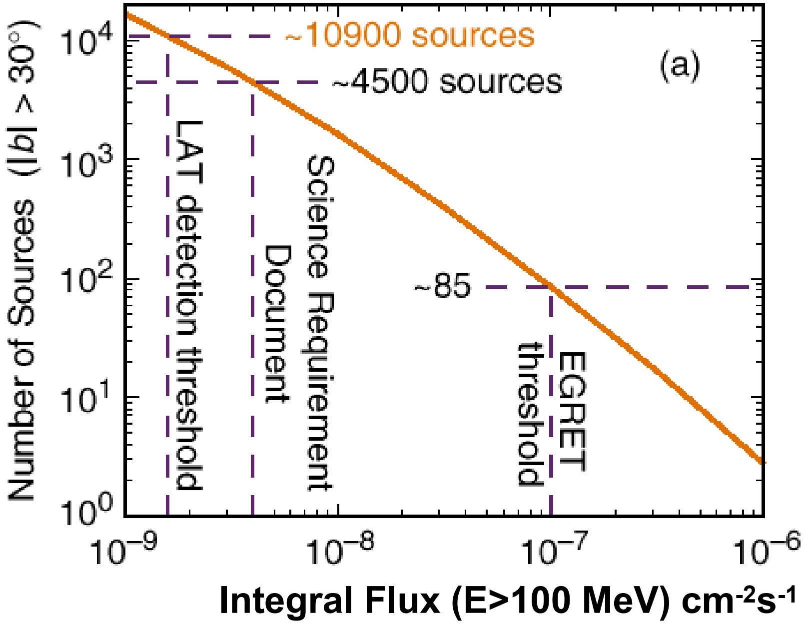
models: same population of HE electrons produces both components





AGN: What GLAST Will Do

EGRET has detected ~ 70 AGN. Extrapolating, GLAST should expect to see dramatically more – many thousands:



- Allows a statistically accurate calculation of AGN contribution to the high energy diffuse extra-galactic background.
- Constrain acceleration and emission models. How do AGN work?
- Large acceptance and field of view allow relatively fast monitoring for variability over time -- correlate with other detectors at other wavelengths.
- Probe energy roll-offs with distance (light-light attenuation): info on era of galaxy formation.
- Long mission life to see weak sources and transients.

Joining the unique capabilities of GLAST with other detectors will provide a powerful tool.

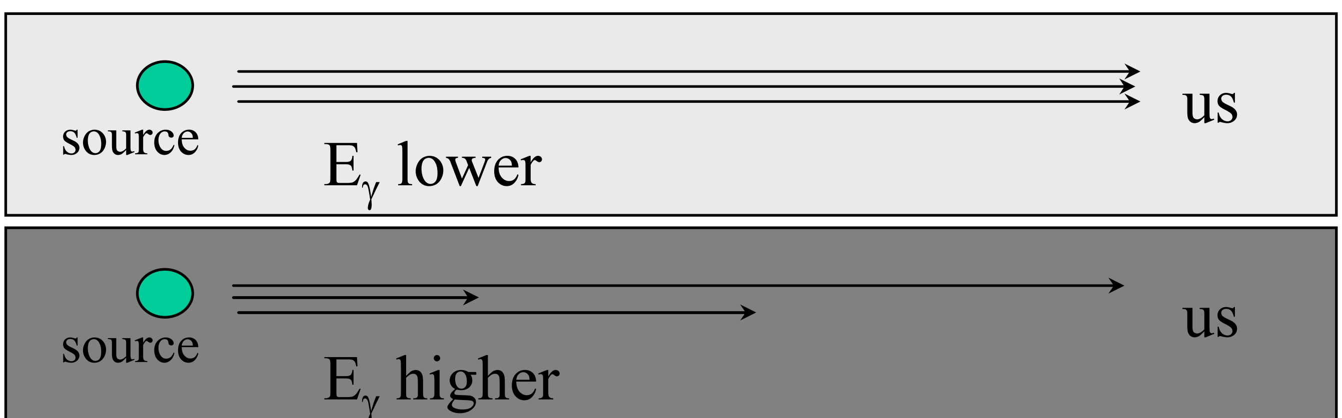
AGN, the EBL, and Cosmology

IF AGN spectra can be understood well enough, they may provide a means to probe the era of galaxy formation:
(<u>Stecker</u>, De Jager & Salamon; Madau & Phinney; Macminn & Primack)

If $\gamma\gamma$ c.m. energy > $2m_e$, pair creation will attenuate flux. For a flux of γ -rays with energy, E, this cross-section is maximized when the partner, ε, is

$$\varepsilon \approx \frac{1}{3}\left(\frac{1\,TeV}{E}\right)eV$$

For 10 GeV- O(100) GeV γ - rays, this corresponds to a partner photon energy in the <u>optical - UV range</u>. Density is sensitive to time of galaxy formation.



GLAST Can Probe the Optical-UV EBL

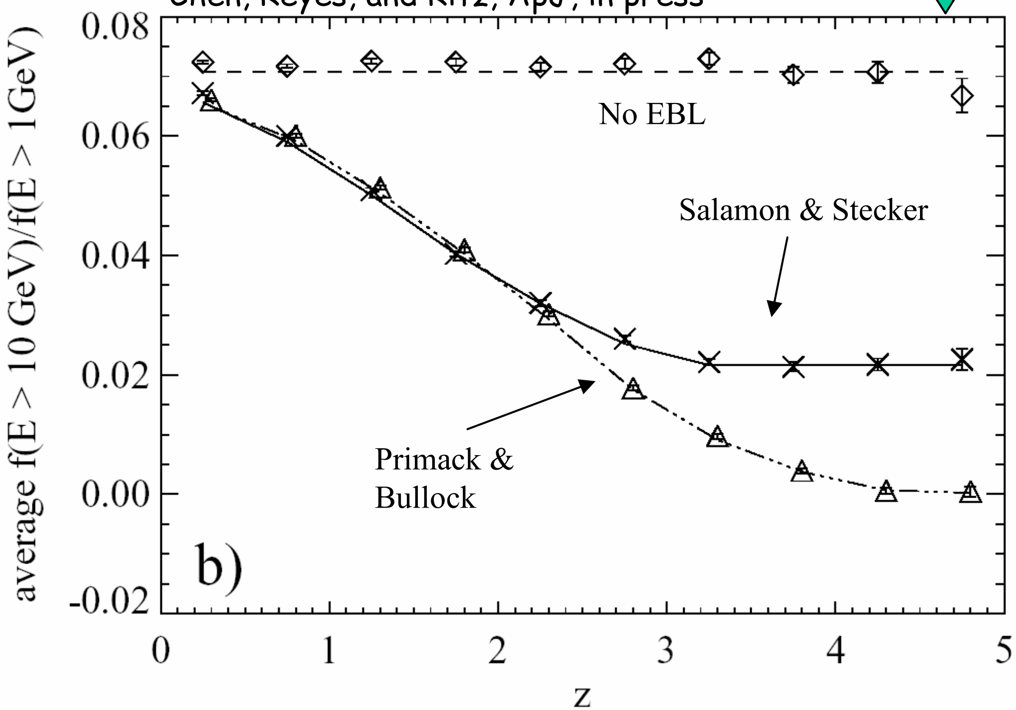
- **Important advances offered by GLAST:**

  (1) thousands of blazars - instead of peculiarities of individual sources, look for systematic effects vs redshift.

