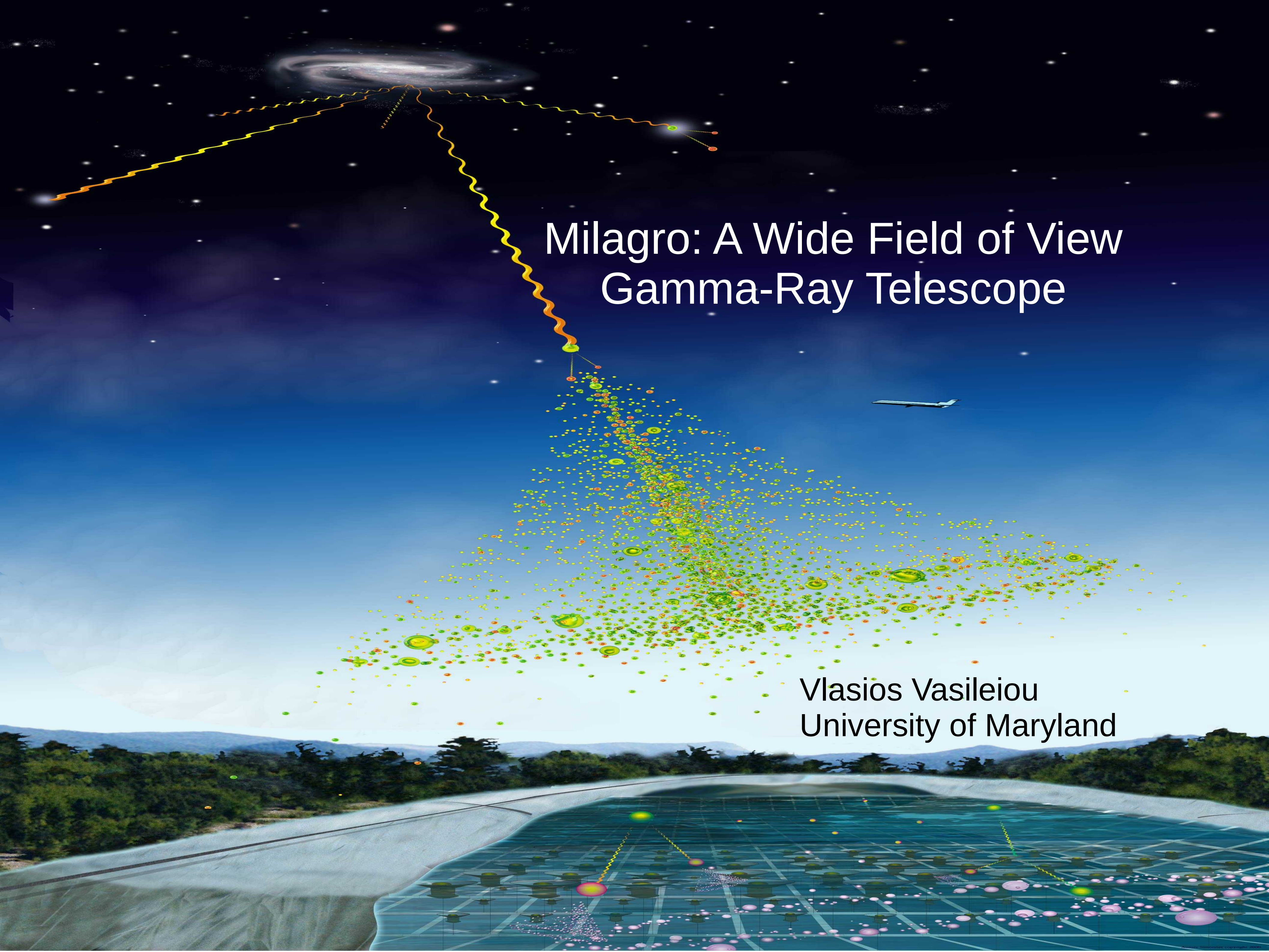


Milagro: A Wide Field of View Gamma-Ray Telescope

Vlasios Vasileiou
University of Maryland

Outline

- *Milagro*
- *Simulation of Milagro*
  - *Photomultiplier Tube Tests*
  - *Performance of the simulation*
- *Gamma-Ray Bursts*
  - *Milagro's Blind GRB-Search*

Milagro: A TeV Gamma-Ray Observatory

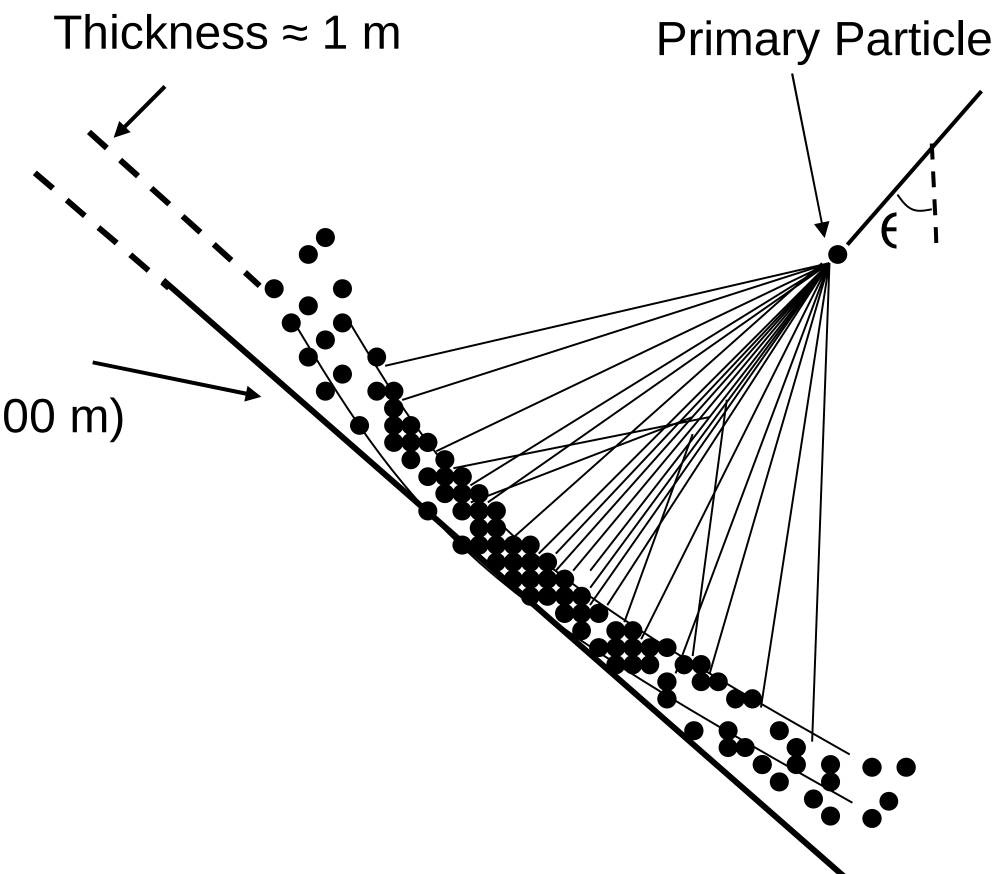
- *TeV Gamma-Ray Observatory*
- *Wide field of view (2 sr) & large duty factor (>90 %)*
  - *Good for observing transients and extended objects and for unbiased complete sky surveys*
- *Located at the Jemez Mountains near Los Alamos, NM*
  - *2630 m altitude*
  - 750 g/cm^2 overburden (73% of Atmosphere)
- Trigger rate ~1700Hz
  - Almost all triggers from hadron-induced showers
- Two components -> Central Pond + Outrigger Array

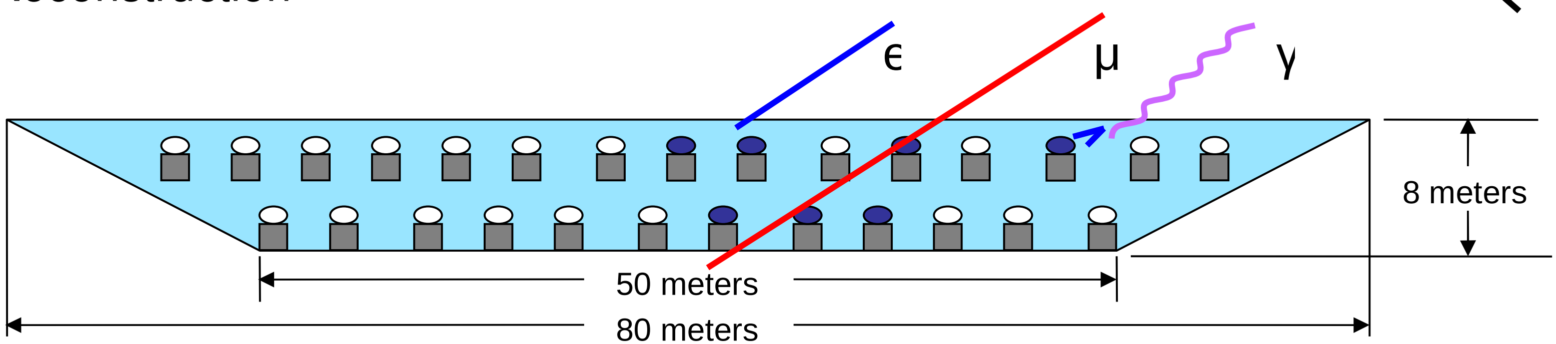
The Central Pond

- 24 Million liter reservoir of highly purified water
- 80m x 60m x 8m (depth) (5000 m[2])
- 723 PMTs arranged in two layers
  - Air Shower Layer:

    450 PMTs under 1.4 m of water
    - Triggering
    - Direction Reconstruction
  - Muon Layer:

    273 PMTs under 6m of water
    - Background Rejection
    - Energy Reconstruction

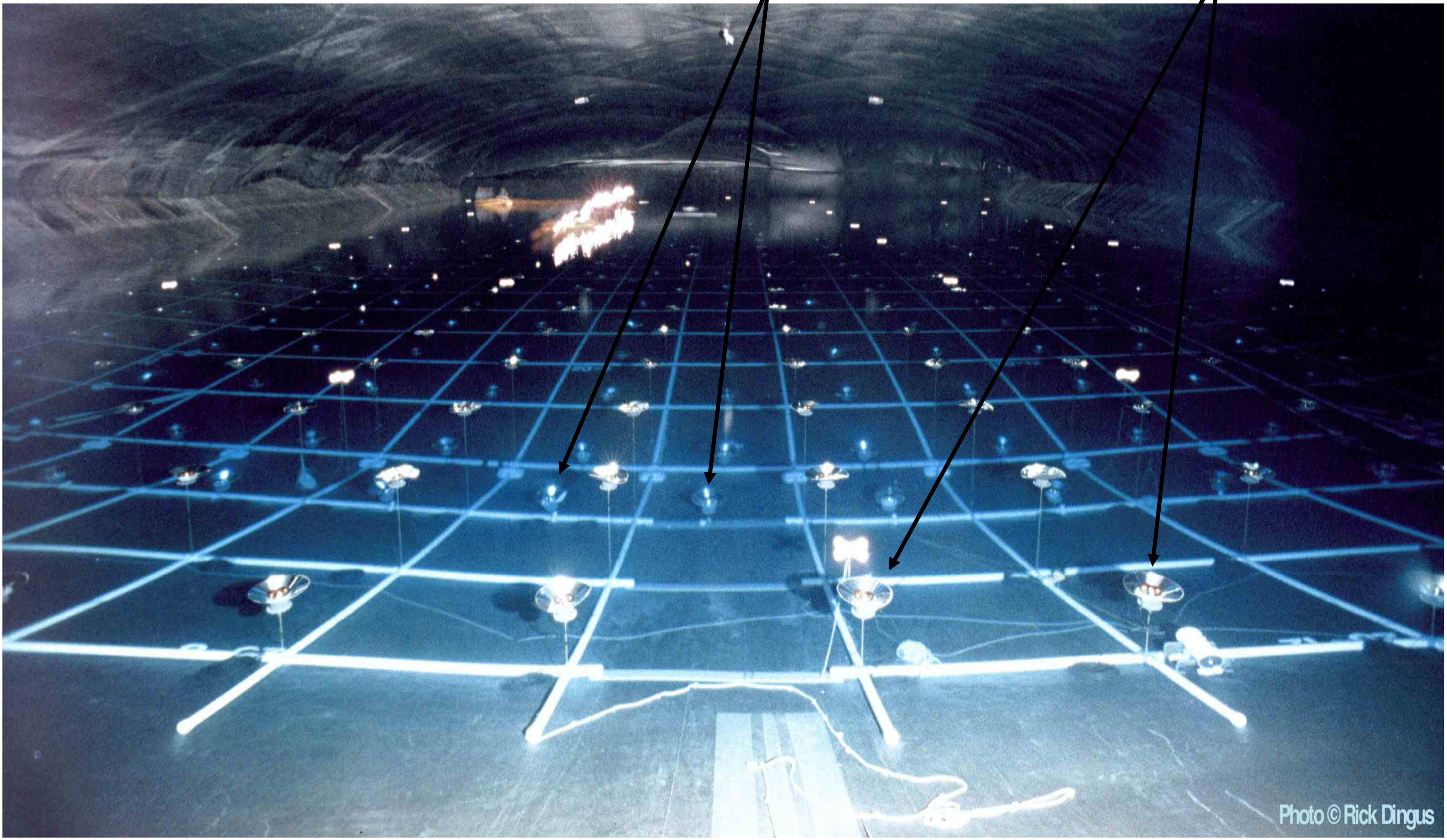




The Pond

Muon layer PMTs

Air Shower layer PMTs



60 meters

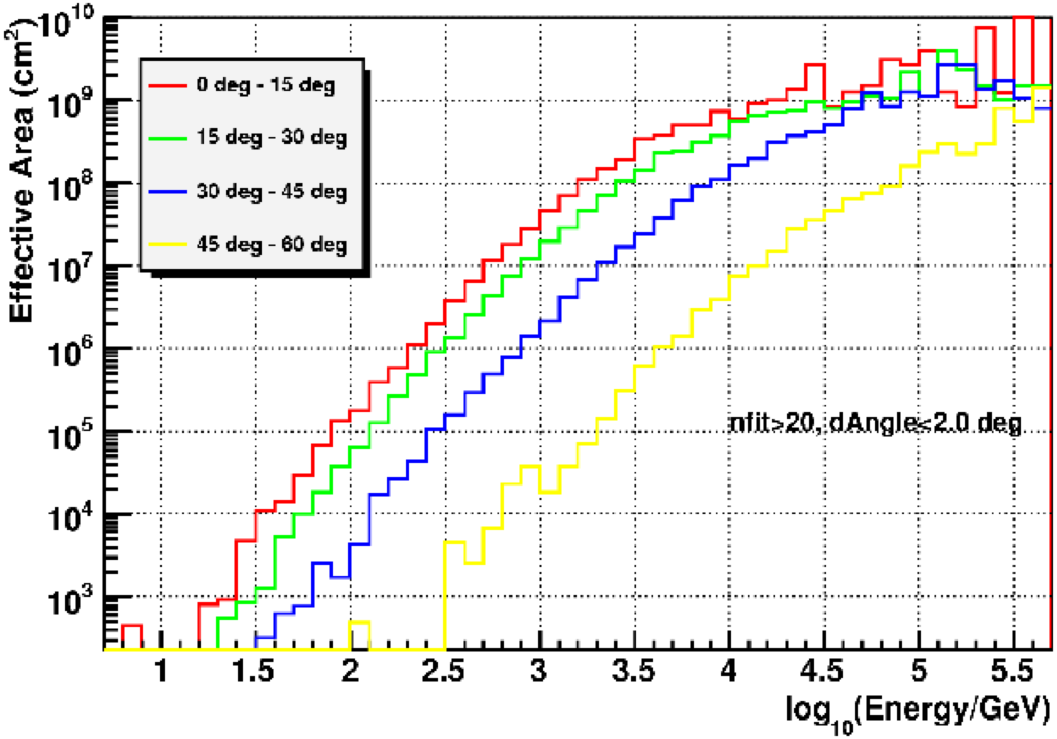
The Outrigger Array

➢ Outrigger Array

- 175 Water tanks spread over 40,000 m^2
- Contain water and a downwards facing PMT
- Added 2003
- Improved
  - ❖ Effective area
  - ❖ Angular resolution
  - ❖ Energy resolution
  - ❖ Background rejection

Milagro's Performance

- *Angular reconstruction accuracy 0.3°-1.4°*
- *Most of the effective area at TeV energies*
  - *~10^3 m^2 @ 1 TeV*
  - *~10 m^2 @ 100 GeV*
- *Median energy of triggers ~few TeV (for a Crab-like source)*
- *Improvement in sensitivity from Gamma-Hadron discrimination + event weighting techniques ~2.5*
- *Crab-like source*
  - *Milagro ~8σ/sqrt(year)*



Simulation of the Milagro Detector

Step 1. Extended Air Shower Simulation with CORSIKA

- *CORSIKA*
  - *Program for detailed simulation of Extensive Air Showers (EAS) initiated by high energy cosmic-ray particles.*
  - *Provide information about EAS particles at Milagro's altitude*
- *Physics simulation*
  - *In our energy range, Corsika's physics package is (we believe) accurate*
  - *EGS4 for EM interactions*
  - *FLUKA for low energy hadronic interactions (E<80 GeV)*
  - *EPOS for higher energy hadronic interactions*
    - *Theory (Parton-Based Gribov-Regge Theory) + experiment (H1, Zeus, RHIC, SPS) driven*

