The Cronin Fest
September 8-9, 2006.

Cosmic Ray Studies to 10^{16} eV

(The CASA-MIA Experiment: its motivation and how it was achieved)

Rene A. Ong (UCLA), for the
CASA-MIA Collaboration

Definitions

Cosmic Rays: Particles (mostly charged) that are produced astrophysically and that bombard the atmosphere.

TeV: 10^{12} eV.
PeV: 10^{15} eV.
EeV: 10^{18} eV.

UHE: Ultra High Energy
Energies above 100 TeV, or 10^{14} eV.

CASA-MIA: Chicago Air Shower Array – MIchigan Anti Array

OUTLINE

- **Scientific Motivation for CASA-MIA**
  - Cosmic Rays and their origin
  - The tale of two sources: Cygnus X-3 & Hercules X-1
- **A New Direction**
  - Jim’s vision.
  - The people involved.
  - How it happened: building and operating CASA-MIA.
- **The Science of CASA-MIA**
  - Primary scientific results and impact.
  - Other directions.
- **Conclusions**

Cosmic Rays

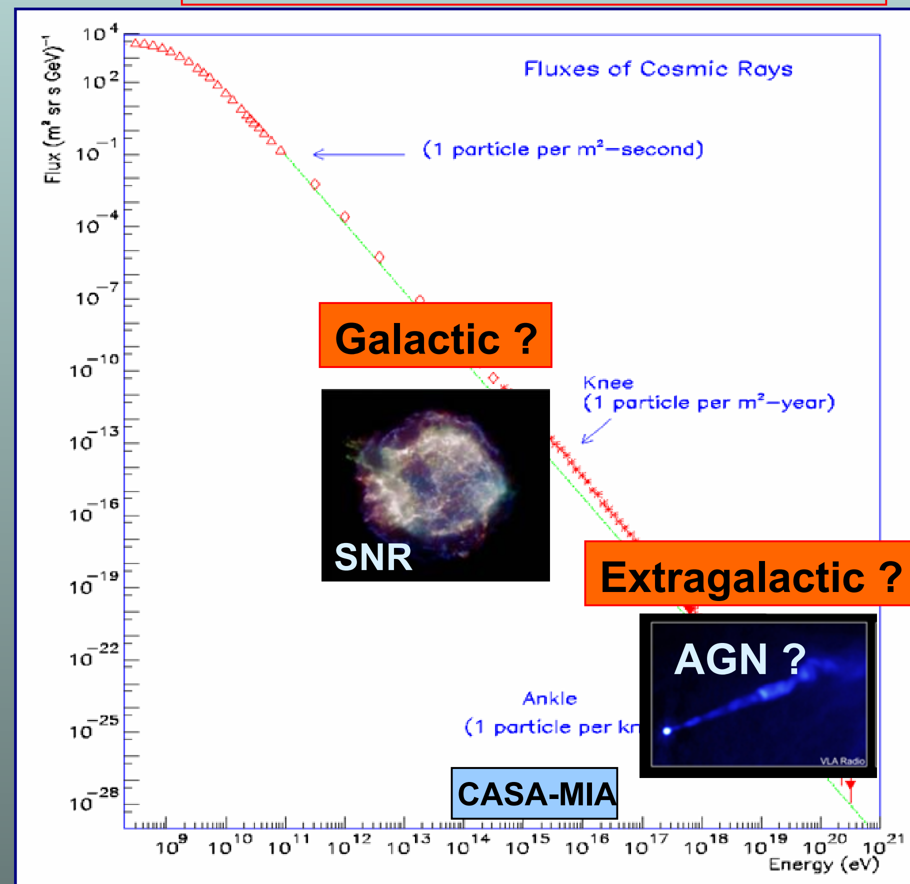
1912: Discovery by
Victor Hess

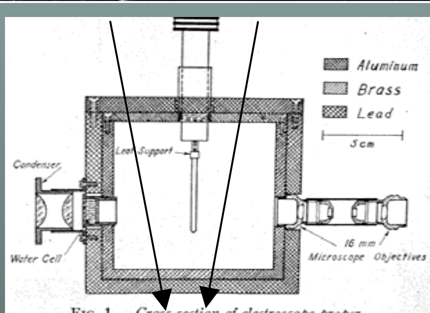
Many years of research followed –
especially connected with Univ. of Chicago.

Key Properties:

1. Particles
2. Charged
3. Energetic
4. Isotropic

Cosmic Ray Energy Spectrum





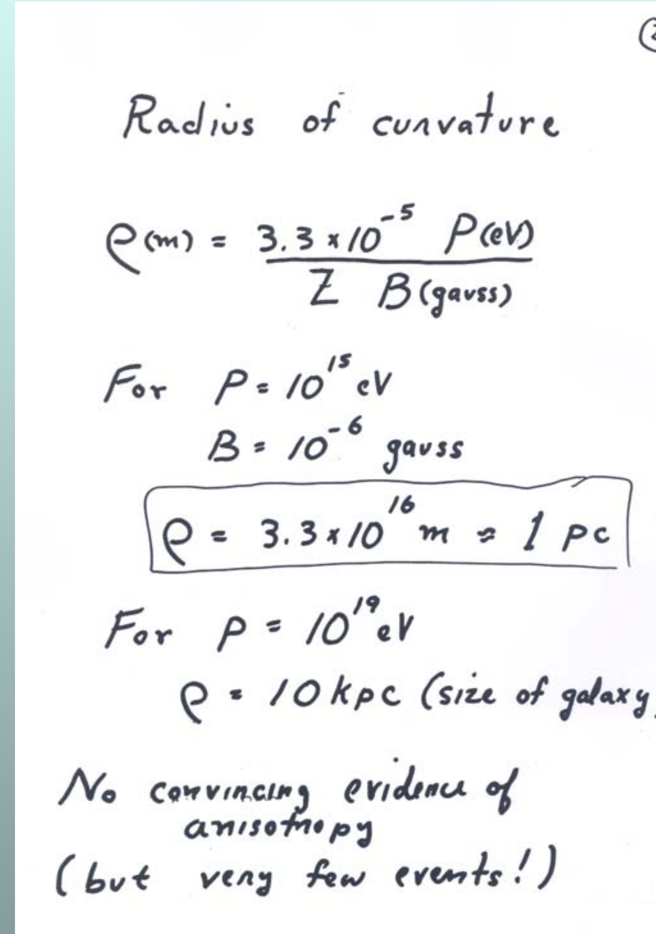
Electroscope

Cosmic Rays

Fascinating objects:

- Key source of extraterrestrial material.
- Abundant and replenished.
- Reaching remarkable energies.

Their origin is a 90 year old mystery !


(2)

Radius of curvature

$$\rho(m) = \frac{3.3 \times 10^{-5}\ P(eV)}{Z\ B(gauss)}$$

For $P = 10^{15}$ eV
$B = 10^{-6}$ gauss

$\rho = 3.3 \times 10^{16}$ m ≈ 1 pc

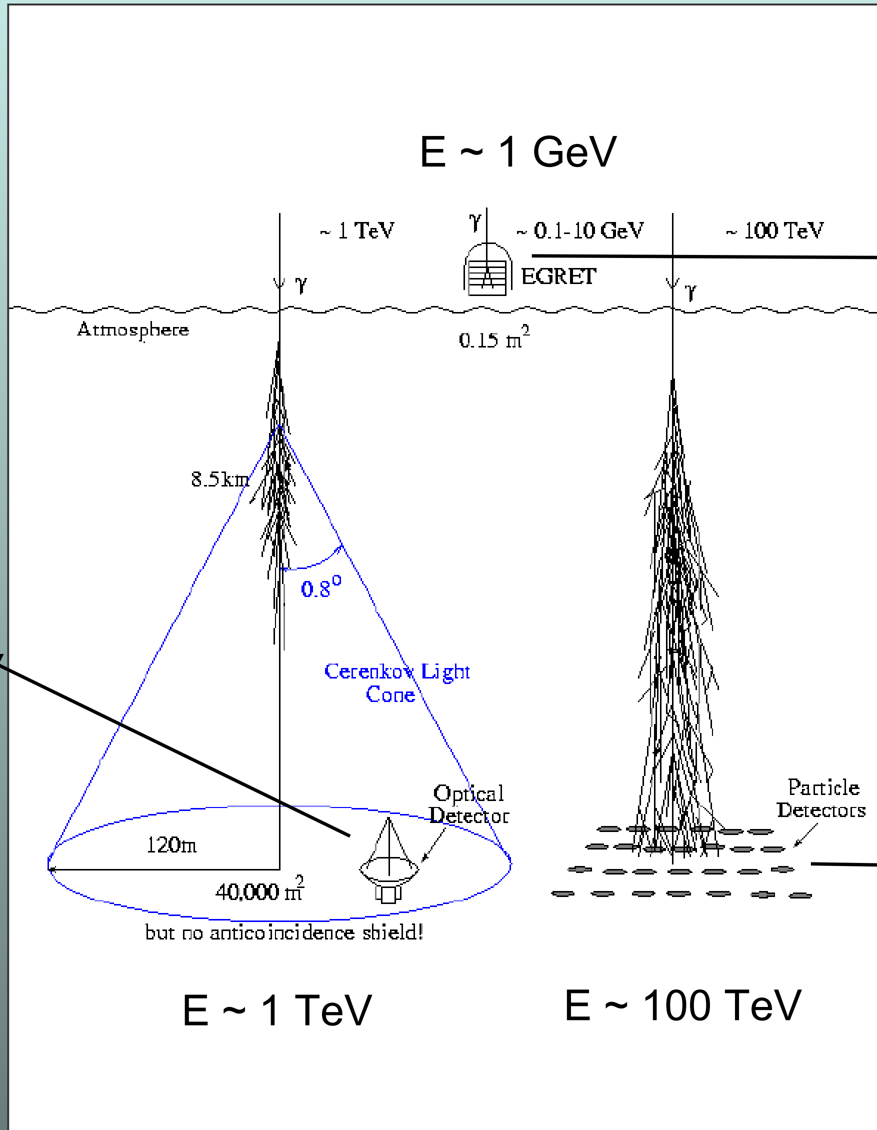
For $P = 10^{19}$ eV
$\rho = 10$ kpc (size of galaxy)

No convincing evidence of anisotropy
(but very few events!)