  (2) key energy range for cosmological distances (TeV-IR attenuation more local due to opacity).

- Effect is model-dependent (this is good):

Chen, Reyes, and Ritz, ApJ, in press



Caveats

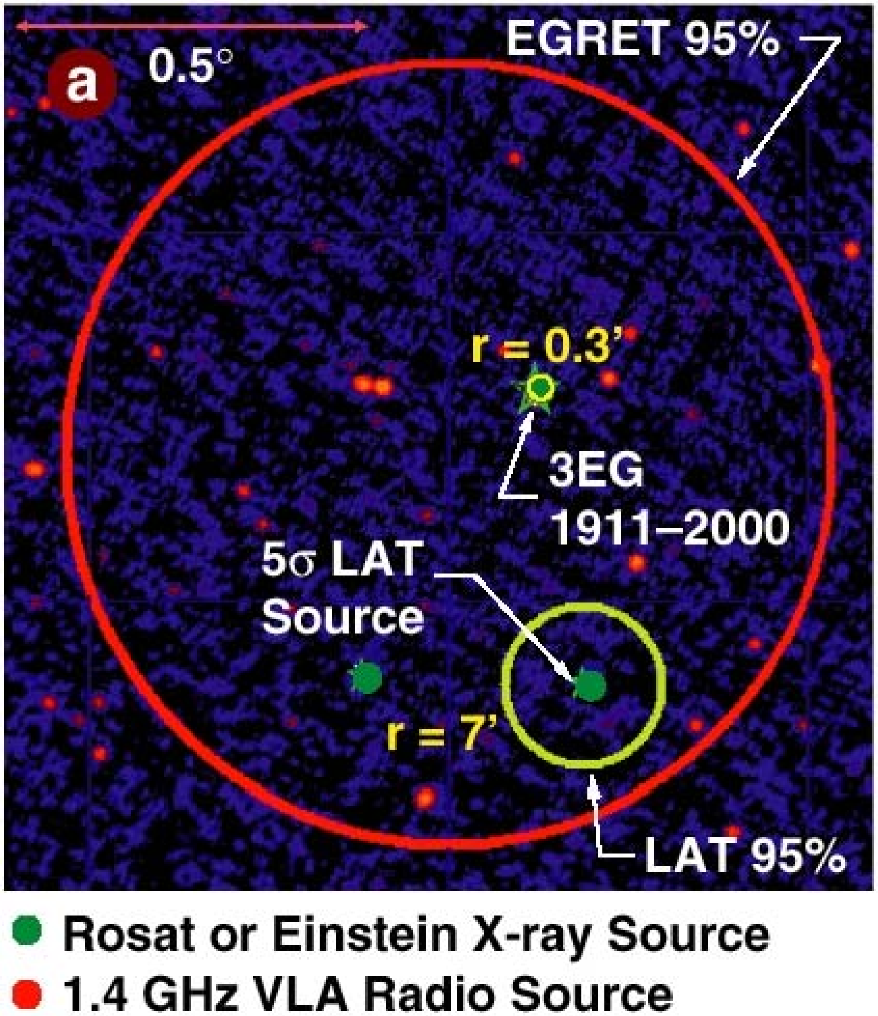
- How many blazars have intrinsic roll-offs in this energy range (10-100 GeV)? (An important question by itself for GLAST!) Again, power of statistics is the key.
- What if there is conspiratorial evolution in the intrinsic roll-off vs redshift? More difficult, however there may also be independent constraints (e.g., direct observation of integrated EBL).
- Must measure the redshifts for a large sample of these blazars!

Important advances in TeV range

- probes IR density at lower redshift
- Spectra over a range of distances
  - Mrk421 z=0.03
  - Mrk501 z=0.034
  - ES1959+650 z=0.047
  - H1426+428 z=0.129

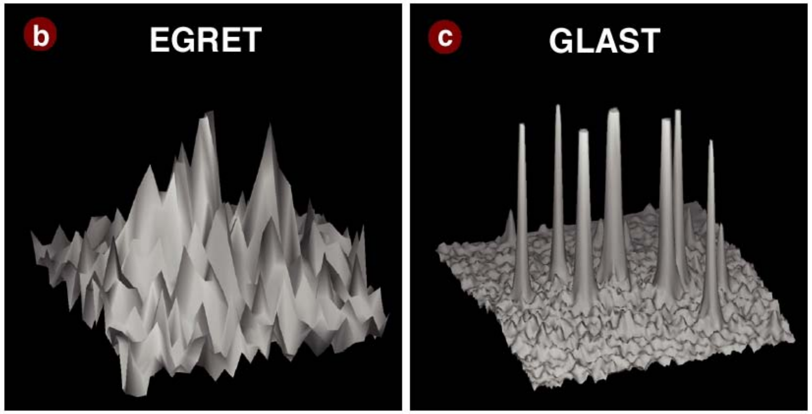
Unidentified Sources

172 of the 271 sources in the EGRET 3rd catalog are "unidentified"



EGRET source position error circles are ~0.5°, resulting in counterpart confusion.

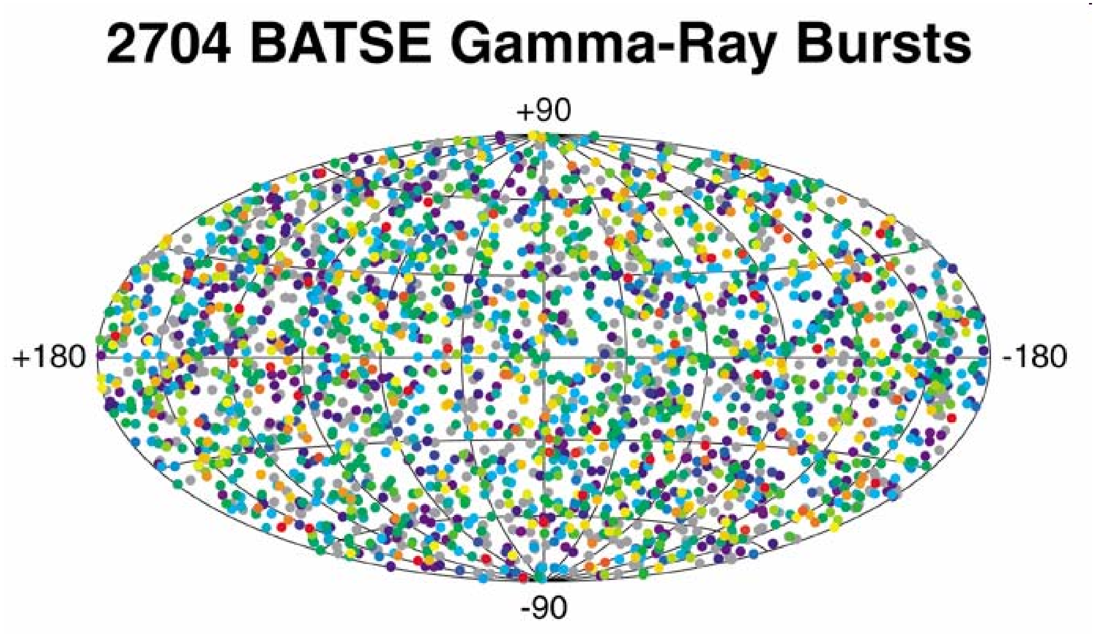
GLAST will provide much more accurate positions, with ~30 arcsec - ~5 arcmin localizations, depending on brightness.