Step 2. Simulation of the detector with GEANT4

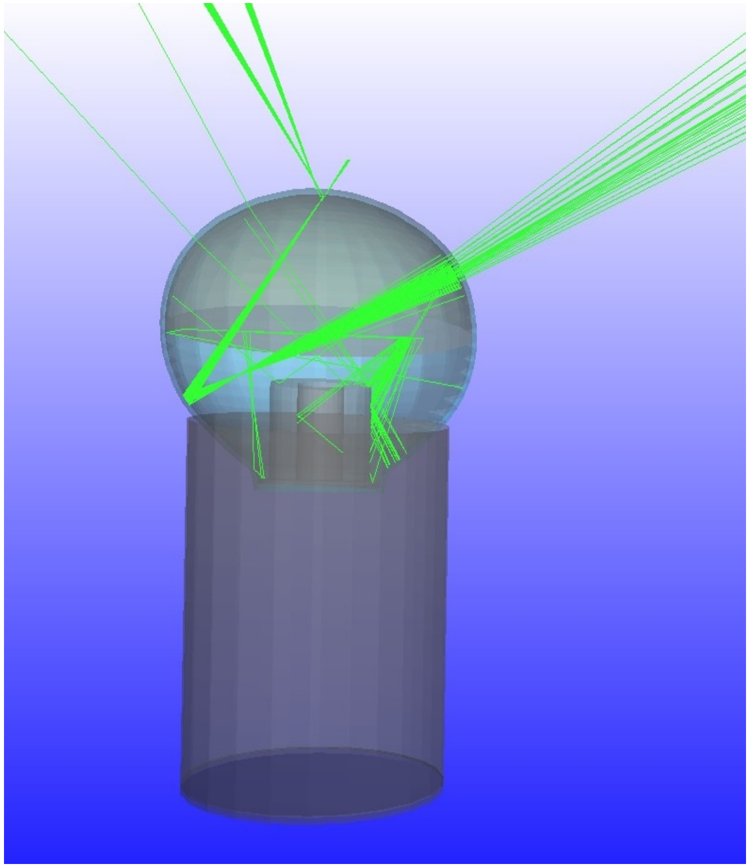
- *Corsika EAS particle information -> Milagro detector simulation*
- *GEANT4*
  - *C++ Simulation Toolkit from CERN*
  - *Written for the needs of the LHC*
  - *Powerful, transparent and easily extendable*
    - *We've debugged and modified it to match our simulation needs (speed + accuracy).*
  - *Physics simulation in GEANT4 overall the best available in HEP.*

Step 2. Simulation of the detector with GEANT4

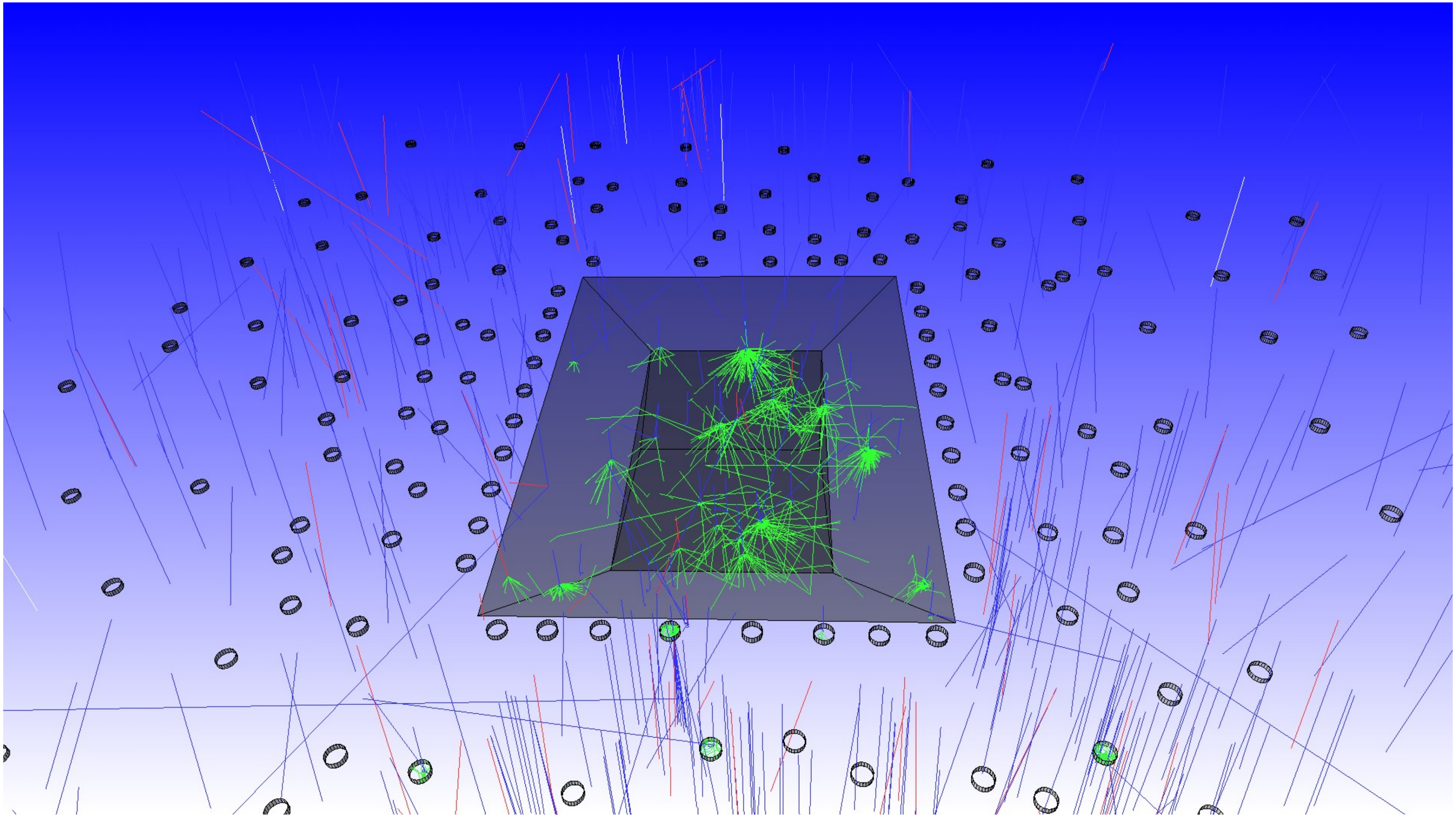
- *We found that, correct simulation of the scattering & absorption of Cherenkov photons is essential for the agreement between MC and data*
  - *Surface reflectivities*
    - *From experimental measurements, theory, (or guesstimates)*
  - *Water properties*
    - *Absorption length by our periodic measurements*
    - *Scattering*
      - *Rayleigh (not dominant)*
      - *Mie (forward scattering, not included in GEANT4)*
        - *Extended GEANT4 physics to include Mie-scattering of optical photons in the water.*

PMT Model

- *Full optical simulation of the PMTs*
- *Reflections/refractions/absorptions are fully simulated for all parts of the PMT*
- *Using the complex refractive index of the photocathode material and its thickness we can calculate the photocathode absorptivity and reflectivity vs energy and incidence angle.*
  - *Gives correct detection efficiency vs incidence angle*
  - *Predicts the increased detection efficiency caused by reflections by the internal parts of the PMT towards the inside surface of the photocathode*
- *Model adopted from GLG4SIM (Generic Liquid GEANT4 SIMulation) http://neutrino.phys.ksu.edu/~GLG4sim/*



Visualization of an event



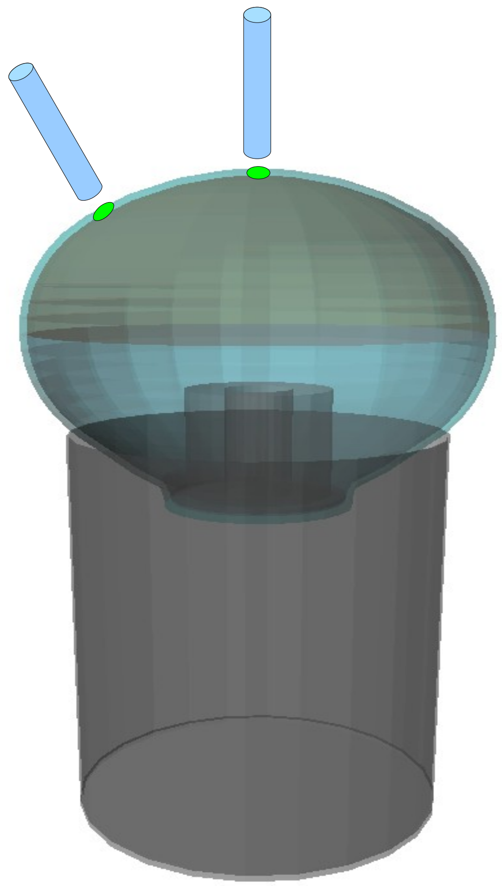
- *1 TeV proton from zenith*
- *Green -> Cherenkov photons (1/300 thinned)*
- *Red -> e-, e+*
- *Blue -> gammas*
- *White -> mu-, mu+*

Step 3. Preparing the MC data for analysis

- *Add noise*
  - *1 PE noise (dark noise, light leaks etc)*
  - *Overlay hits produced by low energy (non triggering showers) that come in time with the shower that caused the trigger*
  - *Match scaler rates and distribution of the size of hits when non triggered*
- *Apply Photocathode-Uniformity Corrections*

Photocathode-Uniformity Tests

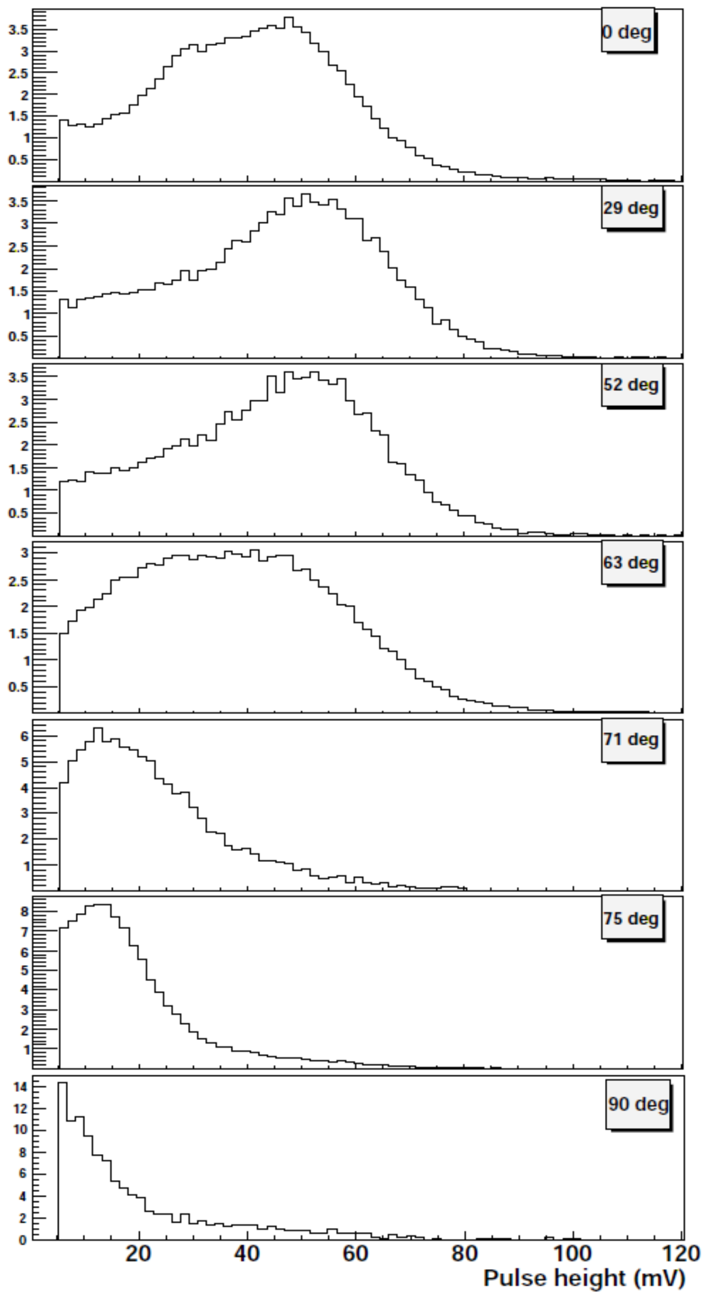
- *Hamamatsu R5912 Photomultiplier tube*
- *8'' semi-spherical bialkali photocathode*



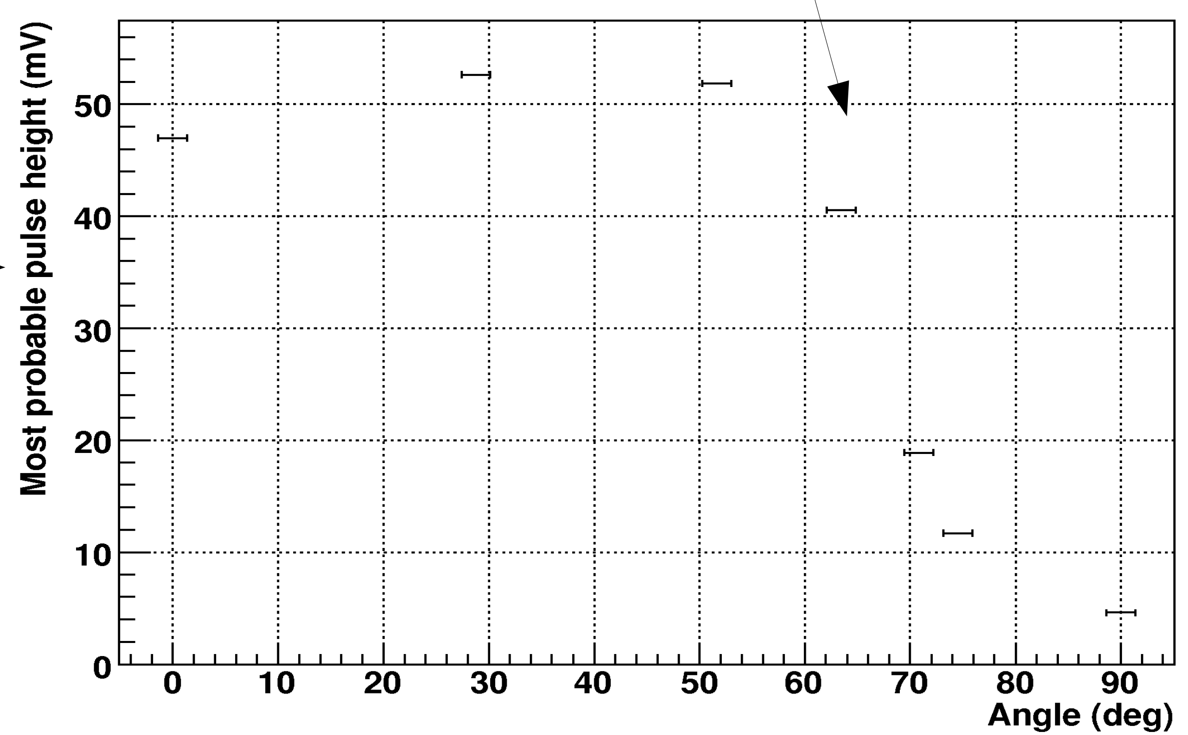
- *Illuminated various spots on the surface of the photocathode*
- *Examined PMT properties for each illumination point*
  - *PMT Efficiency*
    - *DC light source -> PMT -> Scaler*
  - *PMT Gain*
    - *Pulsed light source -> PMT -> Oscilloscope*

Gain vs illumination position

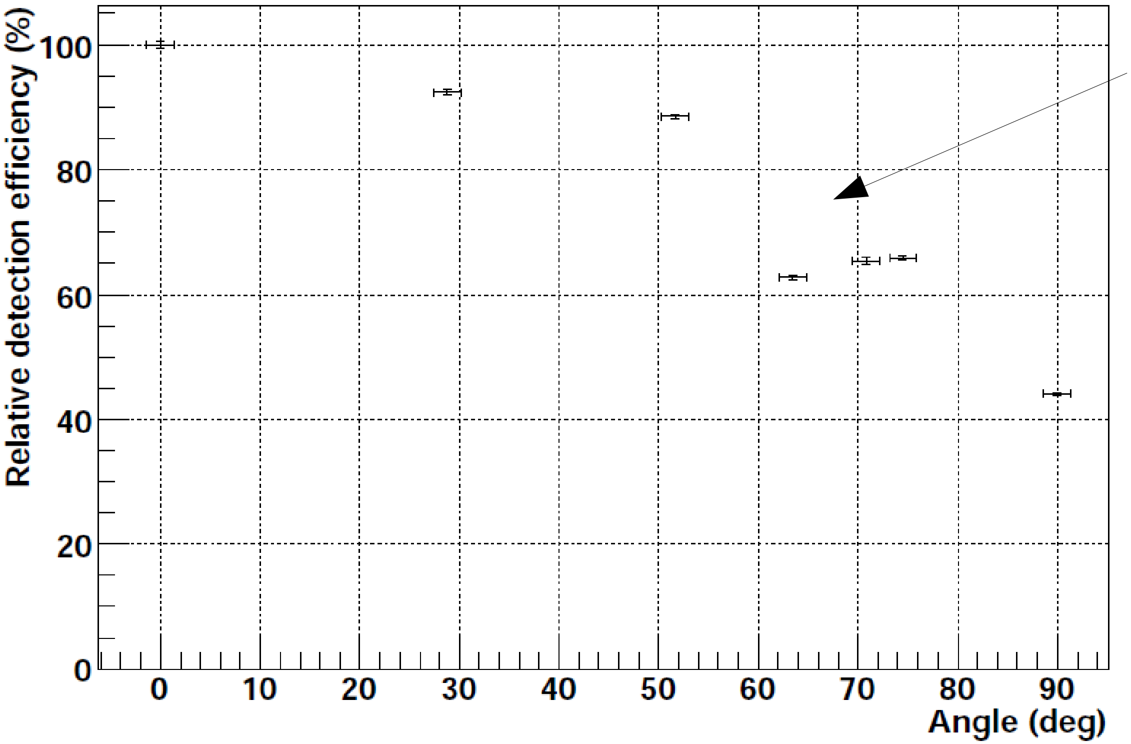
Effect present for different supply voltages and PMT orientations (vertical vs horizontal)



