WHAT HAS BEEN FOUND WITH MILAGRO?

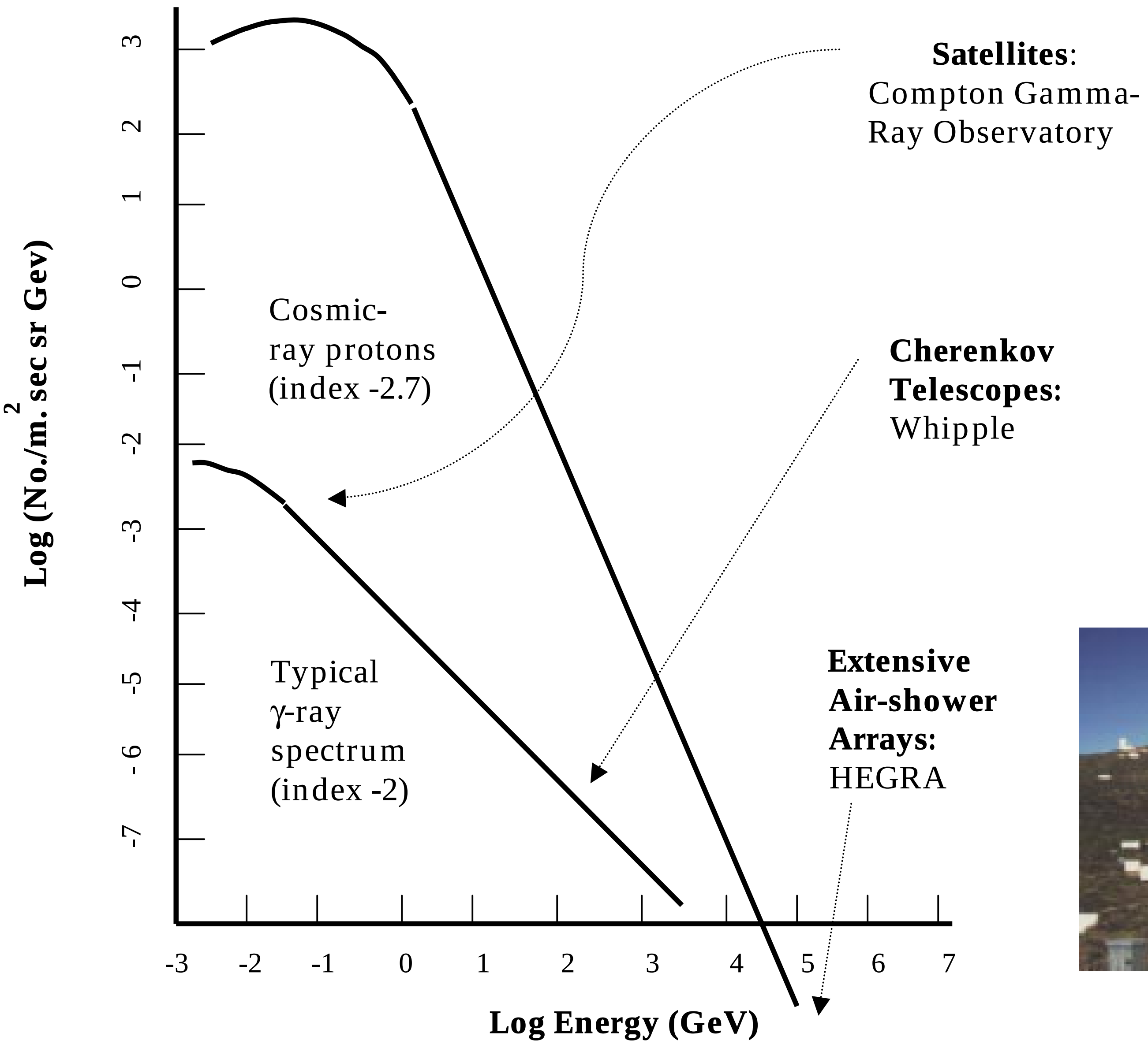
D. Coyne (UCSC) Oct. 16, 2001

The Milagro VHE Gamma-ray Telescope
(Fenton Hill, New Mexico)

Define "FOUND"

- 1. Does the technique work?
- 2. Is the detector complete?
- 3. Has significant astrophysics been done?
- 4. Can profound astrophysics be done?

The techniques of γ-ray astrophysics



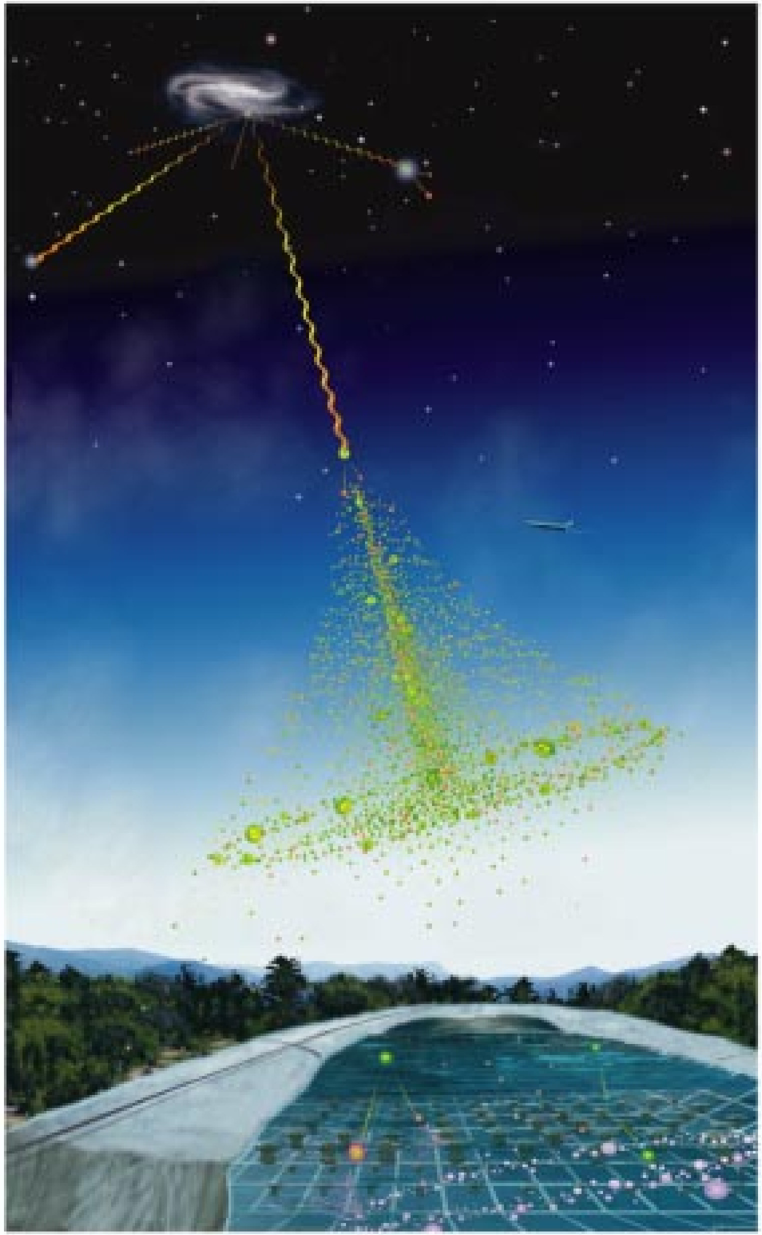
Lessons learned from γ-ray observations

→ The γ-ray sky is interesting in any wavelength where one has sensitivity.

→ The γ-ray sky is full of transient phenomena on all time scales, with apparitions which are largely unpredictable.

Similar to the lesson learned in the 60's when counter experiments competed with bubble-chambers (and later solenoidal detectors), a survey instrument which casts a broad net is complementary to a precise device doing detailed measurements.

The Milagro telescope was motivated by a need for greater sensitivity, wider energy range, large angle field-of-view, and large duty-cycle considerations. The idea of a large ground-based continuous medium water Cherenkov detector was first tested by the CYGNUS collaboration using backyard plastic swimming pools.



Computer image by Aurore Simonnet, (UCSC) © 2000

The generation and detection of a γ-ray shower via Milagro

γ from galactic or extragalactic source up to ~ 0.5Gpc.

Pair production at ~ 20 km.

Mostly EM cascade to ground level.