Cygnus region (15x15 deg)

Gamma Ray Bursts

Bursts are isotropic and non-repeating (as far as we can tell):



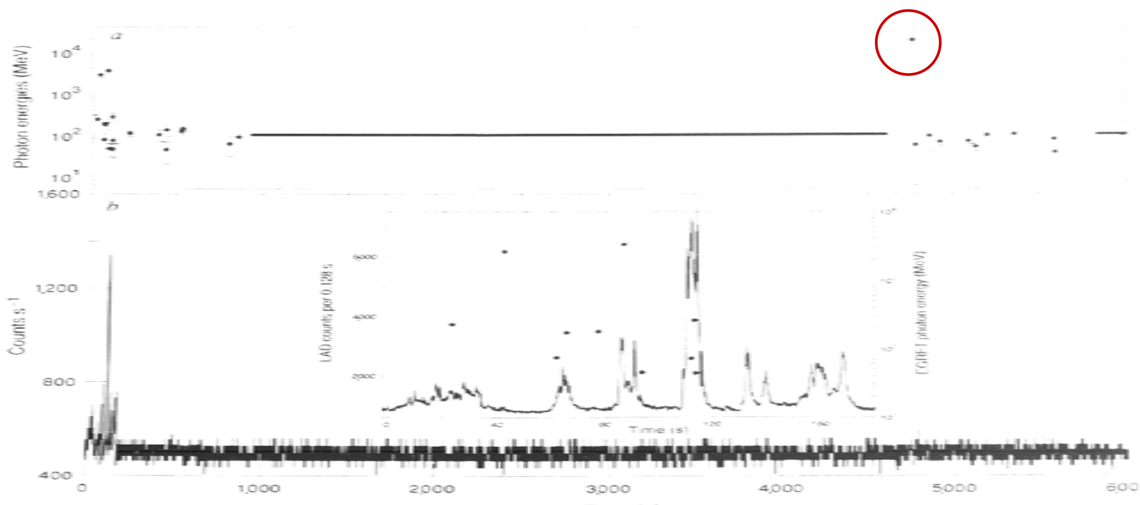
=> important to view as much of the sky as possible

Gamma Ray Bursts

GRBs discovered in 1960's accidentally by the Vela military satellites, searching for gamma-ray transients (guess why!) The question persists : What are they??

New result: GRB030329 unambiguous supernova association!

EGRET has detected very high energy emission associated with bursts, including a 20 GeV photon ~75 minutes after the start of a burst:



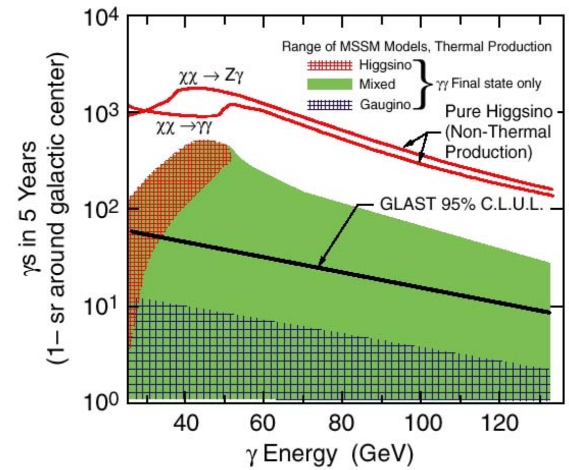
+ **Milagrito** evidence for TeV emission from GRB 970417 ApJ 533(2000)533.

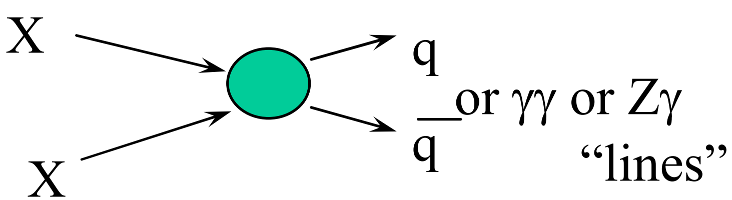
Hurley et al., 1994

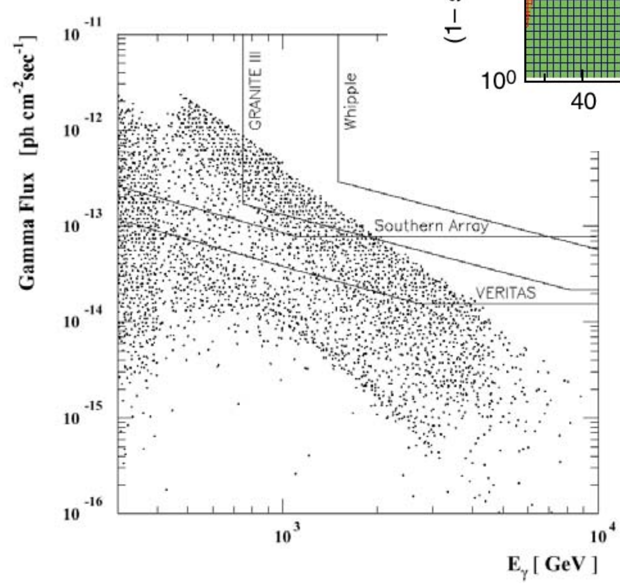
Future Prospects: GLAST will provide definitive information about the high energy behavior of bursts: LAT and GBM together will measure emission over >7 decades of energy.
Place your bets on additional TeV burst detections!

Particle Dark Matter

Some important models in particle physics could also solve the dark matter problem in astrophysics. If correct, these new particle interactions could produce an anomalous flux of gamma rays.