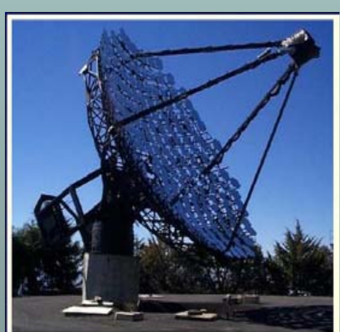
JWC Calculation

Need <u>neutral particles</u> to do Astronomy.
Can detect γ-rays using air showers.

Detecting Gamma Rays



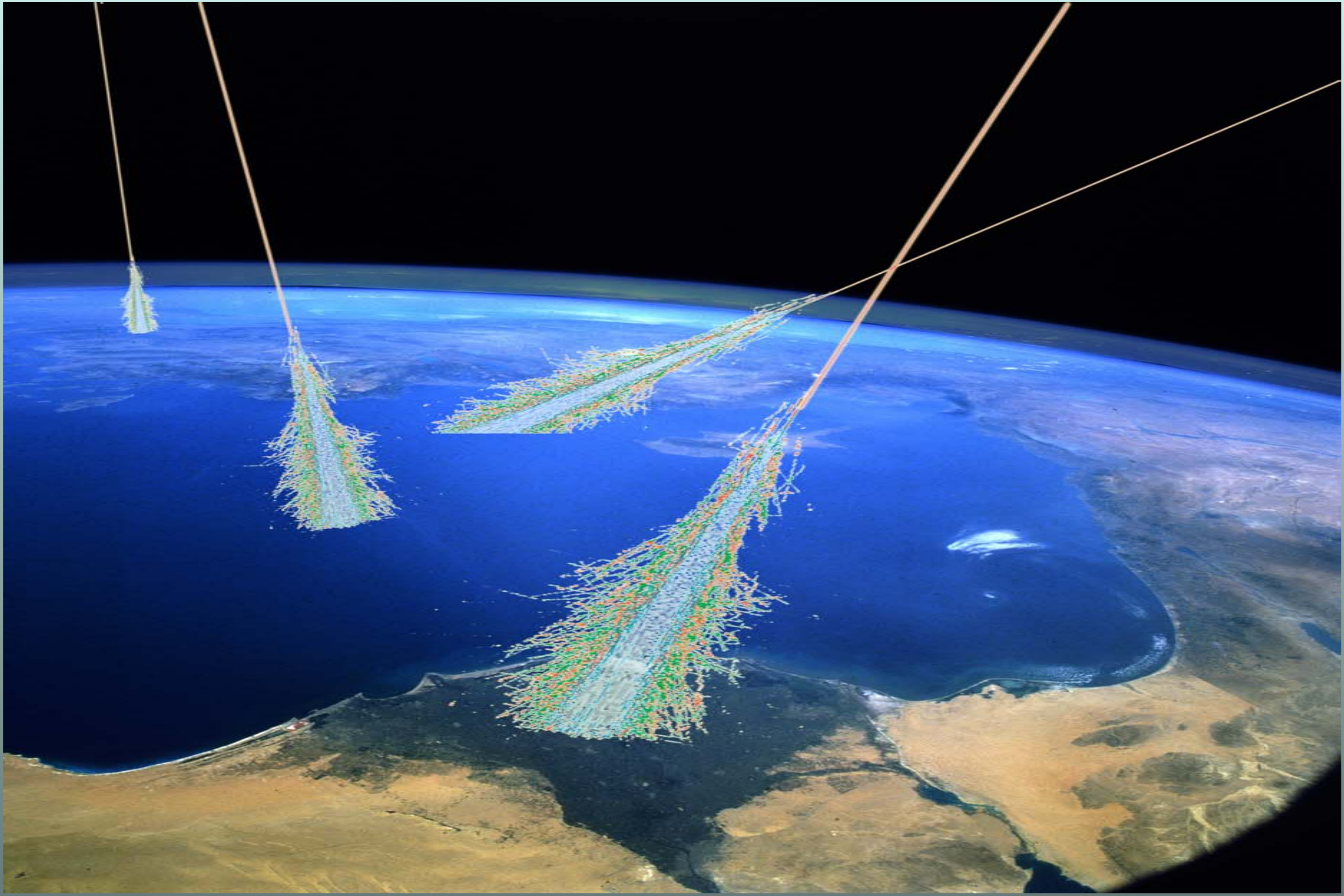
Compton Gamma Ray Observatory



Whipple atm. Cherenkov telescope

CASA-MIA

Extensive Air Showers

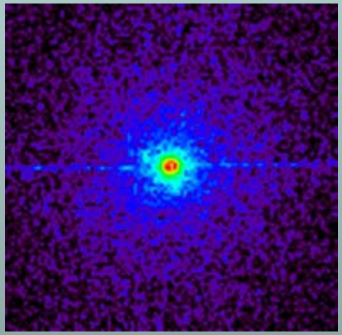


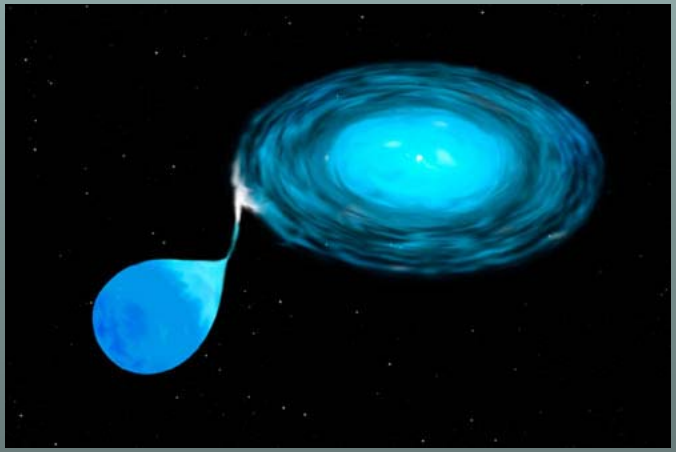
A Tale of Two Sources

In early 1980's, several air shower experiments saw intriguing results when examining showers arriving from a certain type of astronomical source.

The sources were X-ray Binaries:

Cygnus X-3
(Chandra)





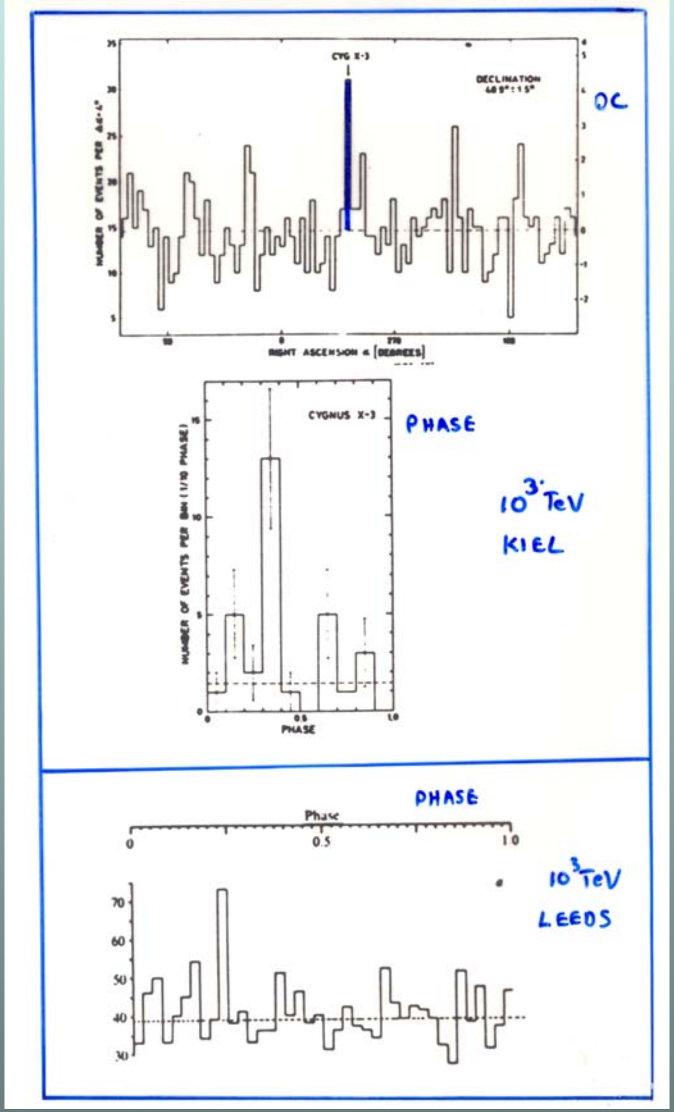
Air Shower Results (1980-1985):

- Excess of events from direction of X-ray binaries Cyg X-3, Her X-1.
- Periodic signature (4.8 hr for Cyg X-3).
- Large fluxes → large UHE luminosities.
- Small experiments, weak significances.