(Note that hadron-initiated cascades have many high-Pt interactions and develop multiple cores)

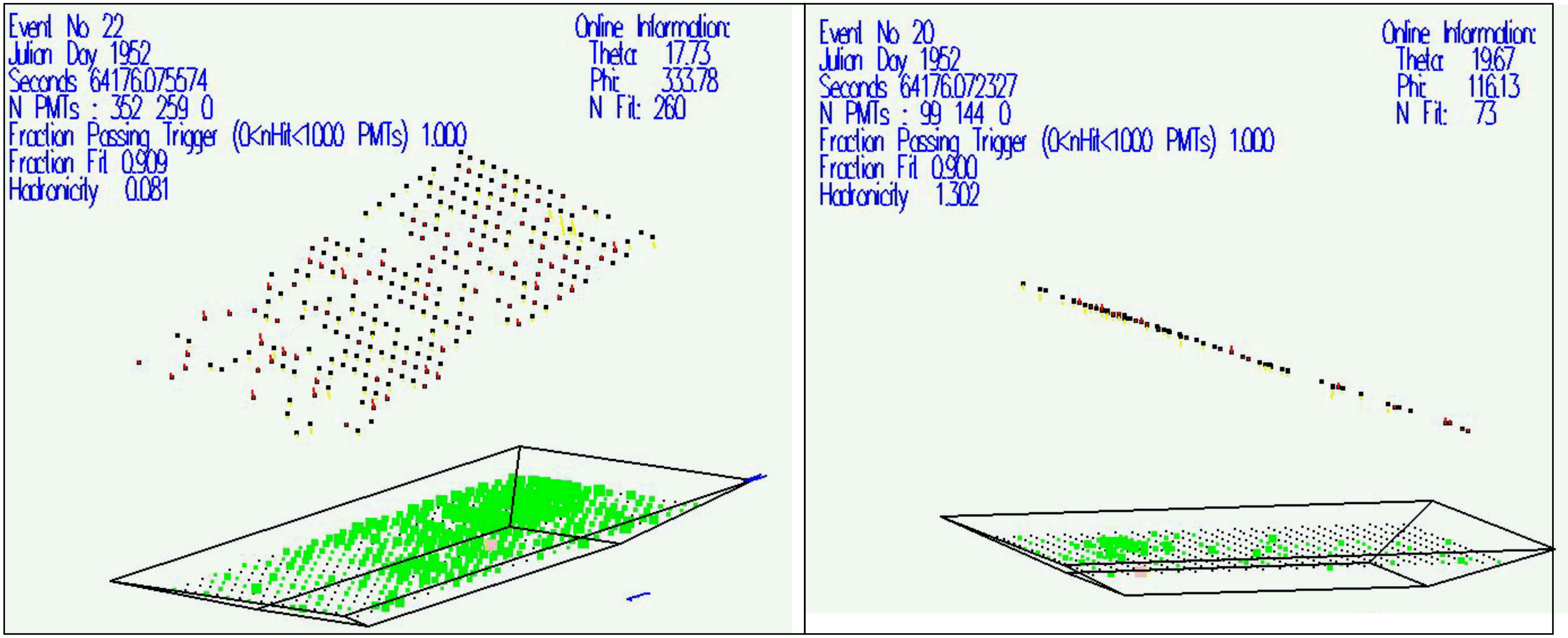
Snapshot of ~planar shower front.

Enters continuous medium at O(~ 10's) of MeV.

Compton recoils and other charged particles Cherenkov in water (0 to -8 m).

UV detection by phototubes at -1.5 and -7 m, as Cherenkov pattern evolves in water. Lowest level detects muon patterns and general γ/h differences.

Timing, pulse height, core and source location with Milagro

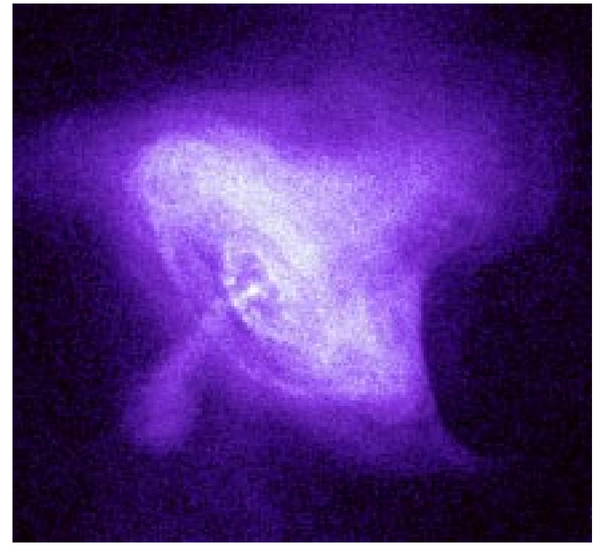


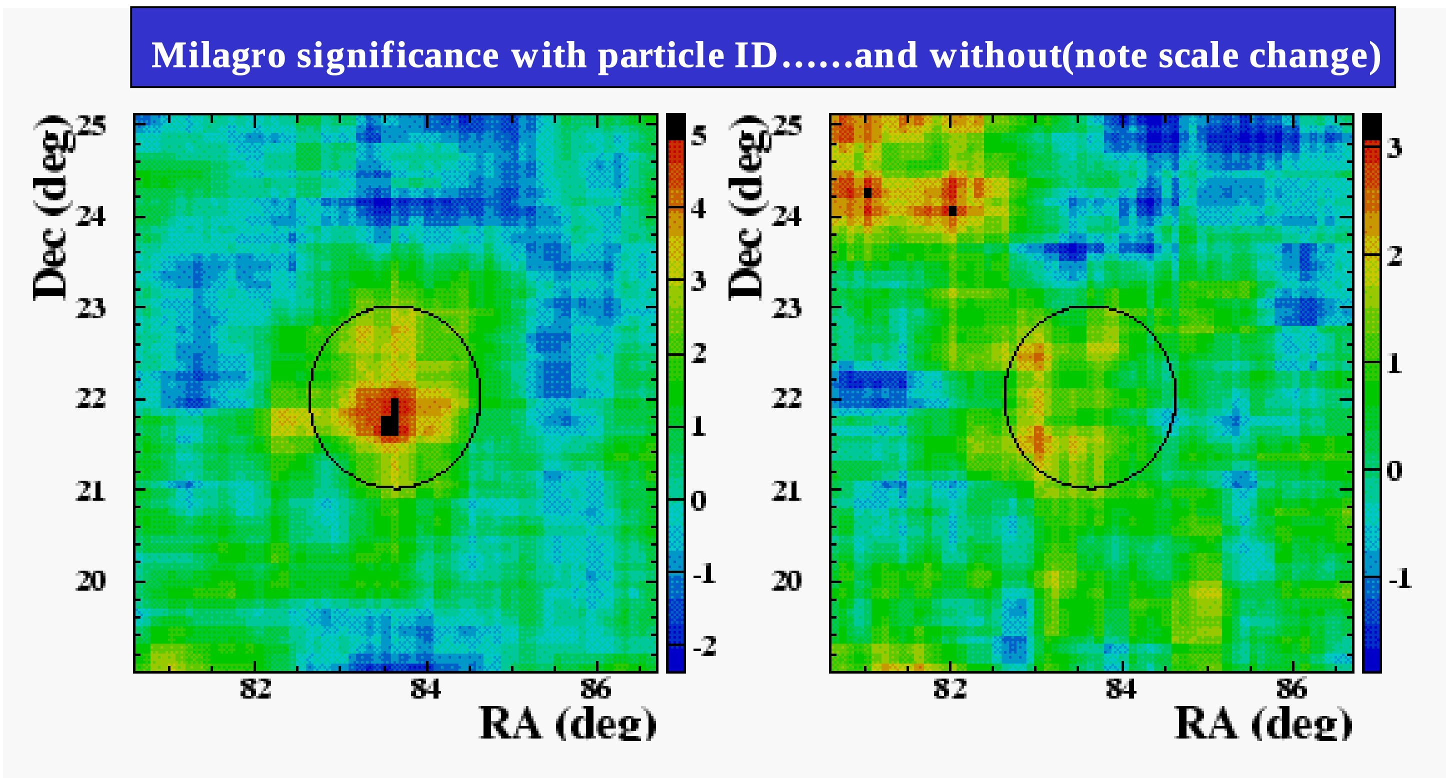
The general technique works…but this does not prove that Milagro detects γ rays from within the cosmic ray background.

This does.

The Crab nebula as seen by amateur Rich Jacobs
…
and in x-rays by Chandra…

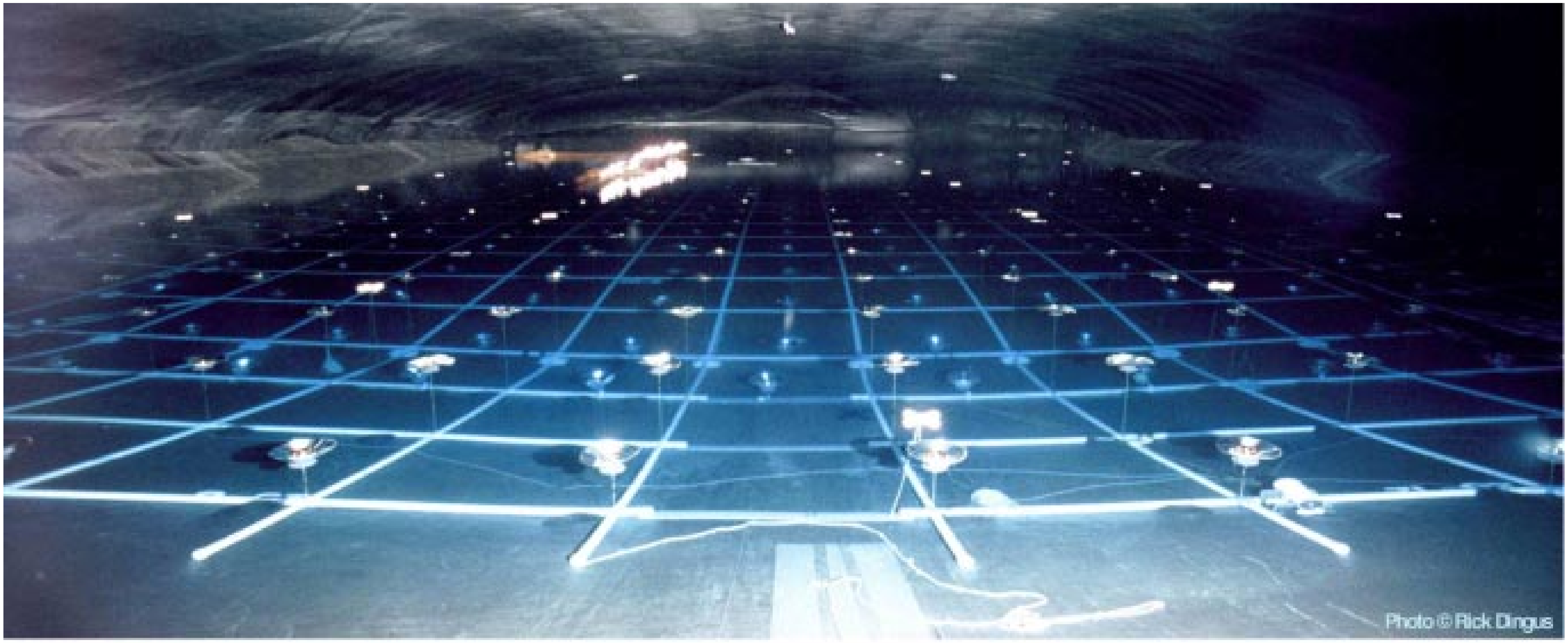
and in TeV photons by Milagro (below).