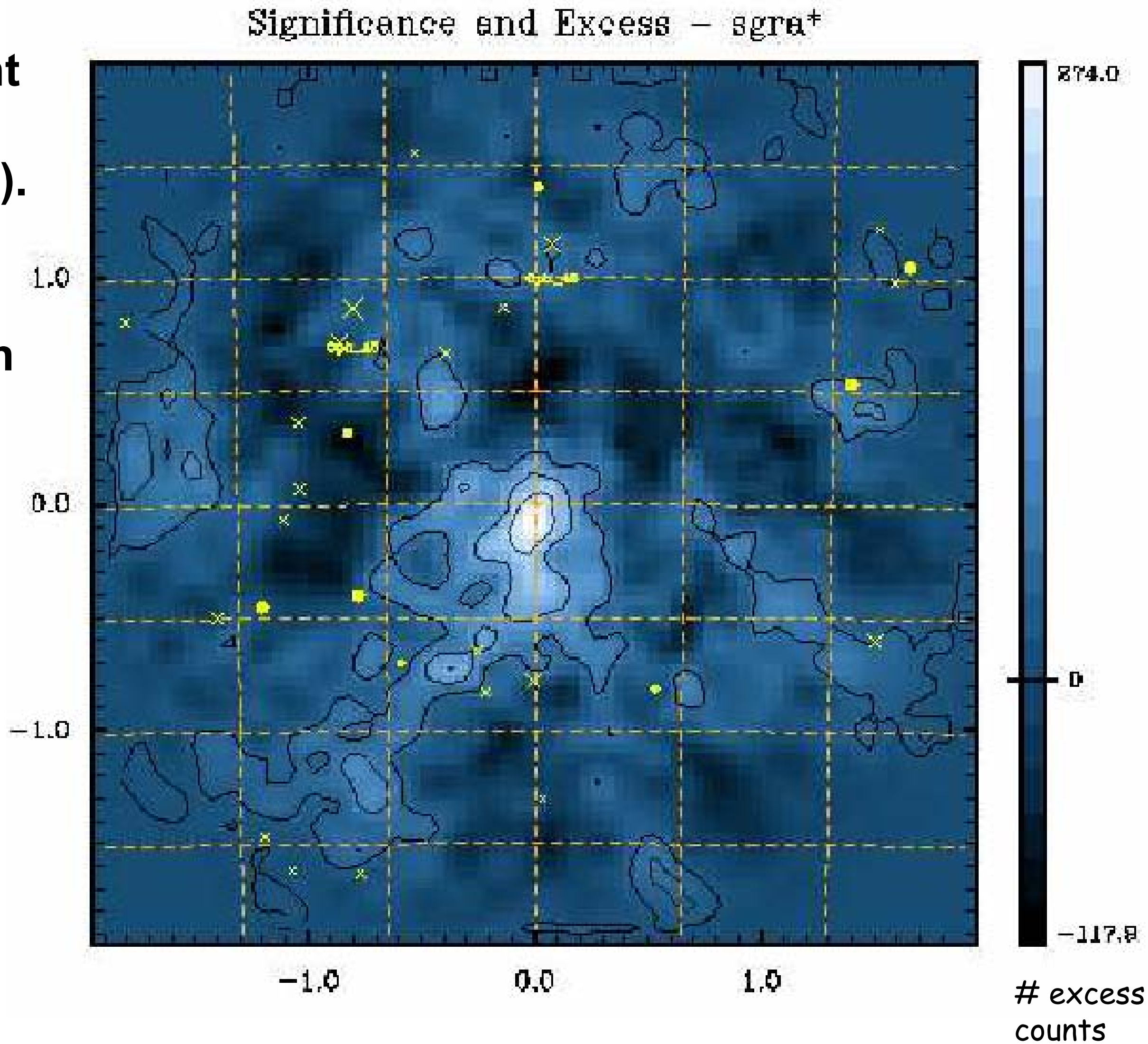


Bergstrom, Ullio, and Buckley (1998)

Just an example of what might be waiting for us to find!

Whipple Observation of Galactic Center

- Region includes a bright EGRET unidentified source(2EG J1746-2852). Complicated region!
- Many good reasons to expect gamma emission (supermassive black hole, CR interactions, neutralino annihiliation?,…).
- Whipple now reports 3.7σ excess (E>~2TeV, 16 hrs observation). Further observations and analysis underway. Stay tuned.



Supernova Remnants as Accelerators

What is the origin of cosmic rays? What are the acceleration mechanisms?

Seminal work: Fermi (1949)

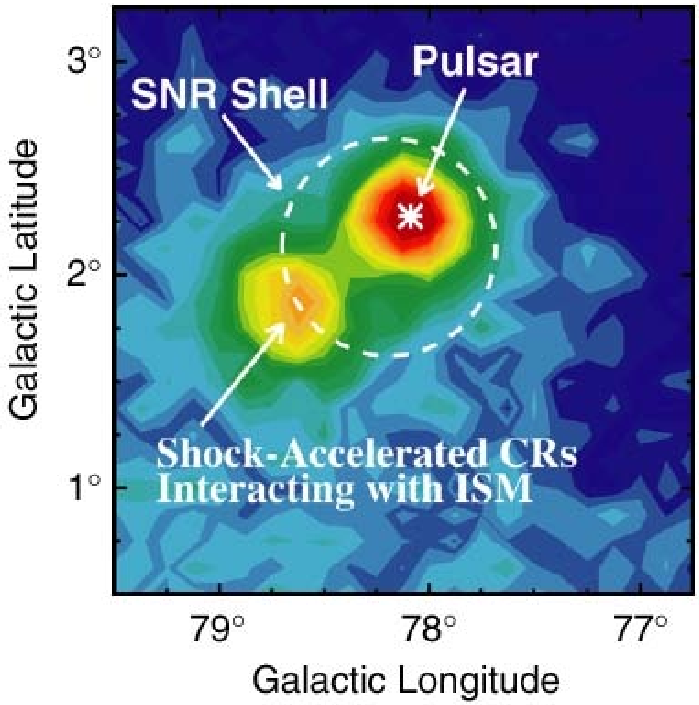
Current ideas: shock acceleration from supernovae (< 30% of released energy sufficient to produce all cosmics up to ~ 10^{14} eV)

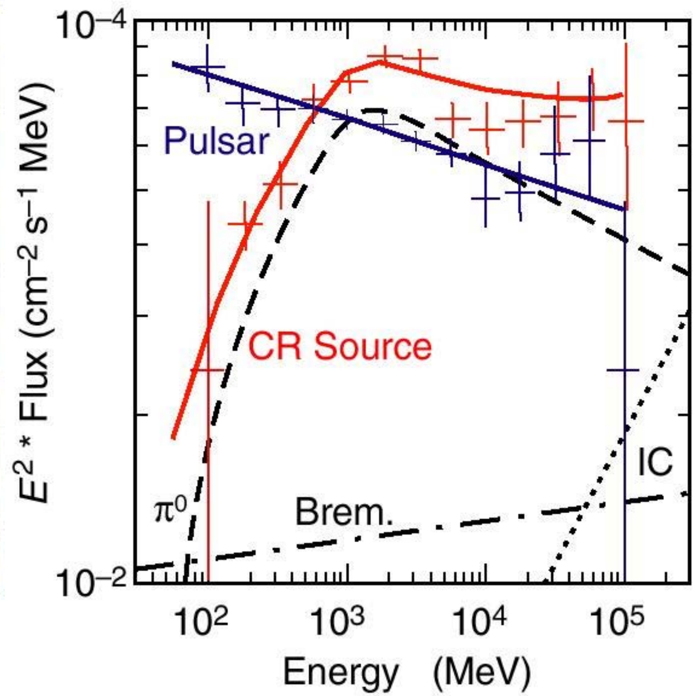
expect: interaction of CR's with gas swept up by blast should produce $\pi^0 \longrightarrow \gamma\gamma$. Flux O($10^{-7}$ ph/cm^2/s) at 1kpc.

Many shell remnants resolvable in other bands. Subtended angle can be O(1°).