Great excitement and interest: could these sources be the origin of the HE cosmic rays ?

Cygnus X-3

Results 1983



Kiel Experiment:
claim 4.4σ signal.

4.8 hr periodicity

Haverah Park
~ 4σ effect.

Experiment Details

28 counters, each 1 m^2
Energy: 1-10 PeV

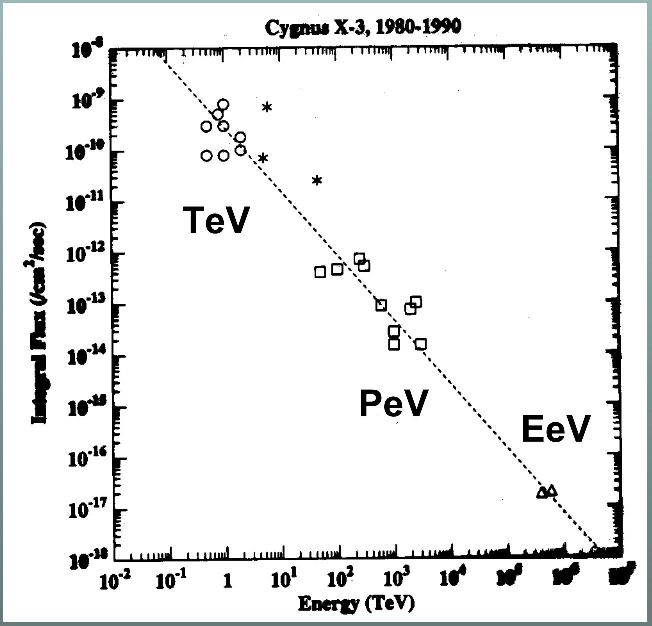
4 large water
Cherenkov detectors.
Energy > 1 PeV

The Mystery Deepens

- Evidence for another source Her X-1.
- Detectors at other energies seem to confirm these sources.
- More muons than expected from gamma-ray primaries.

Are the primary particles not gamma rays, or could gamma rays behave differently at these energies ?

Compilation of positive results on Cygnus X-3, 1980-1990.



The Road to CASA-MIA

- Starting around 1985, there several groups began to develop new, more capable air-shower experiments.

- A key effort was initiated by the Univ. of Utah and Univ. of Michigan groups at Dugway Proving Grounds (Utah). The idea was for a large muon buried array to complement a surface array → Utah-Michigan Experiment.

- HEP Seminar on May 15, 1985

  George Cassiday (Utah)

  "High Energy Physics as seen by a Fly's Eye"

Jim Cronin quickly immersed himself in methodology and techniques of air shower physics.

Jim's Vision

- Construct a much larger, much more sensitive array. Goal is to quickly verify these anomalous sources and measure their properties in detail or rule them out without regard to periodicity.

- Definitive experiment with state-of-the-art design.
  1. 1064 detectors covering 480m x 480m.
  2. On board analog, digital electronics, HV, calibration, etc.
  3. Distributed intelligence: CPU, memory, ENET.
  4. Multiple counters/detector, simplified counters.

- Couple surface array with large μ array to reject hadrons.

  Key contribution by our colleagues at Univ. of Michigan.

CASA-MIA Concept

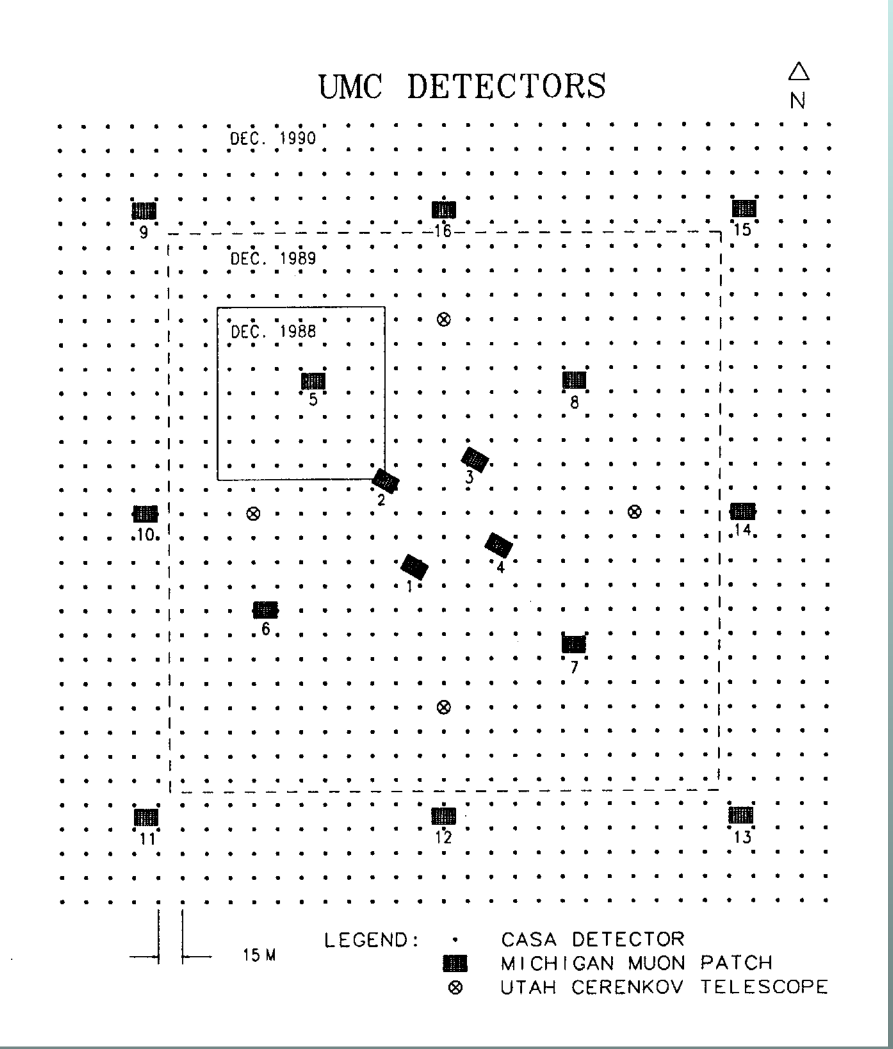
A PROPOSAL FOR A LARGE SURFACE ARRAY AT FLY'S EYE II

Myron K. Campbell, James W. Cronin, Kenneth G. Gibbs, Hans Krimm,
Nicholas Mascarenhas, Dietrich Möller, Brian J. Newport,
Michael Pertel, Leslie J. Rosenberg, Harold Sanders,
and Mark E. Wiedenbeck.
Enrico Fermi Institute, University of Chicago
Chicago, Illinois, 60637 USA