Is the detector complete?

1997:	MilaGrito	One layer, 228 tubes under ~1 m water.
1999	MiLagro	Two layers, 450 & 273 tubes under 1.5 & 7 m.
2000+	Milagro	Same, but with ~66 water tanks; expect full complement of 150 in 2002.



Milagro Specifications

CAPABILITIES (without outriggers)

Duty cycle: >95% (24hr / day, independent of weather)

Field of View: >1.8sr, sweeps out 7.4 sr. / day

Data rate: 2000Hz, ~40 Tbyte / year

Timing resolution: <.3ns

Angular resolution: 0.75°, better for selected samples

Energy resolution: use a log scale!

Energy threshold: 200GeV (soft)

Median energy: 4.7 TeV (n=-2.4)

Upper limit: 30-100 TeV (soft)

Hadron rejection: 91% with 54% retention of γ (crude preliminary)

HARDWARE

Pond:	60x80x8 m (6Mgal),
Altitude:	8600 ft. (750 g / m)
Phototubes:	20cm 10-stage Hamamatsu R5912SEL; UCI encapsulation
Acquisition:	Custom LANL / Fermilab design
Timing / charge logic:	Custom analog / digital UCSC design
Outrigger tanks:	170 (when completed) over 200x200m

PEOPLE

The Collaboration (with Utah=Wisconsin, +T.DeYoung)

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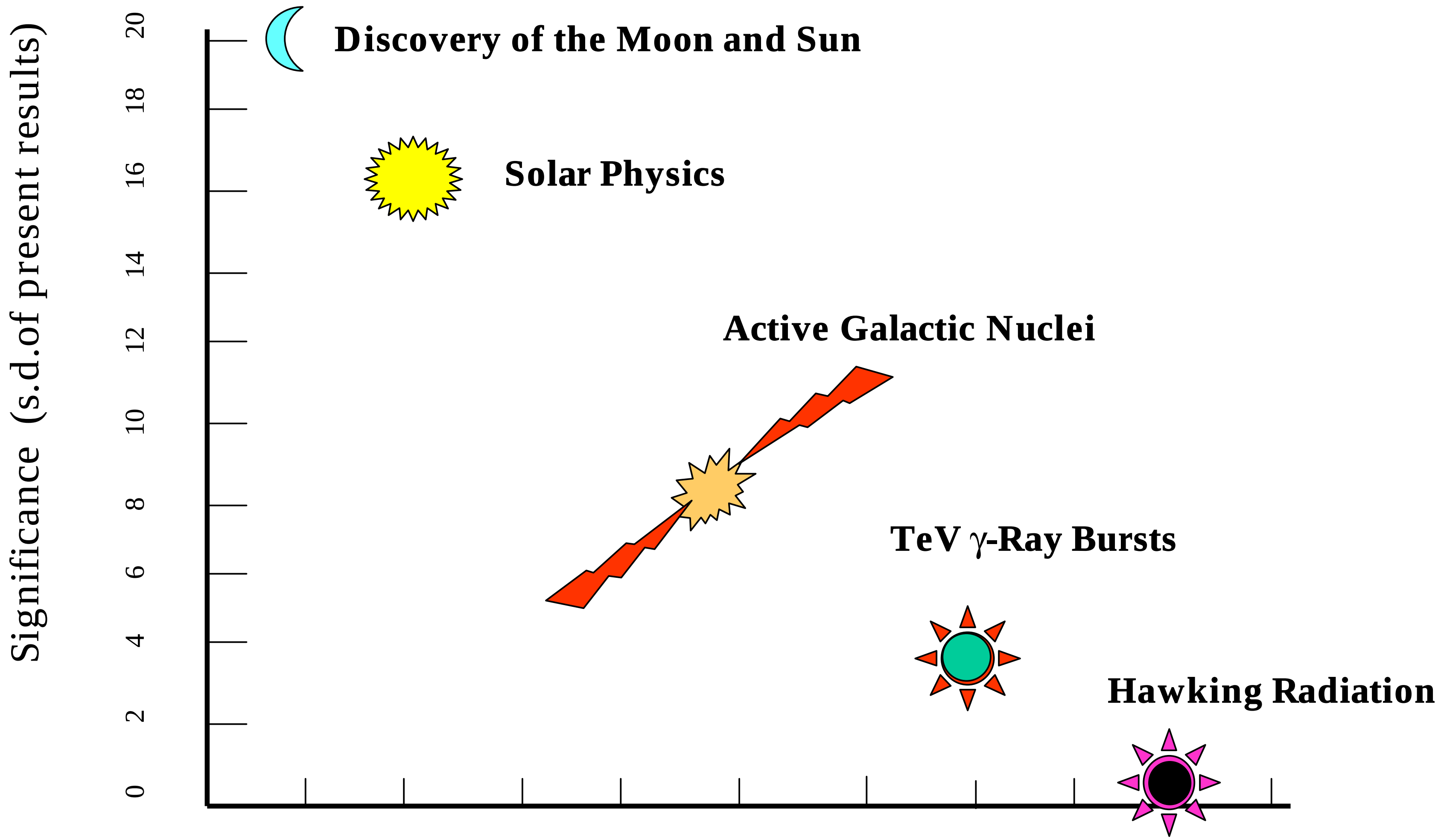
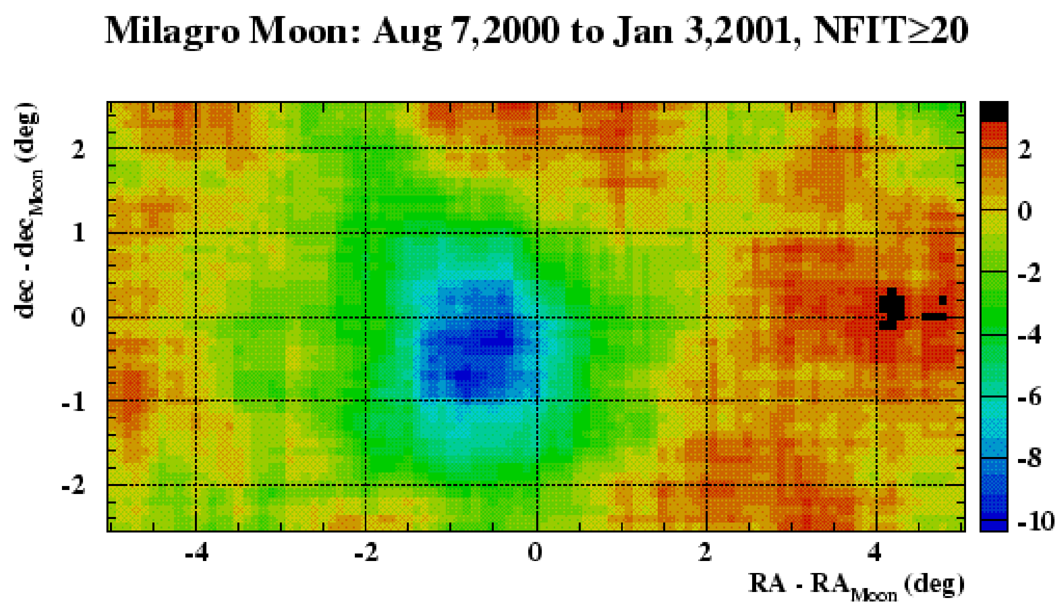
Has the detector done significant astrophysics?

Can the detector do profound astrophysics?