Gain significantly reduced near the edge of the PMT



Detection efficiency vs illumination position



Detection efficiency considerably lower near the edge of the PMT

Angle (deg)	Relative detection efficiency (%)		
	PMT #1024	*PMT #394*	*PMT #992*
0	100±0.5	100±0.5	100±0.8
29	92.4±0.5		
52	88.7±0.3		
63	62.7±0.3		
71	65.5±0.6		
75	65.9±0.3		
90	44.1±0.2	30.8±0.1	33.4±0.1

Effect present on all available PMTs

Step 3. Preparing the MC data for analysis

- *The PMT tests showed that the efficiency & gain of the PMT are lower than what we thought*
- *Effect caused by non-uniformities in the collection efficiency*
- *Apply these effects to the MC results*
  - *Reject PEs based on a position-dependent detection efficiency*
  - *Sample a pulse charge for each PE based on the position-dependent pulse-height distributions*
- *Result -> PMT efficiency reduced*
  - ✓ *Better agreement between MC and data*
  - ✓ *Number of muons produced by the PMTs of the muon layer now agrees with the data*
  - *PE-scale changed -> Various distributions that depend on the size of the hits changed*

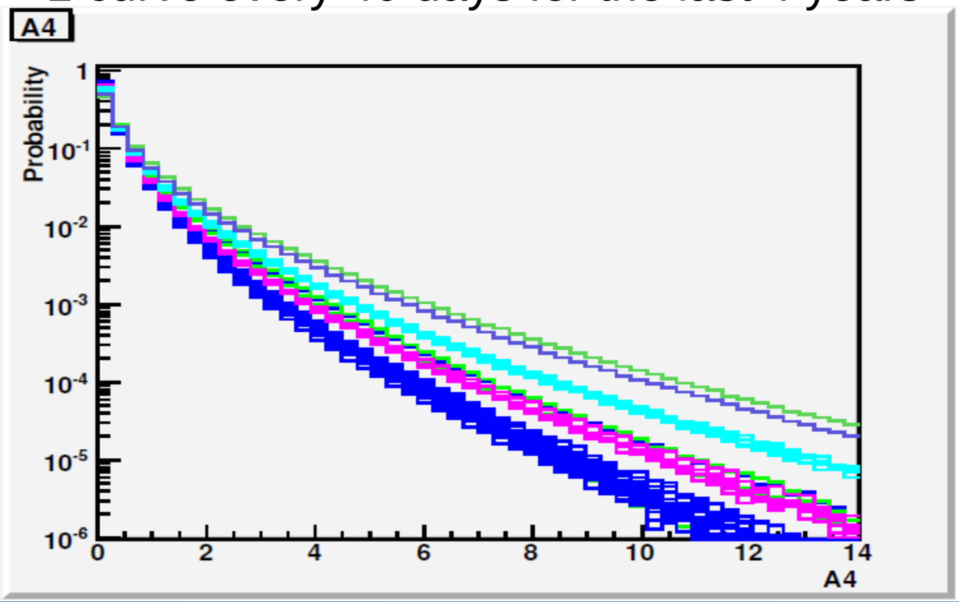
Step 3. Preparing the MC data for analysis

- *Simulate the electronics*
- *MC Data ready for analysis using the same algorithms as the ones used for the experimental data.*

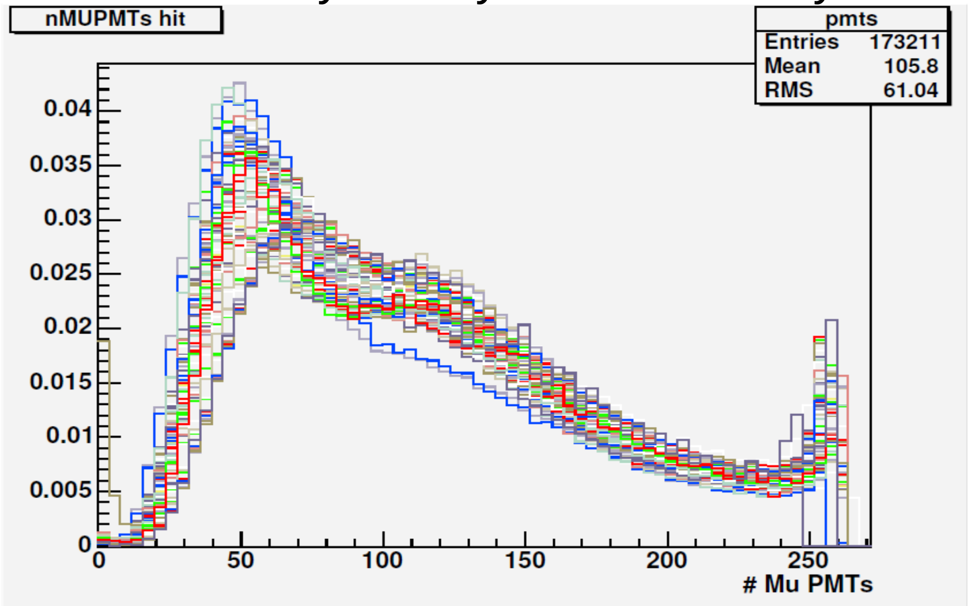
The verdict...

- *Does the simulation match the data?*
- *Yes and no...*
- *The data doesn't match the data..*
- *Over the 7 years Milagro has been collecting data we had many changes:*
  - *Baffles, broken calibrations, water quality, pond-surface freezing, air accumulating under the cover, PMTs dying, triggering system problems*
  - *Data properties changing with time*

1 curve every 40 days for the last 4 years



1 curve every 20 days for the last 3 years



Dealing with the variability of Milagro data

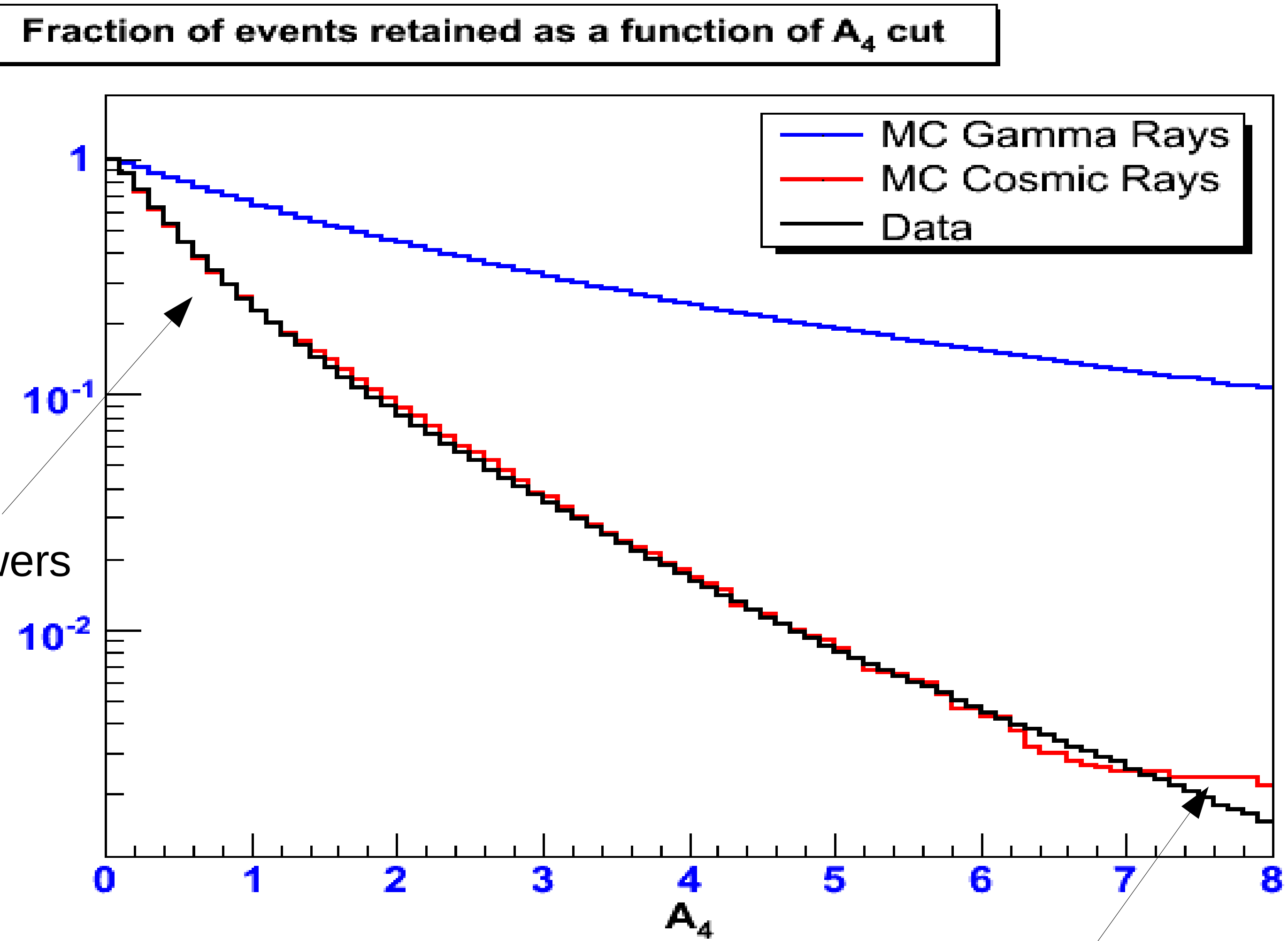
- *Solution*
  - *Identified which experimental parameters changed over time and quantified their influence on the data through simulations*
  - *Broke up the Milagro data in “epochs”*
    - *Started using the appropriate simulation configuration for each epoch*
  - *Applied “rescaling factors” to the data of each epoch to make them more uniform*

Simulation performance

- *Result*
  - *Data now, overall more stable over time and especially in the same epoch*
  - *There is good or excellent agreement between most of the predictions of the MC and the data*
    - *Agreement between MC and data depends on our knowledge of the state of the experiment -> best agreement with the data of the last years*
    - *The variables that are harder to match are the ones that change the most in the data -> the ones that are most sensitive to experimental conditions*
  - *For future analyses we'll try to use the variables we know are stable*

Gamma-Hadron Discrimination Parameter

- *A4 parameter shows how gamma-like an event is*
- *Fraction of events passing an A4 cut*

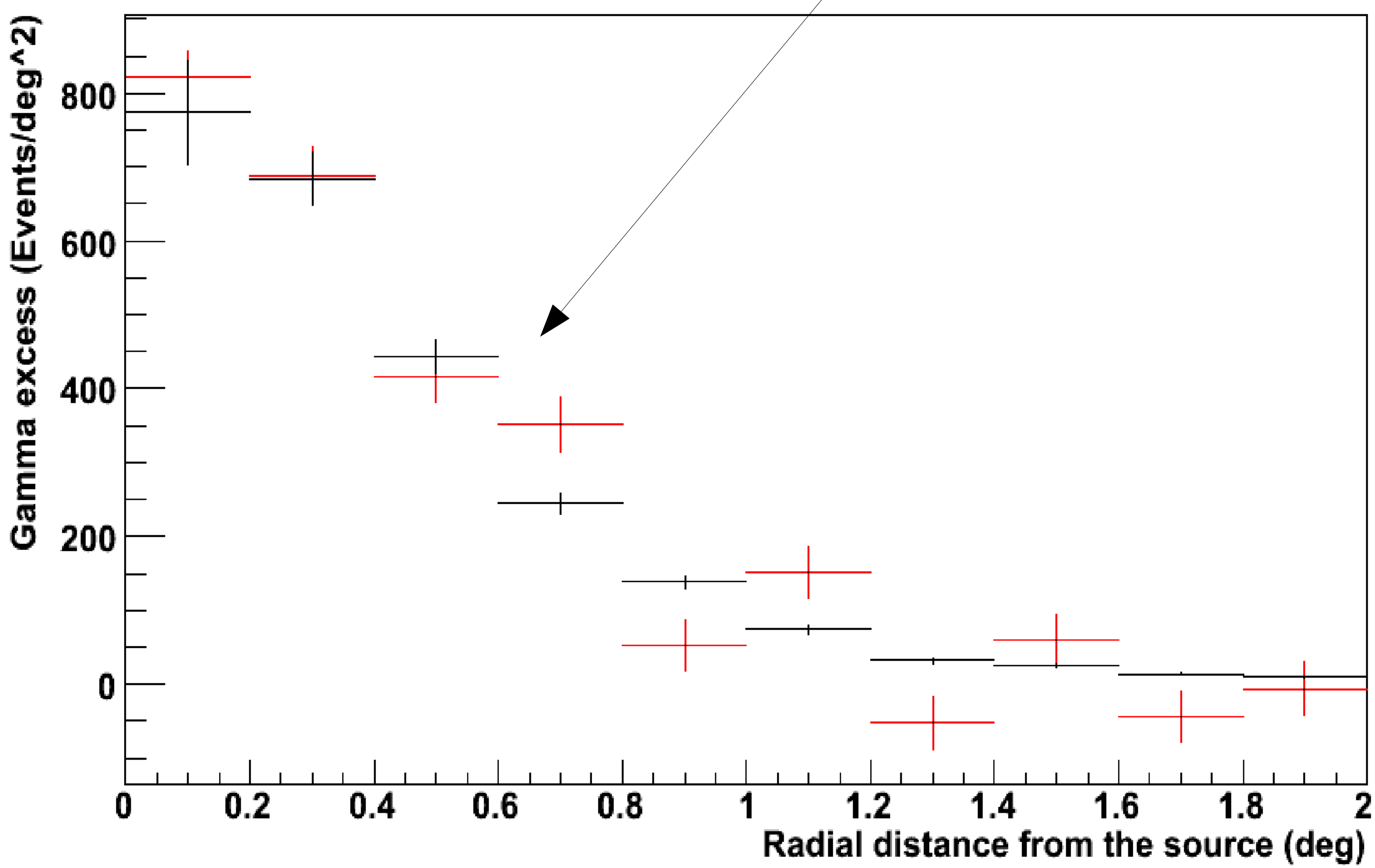


Excellent agreement between MC and Data for hadronic showers

Not enough statistics

Point Spread Function

Profile of the γ-ray signal from the Crab.
Black points are for data and red for simulation of gamma showers.



Simulation Performance

- *MC gamma-ray rate from the Crab agrees to a factor of 10%*
- *MC cosmic-ray rate agrees to a factor of ~10%*
- *Excellent or very good agreement*
  - *Number of PMTs hit per event*
  - *Number of Photons detected per event*
  - *Distribution of the reconstructed core locations*
  - *Number of photoelectrons a muon creates in the PMTs of the bottom layer*
  - *Distribution of the reconstructed zenith angles or core locations*
  - *etc*

Gamma-Ray Bursts

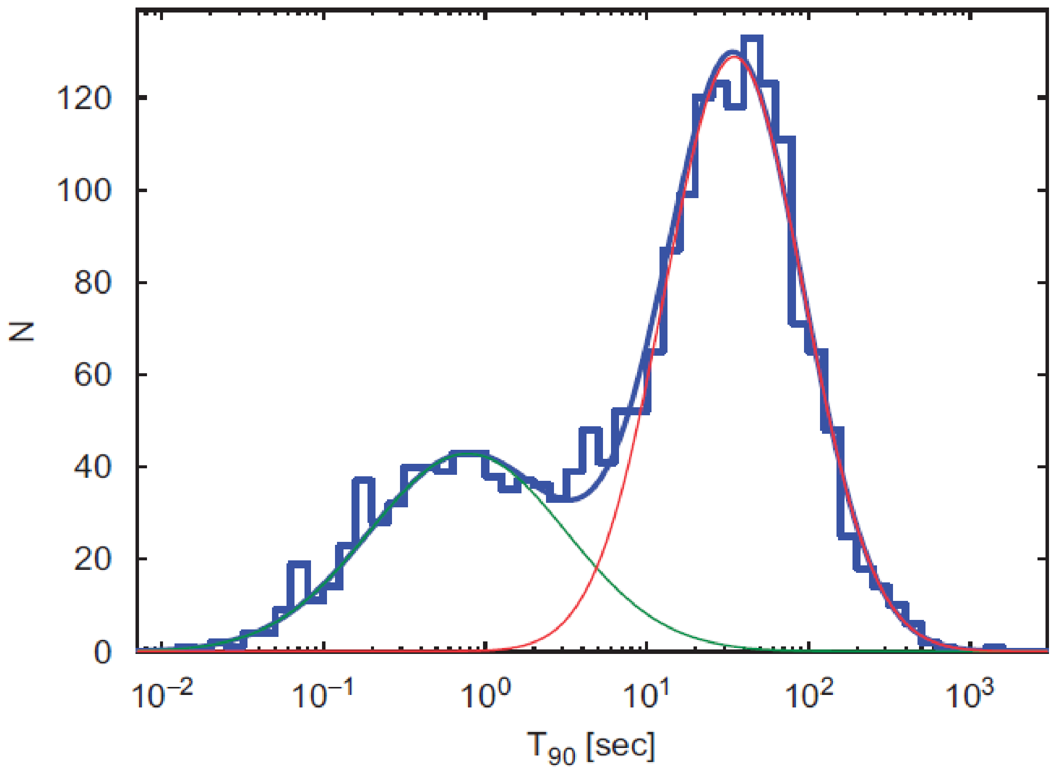
(and a blind search for them with Milagro)

Gamma-Ray Bursts

- *The most bright events in the gamma-ray sky (10^{-8} – 10^{-3} ergs/cm^2)*
- *Cosmological distances*
- *Non-thermal spectra*
- *Prompt emission*
  - *Duration 10ms to >100sec*
    - *Bimodal distribution*
  - *Primarily observed in the keV – MeV range*
- *Followed by an afterglow*
  - *Exponential decrease in intensity (t^{-1},t^{-2})*
  - *Observed in soft X-rays, visible, IR and optical wavelengths*