Abstract

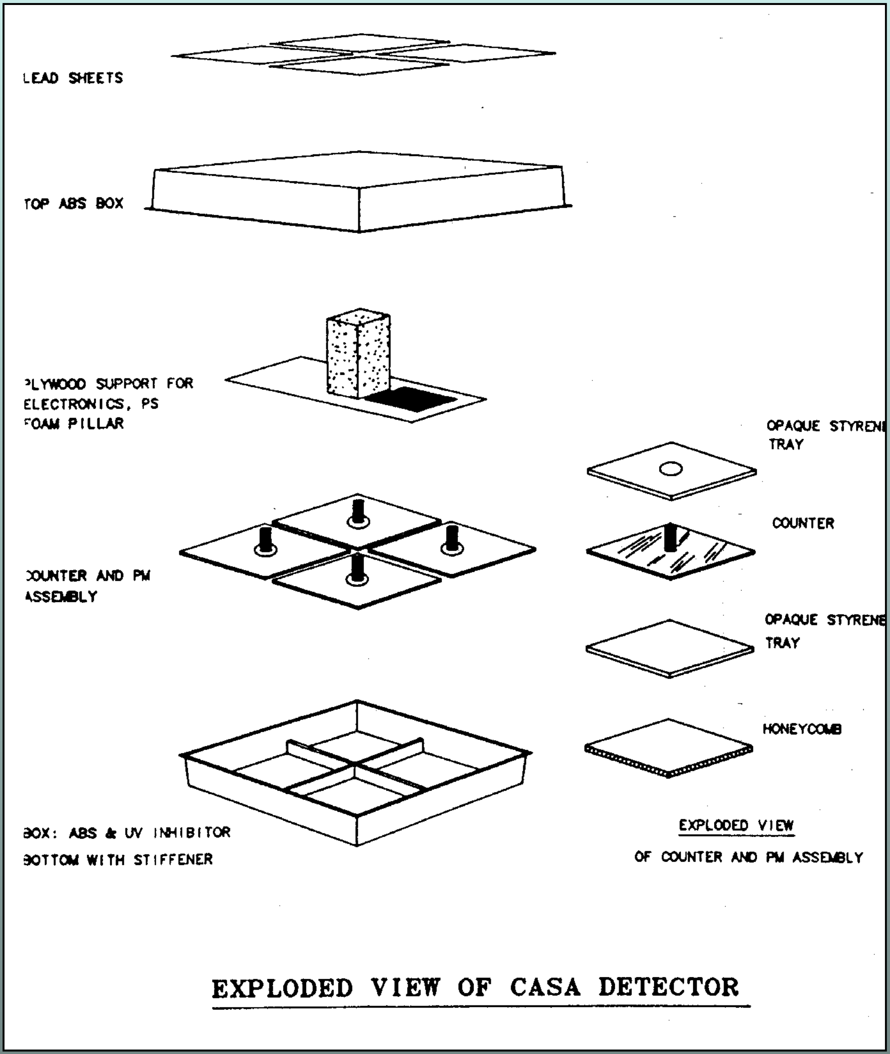
We propose to build a surface array consisting of 1064 particle detectors of 1.5 m^2 area each. This array will surround the Fly's Eye II detector at Dugway, Utah. The proposed array is intended to search for point sources of extensive air showers. The particle detectors will be placed on a square grid with a spacing of 10 m, the effective area of the array is ~ 10^5 m^2. The arrival direction of air showers will be measured with a precision of $\leq 0.7°$ (for showers with $N_e \geq 3 \times 10^4$). The surface array will operate in conjunction with a 1200 m^2 muon array which is presently being installed at Fly's Eye II by the University of Michigan. (Observations in parallel with the Fly's Eye

1987 Proposal to NSF

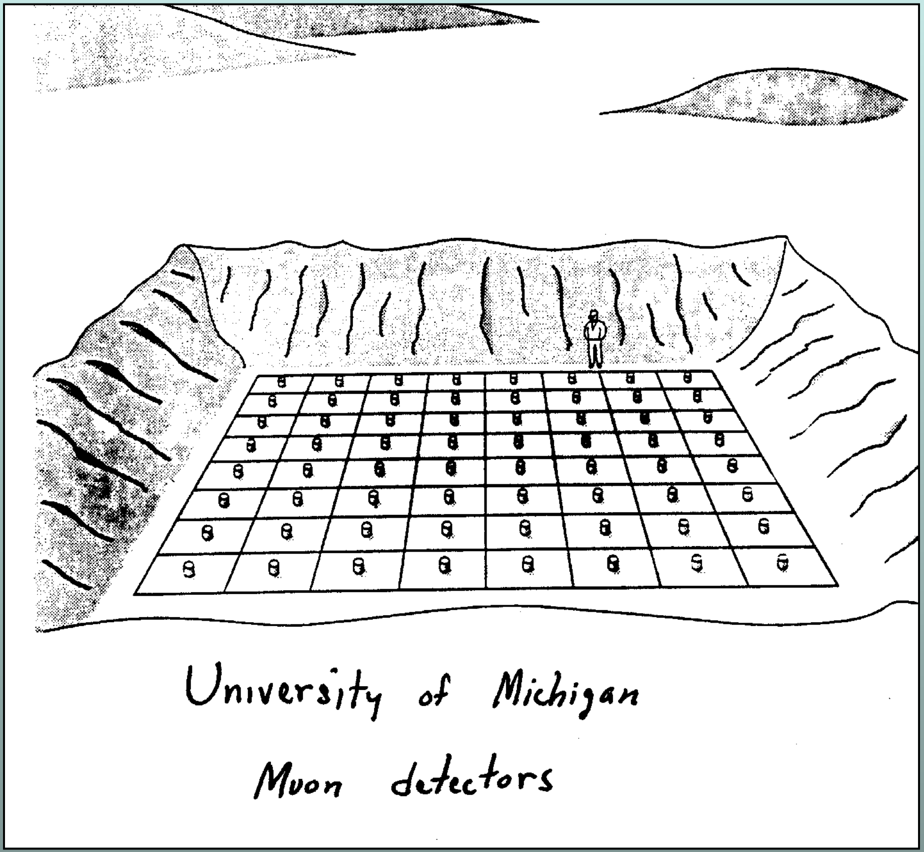


CASA-MIA as completed in 1992.

CASA-MIA Concept



CASA Surface Detector (one of 1089).



MIA underground muon patch (one of 16).

The People Involved

Utah Michigan Chicago Collaboration (over time):

	<u>Chicago</u>	<u>Michigan</u>	<u>Utah</u>
PhDs:	**James Cronin** **Leslie Rosenberg** **Brian Newport** **Ken Gibbs** **Rene Ong** **Brian Fick** **Corbin Covault** **Lucy Fortson** **Mark Chantell**	**Dan Sinclair** **Jack van der Velde** **Jim Matthews** **Dave Nitz** **Kevin Green (→ Chicago)**	**David Kieda**
G. Students:	**Nick Mascarenhas** **Hans Krimm** **Tim McKay** **Alex Borione** **Joseph Fowler** **Scott Oser**	**M. Catanese** **A. Glasmacher**	
And …	**Mike Cassidy, Marty Dippel, Marypat Sharer, Aspasia Sotir-Plusis** **<u>Large number of undergraduate students</u>; many senior thesis students.**		
Early on:	**D. Mueller** **H. Sanders** **M. Wiedenbeck**	**D. Ciampa** **J. Kolodziejczak**	**G. Cassiday** **Utah Group**

People

Chicago Group (minus JWC)
γ90 Conference, Oct. 1990, Ann Arbor, MI

UMC Group (some of)
ICRC, July 1991, Dublin, Ireland

Joseph Fowler's Ph.D.
December 1999, Chicago, IL

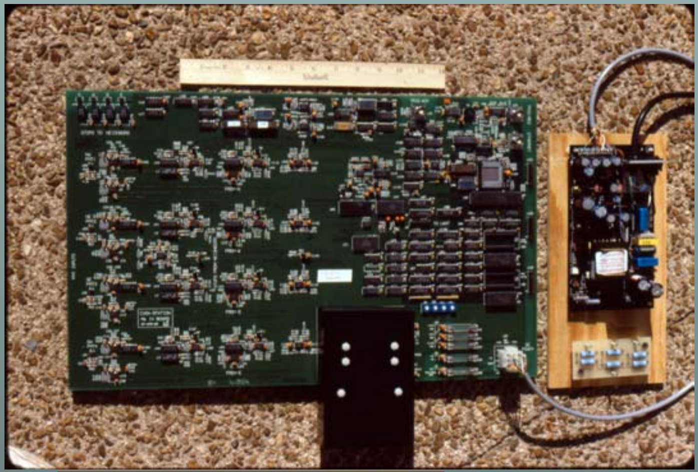
Building CASA at Chicago

Scintillator sheets.

Glueing counters (done by JWC).

Finished counters.

Kilometers of cable.



Building boards.

Shipping detectors

JWC's Leadership

Simulations.

J.W.Cronin
CASANOTE 89-20
28 June 1989

Monte Carlo Calculation of Rates
for the Forty-nine Station CASA Array

We have calculated the rate expected for the present forty-nine station array using the shower curves for protons as given in the paper of Fenyves et al. (Phys. Rev. 37, 649, 1988). The shower size as a function of atmospheric depth is flatter for proton-induced showers than for gamma ray-induced showers (see Fig. 1). At 860 gms, for an incident energy of 10^{14}eV, the mean shower size for protons is 0.57 of the size for gamma rays. At sea level the sizes are about the same. This fact explains why we found the predicted rates agreed with measured rates at Chicago and Cleveland, while the measured rate was too low at Dugway.

J. W. Cronin
Feb 17, 1987

Some specifications for analog electronics

- Use 10 bit ADC 1024 channels

TDC Least count ~ 0.2 nsec
Range ~ 200 nsec

Discriminators · low level 0.015 volts ←
high level 0.045 volts
minimum particle ≥ 0.10 volts

Charge (PM into 100 Ω)

$q(\text{min part}) = 10^{-3}\,\text{amps} \times 10^{-8}\,\text{sec} \approx 10^{-11}\,\text{coulombs} = 10\,\text{picocoul}$

– Maximum ≈ 25 particles ≈ 250 picocoulombs

Charge – digital conversion 0.25 picocoulombs / channel

Calibration:

Time – Time between start and common stop is 20 – 170 nsec in 16 intervals of 10 nsec increments. Standard pulses applied directly to time-to-amplitude converters. Clock calibration 0.1% over 200 nsec.