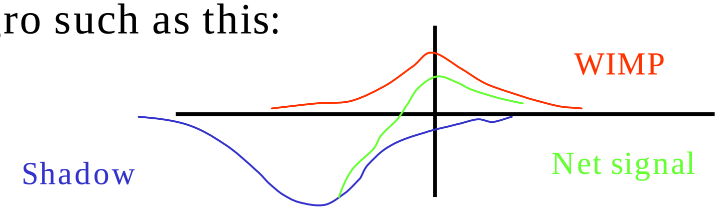


Finding the Sun and Moon by their cosmic-ray shadows



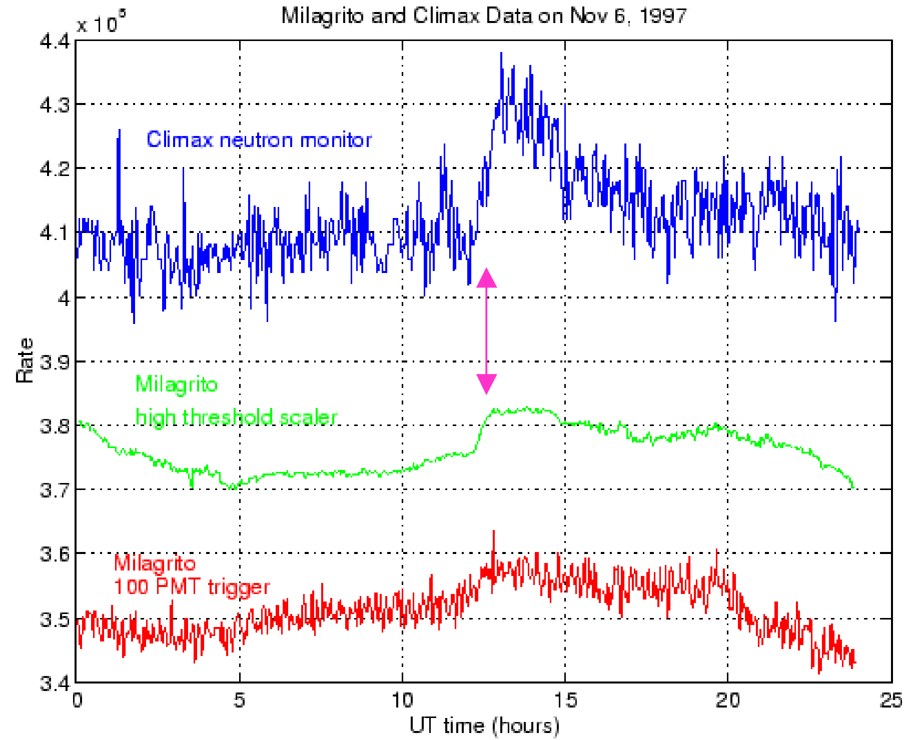
This makes a good joke, but in addition:

- The displacement of the Moon gives the systematic pointing error. Note magnetic displacement!
- The magnetic displacement (for selected data) provides a means for absolute energy calibration.
- The appearance (or not) of the anti-Moon sets limits on the cosmic ray component of anti-nuclei.
- The similar treatment of the Sun shadow is more difficult because the Sun has a magnetic field. However, if the Sun is a reservoir of WIMPs, then their annihilation products (0.1-10 TeV gammas from neutralinos) might yield a signal in Milagro such as this:

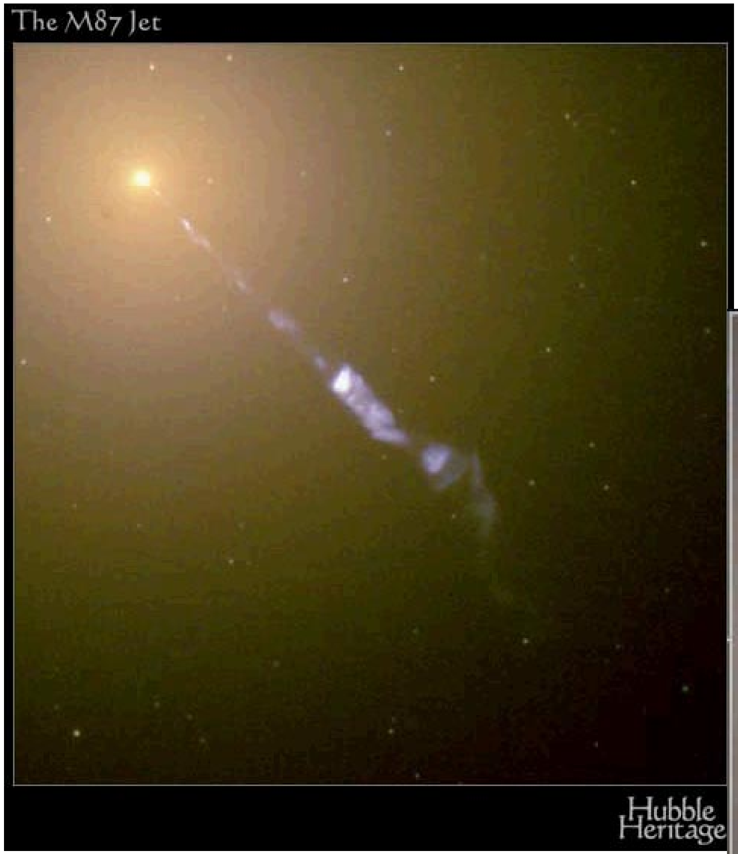


Solar Physics

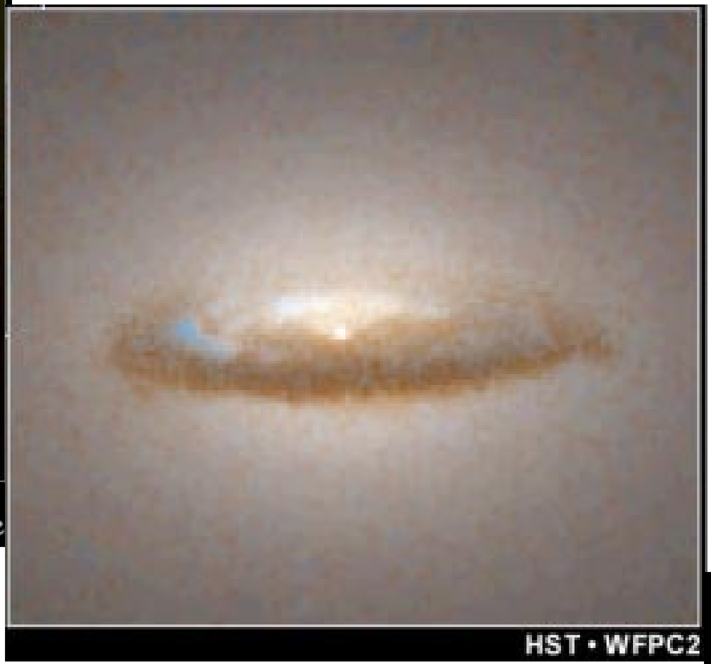
- Event simultaneous with other detectors finding Nov 6, 1997 coronal mass ejection.
- 'Grito found a jump in the scaler system counts 23x rms background.
- Interpretation consistent with Climax neutron monitors is that 'Grito has shown that solar primaries are present with >10 GeV energies.
- Presented (by UNH) at conferences, but collaboration deferred publication pending finding more such events during Solar Maximum with Milagro. Collaboration will now publish several such events.
- Advertisement: Collaboration seeks solar physicist; data awaits you!



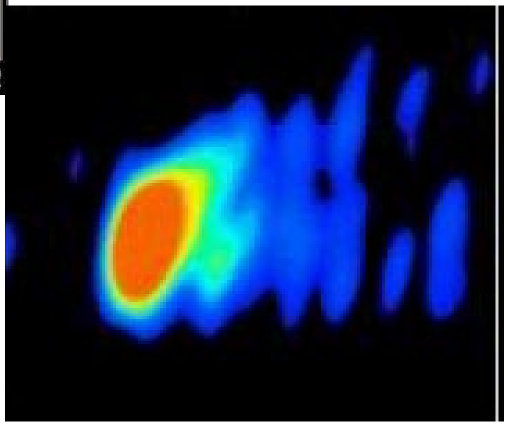
Unraveling the puzzle of Active Galactic Nuclei



AGN Jet of M87; (HST)
Scale: O(100,000 ly)



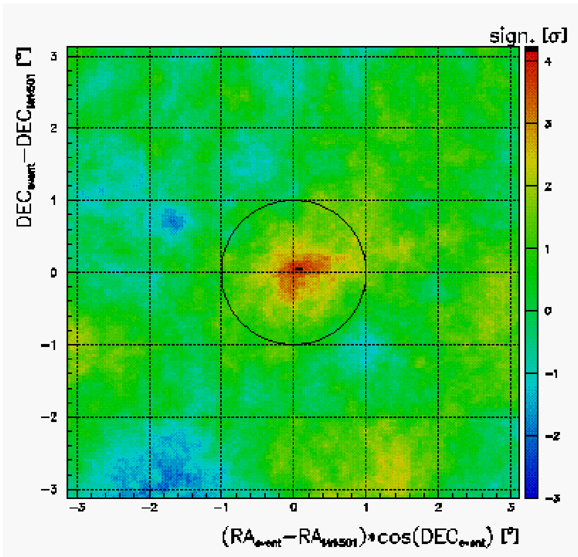
Accretion Disk of NGC7052; HST
Scale: O(4000ly)

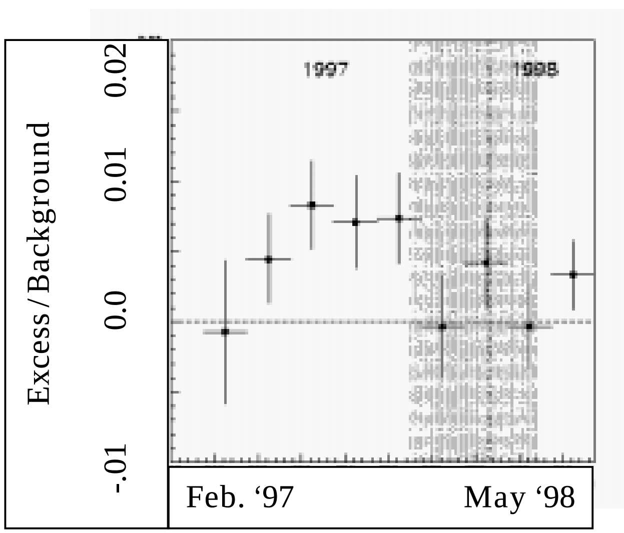


Black Hole Core of M87; VLB
Scale: O(0.1ly)