GLAST can resolve SNRs spatially and spectrally:

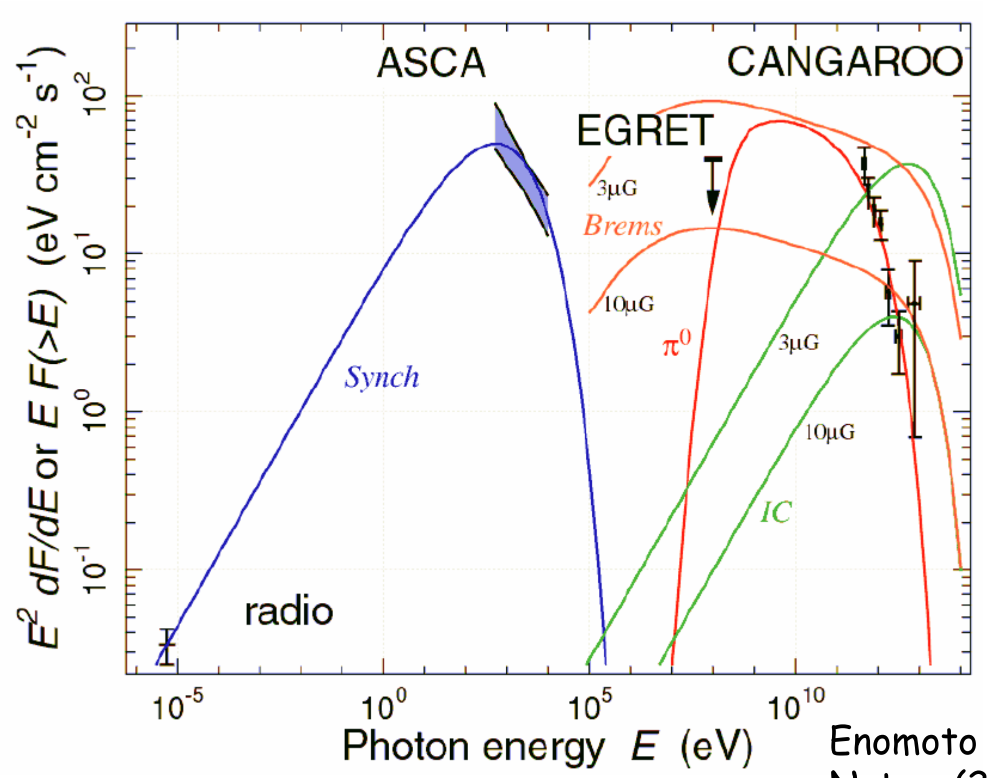
(S. Digel et al, simulation of γ–Cygni)





Cosmic Rays and TeV SNR Observations

- **TeV emission in supernova remnants has been discovered by ground-based observatories, including:**
  - **Crab Nebula (1989/Whipple), PSR1706-44 (1995/CANGAROO), Vela (1997/CANGAROO), SN1006 (1997/CANGAROO), RXJ1713.7 (1999/CANGAROO)**

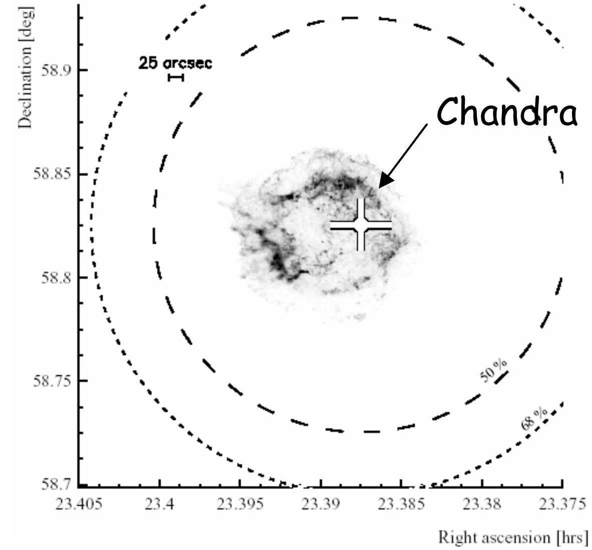


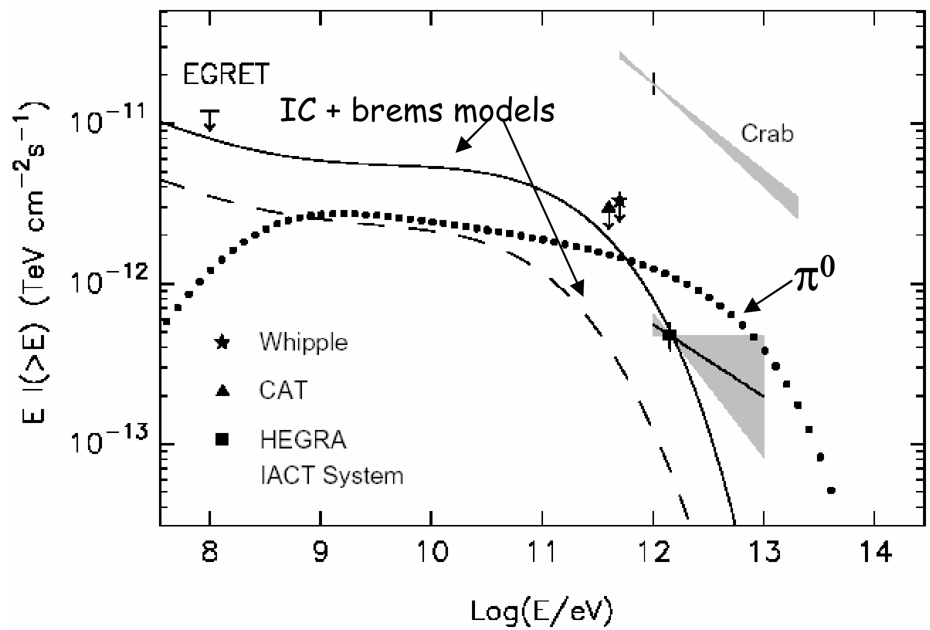
Enomoto et al., Nature(2002)

Synchrotron emission => expect Bremsstrahlung and Inverse Compton (IC) components if electron acceleration. Interpretations for the origin of cosmic ray protons not yet clear.

HEGRA TeV Observations of CasA

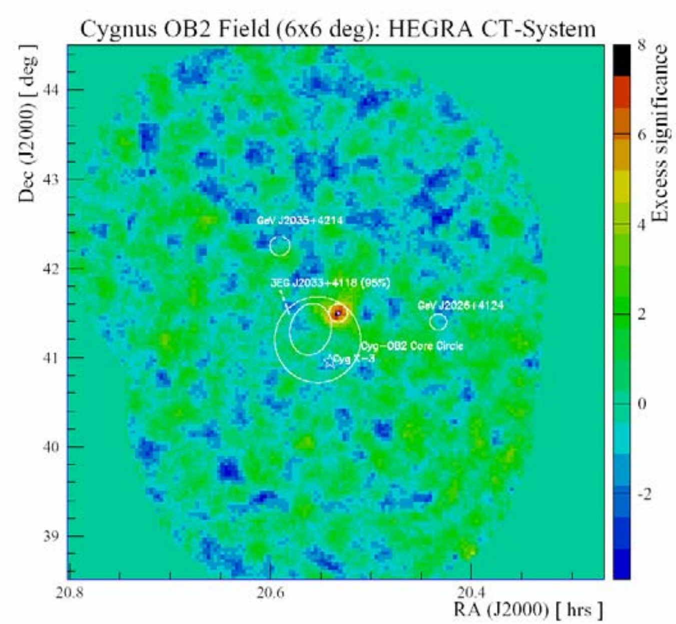
- Cassiopeia A bright shell-type supernova remnant at ~3.4 kpc
- Hard synchrotron X-ray spectra => accelerated electrons to ~100 TeV.
- => TeV gamma from inverse Compton and bremsstrahlung.
- HEGRA observation (at ~5σ) confirms acceleration hypothesis, but
  - electrons?? protons??
- Much more work to do to understand CR proton acceleration!