LEDs. Programable in any combination (4 bits) Flashed on receipt of trigger broadcast pulse. (Permits nearly simultaneous trigger adjacent boxes to check cross connects)

Electronic design.

19 April 1988
J.W. Cronin

What are people doing? View of J.W.C.

Hans --directing mechanical construction.

Tim --mechanical construction, developing programmable array logic for board timing (resets, enables, etc.).

Nick --testing new board, developing real prototype of HV, documenting with Joe Ting all the modifications on the board.

René --developing repeaters, current source, and their packaging. Testing ethernet repeater between two boards. Designing reboot circuit.

Leslie --developing software so boards can be run with trigger box, designing some remaining circuits (e.g., DAC circuits for control of discrimination and HV). Looking after growth of computer system, supervising Telesis drawings.

Brian --developing faster and more rugged software for onboard computer, creating the documentation, short term adjustment of ROM's.

Ken --trigger box, mechanical construction, developing plans for work at Dugway.

Joe --working with Nick to document and revise drawings of circuit.

Harold S.
Mike P. } wisdom

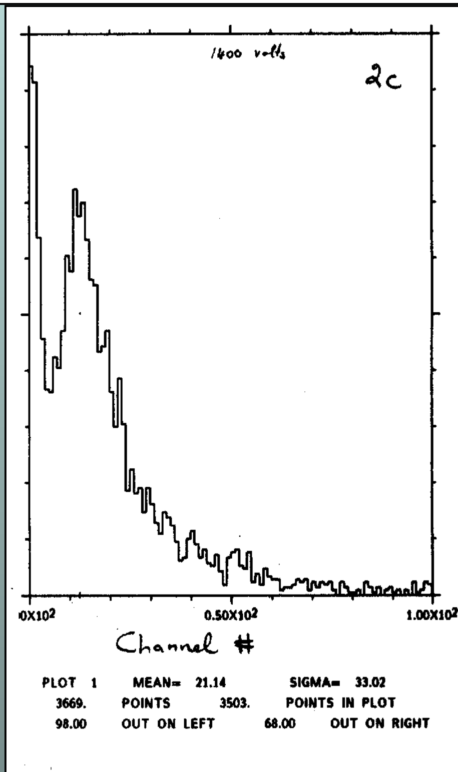
To be done

Oversight.

Analysis a la JWC

CASANOTE 12
J.W. Cronin
Nick Mascarenhas
7 June 1988

Observation of Minimum Ionization in the CASA Geometry.



Detecting minimum ionizing particles.

CASANOTE 29-90
J.W.Cronin

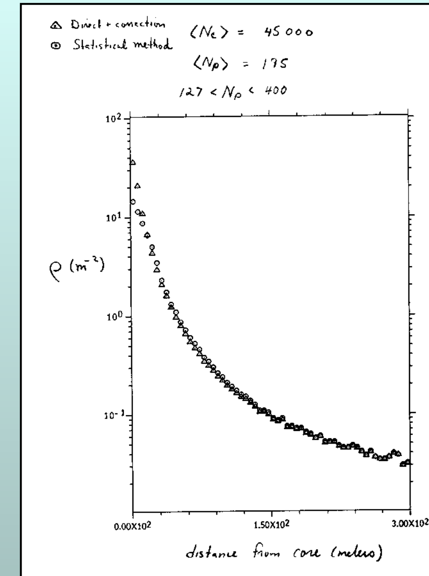
Lateral Distributions of Electrons and Muons; Selection of Muon Poor Events

This is a preliminary note on these topics stimulated by Jack Vander Velde's note of 9 March, 1991

I. Lateral Distribution of Electrons.

CASA, using cosmic rays, establishes the pulse height in each counter which on the average corresponds to a minimum ionizing particle. This can be used to measure directly the mean density of an ensemble of showers ordered by the number of detected particles. We have made a study of this for vertical showers ($\cos\theta_z > 0.98$).

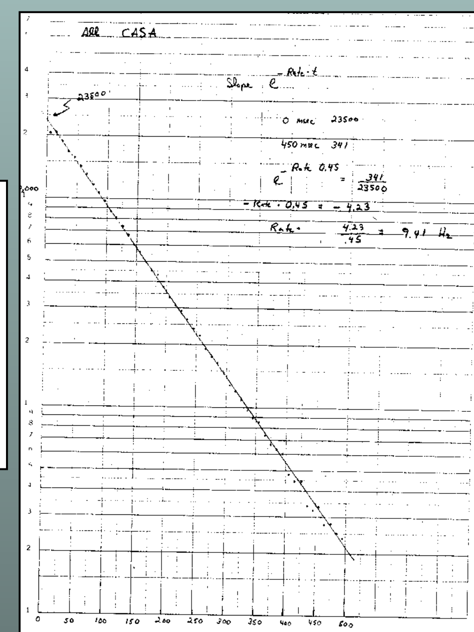
Reconstruction techniques.



CASANOTE 26-90
James W. Cronin
26 July 1990

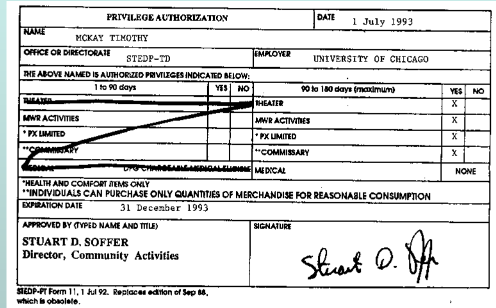
Dead Times, Triggering, and Merging Efficiency

We analyze run 3907 with 529 detectors to examine the dead time of the CASA data acquisition and the Michigan data acquisition by means of the merged events. In Figs. 1 and 2 we plot the interval distributions for CASA data and merged data. The interval is the time between the i^{th} and $(i+1)^{th}$ event. The slopes of both curves are identical with a rate of 9.42 Hz. The depletions in the first bin are indicative of the respective dead times.



Measuring triggering rates and deadtimes.

Dugway Proving Grounds


PRIVILEGE AUTHORIZATION

DATE: 1 July 1993

NAME: MCKAY TIMOTHY

OFFICE OR DIRECTORATE: STEDP-TD | EMPLOYER: UNIVERSITY OF CHICAGO

THE ABOVE NAMED IS AUTHORIZED PRIVILEGES INDICATED BELOW:

1 to 90 days	YES	NO	90 to 180 days (maximum)	YES	NO
THEATER			THEATER	X	
MWR ACTIVITIES			MWR ACTIVITIES	X	
* PX LIMITED			* PX LIMITED	X	
**COMMISSARY			**COMMISSARY	X	
MEDICAL DPG CHARGEABLE MEDICAL CLINIC			MEDICAL	NONE	

*HEALTH AND COMFORT ITEMS ONLY
**INDIVIDUALS CAN PURCHASE ONLY QUANTITIES OF MERCHANDISE FOR REASONABLE CONSUMPTION

EXPIRATION DATE: 31 December 1993

APPROVED BY (TYPED NAME AND TITLE): STUART D. SOFFER, Director, Community Activities

SIGNATURE: Stuart D. Soffer

STEDP-PT Form 11, 1 Jul 92. Replaces edition of Sep 88, which is obsolete.

The road from Salt Lake City to Dugway Proving Grounds.

Approaching the CASA site.

Denizens of the desert.

Attention to Detail !

Then calculate the time in NSEC for each stop. Hence forth one would continue in nanosec. This should be carried with a precision of 0.1 nsec. Then the slew correction is without the "3.2".

Dec 21, 1988

To: CASA Physicists

From: René Ong

Re: Analysis meeting of Nov. 16, 1988

The first meeting of CASA physicists to disucss offline matters was held on Nov. 16, 1988. This meeting was set up to initiate discussion on offline software and physics analysis issues not normally covered in the regular meeting. It was agreed that that future analaysis meetings will be held (when needed) on **Tuesdays, 1:30 pm**. Present at the first meeting were JC, KG, PH, NM, RO, and LR.

Nick was asked to discuss some of the analysis procedures he uses to study the data from the array at Dugway. The following summarizes his discussion:

1. Pedestals are found on all ADC channels by looking at counters that are not hit in stations that are alerted. A counter that is not hit is defined by # channels > 1020.
2. Pedestals are subtracted from the raw count values for local times, cross times, and pulse heights.
3. Slewing corrections are applied to the local and cross times. The correction has the form:

$$CH_{cor} = CH_{raw} - \frac{3.2 \cdot (115)}{(10 + PH)} ,$$

where CH_{raw} is the raw number of ADC channels after pedestal subtraction, PH is the pulse height (in channels), and CH_{cor} is the number of ADC channels after slewing corrections. Only **reasonable** times are corrected, i.e. those having # channels < 400.

4. The six possible time differences within a station are determined. Only reasonable times are used. The **counter offsets** (intra-station timing offsets) are determined from the mean of the time difference distributions using the data down to 10% of the peak. Within a given station there are three independant counter offsets, therefore, a convention has been adopted: the offsets are referenced with respect to Counter 1 (NW); they can be positive or negative. ✓
5. The counter offsets are subtracted from the local times in each station.