Milagro AGN Studies

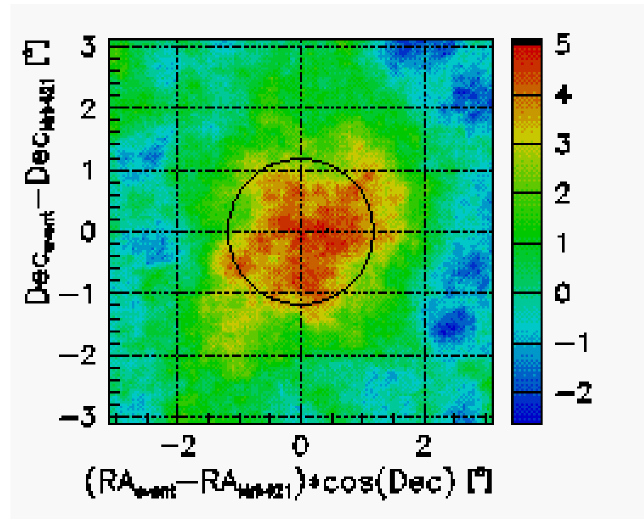
'Grito result on Markarian 501 (2/8/97-5/7/98)

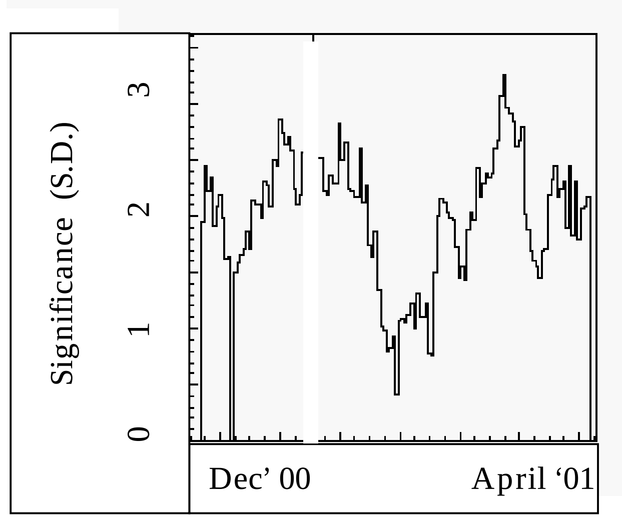




Light curve in 50-day intervals

Milagro result on Markarian 421 (12/15/00-4/17/01)





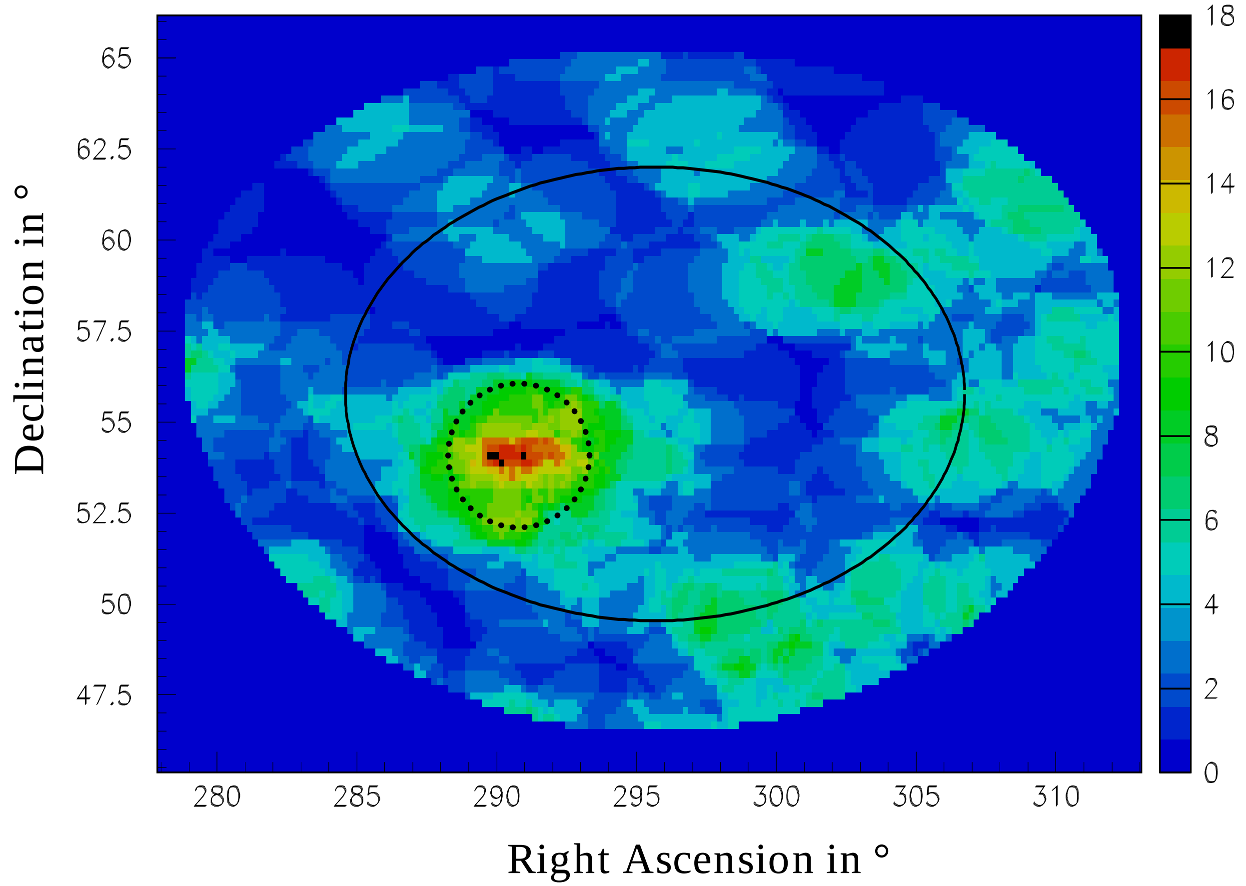
Running light curve in daily 30-day accumulations

REMEMBER: DONE WHILE DOING 26 OTHERS!

Milagro Searches for γ-Ray Bursts (triggered & un-triggered)

BATSE 1-sigma in space

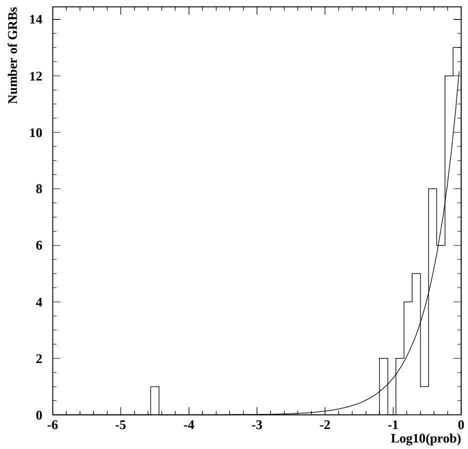
‘Grito 2-sigma in space



Triggered ‘Grito detection of GRB970117a in coincidence with BATSE
(within 1 s.d. in position and in the same 7.9 sec “T90” interval)

Published in Astrophysical Journal Letters 525 (1999) L25-L28

MILAGRITO AS A COINCIDENCE EXPERIMENT:

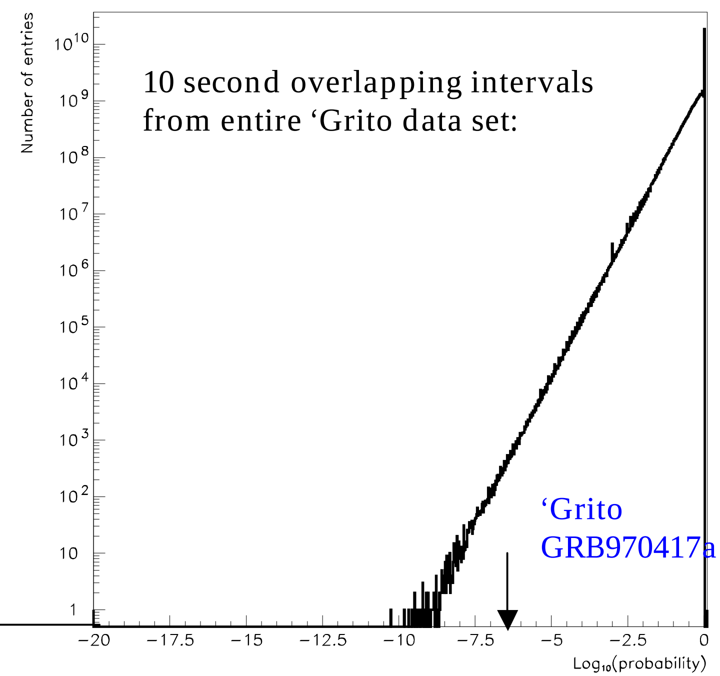


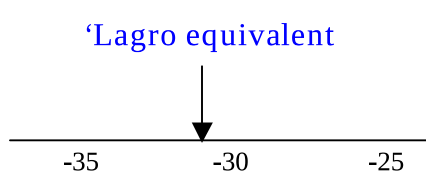
The distribution of the probabilities of the 54 candidate bursts.
(This probability is defined as the chance that a random fluctuation would result in a lower value than the smallest Poisson probability found for any of the many spatial bins searched for that candidate)

The final probability that some candidate of the 54 would fluctuate as much or more than candidate GRB970417a is 1.5×10^{-3}.