Duration of GRBs from BATSE

- *T_{90} distribution of BATSE bursts*
- *Bimodal distribution, implies two different kinds of progenitors.*

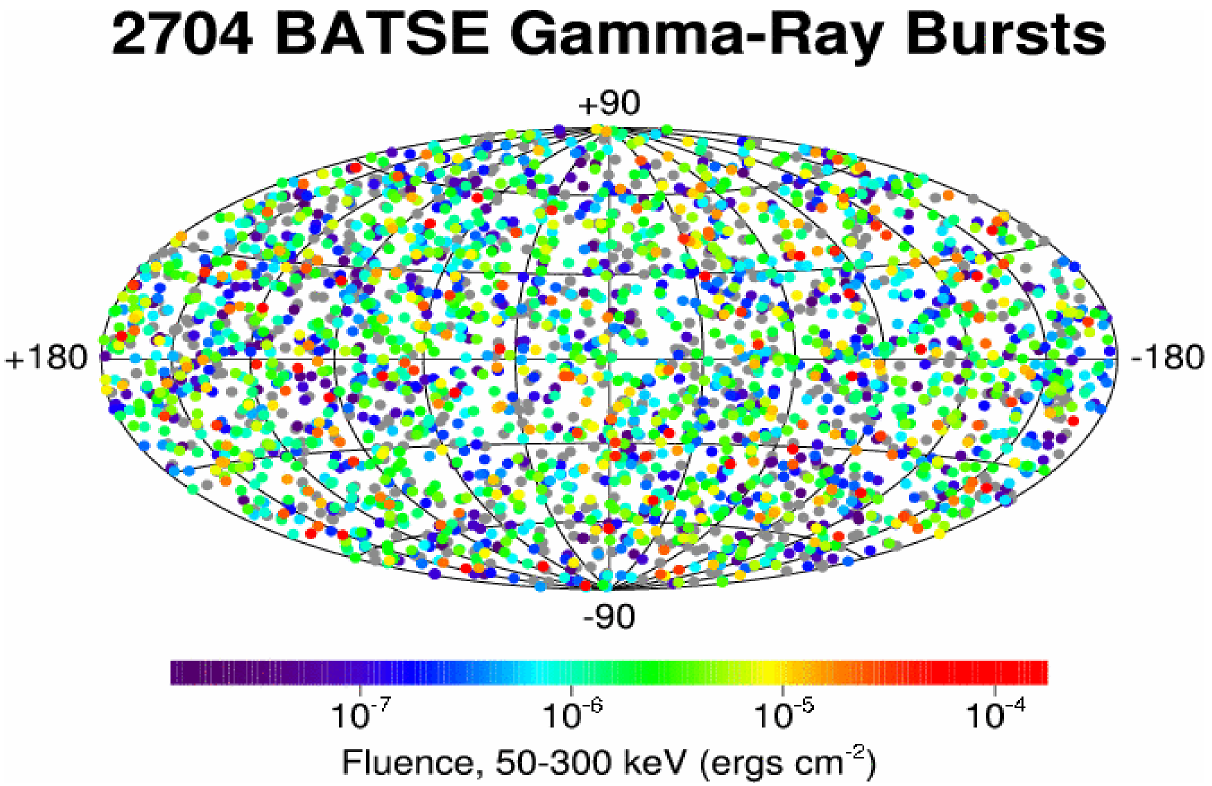


Horvath, 2002

**T90 is the duration encompassing the 5th to the 95th percentiles of the total counts in the energy range 20–2000 keV.*

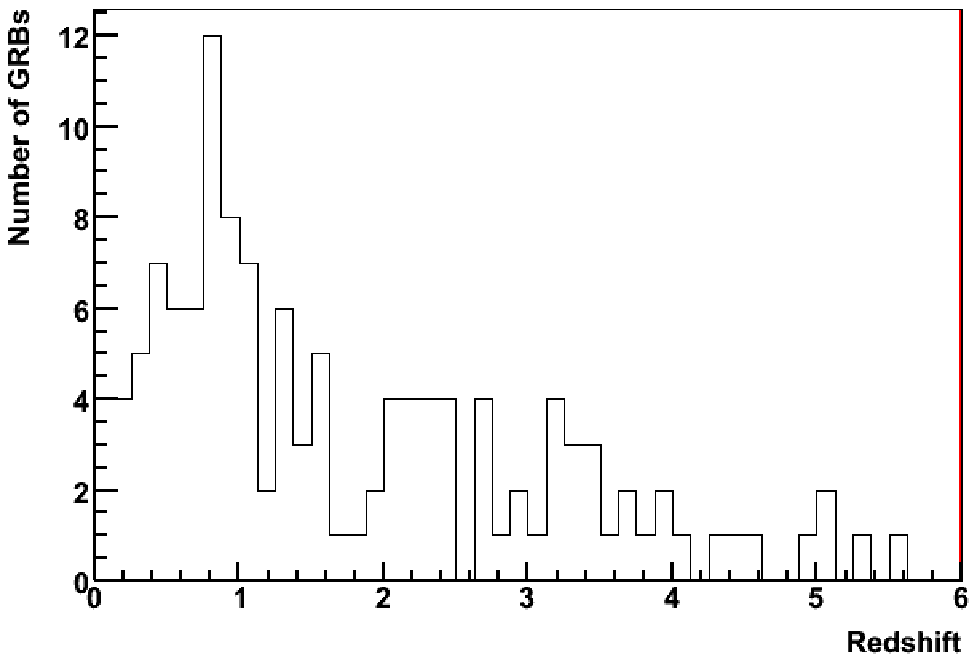
Isotropy of GRBs

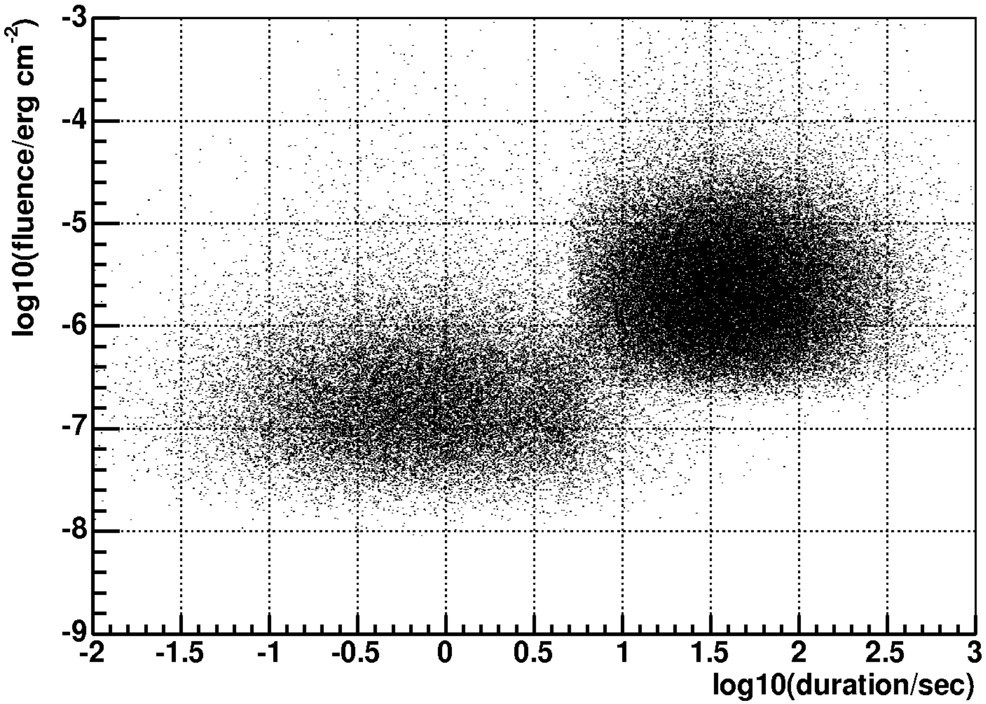
- *Galactic vs Extra-Galactic*
- *BATSE found that GRBs are distributed isotropically over the sky.*
- *A galactic origin for GRBs would likely result in a clustering about the galactic plane.*
- *Still doesn't exclude an extended galactic halo*



Meegan et al., Nature 1992

Distance and Energetics



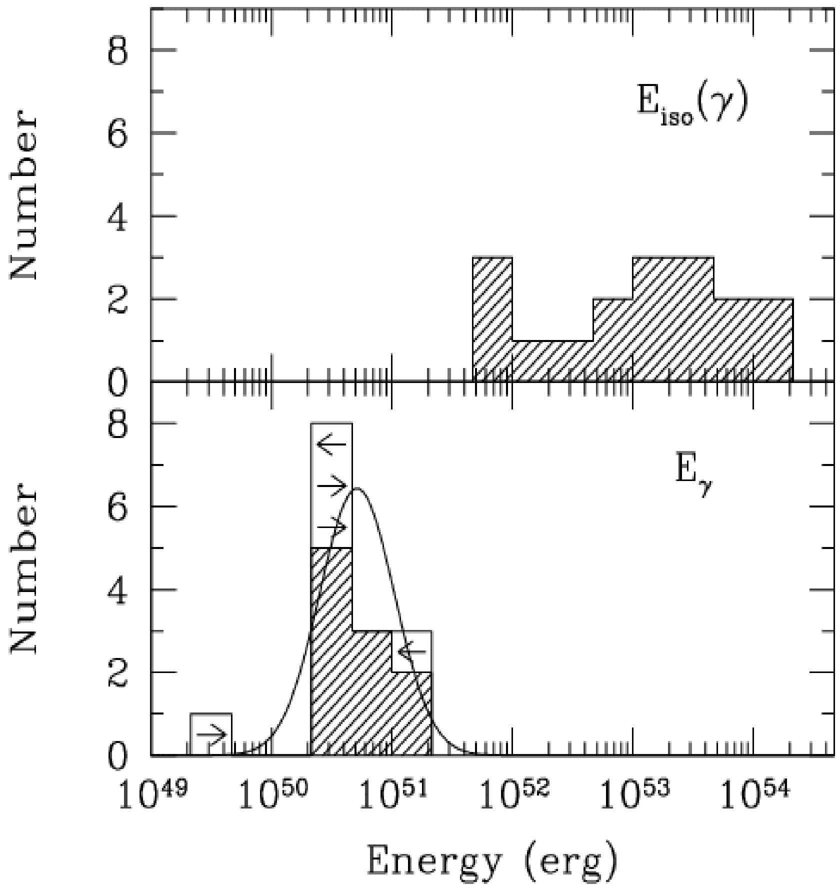


- *Redshift measurements made possible using arcsec localizations of the GRB afterglows*
- *GRBs come from cosmological distances*
- *Measured fluences: 10^{-8}-10^{-3} erg/cm^2*

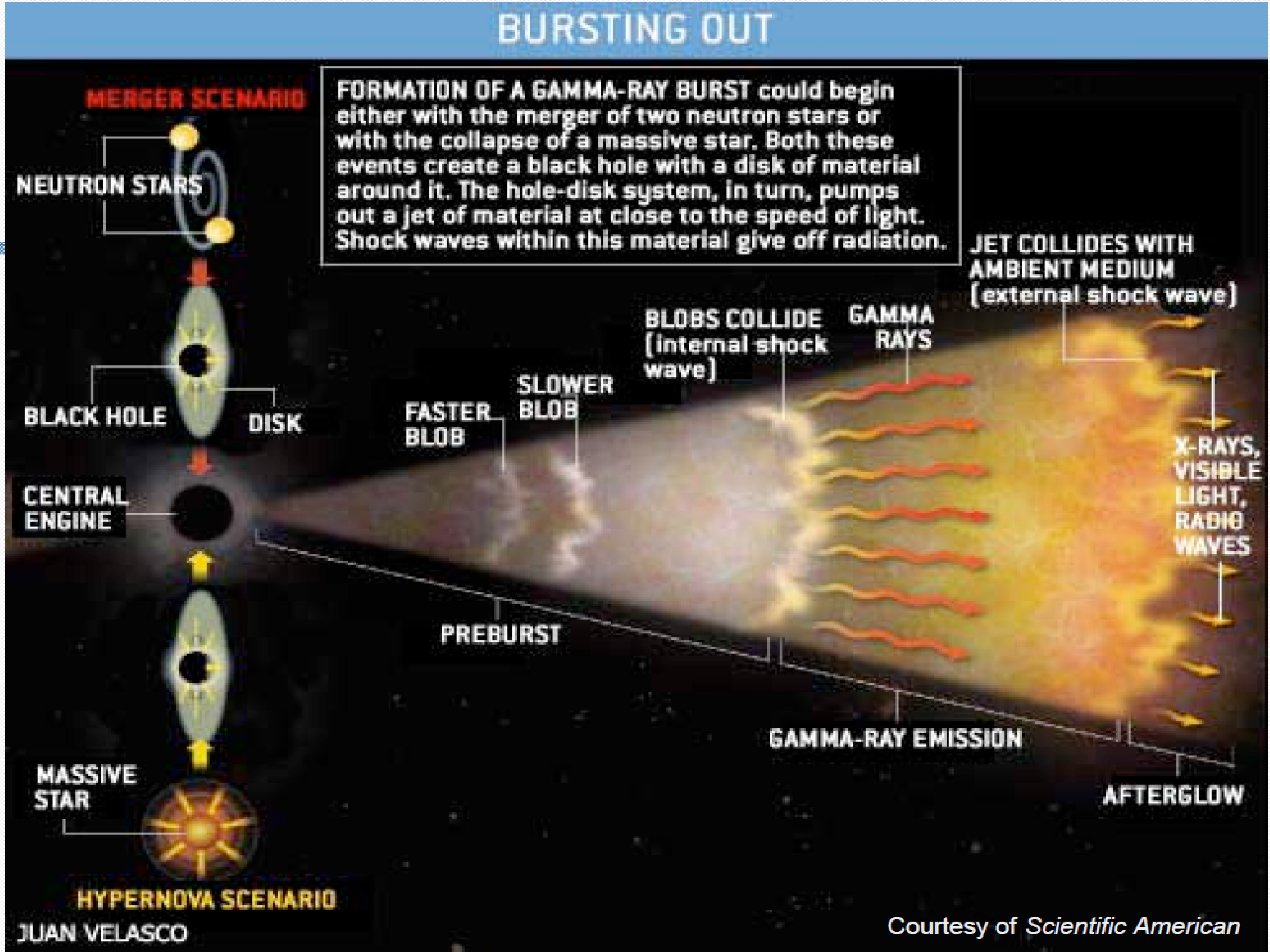
These fluences and redshifts imply an isotropic energy release E_{iso}~10^{51} - 10^{54} ergs from GRBs

Beaming corrections to emitted energy

- *There are many reasons to believe that GRB emission is beamed (relativistic beaming, GRB emission mechanism)*
- *Beaming angle can be measured by breaks in the afterglow lightcurves*
- *After correcting for the case of a beamed geometry, isotropic energy released ~5*10^{50}ergs*
- *GRB emission now comparable with the emission from supernovae*



D. A. Frail. Astro-ph/0311301

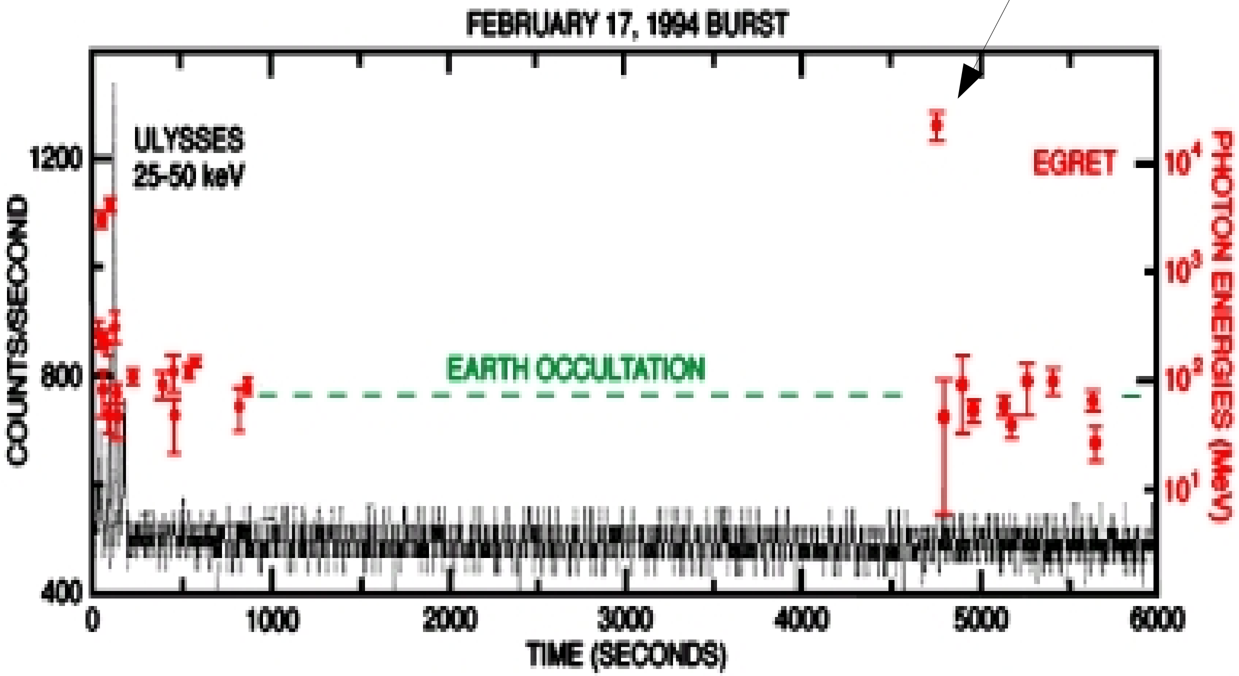

BURSTING OUT
MERGER SCENARIO
FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.
NEUTRON STARS
BLACK HOLE
DISK
CENTRAL ENGINE
MASSIVE STAR
HYPERNOVA SCENARIO
FASTER BLOB
SLOWER BLOB
BLOBS COLLIDE (internal shock wave)
GAMMA RAYS
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
X-RAYS, VISIBLE LIGHT, RADIO WAVES
PREBURST
GAMMA-RAY EMISSION
AFTERGLOW
JUAN VELASCO
Courtesy of Scientific American