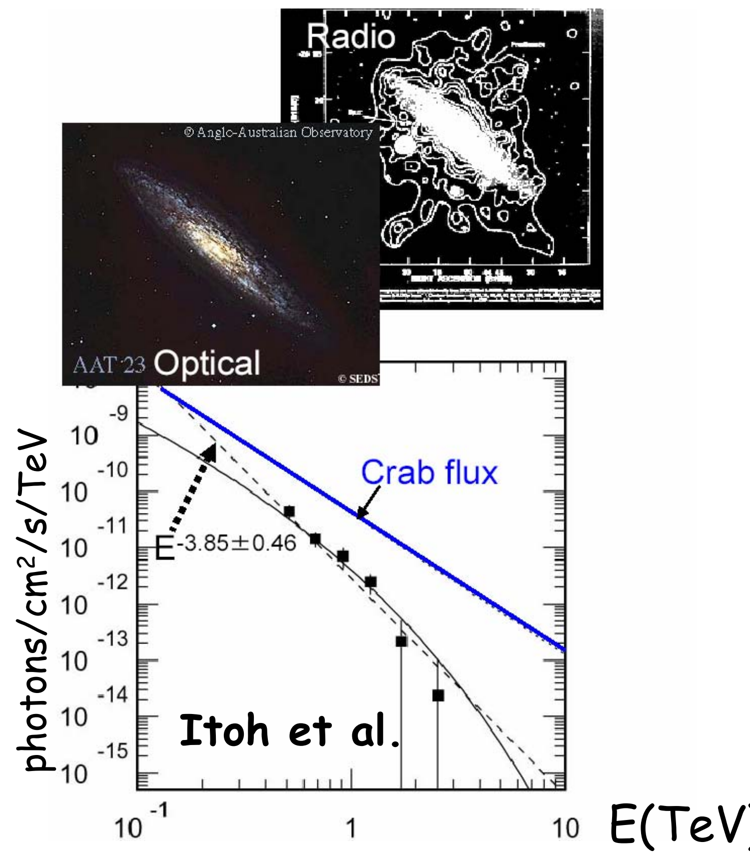
Related TeV Observations on CR Origins

- **HEGRA serendipitous discovery of 1st TeV unidentified source, centered in the core of Cygnus OB2 star forming region (near UNID EGRET source 3EG J2033+4118)**



- **Could imply energy source not co-located with gamma source => accelerated hadrons interacting with a local, dense cloud. Other interpretations possible.**

- **CANGAROO-II detection of nearby edge-on galaxy, NGC253, ~2.5 Mpc away. First TeV detection from another normal-sized spiral galaxy (like ours).**



Testing Lorentz Invariance

- **Lorentz Invariance breaking models can lead to different maximum velocities by particle type (Stecker&Glashow, Coleman&Glashow):**

Stecker:
$$c_e \equiv c_\gamma (1+\delta), \quad 0 < |\delta| << 1$$

  - **For δ<0, photons can decay to e+e- pairs if** $E_\gamma > m_e \sqrt{2/|\delta|}$ **Observations of the Crab (E>50 TeV) implies** $-\delta < 2\times10^{-16}$
  - **For δ>0, superluminal electrons will emit vacuum Cerenkov radiation and the threshold for pair creation will be altered. Cosmic ray data and inferred information from Mrk501 blazar observations =>** $\delta < 3\times10^{-14} - 1.3\times10^{-15}$**.**

- **Some classes of QG models imply a linear photon velocity dispersion (Amelino-Camelia et al., Ellis, Mavromatos, Nanopoulos):**

$$V = c\,(1 - \xi \cdot \frac{E}{E_{QG}} + \ldots)$$

Use GRBs! Effects could be O(100) ms or larger, using GLAST data alone.
But ?? effects intrinsic to bursts?? **Representative of window opened by measurements at such large distance and energy scales.**

References: On-going Imaging ACTs

- HEGRA
  - http://www.mpi-hd.mpg.de/hfm/CT/CT.html
- CAT
  - http://lpnp90.in2p3.fr/~cat/index.html
- Whipple
  - http://veritas.sao.arizona.edu/VERITAS_whipple.html
- SHALON
  - see, e.g., http://www.copernicus.org/icrc/papers/ici7238_p.pdf
- TACTIC
  - http://www-ik3.fzk.de/~haungs/tactic.html
- Crimea
  - http://www.crao.crimea.ua/craoinfo/gamma.html

References: On-going Solar Arrays

- **CELESTE**
  - http://wwwcenbg.in2p3.fr/extra/Astroparticule/celeste/e-index.html
- **STACEE**
  - http://www.astro.ucla.edu/~stacee/
- **Solar-2**
  - http://solartwo.ucr.edu/

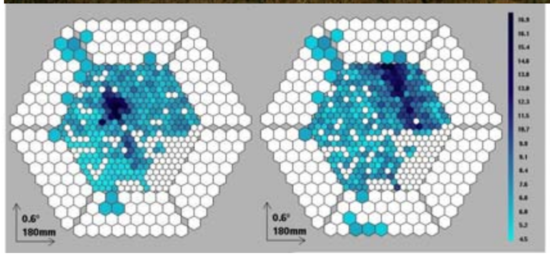
References: On-going Particle Arrays

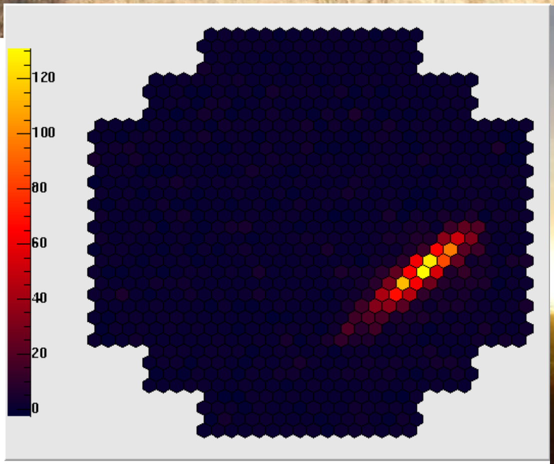
- **Milagro**
  - http://www.lanl.gov/milagro/
- **Tibet Array**
  - http://www.icrr.u-tokyo.ac.jp/em/index.html
- **ARGO**
  - http://www.roma2.infn.it/research/comm2/argo/