More complicated for TDC. At the time of the meeting Nick worked on assumption that slopes of the TDC in Δcounts/Δtime were identical for all channels. If slopes are slightly different one needs to take the time calibration to establish slope and intercept for each TDC channel.

Deploying CASA in Utah

Completing CASA

Box (16,16) done !

CASA-MIA, Fly's Eye 2, and trailers.

1089 done !

Problems … and solutions

- Weird gain measurements in Chicago → PMT shielding.
- Water and snow damage → covers on each box.
- Board crashes → commercial ENET repeaters.
- April 22, 1991.

Lightning Strike of April 1991
Disabled CASA for 7 months
→ Huge repair effort.
→ Protection grid and fiber optics.

Living in Utah

> *"My two great loves are physics and desert country."*
> *J. Robert Oppenheimer*

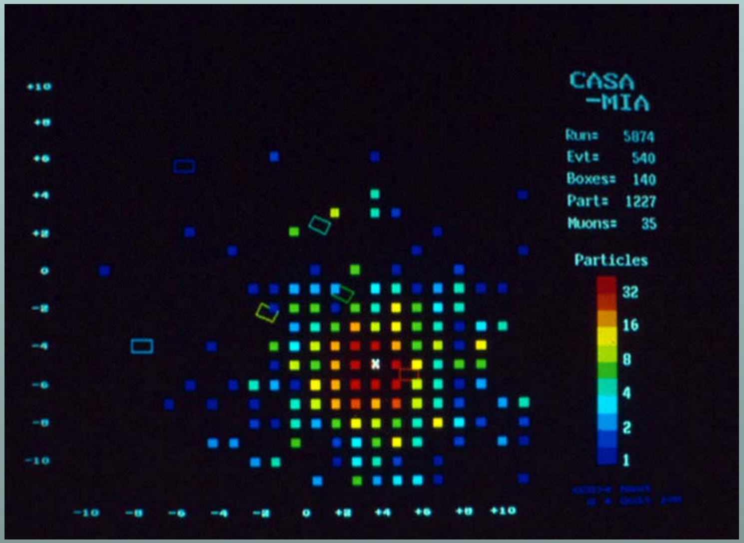
Maintaining CASA-MIA was a wonderful experience.

- Long single-person shifts, except for "raiding parties".
- Much physical labor (daytime).
- Standard routines of daily life and repairs.
- Trailer living & no running water, but beautiful scenery!

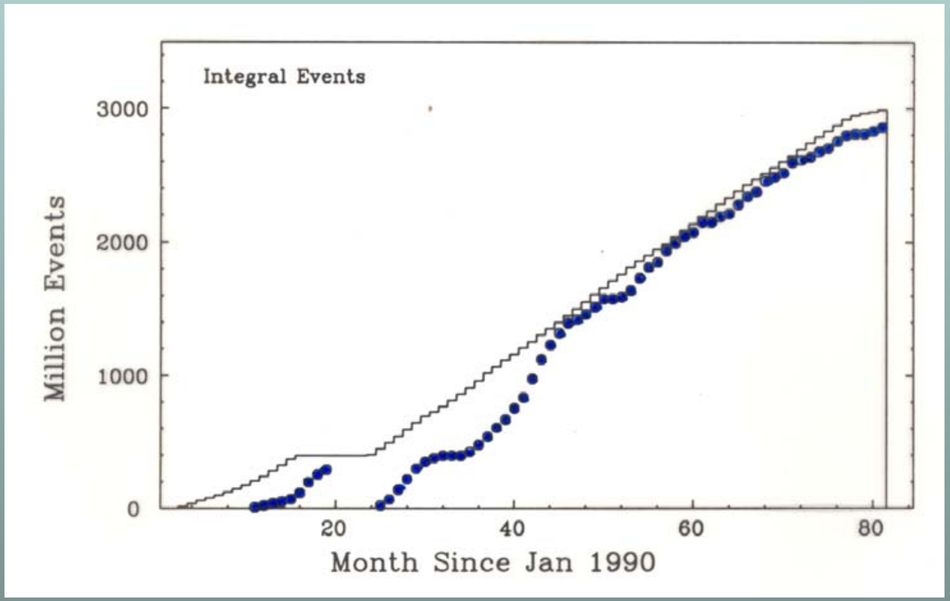
Operations & Performance

After January 2002, CASA-MIA operated successfully for five years.
All performance characteristics were achieved or surpassed.

Enormous data sample: 1.5M events collected per day. 2000 tapes !



CASA-MIA Event



Analysis set up to process the data;
run by army of devoted <u>students</u> to keep up.

CASA-MIA Journal Papers

Paper	Ref.	Comment
"Search for Discrete Sources of 100 TeV Gamma Radiation."	PRD 45, 4385 (1992)	Initial results based on 49 detector array.
"A Northern Sky Survey for Astrophysical Point Sources of 100 TeV Gamma Radiation."	ApJ 417, 742 (1993)	General survey of entire overhead cky.
"Observation of the Shadows of the Moon and Sun using 100 GeV Cosmic Rays."	PRD 49, 1171 (1994)	Important calibration; rules out a mostly heavy composition.
"A Large Air Shower Array to Search for Astrophysical Sources Emitting γ-rays with Energies > 10^{14} eV."	NIM A346, 329 (1994)	Detailed instrument paper.
"A Search for Ultrahigh-Energy Gamma Rays from EGRET-Detected AGN using CASA-MIA."	ApJ 469, 572 (1996)	Limits well below extrapolation from EGRET energies.
"High Statistics Search for Ultrahigh Energ γ-ray Emission from Cygnus X-3 and Hercules X-1."	PRD 55, 1714 (1997)	Limits on steady, periodic and transient emission from key binary sources.
"A Search for Ultrahigh Energy Gamma-Ray Emission from the Crab Nebula and Pulsar."	ApJ 481, 313 (1997)	Emission from standard candle source turns over at high energies.
"Limits on the Isotropic Diffuse Flux of Ultrahigh Energy γ Radiation."	PRL 79, 1805 (1998)	General stringent limit on any source of diffuse radiation.
"Constraints on Gamma-Ray Emission from the Galactic Plane at 300 TeV."	ApJ 493, 175 (1998)	Molecular cloud emission constrained and spectral hardening ruled out.
"The Cosmic Ray Energy Spectrum Between 10^{14} and 10^{16} eV."	AP Phys 10, 291 (1999)	Differential spectrum measured; knee is not sharp, but a smooth transition.
The Cosmic Ray Composition between 10^{14} and 10^{16} eV."	AP Phys 12, 1 (1999)	Composition is mixed a lower energies, becoming heavier as energy increases.

Key Results

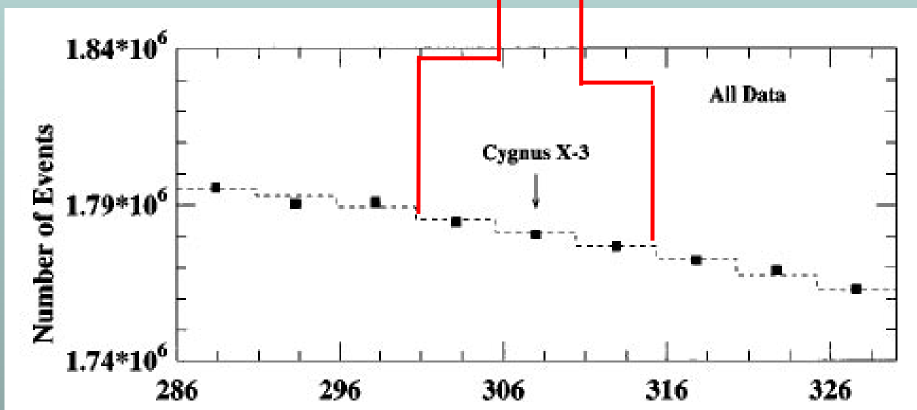
A. Point Sources

Regarding its primary scientific objective – detection of γ-ray point sources – CASA-MIA was not successful.

- Stringent limits were set on emission from the most interesting sources at levels well below previous reports.
- Searches for transient and period emission were carried out, along with a general survey of the overhead sky.
- The point source limits, coupled with the survey, place a typical constraint on source luminosity of $\mathcal{L} < 10^{36}$ erg/s – this largely rules out a small number of source explaining the origin of CR's.