HE & VHE Emission from GRBs

- *Leptonic origin*
  - *Inverse Compton scattering of synchrotron photons (SSC), X-ray and UV-flare photons and photons from reverse shocks*
- *Hadronic origin*
  - *If GRBs create UHECR, then the energetic protons might emit energetic photons via synchrotron emission.*
    - *10^{20}eV protons --> up to 300GeV photons*
  - *π_0 decay*
    - *π_0 production from pγ or pn collisions in the prompt phase, and subsequent decay of the π_0*

High Energy Emission from GRBs

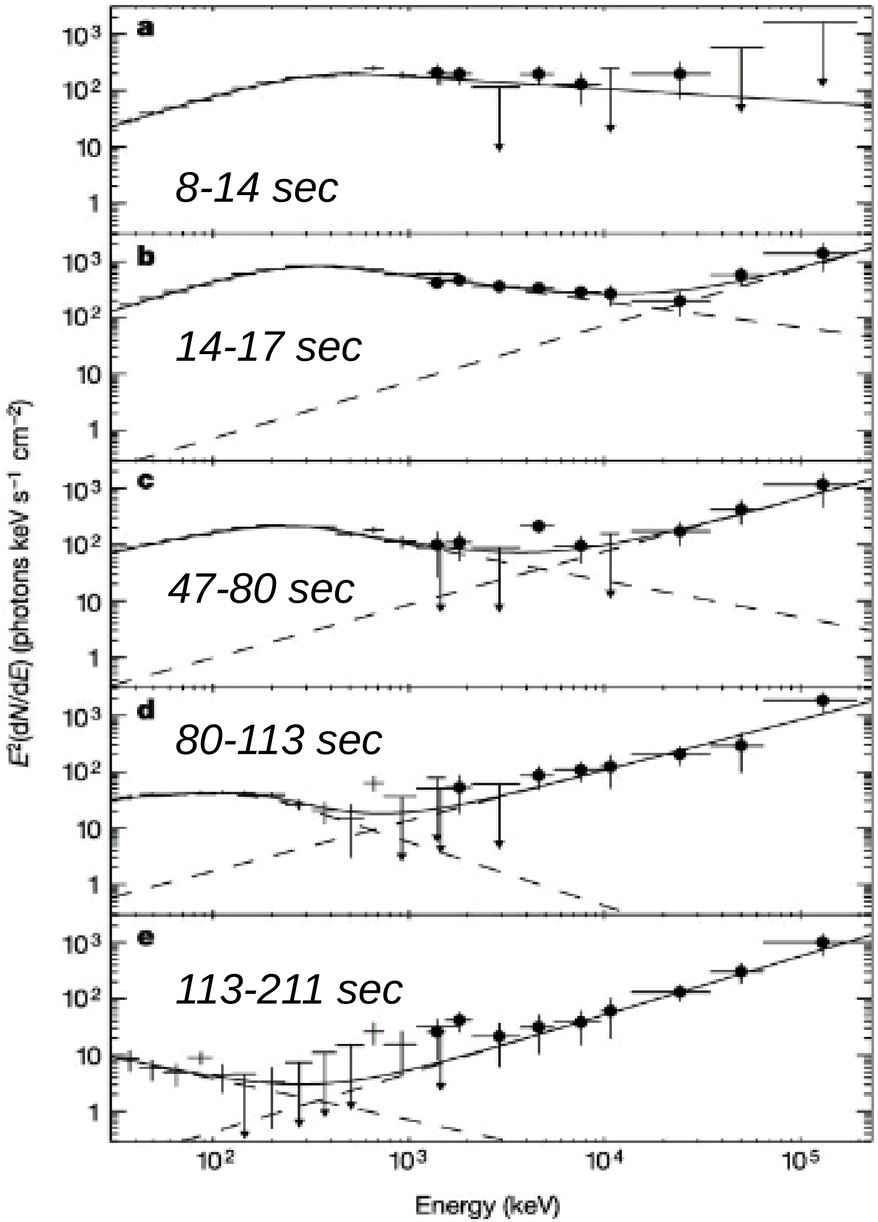
- *High Energy Observations*
  - *EGRET: 0.03-30GeV range*
    - *Detected photons above 100MeV from 4 GRBs*
    - *GRB940217: 2 photons at ~3GeV, 1 photon at 18GeV, 90 mins after the prompt emission*



Hurley et al., 1994

Signs of VHE Emission

- Combined BATSE and EGRET data from GRB941017
- *A distinct high energy component extending to at least 200MeV with no sign of a cutoff.*
- *Component could possibly continue to GeV energies*

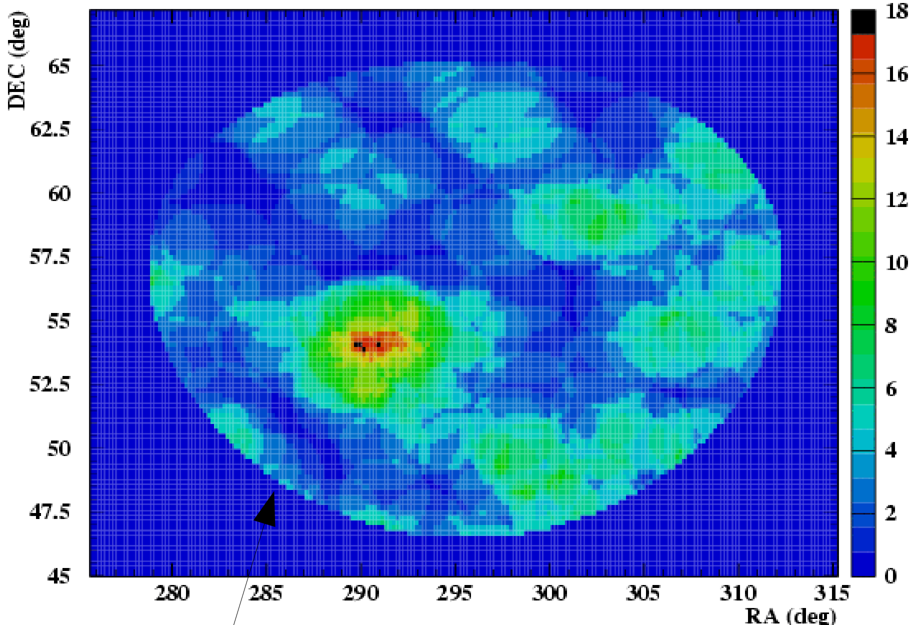


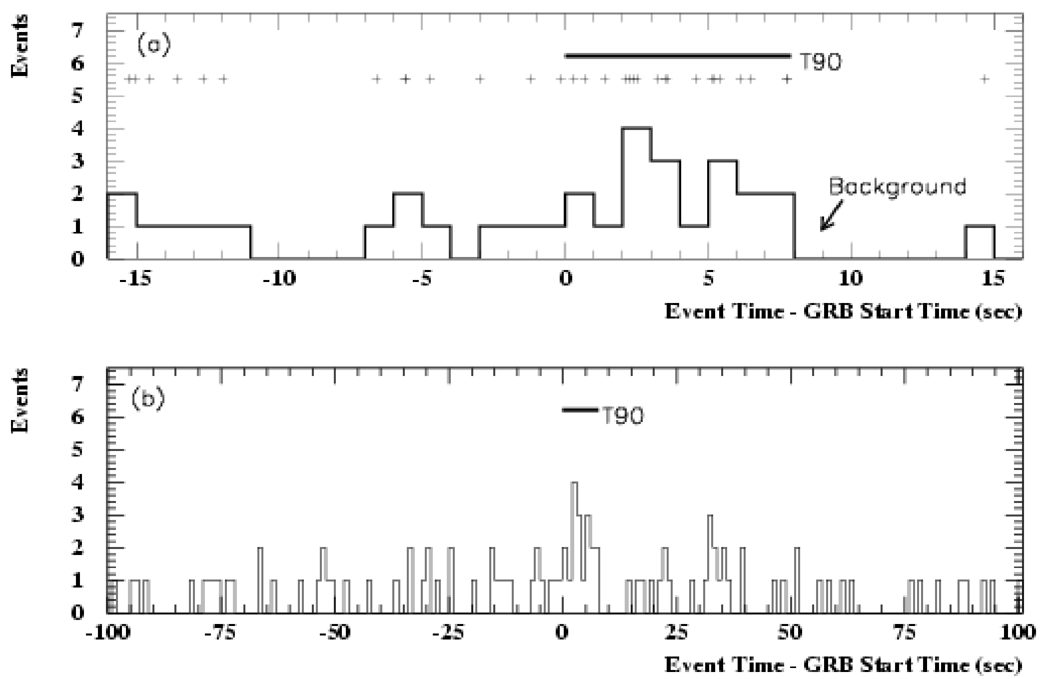
Gonzalez, et al., Nature 424, 847 (2003)

Milagrito

- Milagrito: Observation of the BATSE GRB970417 at GeV energies with 3σ significance.

Events detected by Milagrito



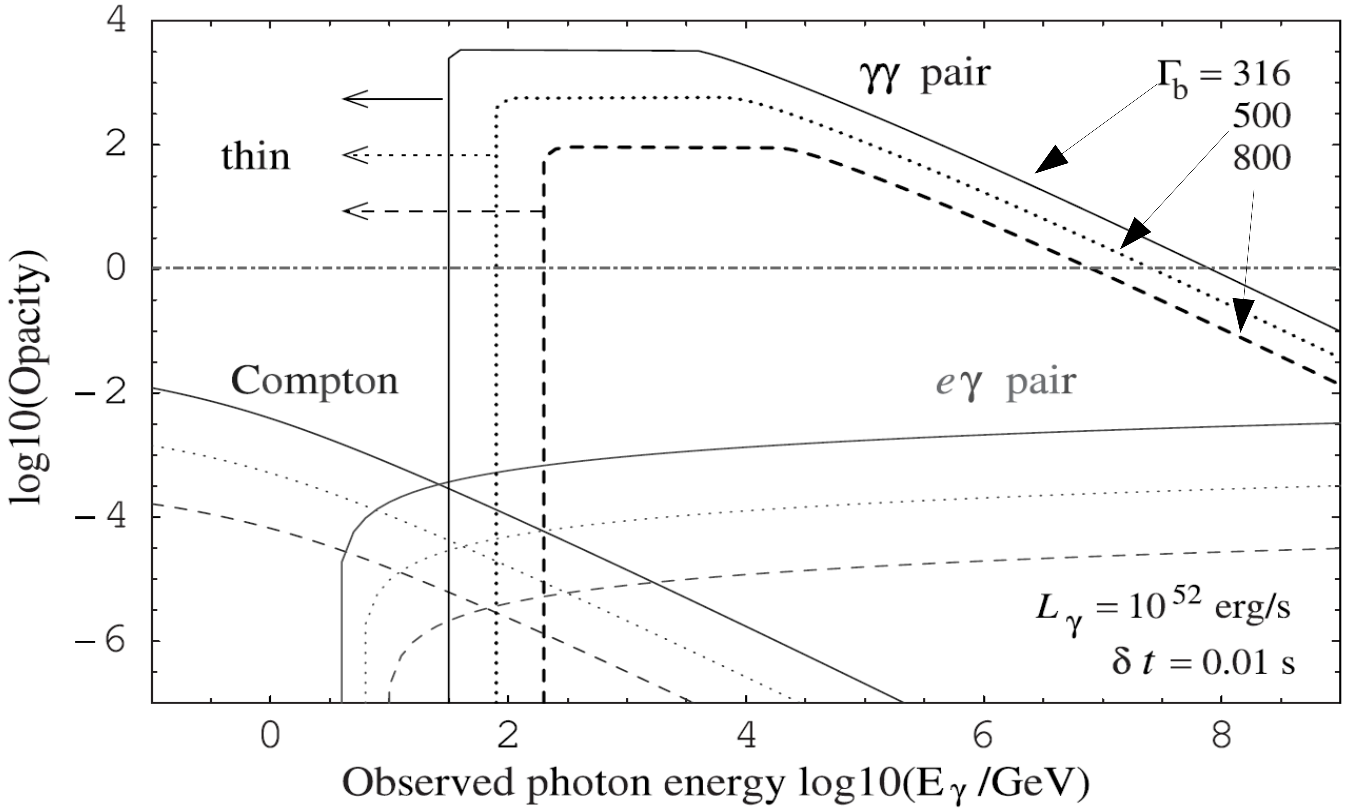


Batse error box

Atkins et al., 2000

Absorption of VHE Photons

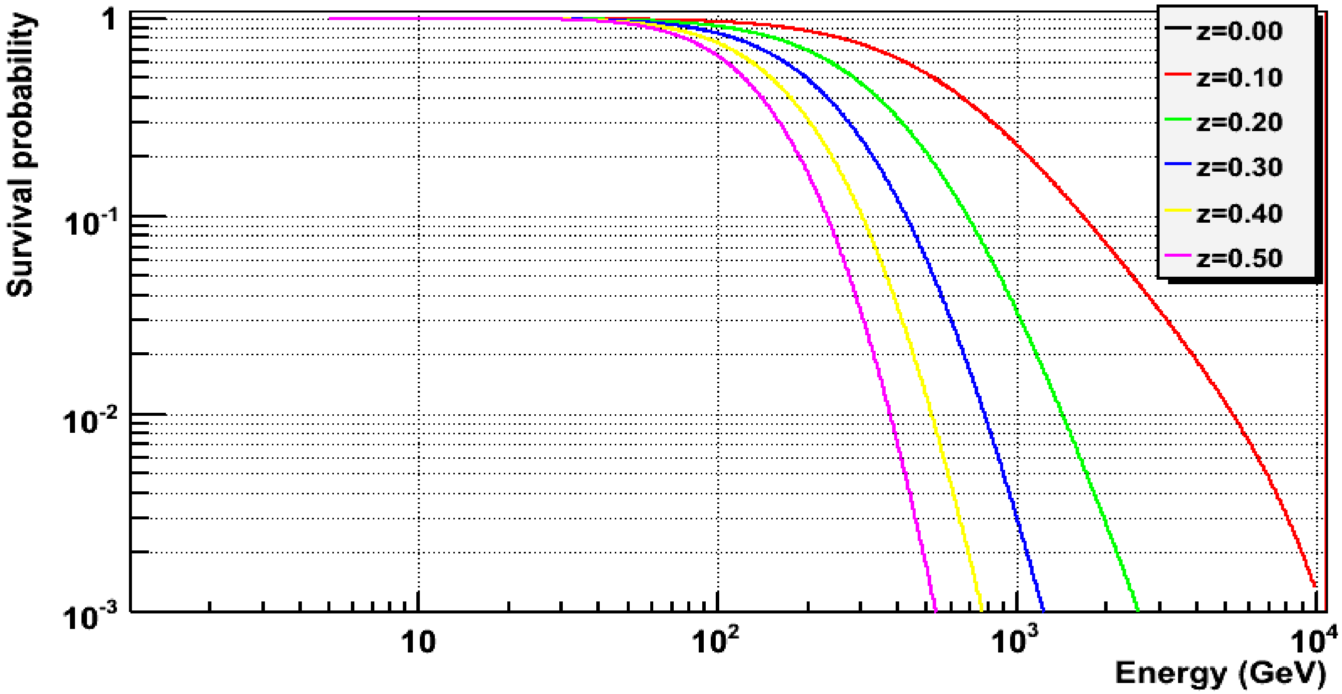
- *Absorption at the source*
  - *GRB Fireball very dense --> opaque to higher energy photons*
  - *$\gamma\gamma \rightarrow e^+e^-$ dominates*
  - *Very high bulk Lorentz factors can lower the opacity*