Future ACTs

- HESS
  - Array of four 12m telescopes in Namibia. Structures complete. Two cameras complete. Fully operational in 2004.
  - http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html
- CANGAROO-III
  - Array of four 10m telescopes in Australia. Two telescopes in operation. Fully operational in 2003.
  - http://icrhp9.icrr.u-tokyo.ac.jp/c-iii.html
- MAGIC
  - One 17m telescope in La Palma (Canary Islands). Operational in 2004.
  - http://hegra1.mppmu.mpg.de/MAGICWeb/
- VERITAS
  - Array of four 12m telescopes in Arizona, operational in 2005. Will propose plan to increase to seven in 2007.
  - site issues resolved
  - http://veritas.sao.arizona.edu/

Future ACTs Under Construction





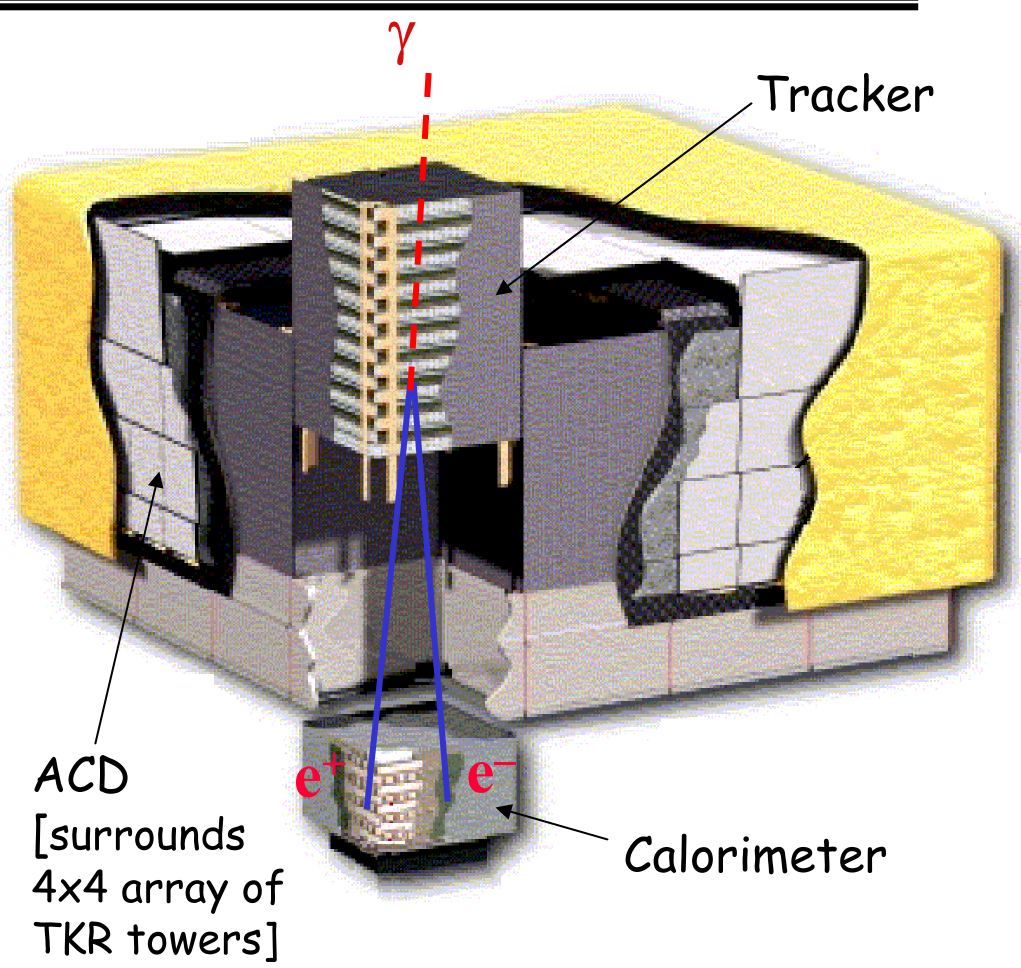
VERITAS
Prototype

Future Space-based Observatories

- AGILE
  - Project centered in Italy
  - Launch 2005.
  - Silicon strip tracker (38cm x 38cm), mini-calorimeter (1.5 X_0 on axis), anticoincidence system.
  - http://agile.mi.iasf.cnr.it/Homepage/
- GLAST
  - Large, international collaboration. LAT is managed at SLAC, GBM at Max Planck and Marshall, mission at Goddard.
  - Launch 2006
  - Silicon strip tracker (1.6m x 1.6m), hodoscopic calorimeter (8.4 X_0 on axis), anticoincidence system.
  - http://www-glast.stanford.edu and http://glast.gsfc.nasa.gov
  - Data will be made public through a Science Support Center

Overview of GLAST Large Area Telescope (LAT)

- Precision Si-strip Tracker (TKR)
  18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- Hodoscopic CsI Calorimeter(CAL)
  Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, robust hardware trigger and software filters.



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

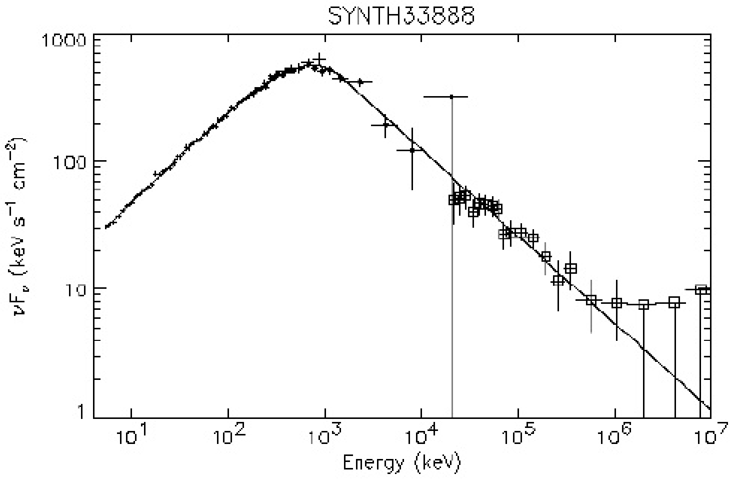
GLAST Burst Monitor

- provides spectra for bursts from 10 keV to 30 MeV, connecting frontier LAT high-energy measurements with more familiar energy domain;

Simulated GBM and LAT response to time-integrated flux from bright GRB 940217

Spectral model parameters from CGRO wide-band fit

1 NaI (14 º) and 1 BGO (30 º)



- provides wide sky coverage (8 sr) -- enables autonomous repoint requests for exceptionally bright bursts that occur outside LAT FOV for high-energy afterglow studies (an important question from EGRET);
- provides burst alerts to the ground.