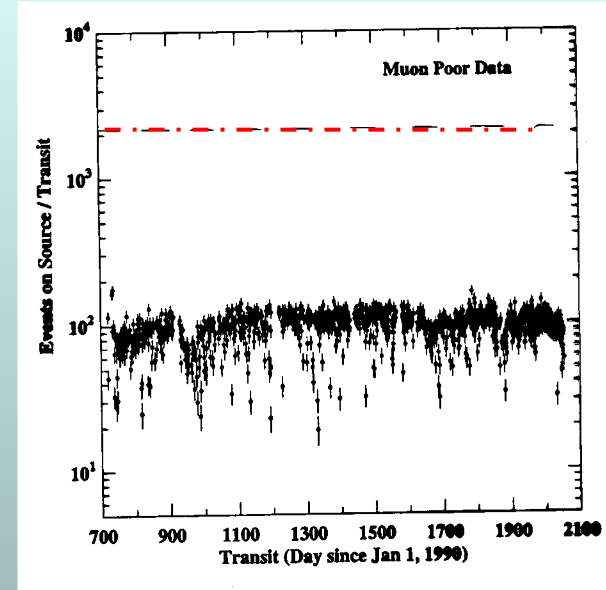
Cygnus X-3

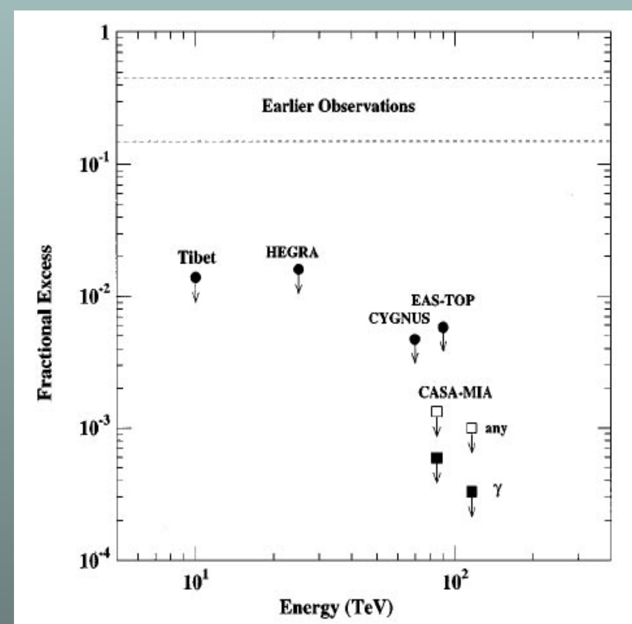
170,000 evts
~180σ



Scan in right ascension.

Daily limits





Flux limits

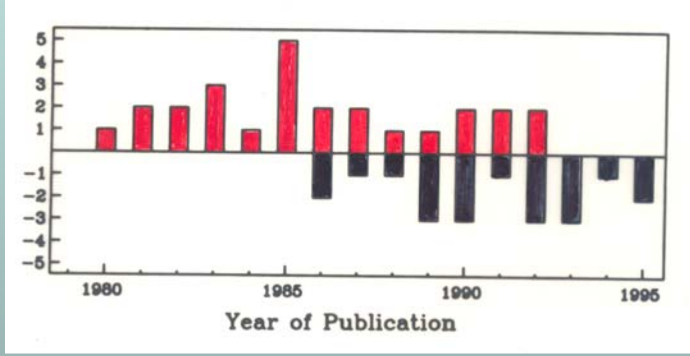
CASA-MIA limits factor of 100 lower than earlier results.

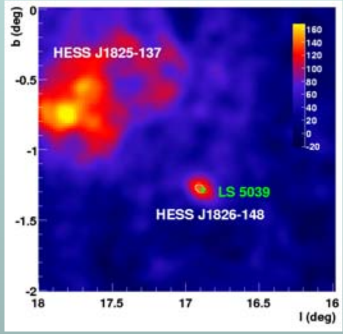
Epilogue: Cygnus X-3

X-ray Binary Systems, like Cygnus X-3, were definitively ruled out as bright sources of 100 TeV gamma radiation.

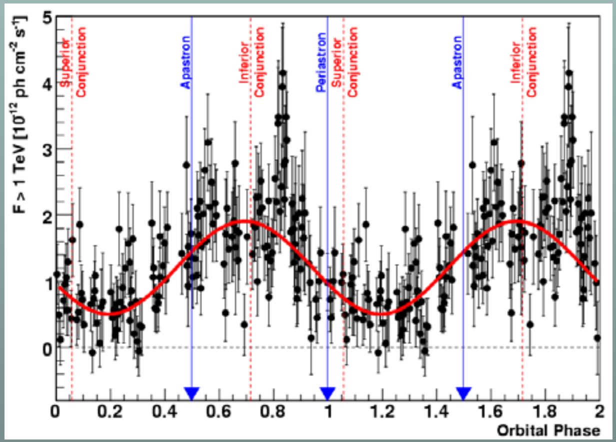
Pos

Neg





LS 5039
HESS image
and phase plot.



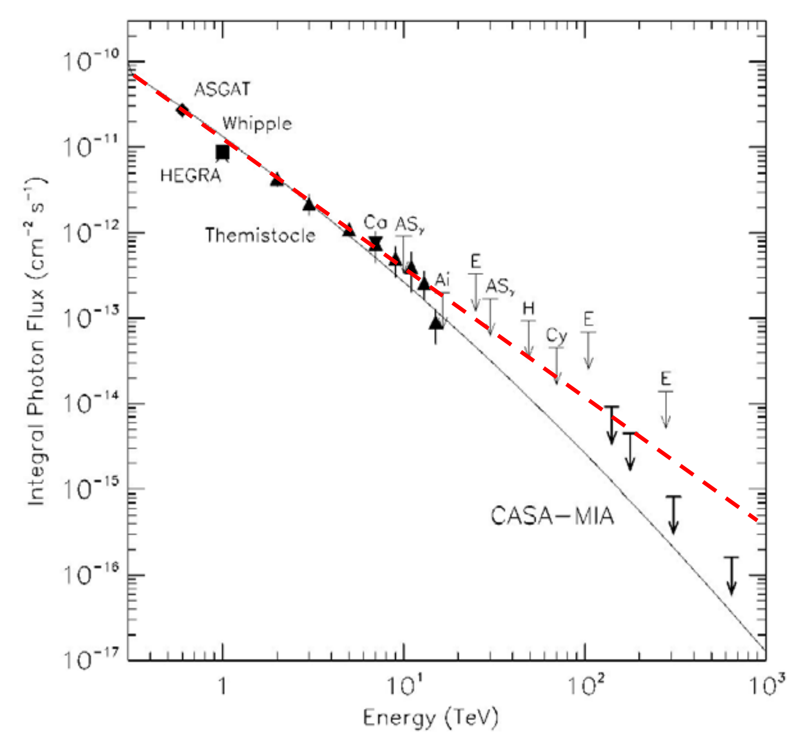
But …

HESS and MAGIC have very recently detected TeV emission from other X-ray binary systems, called μquasars. The emission is periodic!

Perhaps we were on the right track after all !

Crab Nebula

The Crab is a beautiful source, detected at almost all wavelengths. CASA-MIA data showed that the UHE emission must roll over.



Crab Nebula results (1997).

Now, 50 TeV radiation has been detected by atmospheric Cherenkov telescopes.

B. Diffuse Sources

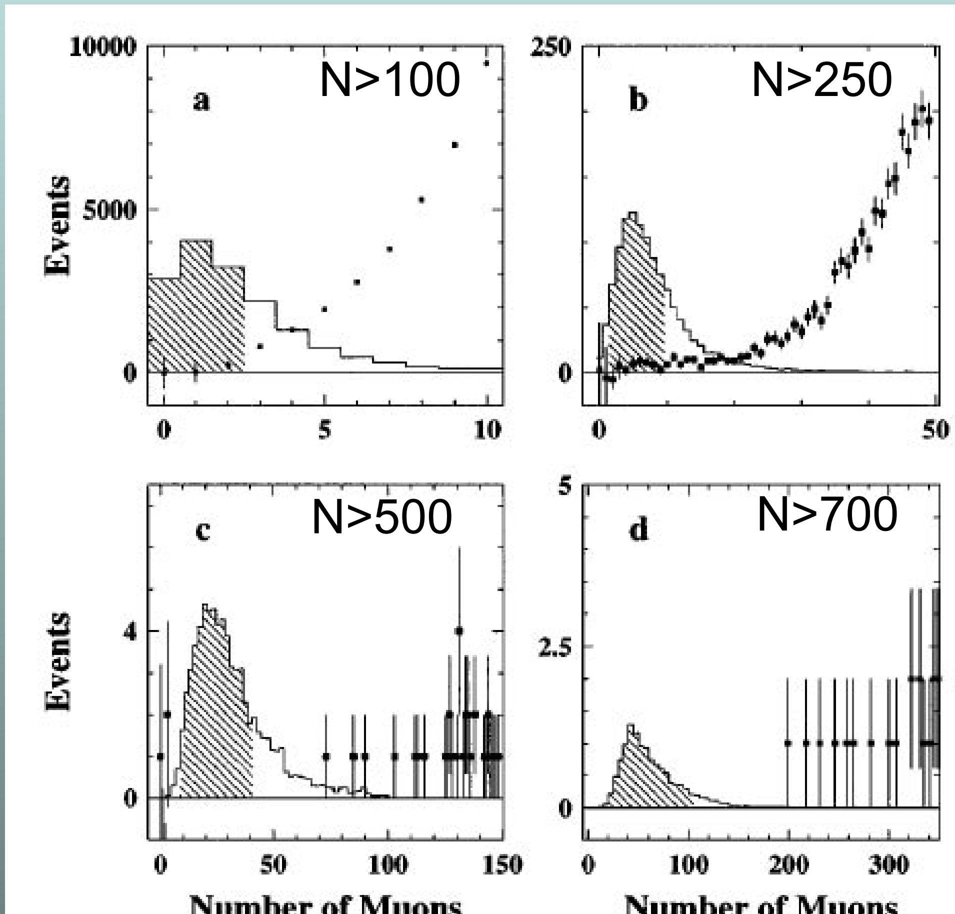
Using the large muon detector to separate gammas and hadrons, CASA-MIA studied sources of diffuse γ-ray radiation with great sensitivity.