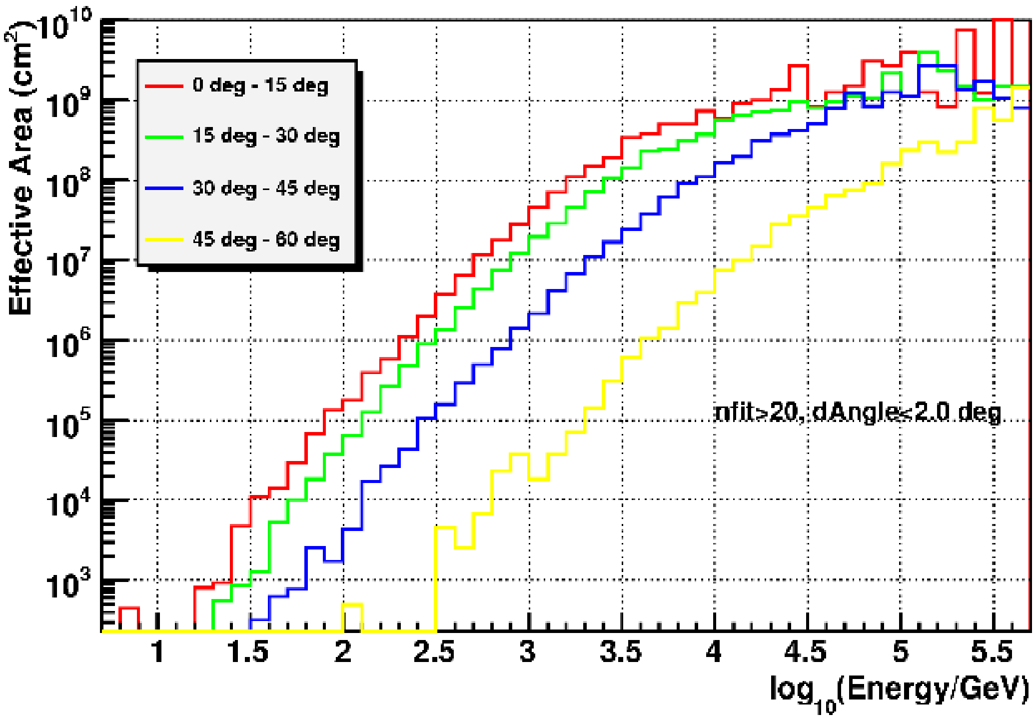
Razzaque et. al 2004

Absorption of VHE Photons

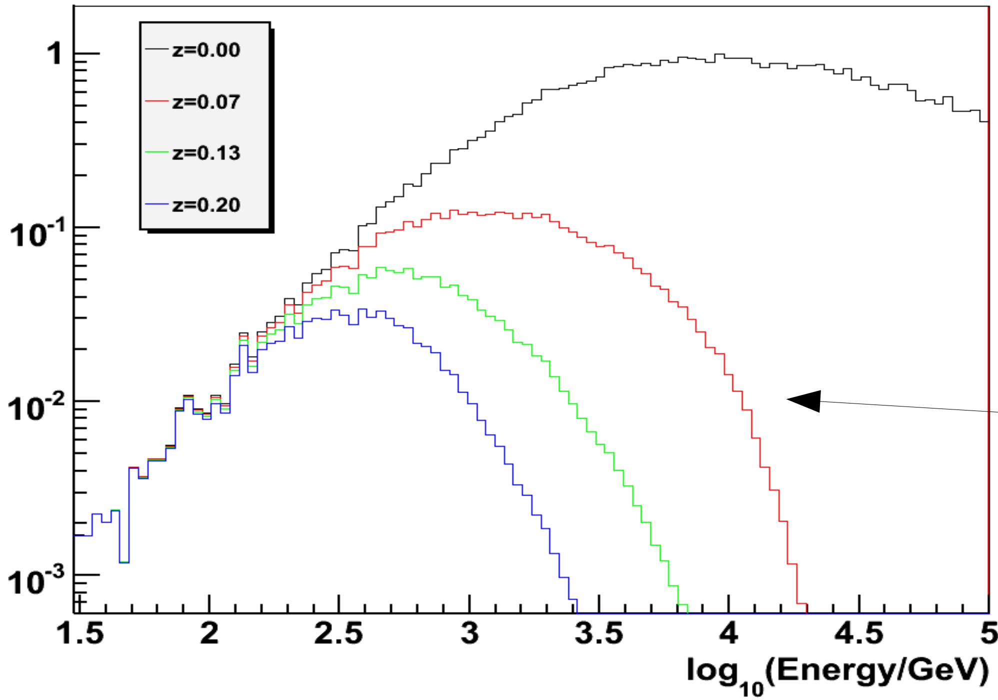
- *Absorption from the Infrared portion of the Extra-Galactic Background Light (EBL)*
  - $\gamma_{VHE}+\gamma_{IR}\text{->}e^{-}e^{+}$
  - *Limits the "volume" of the observable universe in GeV-TeV energies*



Effects of IR Absorption



Energy distribution of triggered events vs redshift for a -2.2 exponential spectrum



IR absorption removes the high energy events that Milagro is most sensitive at

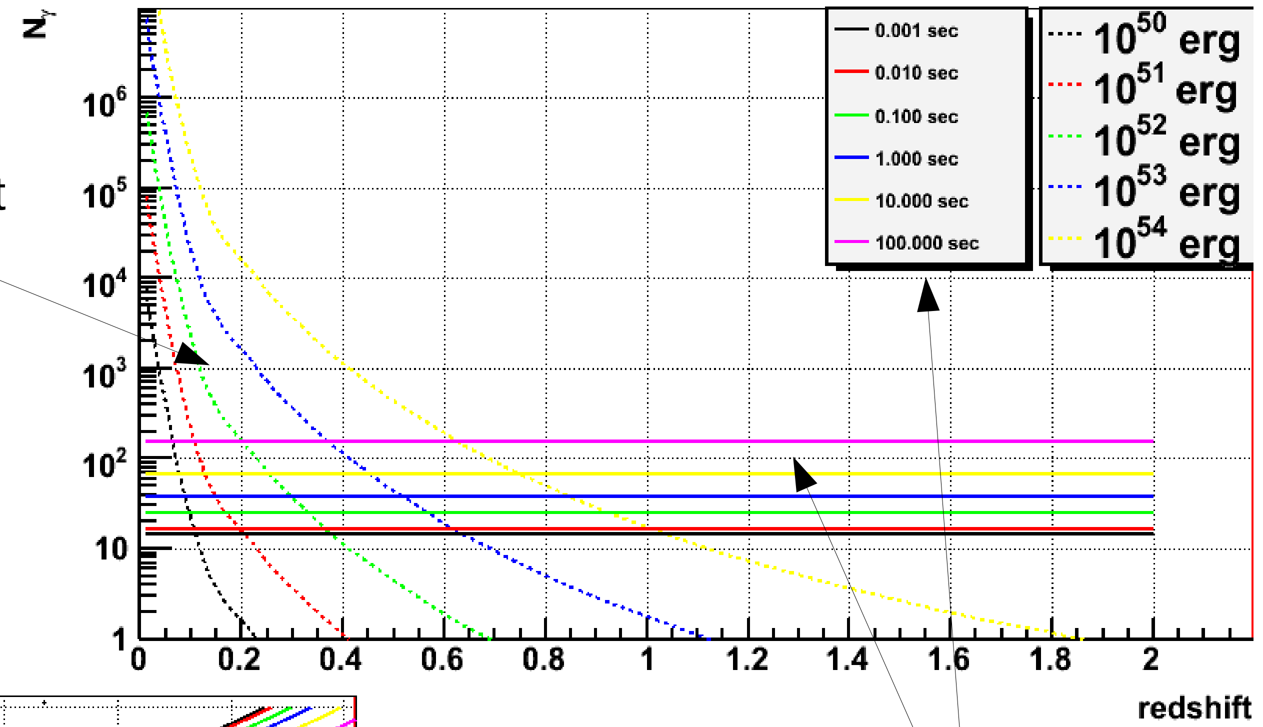
Why Study the Very High Enery Emission?

- *Resolve the contribution of the VHE gamma-ray emission to the total emitted energy*
- *Constrain the hadronic component of the GRB fireball and the potential for emission of ultra high energy Cosmic Rays and Neutrinoes*
- *Provide unique info about the compactness, the emission region size, the dynamics (Lorentz factors)*
- *Understand the progenitor in order to understand the local environment that hosts GRB population*
- *Probe the EBL at high redshifts -> galaxy formation and evolution history*
- *Tests of Lorentz invariance*

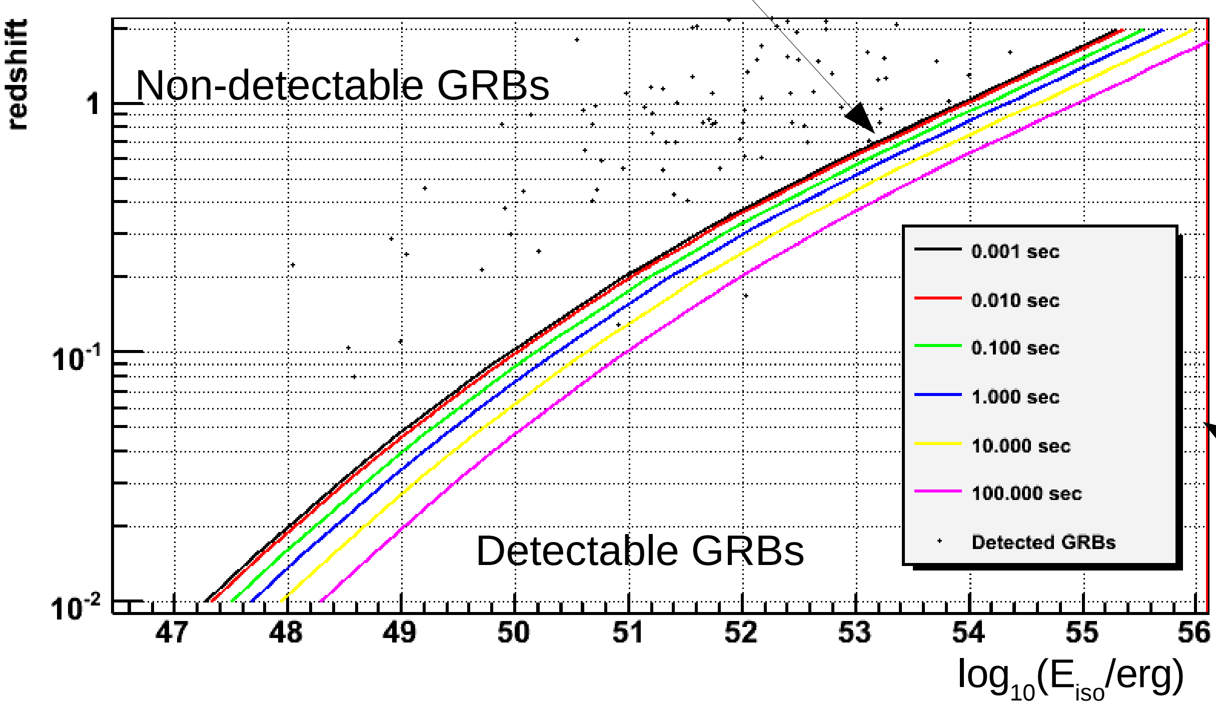
The Blind Search for Gamma-Ray Bursts

Number of events Milagro can detect from a GRB

Number of events caused by GRBs of different isotropic energy emission (in the GeV - TeV range) versus redshift



Maximum detectable redshift vs isotropic emission from a GRB



Minimum number of events needed for a detection for different durations

Milagro can expect to detect only nearby (z<~0.5) GRBs (few GRBs/year)

GRB Searches with Milagro

- *Triggered Searches -> Search in coincidence with a trigger from an external instrument*
  - *E>100 GeV -> Using reconstructed events (blind or triggered)*
  - *E<100 GeV -> Using the scalers (hit rates of individual PMTs)*
- *Blind search (this one)*
  - *Search the entire Milagro data set for a significant excess above the background.*
  - *Unknowns: location, start time, and duration.*
  - *This search is also sensitive to any kind of transient VHE emission (primordial black hole evaporation, soft gamma-ray repeaters etc.)*
  - *Can be used to trigger other detectors*
    - *A version of this search analyzes the online data in real time and is set to send GCN alerts in case an interesting event is detected.*

Search algorithm

- *Search blindly over multiple durations (160ms to 6 mins), start time and location.*
- *For the 1$_{st}$ duration , say T_{DUR}*
  - *Start at $t=t_0$*
  - *Make a finely binned (0.2^o bins) skymap (RA-Dec) with the events from $t_{start}=t_0$ to $t_{stop}=t_0+T_{DUR}$*
  - *Scan a "search bin" over that map*
    - *Calculate expected # of background events*
    - *Count events in the bin*
    - *Calculate Poisson probability that the measured number of events is just a fluctuation of the background*
    - *Move bin by 0.6^o and repeat until all the map is scanned*
  - *Create a new map with t_{start} and t_{stop} advanced by $0.1*T_{DUR}$*
- *Do the same for all durations*
- *Do the same for all times*

Search Details

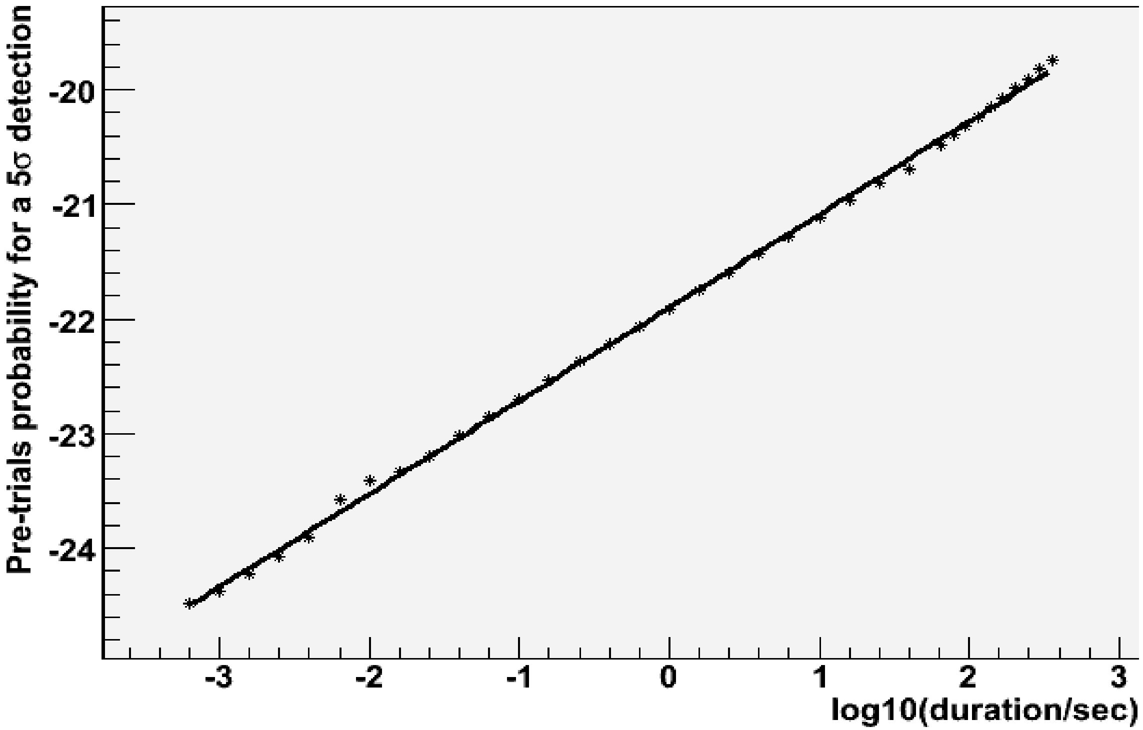
- *Optimizations*
  - *Sensitivity*
    - *Optimize bin size vs duration and zenith angle*
  - *Speed*
    - *Sample more finely around a location in the sky (every 0.2^o instead of every 0.6^o) in case a low probability is found*
    - *An alternative search algorithm for very low durations (dur<0.2sec)*
      - *Instead of scanning the search bin all over each skymap,*
        - *Make a table of the locations where more than 2 events are present*
        - *Evaluate just these locations*
    - *Speed optimizations help with sensitivity too because we can afford the time to search more finely in the duration space.*

Trials and Probability Thresholds

- *Large data set + oversampling → large number of trials*
  - *For the 1 second search this yields ~10^{13} trials per year.*
  - *Use data to find the effective number of trials and then adjust the detection thresholds.*

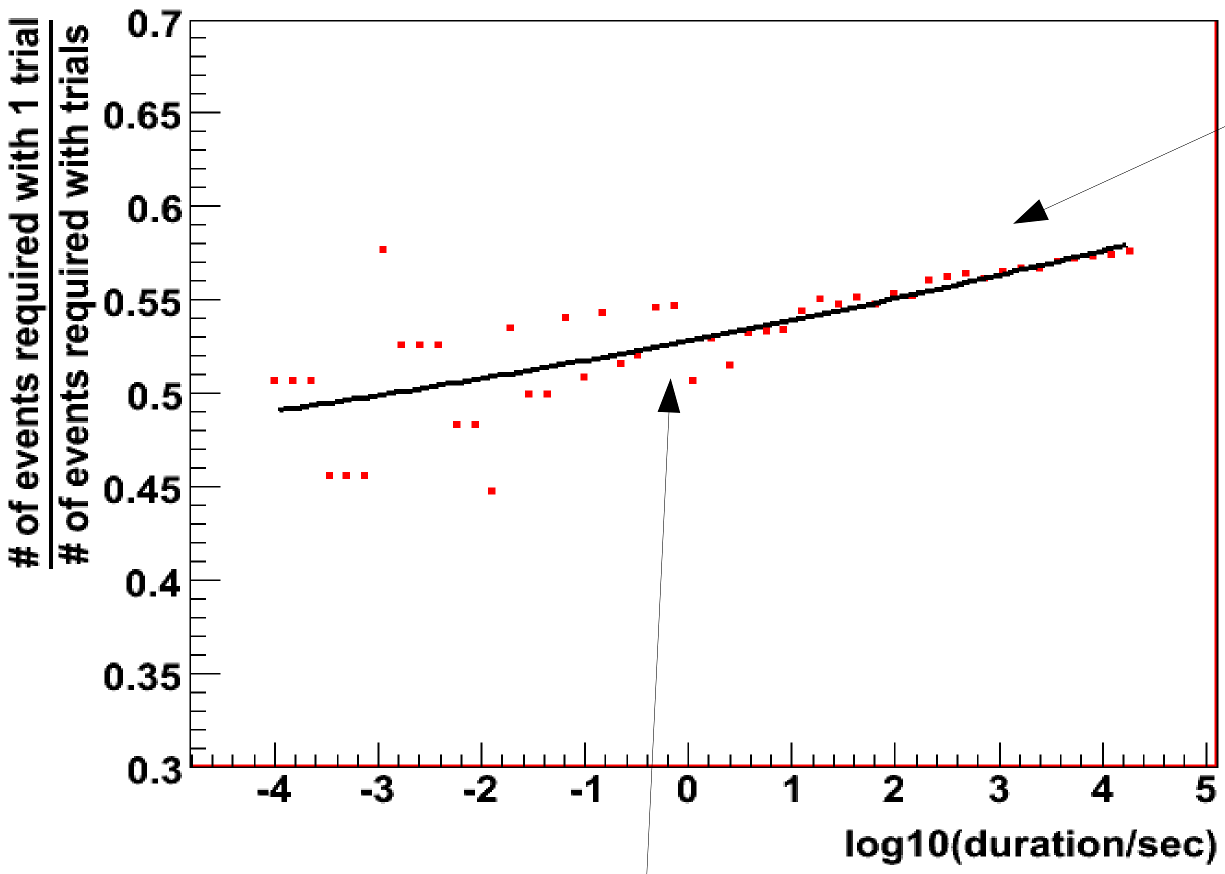
Pre-trials probability for a 5σ detection

Calculation includes number of trials from sampling in space/time, total duration searched and number of durations searched



Loss of sensitivity due to the big number of trials

Because of the big number of trials we need about double the signal to be able to make a detection.