Fellow Travelers

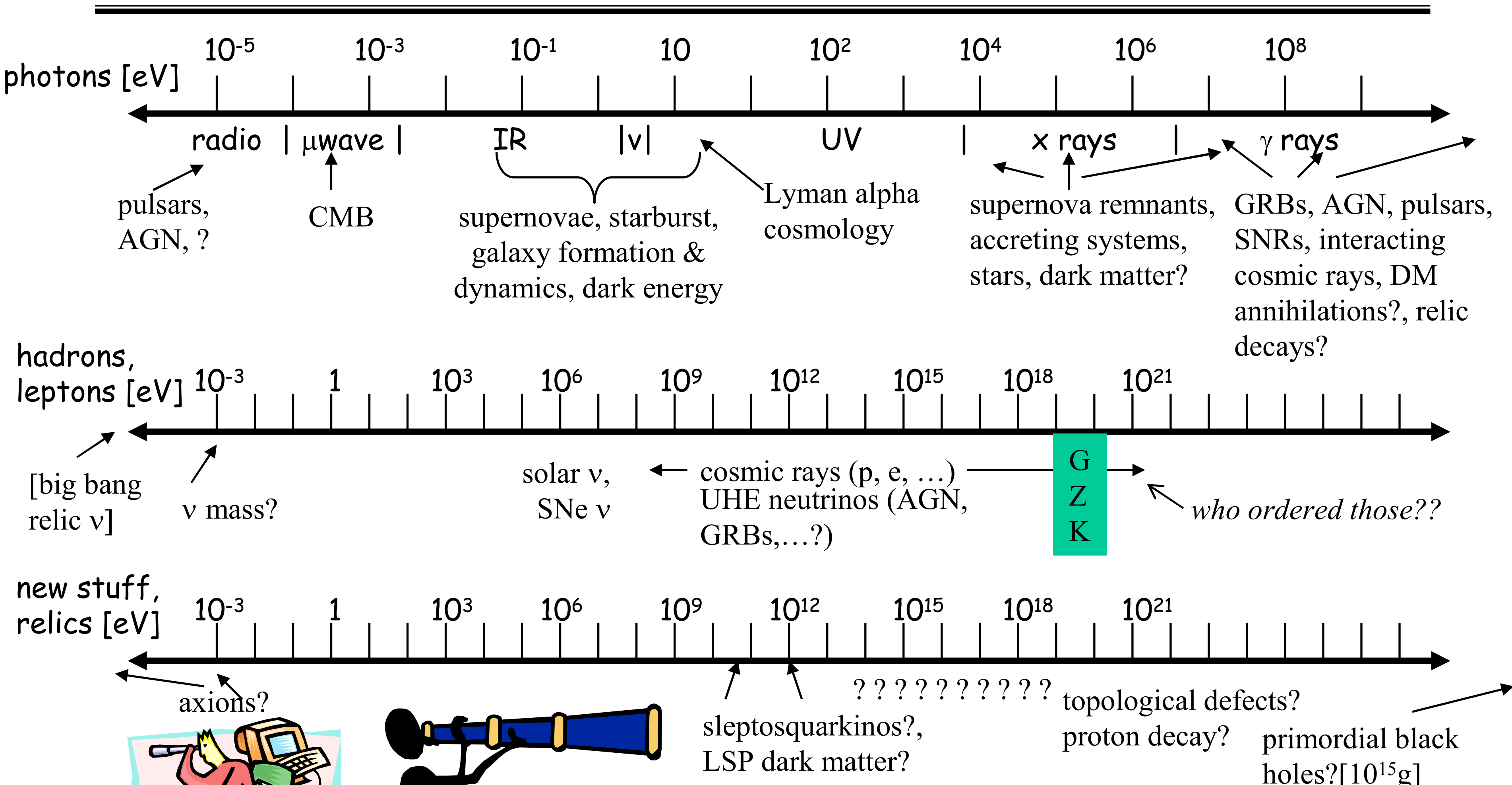
- HETE-2
  - http://space.mit.edu/HETE/
- SWIFT
  - http://swift.gsfc.nasa.gov/
- INTEGRAL
  - http://isdc.unige.ch/index.cgi?Home+home

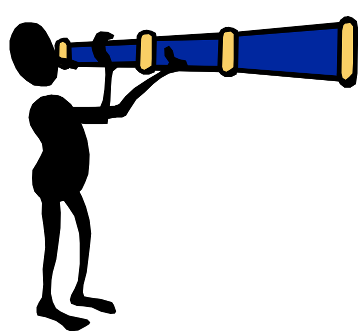
Bigger Context: “The Universe as a Laboratory”

Address fundamental questions, test limits of physical law using most extreme environments, and study the relics from the Big Bang

- **explore black holes: acceleration mechanisms producing high-energy jets; goal to study region around event horizon.**
- **find origin(s) of the highest energy cosmic rays**
- **understand gamma-ray bursts**
- **uncover dark matter**
- **study CMB**
- **test Inflation**
- **search for other Big Bang relics**
- **detect gravity waves**
- **confirm and study the ‘Dark Energy’**
- **Discovery!**

Summary: Cosmic Messengers





+ gravitons: massive binary systems, GRBs?, early Universe, … ????

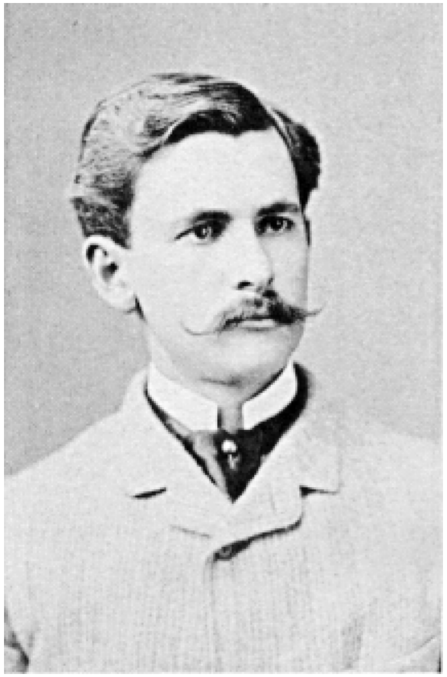
Perspective

- A wide range of interesting and exciting questions at the interface between Particle Physics and Astrophysics.
- Relics offer leaps forward in our ability to explore Nature. Example:

  At the turn of the 20th century, in less than 15 years the smallest distance scale explored shrank dramatically from 10^{-10} m to 10^{-14} m. The discovery of natural radioactivity, a phenomenon from a much higher energy scale than was otherwise accessible at the time by artificial means, made this possible.

Nature offers us these clues to fundamental physics – we just have to be clever enough to look around for them.

The multi-agency process must be efficient …



A. Michelson, 1887

A. Michelson, 1928

Summary

- Gamma-ray observations address many important questions:
  - What is going on around black holes? How do Nature's most powerful accelerators work?
  - What are the unidentified sources?
  - What is the origin of the diffuse background?
  - What is the origin of cosmic rays?
  - What is the high energy behavior of gamma ray bursts?
  - When did galaxies form?
  - What else out there is shining gamma rays? Are there high-energy relics from the Big Bang? Are there further surprises in the poorly measured energy region (10GeV – 100 GeV)?
- Large menu of "bread and butter" science, and <u>large discovery potential.</u> Wealth of new data on the way.
- Important synergy/complementarities among future experiments!
- Part of the bigger picture of experiments at the interface between particle physics and astrophysics.

We expect the gamma-ray community to grow enormously in the era of new experiments!!