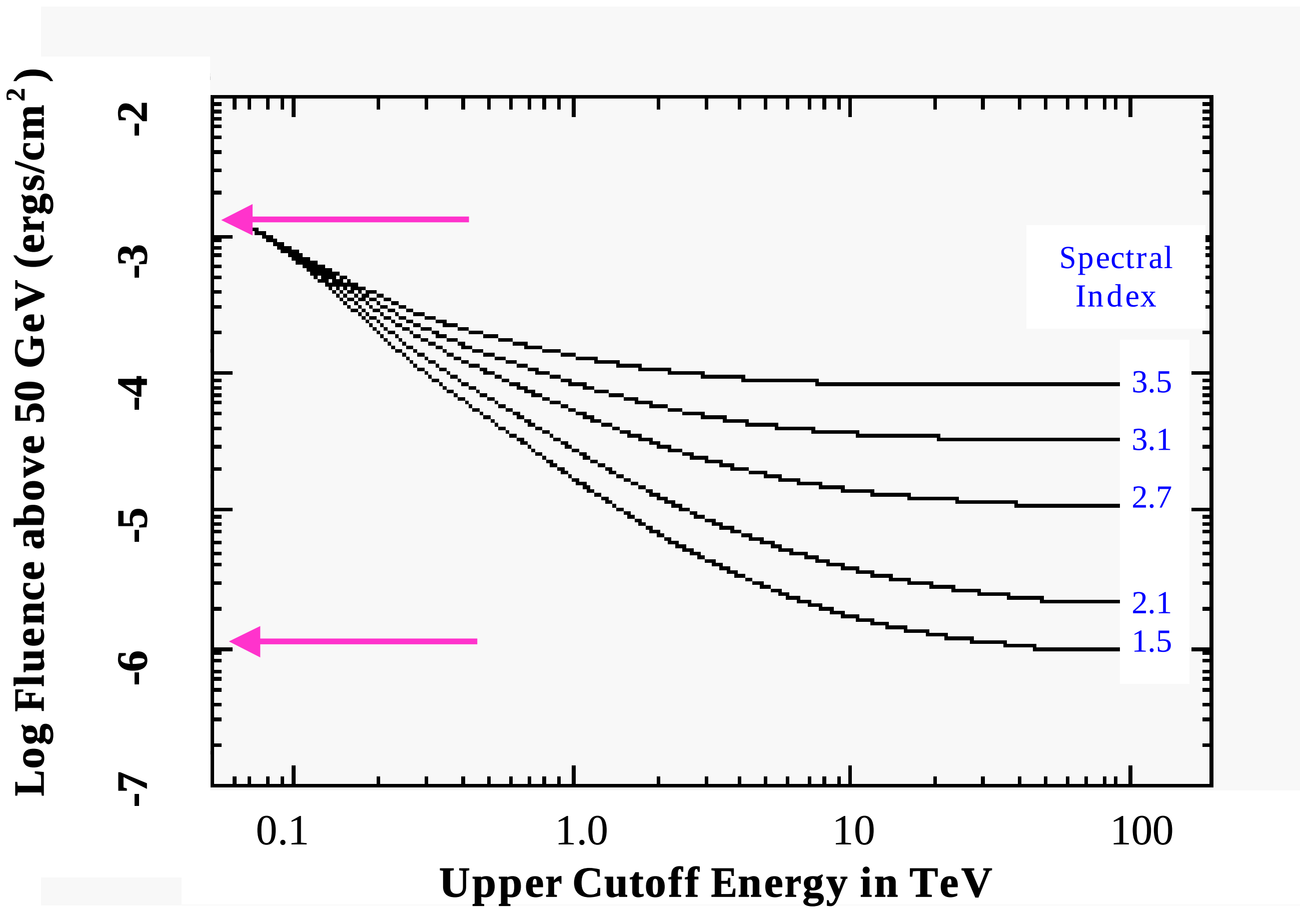
This is the distribution of Poisson probabilities from every space-time (overlapping) bin in the visible sky. Note the position of GRB970417a!

In 'Lagro, a similar strength GRB would appear on such a plot as shown below, serving as a network alert.





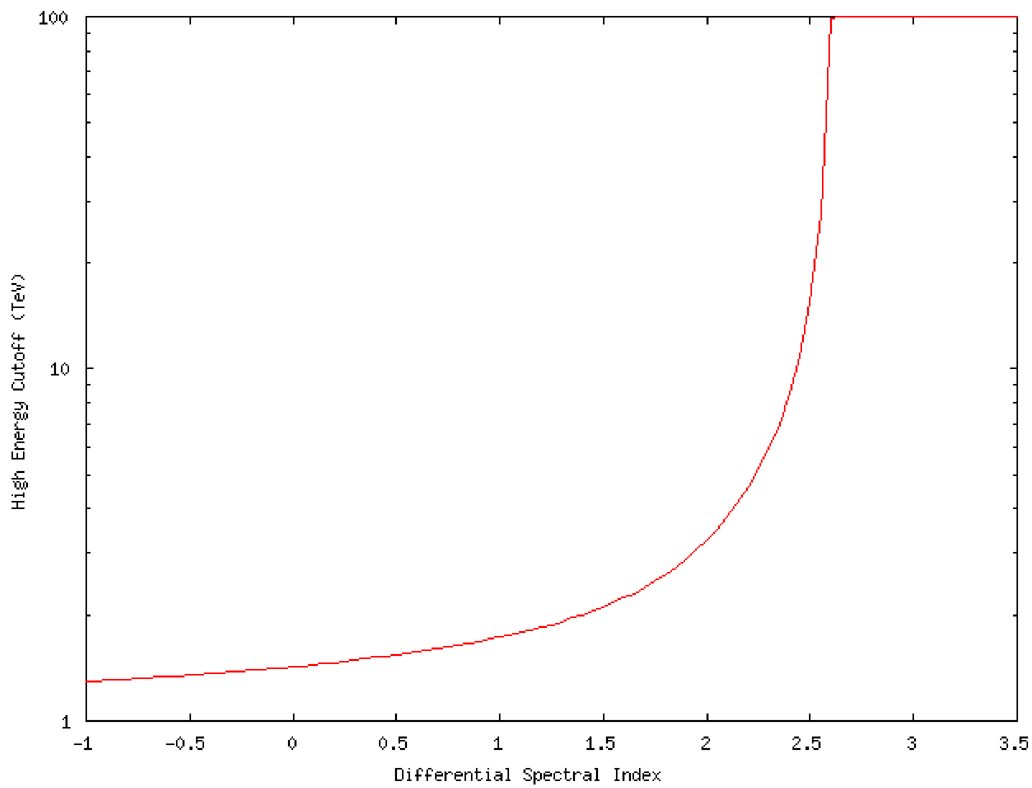
Fluence Constraints on GRB970417a



These curves simply reflect the folding of a model of dN / dE for the source with the MC-calculated effective area of Milagro, constrained by the number of events seen.

Constraints on the spectral behavior of GRB970417a:

The triggered shower events and the continuous scaling of groups of tubes sample the spectrum of a source at different, overlapping regions of energy. This can be used to place constraints on the spectral index of the source as well as the upper energy, if any, at which it ceases to emit gammas.

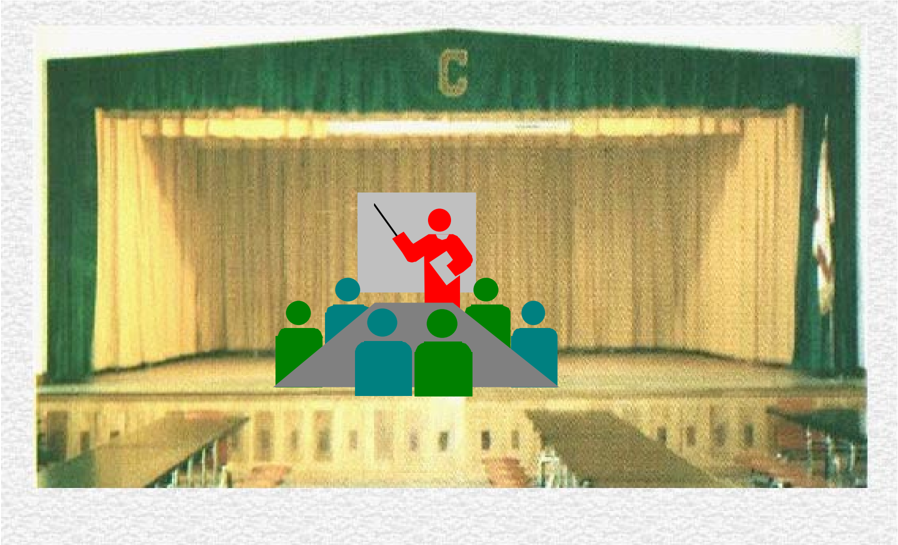


THE REGION BELOW THE RED LINE IS EXCLUDED BY THE COMBINATION OF TRIGGERS AND SCALER COUNTS DURING THE BATSE PERIOD OF THE GRB.

CAVEAT: THIS PRELIMINARY ANALYSIS DOES NOT INCLUDE SYSTEMATIC ERRORS WHICH MIGHT SOFTEN THE CONSTRAINTS.