A search in coincidence with an extrernal trigger has about double the sensitivity of this blind search.

Ratio of events required for a 5σ detection 99% of the time

Optimum bin in the Gaussian regime

- *Define N_{Bin} the number of events in a bin, $\hat{N}_{BG}$ the expected number of events in that bin, N_S and N_{BG} the actual number of signal and background events in that bin and S the significance of that search.*

$$\mathbf{S} \equiv \frac{N_{Bin}-\hat{N}_{BG}}{\sigma\left(\hat{N}_{BG}\right)} = \frac{(N_S+N_{BG})-\hat{N}_{BG}}{\sigma\left(\hat{N}_{BG}\right)} \simeq \frac{N_S+\hat{N}_{BG}-\hat{N}_{BG}}{\sqrt{\hat{N}_{BG}}} = \frac{N_S}{\sqrt{\hat{N}_{BG}}}$$

- *Say we apply a cut or a change in the search method that introduces some efficiency of keeping the background (Eff_{BG}) and signal (Eff_S) events.*

- *The new significance will be:*

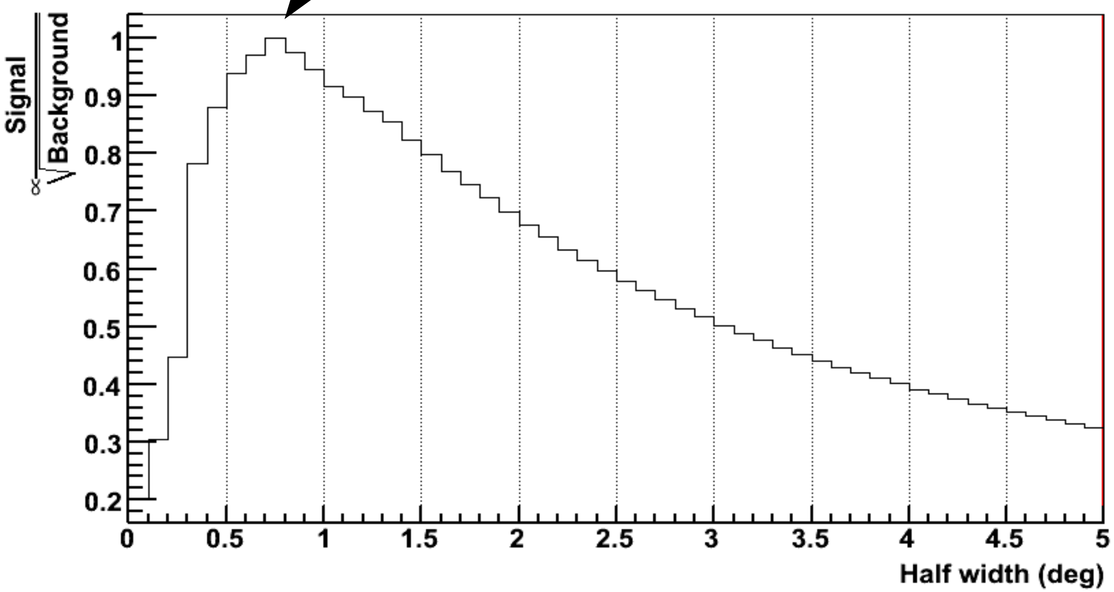
$$\mathbf{S}' = \frac{N_S \cdot Eff_S}{\sqrt{\hat{N}_{BG} \cdot Eff_{BG}}} = \frac{N_S}{\sqrt{\hat{N}_{BG}}} \cdot \frac{Eff_S}{\sqrt{Eff_{BG}}} = \mathbf{S} \cdot \frac{Eff_S}{\sqrt{Eff_{BG}}}$$

- *To find the optimum cut or search configuration we maximize the ratio* $\frac{Eff_S}{\sqrt{Eff_{BG}}}$

Optimum bin size in the Gaussian regime

- *In this case $Eff_{BG}(w)$ is proportional to the area of the bin and $Eff_S(w)$ comes from the point spread function of the detector.*

Optimum bin half-width ~0.8°



For a source at z=0.2
-2.2 spectral index

Optimum bin in the Poisson regime

- *For small statistics (shorter durations) Gaussian statistics cannot be used*
  - *The above equations cannot be applied*
- *Use Poisson statistics to calculate the significance or the probability corresponding to a measurement*
  - *Optimize the bin size by finding the one that minimizes the chance probability P_c*
  - *You can always go back and calculate the significance from the probability:*

$$P_c(n) = \int_n^\infty \frac{dy}{\sqrt{2\pi}} \exp\left(\frac{-y^2}{2}\right)$$

$$n \simeq \sqrt{-2 * ln(P_C)}$$

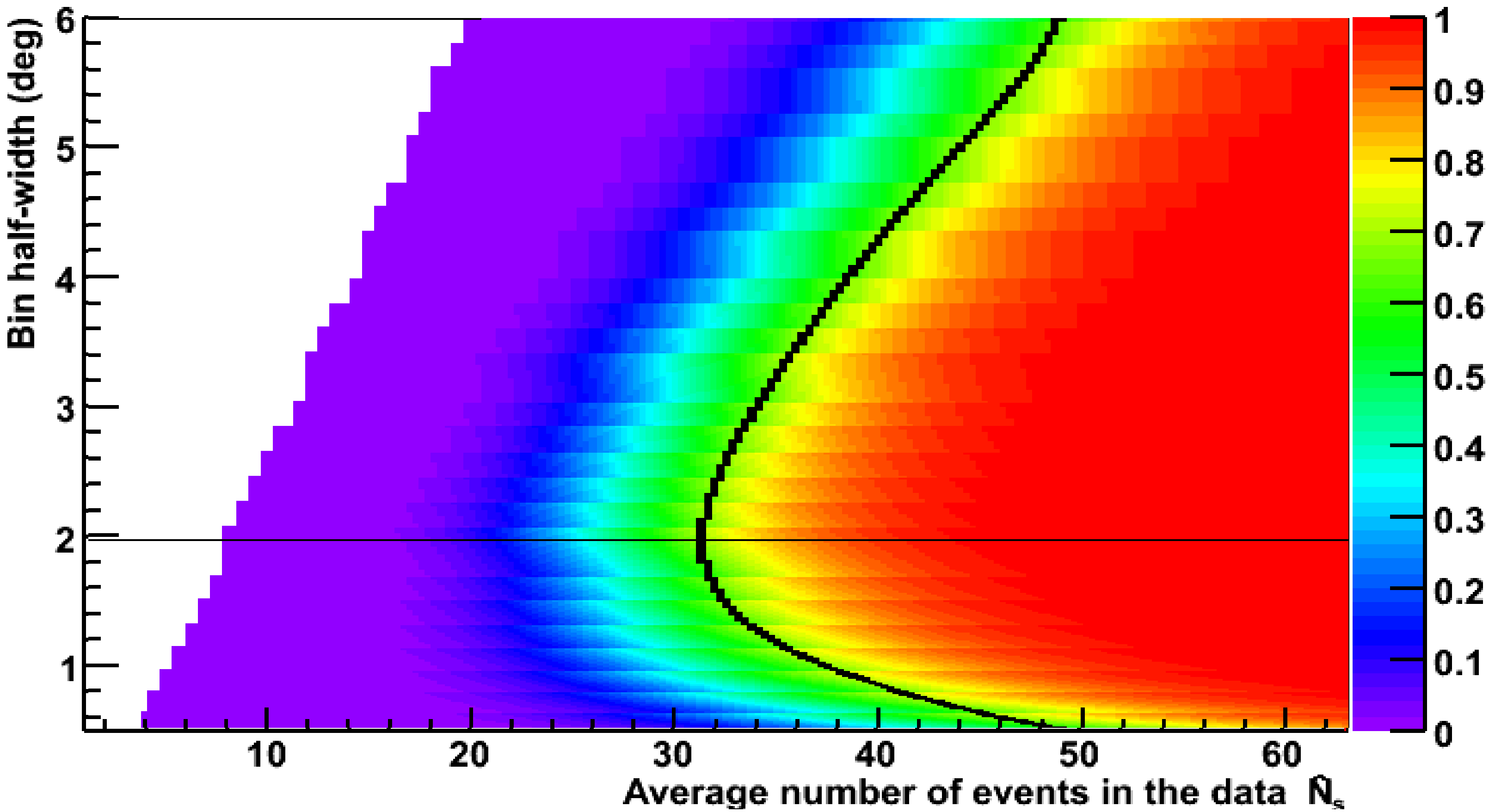
Optimizing the bin size

Most of the signal
but too much background.
Non optimum detection
probability

Almost no detections

Some detections depending
on the bin size

Detection
probability ~1



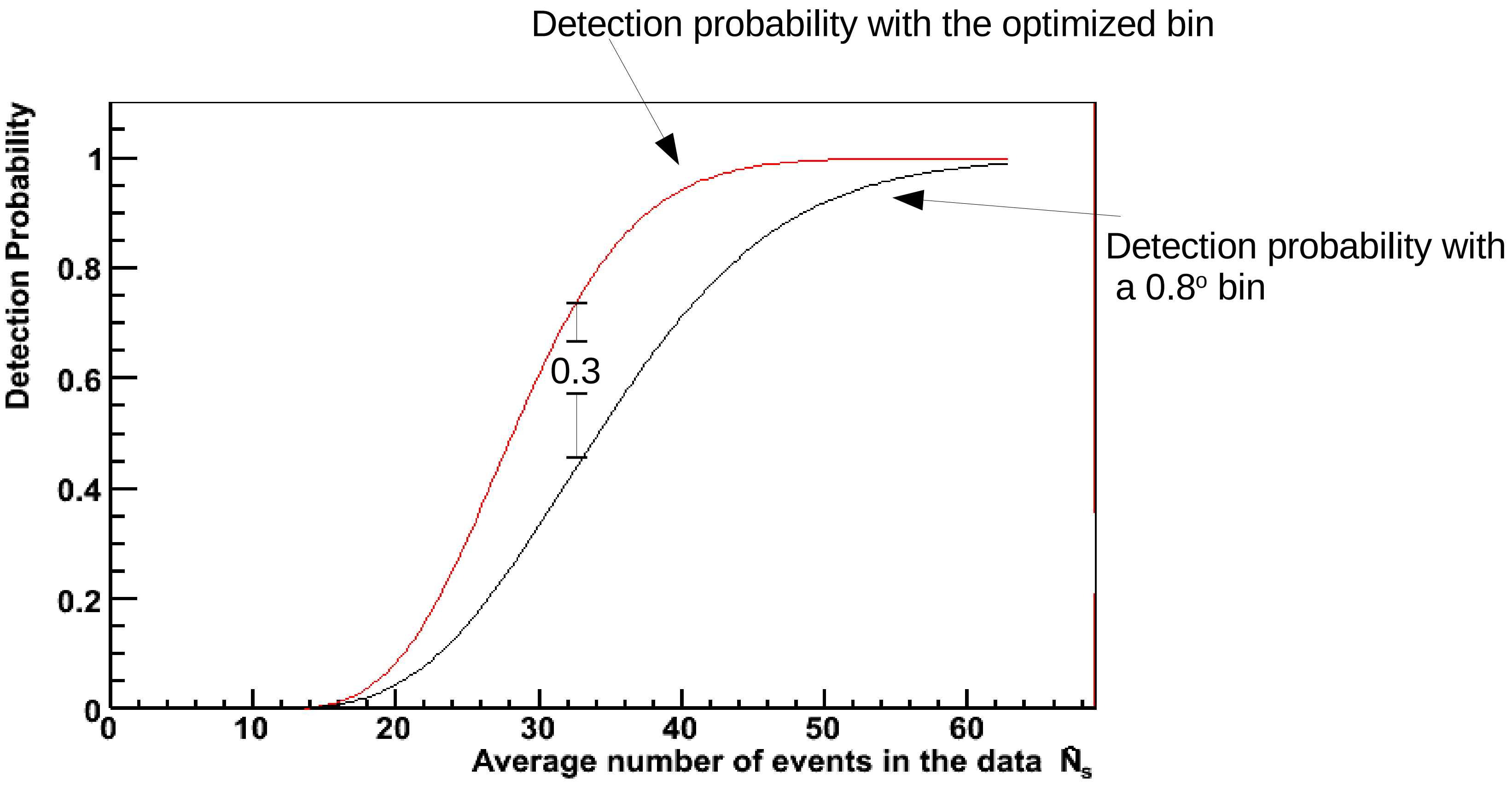
Optimum amount of
signal and background.
Det. Prob. maximized

Small background
Very small signal
Non optimum detection
probability

Detection probability of a signal N_s in the data set vs the bin size

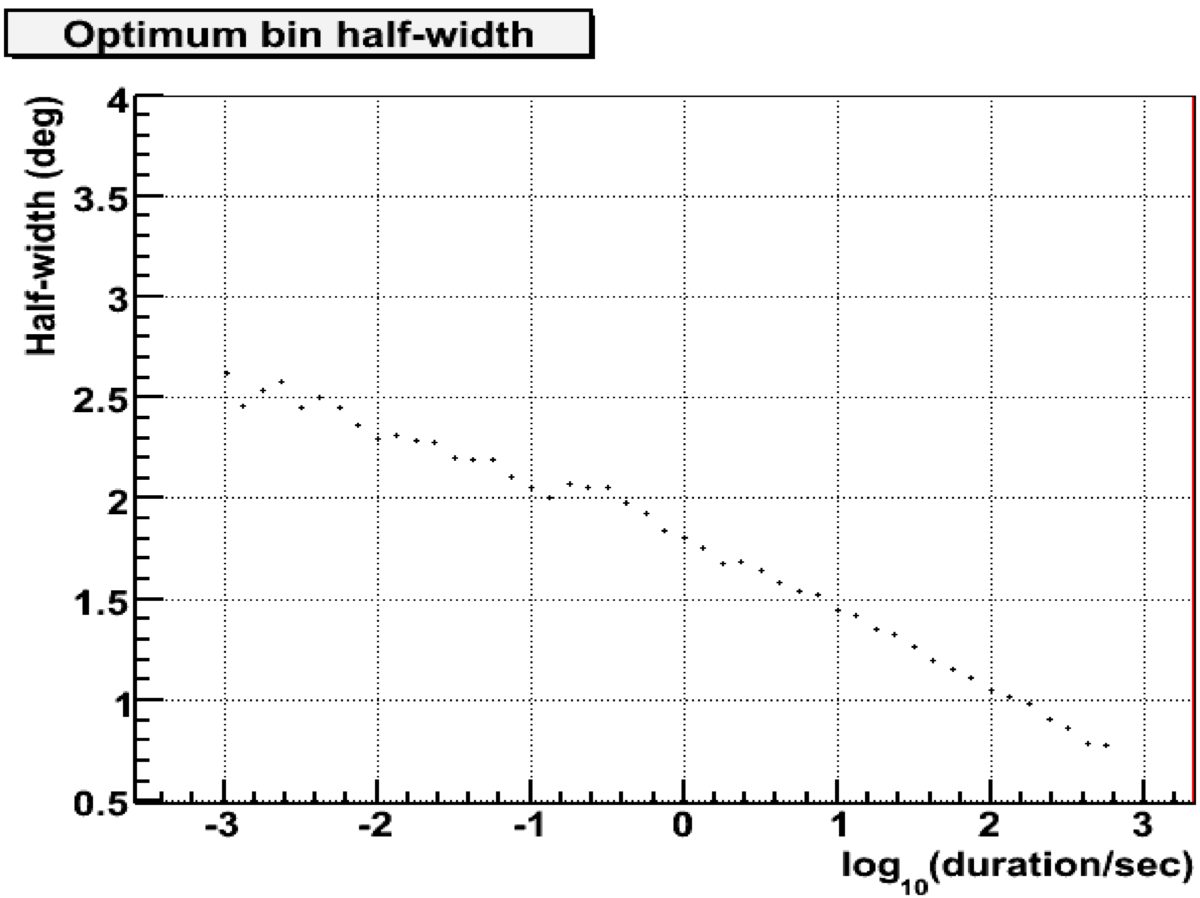
0.3sec duration, 15^o-30^o zenith angle,