3 nice results:

- Diffuse radiation from Galactic Plane – tracing CR interactions with molecular clouds.
- Rapid bursts from arbitrary directions in the sky – constrained short time-scale explosions, such as primordial black holes.
- Search for isotropic emission that would signal any type of new particle produced in the early universe; basic limit on the electromagnetic fraction of the cosmic rays.

Diffuse γ-ray Emission

Number of detected muons.



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Limits on the Isotropic Diffuse Flux of Ultrahigh Energy γ Radiation

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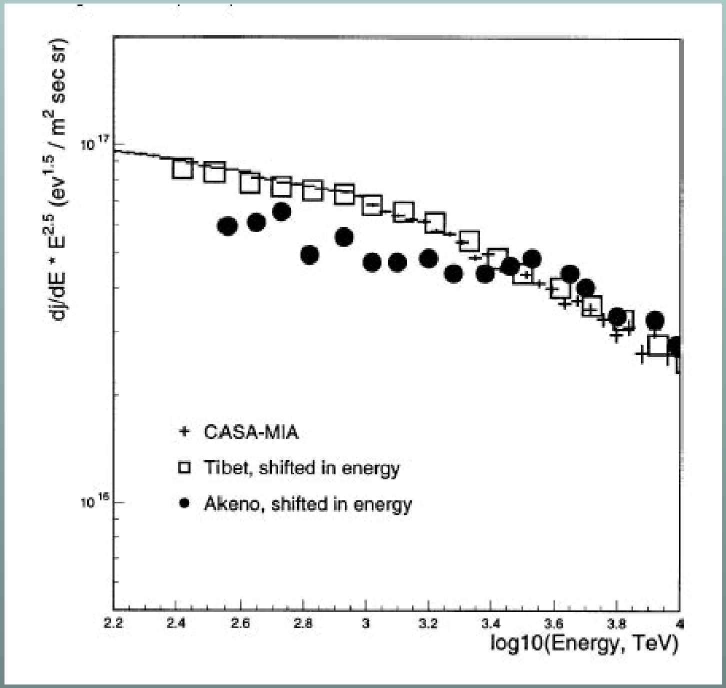
Diffuse ultrahigh energy γ radiation can arise from a variety of astrophysical sources, including the interaction of 10^{20} eV cosmic rays with the 2.7 K microwave background radiation or the collapse of topological defects created in the early Universe. We describe a sensitive search for diffuse γ rays at ultrahigh energies using the Chicago Air Shower Array–Michigan Muon Array experiment. An isotropic flux of radiation is not detected, and we place stringent upper limits on the fraction of the γ-ray component relative to cosmic rays ($<10^{-4}$) at energies from 5.7×10^{14} to 5.5×10^{16} eV. This result represents the first comprehensive constraint on the γ-ray flux at these energies. [S0031-9007(97)03962-8]

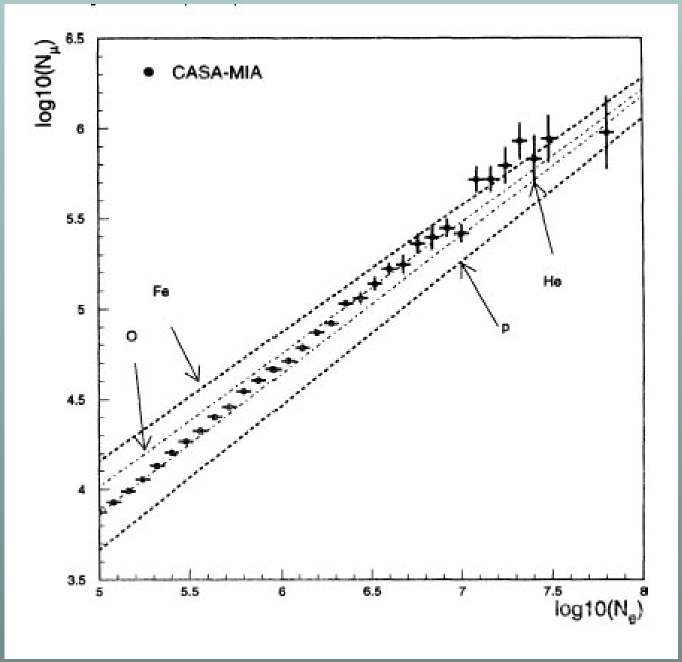
EM fraction of CR's $< 2 \times 10^{-5}$.

C. Cosmic Ray Studies

CASA-MIA comprised a very large, uniform surface array with a large muon detector → excellent capability for measurements of the properties of the UHE cosmic rays.

Of particular interest are the spectrum and composition.



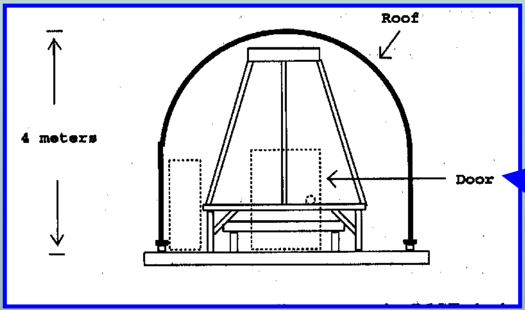


Spectrum: smooth steepening.

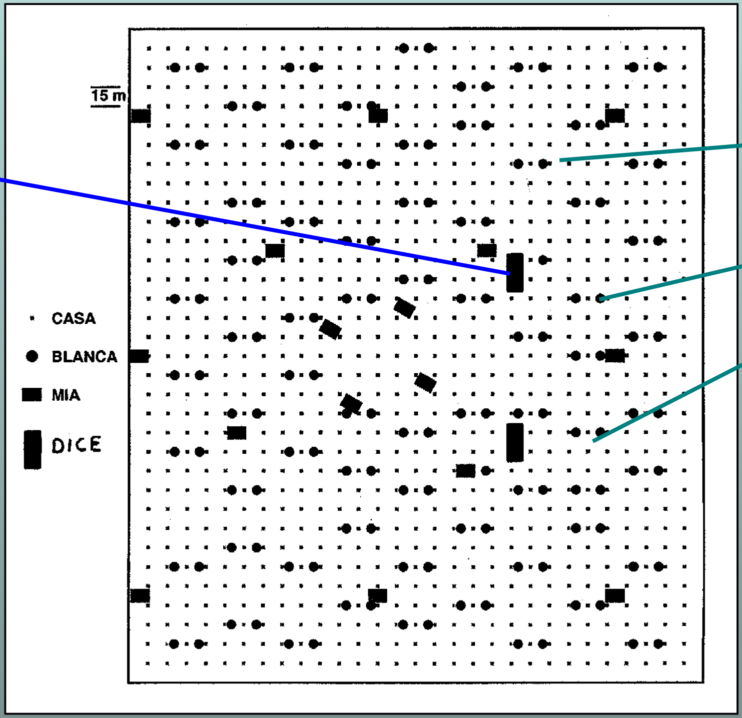
Composition changes from mixed to heavy.

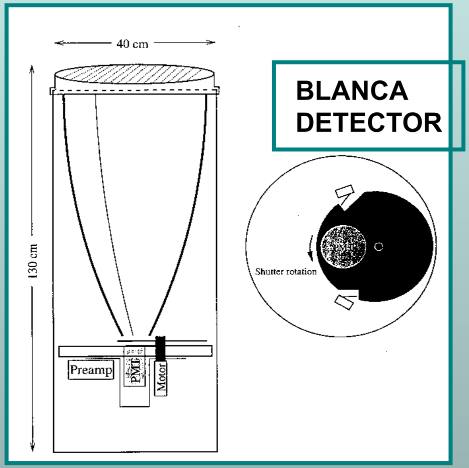
Beyond CASA-MIA

CASA-MIA was augmented by other detectors improve measurements of the properties of the cosmic rays.



DICE
(D. Kieda, S. Swordy)





BLANCA
(L. Fortson, J. Fowler, C. Pryke)

Fly's Eye HiRes

CASA-MIA plus DICE and BLANCA in 1999

Summary – Legacy of CASA-MIA

CASA-MIA placed the strongest constraints on both point-source and diffuse γ-ray emission at ultrahigh energies. The general notion of a few bright and steady sources has been definitively ruled out.

The origin of HE cosmic rays is still an important and active area of research.

In addition, and as important, CASA-MIA:

- Demonstrated the power of detectors with excellent instrumentation and sensitivity. Along with atmospheric Cherenkov telescopes, this brought attention and funding to high-energy astrophysics.
- Brought new people into the field … (many are here today!)
- Led to new directions in particle astrophysics (TeV telescopes, highest energy cosmic rays, and neutrino telescopes).

Acknowledgements

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and most importantly, to JWC.

Happy
Birthday
Jim !