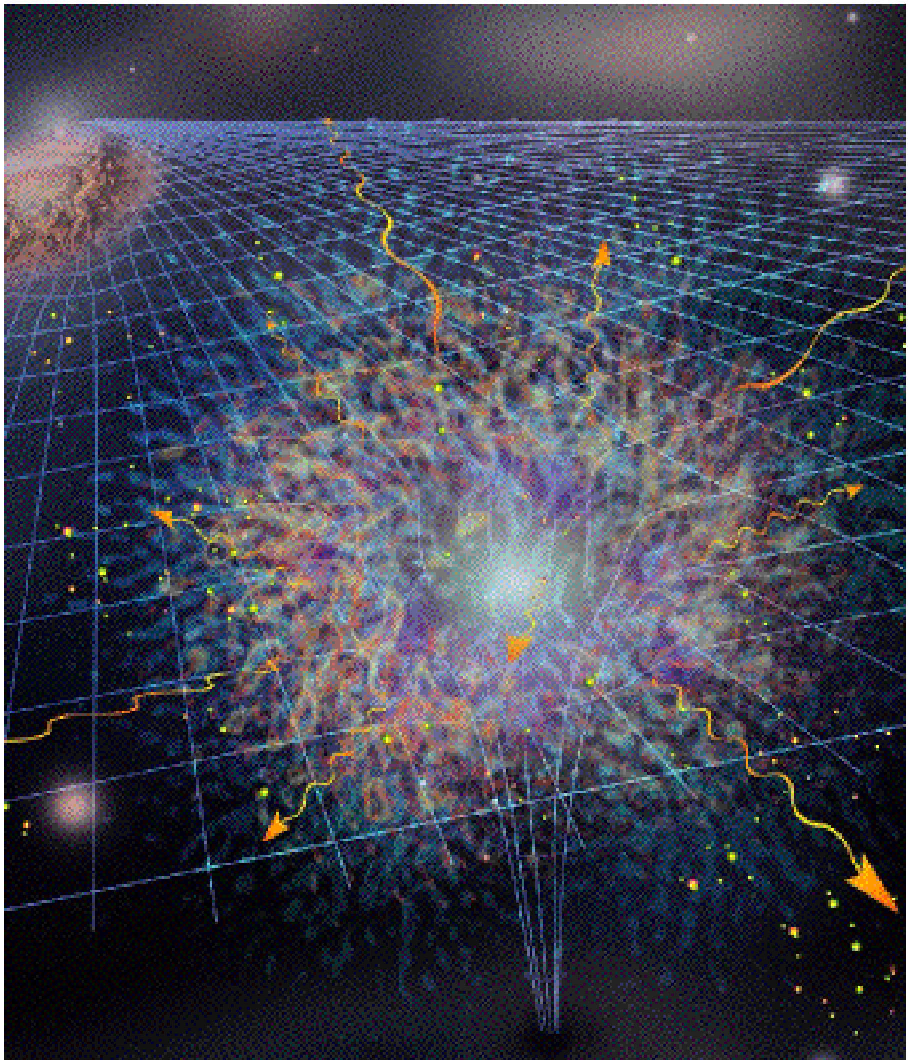
Reserve for updated fluence vs distance plot for grb

The curtain now comes down on Milagro Collaboration results !

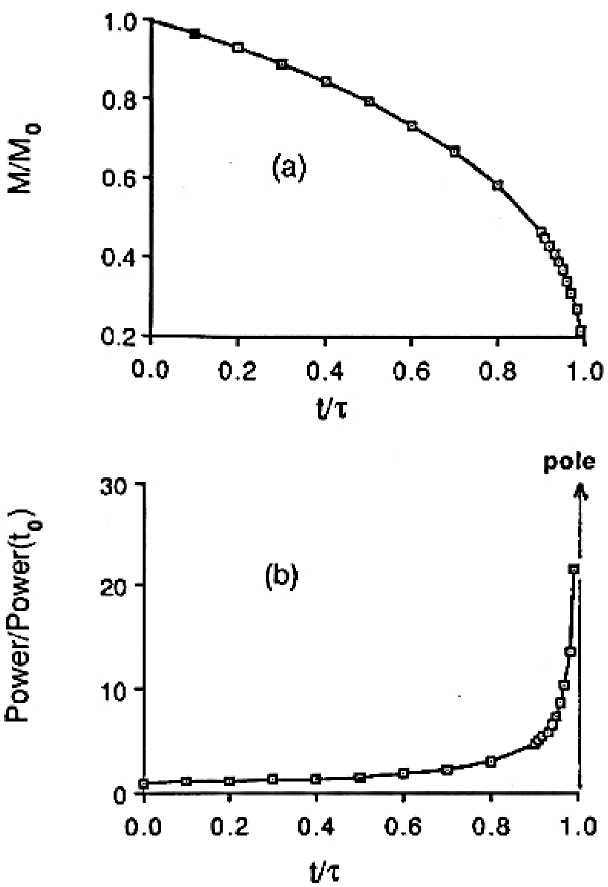


The rest of the talk concerns my own speculations on the prospects for a "profound" discovery: Hawking radiation from a small (primordial?) black hole. I am solely responsible for any extravagances rendered.

What do we expect from an evaporating black hole?



Visualization of PBH 1s before evaporation: Rs = 1 μfermi;
white = 10 TeV; red = 1 TeV.

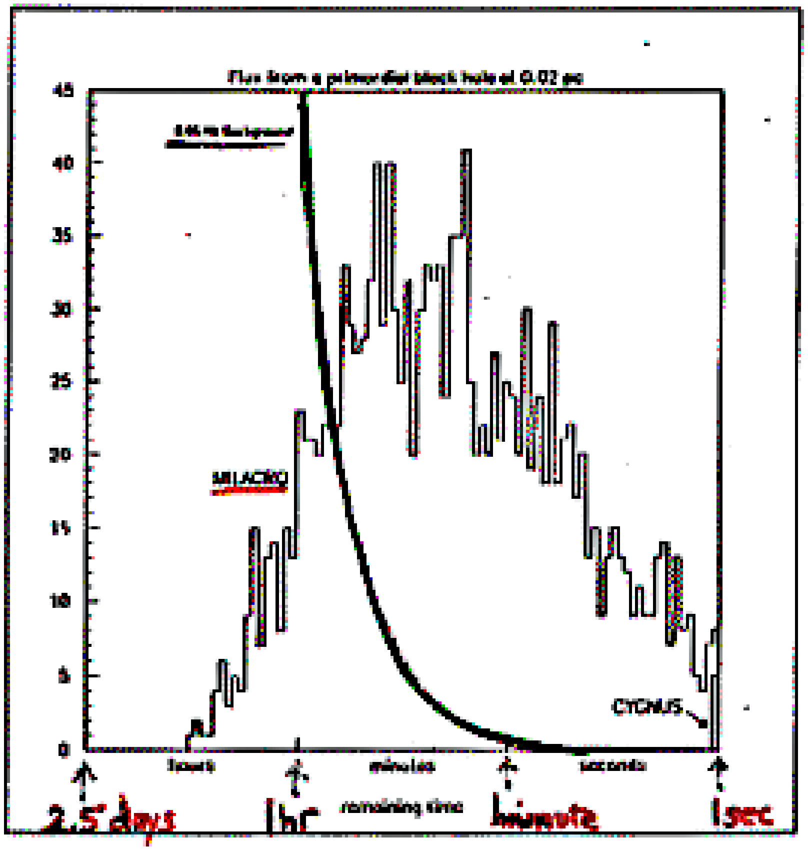


Mass (a) and Power Output (b) from an Evaporating Black Hole

With 1s of life left, peak power is ~10^{30} erg/s

How the Hawking radiation from a nearby exploding primordial black hole might appear in Milagro, remembering that . . .

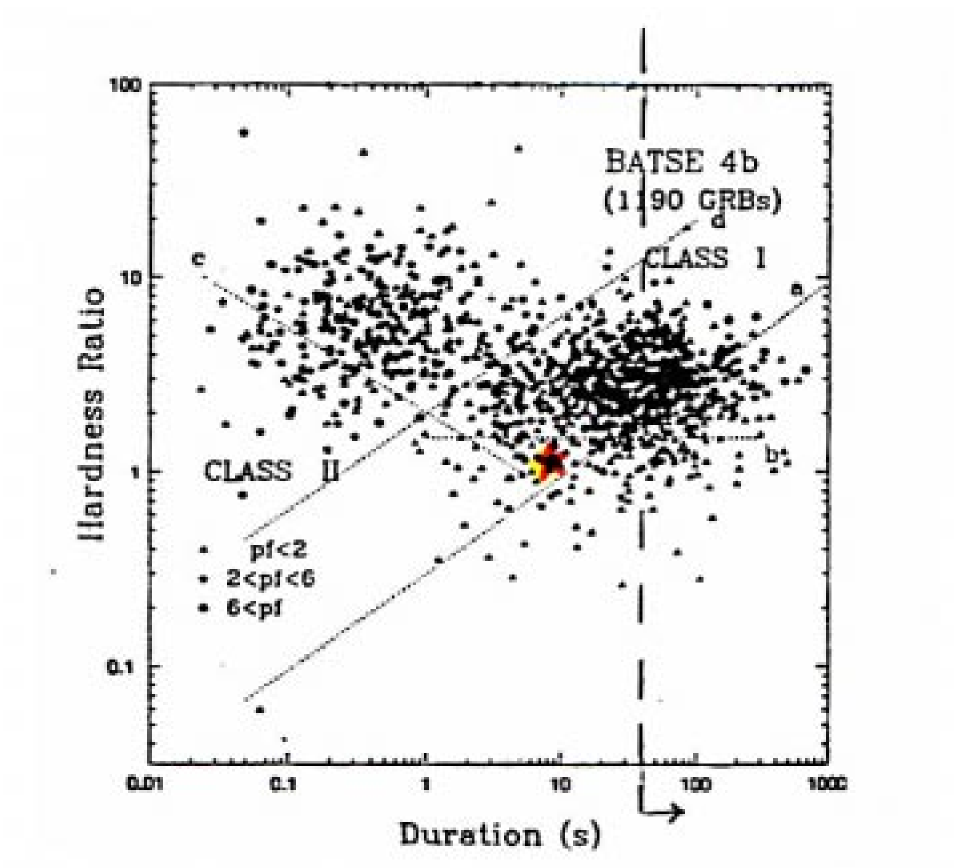
the primary (Hawking) thermal spectrum is transcended by the nature of high energy physics:



- **Fragmentation**
- **Secondary interactions**
- **Shrouds and shocks**
- **Supersymmetry**

<u>Milagro will lower the limits on nearby holes by x500 – x1000</u>

When is a GRB really a GRB and not just a Burst of Energetic Gamma Rays (BOEGR)?