Improvement in Detection Probability



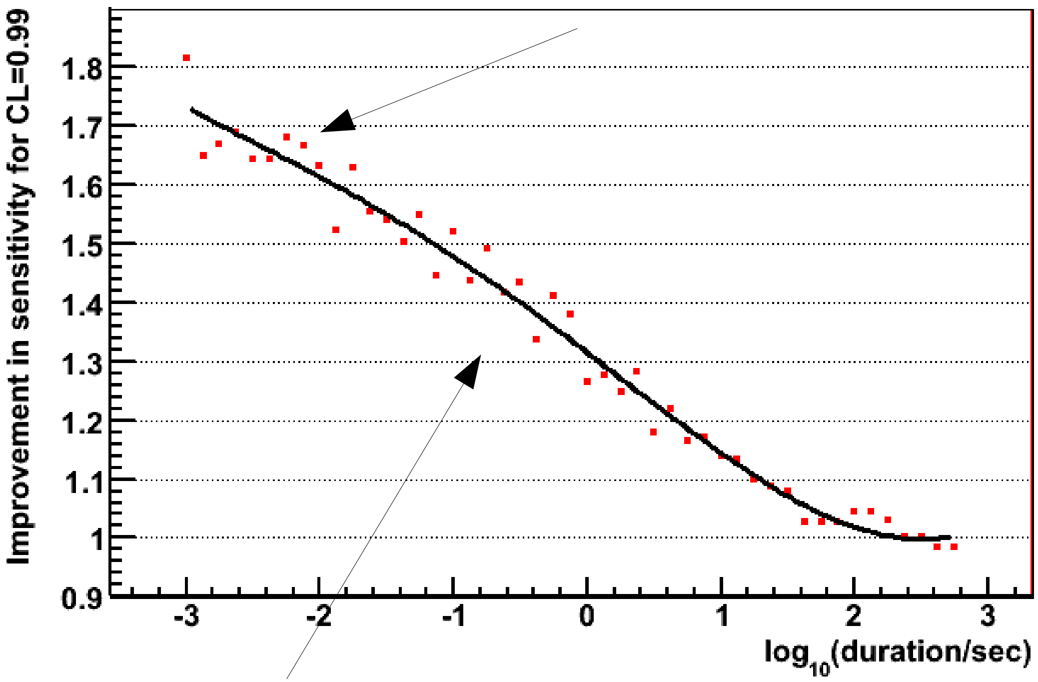
Detection probabilities for t=0.3sec

Optimum bin size



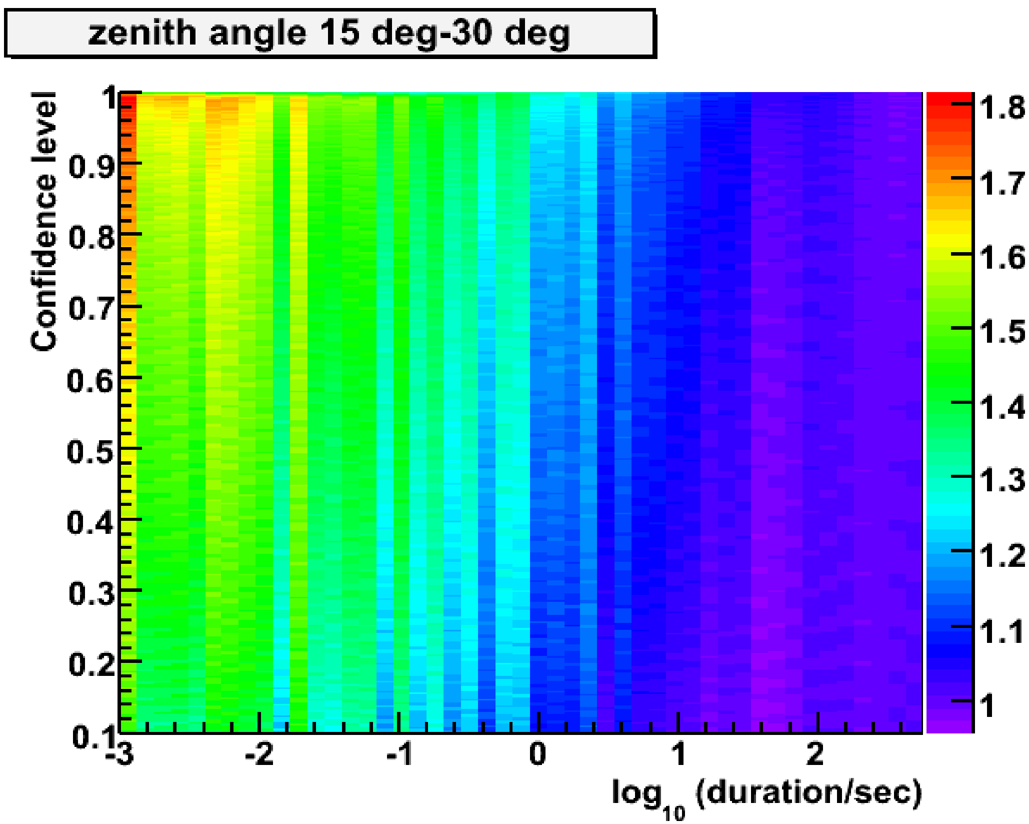
Improvement in sensitivity

Can detect signals (CL=0.99) that are ~40% smaller than the ones detectable with the fixed bin-size



Ratio of the signal needed for a 5σ detection 99% of the times with a 0.8° bin over the signal needed with the optimum bin.

Considerable improvement in sensitivity for the short durations



Improvement in sensitivity for all Confidence Levels

Results

- Searched 4 years of Milagro data, (5/15/2003) to 54234 (5/14/2007)
  - Fixed bin size
  - No significant events have been detected.
  - Results presented at the ICRC
- New search underway with optimized bin size
  - Finishing in about a week
- Generate meaningful physics results
  - Set upper limits on the VHE emission from GRBs
  - Analyze any significant events detected

From Milagro to GLAST

- *GRBs*
  - *200 MeV - 300 GeV emission (answer questions of slide #42)*
  - *Very distant GRBs (z>~6)*
    - *Trace evolution of the universe (SFR, metallicity, intergalactic medium, IR background..)*
- *Diffuse Galactic Gamma-Ray Emission*
  - *Measurements + GALPROP*
    - *Understand diffusion and acceleration of cosmic rays in our galaxy*
    - *Measure density of gas and radiation fields in various locations*
    - *Obtain a background model for point-source searches*
    - *Let us measure the extra-galactic diffuse gamma-ray emission*
    - *Origin of the GeV excess seen by EGRET*

From Milagro to GLAST

- *Diffuse Extra-Galactic Gamma-Ray Emission*
  - *Resolve thousands of AGNs and other point sources -> constrain their contribution to the extra-galactic diffuse emission*
  - *Try to find the sources of the remaining truly diffuse component*
    - *WIMPs? Primordial-Black Holes (PBH)?*
    - *Excellent energy resolution -> spectral signatures*
- *Dark Matter*
  - *WIMPs, PBH*
  - *Anyone care about axions?*
    - *Recent papers propose methods of searching for axion-like particles in the gamma-ray data*
      - *Axion-photon inter-conversions can increase the transparency of the universe to GeV-TeV gamma-rays (test by examining the GeV cutoffs of very distant sources)*
      - *Axion-photon inter-conversions can supress finite energy bands in the MeV-GeV spectra of certain sources (AGNs & radio-galaxies)*

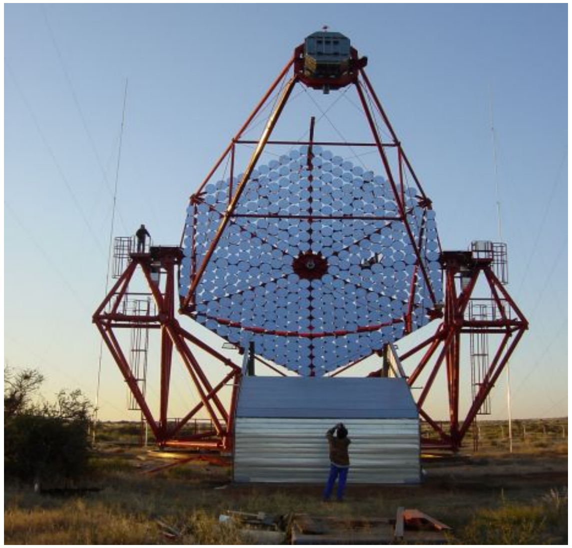
Thank you

Extras

Cosmic Gamma-Ray Detectors

High Sensitivity

HESS, MAGIC, CANGAROO, VERITAS



Energy range GeV-TeV

Large Effective Area ($>10^4$ m^2)

Excellent Background Rejection (>99%)

Excellent Angular Resolution (<0.1°)

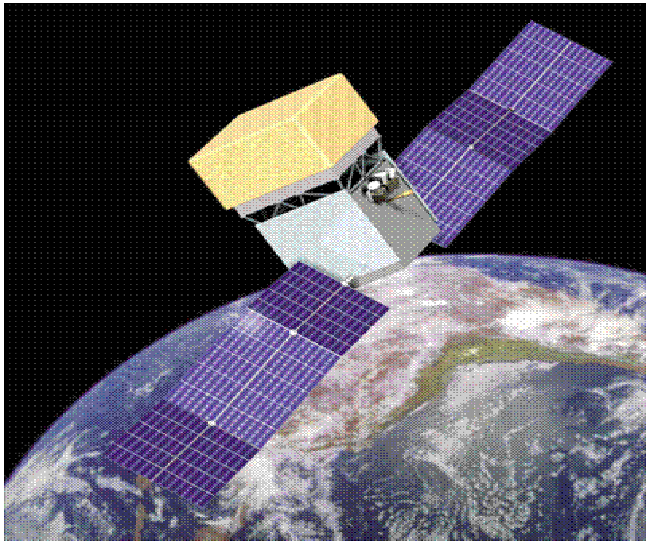
Good Energy Resolution (~20%)

Small Duty Cycle (10%) & Aperture (0.003sr)

- ✓High Resolution Energy Spectra
- ✓High Quality Studies of Known Sources
- ✓Deep Surveys of Limited Regions of Sky
- ✓Source Location and Morphology

Low Energy Threshold

EGRET/LAT



Energy range MeV - GeV

Small Effective Area

“Background Free”

Moderate Angular Resolution

Excellent Energy Resolution (~10%)

Large Duty Cycle & Aperture

- ✓Unbiased Complete Sky Survey
- ✓AGN Physics
- ✓Transients (GRBs, AGN's)

Large Aperture/High Duty Cycle

Milagro, Tibet, ARGO, HAWC(?)

Energy Range GeV-TeV

Large Effective Area

Good Background Rejection (>90%)

Good Angular Resolution (0.3° - 0.7°)

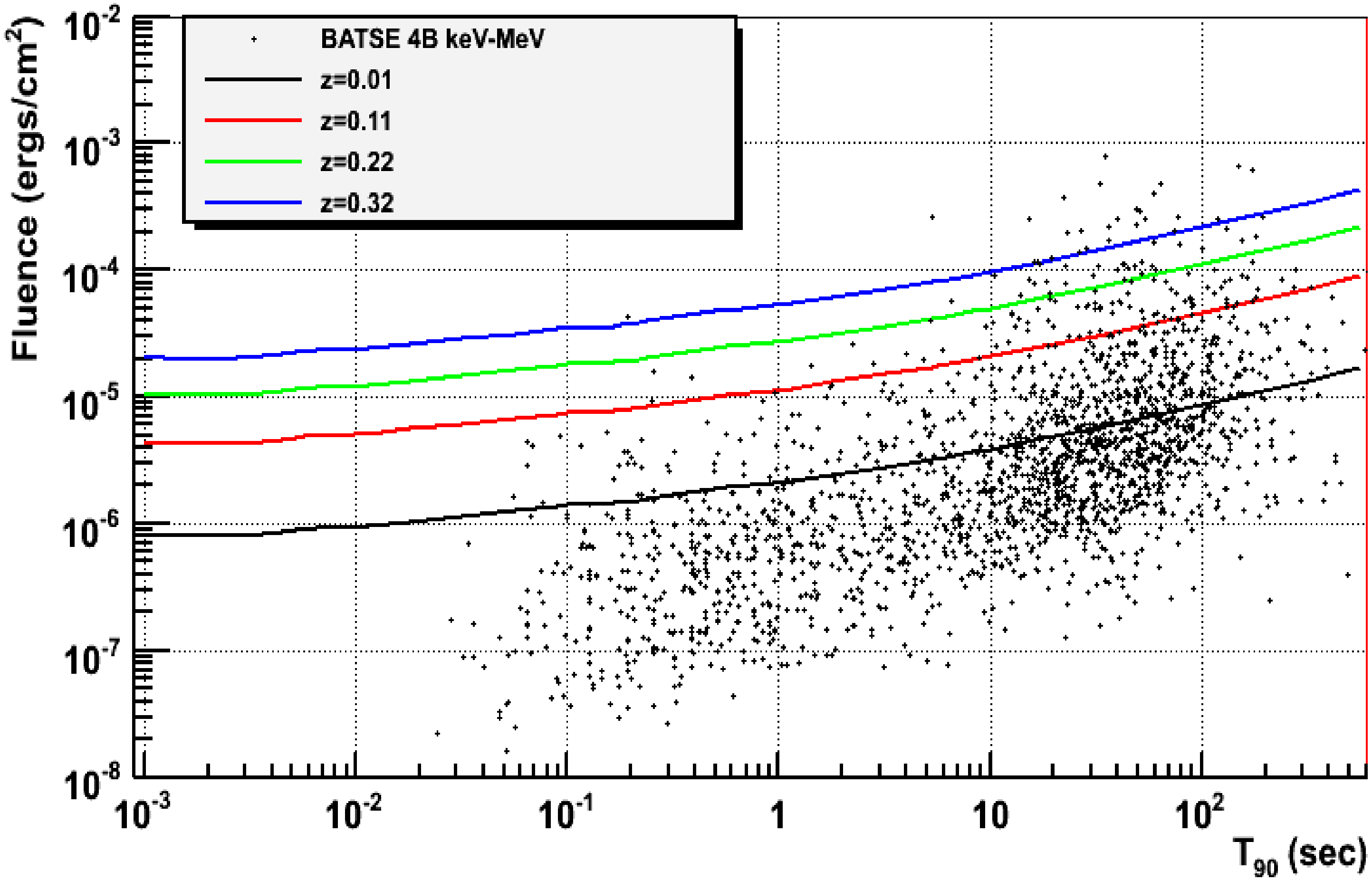
Energy Resolution (~50%)

Large Duty Cycle (>90%) and Aperture (2 sr)

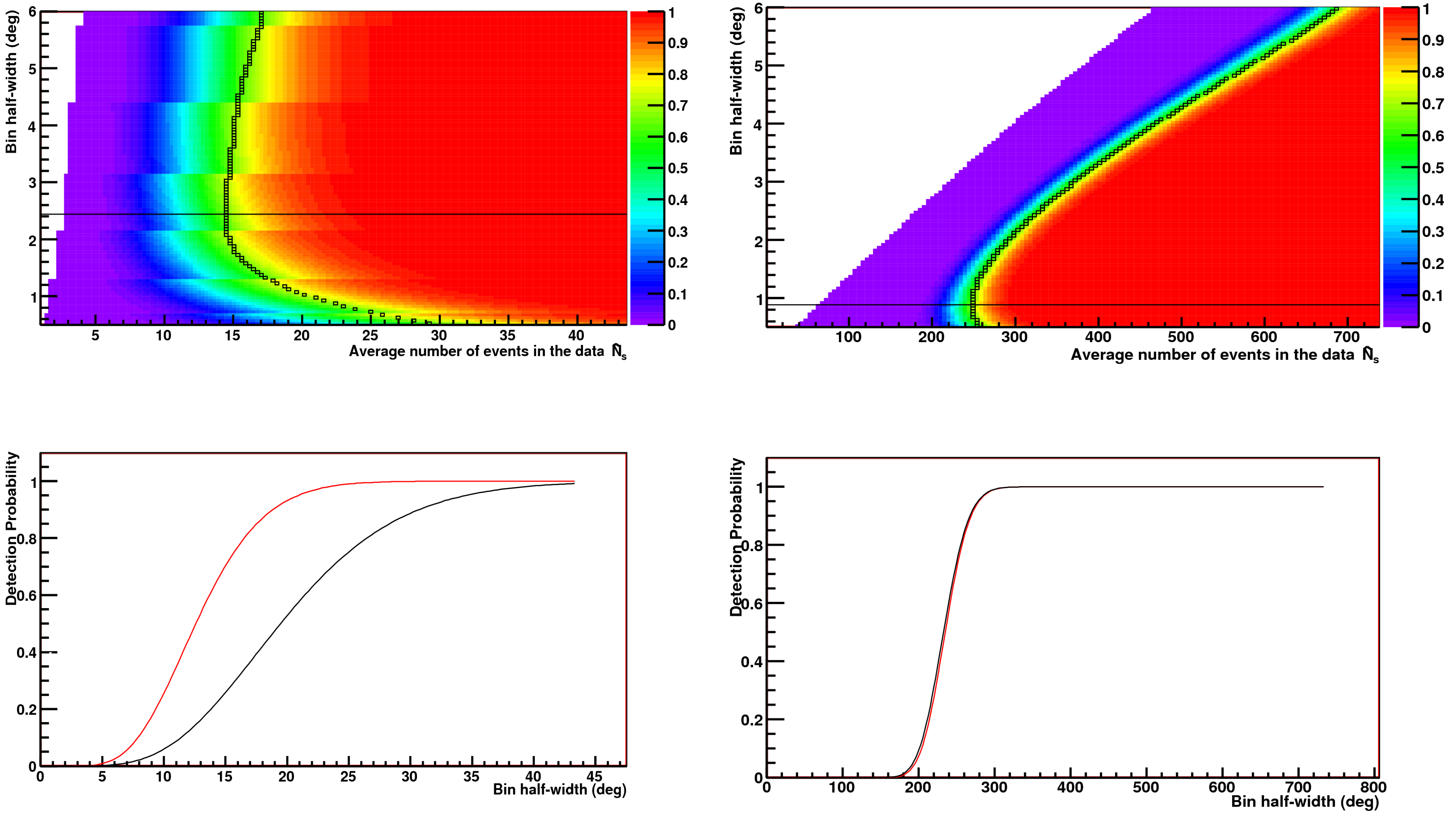
- ✓Unbiased Complete Sky Survey
- ✓Extended sources
- ✓Transients (GRB’s, AGNs)
- ✓Solar physics/space weather

Fluence Sensitivity

- *Integrated fluence from 50GeV-100TeV*
- *For Milagro, this the fluence that reaches the earth (post IR absorption)*
- ***If the GeV-TeV fluence from a nearby burst is comparable to the keV-MeV fluence of BATSE bursts, Milagro should detect the event***



Optimizing the bin size



3ms

3mins

Medium Scale Anisotropy of the TeV Sky