(plot from Belli, 4th Huntsville Proceedings)

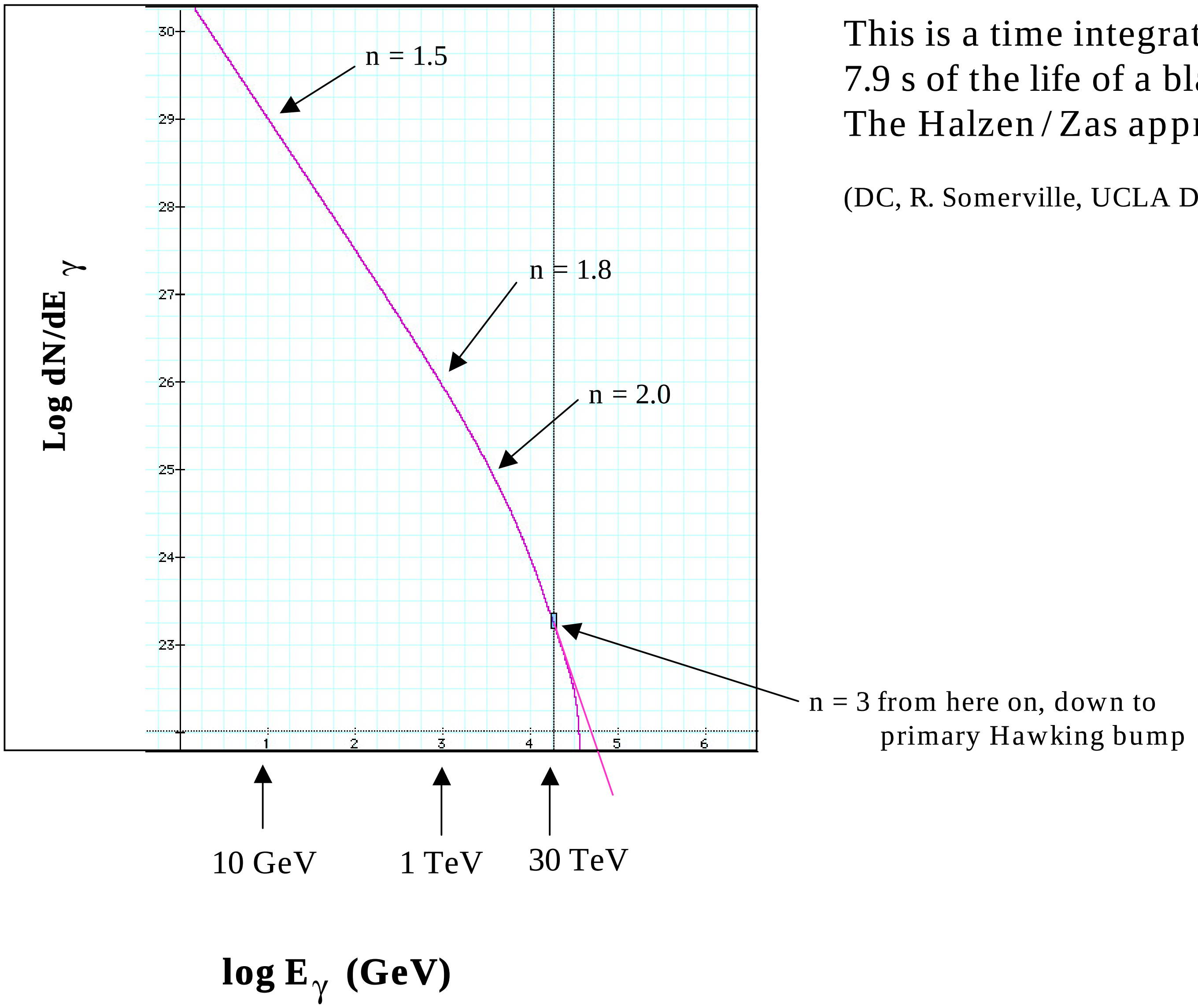
Where in space are the class II's?

Are there more than two classes?

GRB970417a ( ) has only a 1.4% chance of being class II, and 10-20% chance of being I, where it seems a bit out of place.

Investigate it as a candidate for a NEARBY small black hole evaporation.

Using Milagro results & theory to check consistency



This is a time integration of the last 7.9 s of the life of a black hole, using The Halzen / Zas approximation.

(DC, R. Somerville, UCLA Dark Matter Conf., 1998)

Is Hawking radiation really profound?

There are two ways one might discover Hawking radiation "trivially" without leaving home (Earth)!

1. At the LHC, via a possible renormalization of the Planck mass due to extra dimensions.

(see S.Giddings & S. Thomas, High Energy Colliders as Black Hole Factories: The End of Short Distance Physics. SU-ITP-01-30, hep-ph/0106219) (or come to Greg Landsberg's seminar).

2. At SLAC, via measurement of the Unruh effect.

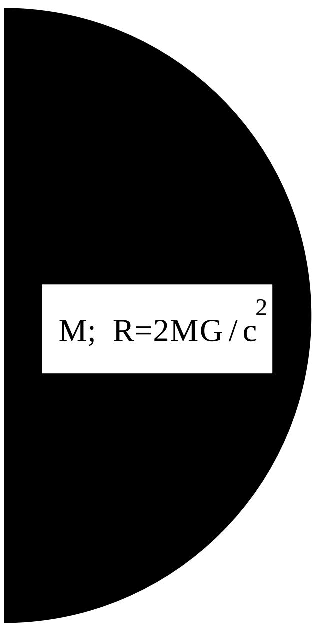
Surely the lecturer must be joking?

Consider the **General Equivalence Principle**, connecting:

The PBH Environment ⟷ The Laboratory Environment

Hawking showed that QFT in a not-too-curved spacetime implies black holes have a temperature T apparent to non-inertial observers at large distances from the horizon:

$$kT = \hbar c^3 / 8\pi GM$$



At the horizon of a black hole, the surface gravity, (via Newton!) is:

$$\kappa = c^4 / 4MG$$
$$= 2\pi ckT / \hbar$$

which is of order $(10^{13}$ gm / M) GeV

Suppose we accelerate a neutral particle in the laboratory with acceleration **a** = $-\kappa$. Then the equivalence principle tells us that in the frame of the particle, an observer would experience all of the effects of a gravitational field, and in particular would experience a thermal bath having temperature:

$$T = \hbar a / 2\pi ck, \text{ the Unruh temperature}$$

To be equivalent to the black hole possessing a T= 1 GeV, the acceleration would have to be

2.6×10^{33} m / s^2 !

Who is Unruh, and how could he do this to Hawking?

Unruh (U. of B.C.) published his result within a year after Hawking [W. Unruh, Phys. Rev. D **14**, 870 (1976)], and had the tools to do it before ! Unruh radiation follows from calculations in the lab frame using the appropriate QFT for the energies involved and taking radiation reaction into account.

Proposals to measure the effect in the lab have been made. Use of large centripetal accelerations in a electron storage ring can lead to limitations of the eventual polarization. The calculations are so difficult that the experts are still arguing about them. No experiment has succeeded in obtaining the needed sensitivity. Pisin Chen has proposed a laser acceleration technique [P.C., Phys. Rev. Lett. 83, 256 (1999)] which might achieve accelerations 10^{25} g**,** or measure kT ~ 100 eV.

As far as I know, the QFT calculations have not been extended anywhere near the MeV/TeV region where, as we will see, black hole particle theoreticians have not feared to tread.

So would the discovery of Hawking radiation not be profound?

Perhaps, but the discovery of small black holes
VIA Hawking radiation would be of monumental import.
WHY?

- Small black holes are created in negligible amounts according To current well-tested theories of inflation
- Post-Big Bang production by various mechanisms would likely alter present cosmologies.
- Irrespective of astrophysics, particle theorists are just now coming to grips with the quantum black hole evaporation process: what is the endpoint? Observation of a physical object a few nanoseconds from that endpoint would lend a certain immediacy to their quest!
- My small role in all of this is to examine Milagro data for any possible detection, however unlikely.

Conclusions

1. The Milagro technique works well already, and has prospects for working even better.

2. The usefulness of a wide-field exploratory instrument for AGN and GRB studies is evident: it is not clear yet whether there are enough close AGN and GRBs to justify scaling up the instrument for greater sensitivity.

3. Milagro is likely to do profound physics only if we have lots of:

WIMPs in the Sun
(or) PBHs in the Oort Cloud
(or) Serendipity!