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The VERITAS Dwarf Galaxy Dark Matter Search

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Argonne VERITAS Group

1. *Brief Review of Astrophysical Evidence for Dark Matter*
2. *Why Look for Dark Matter in Dwarf Galaxies?*
   And why other objects are less favorable for IACTs.
3. *VERITAS Overview and Status*
4. *The VERITAS Dwarf Galaxy Observations*
5. *Analysis of Dwarf Galaxy Observations*
6. *Extraction of Flux Limits*
7. *The Future of the Dwarf Galaxy Dark Matter Search*
   a. *VERITAS Plans*
   b. *AGIS/CTA*

Overview of Evidence for Dark Matter (I)

- Jan Oort in 1930s observed M/L ~ 3 from Doppler shifts of stars in Milky Way galactic plane.
- Fritz Zwicky first noted that luminous matter in galaxy clusters was much less than total mass of cluster
  - velocity dispersion of galaxies within cluster
  - perhaps first to propose to use gravitational lensing to determine cluster masses. (one column letter to editor!!!)
  - Coma Cluster which Zwicky cited as evidence for unobserved mass was a VERITAS observational target earlier in 2008; no signal observed.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

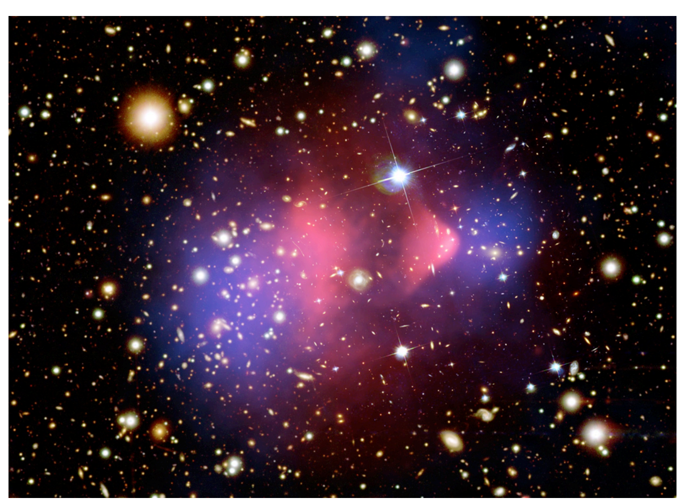
ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

n.b. earlier reference: F. Zwicky, Helv. physica acta, **6**, 110 (1933). also see F. Zwicky, “Nebulae as Gravitational Lenses”,Phys. Rev. **51**, 290 (1937)

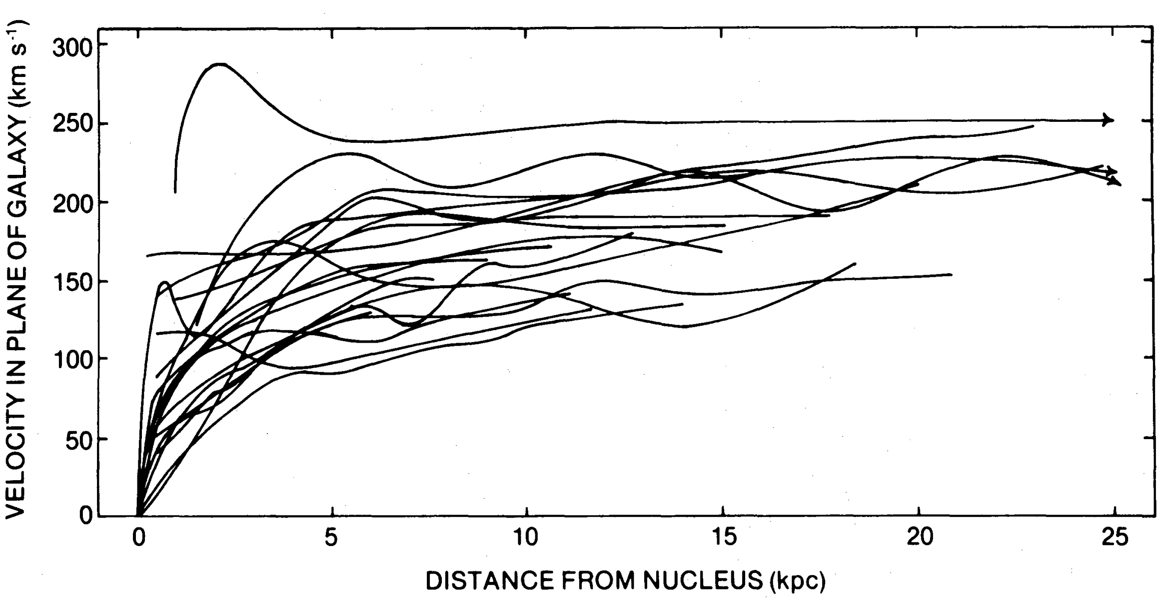
(3) The problem of determining nebular masses at present has arrived at a stalemate. The mass of an average nebula until recently was thought to be of the order of $M_N = 10^9 M_\odot$, where $M_\odot$ is the mass of the sun. This estimate is based on certain deductions drawn from data on the intrinsic brightness of nebulae as well as their spectrographic rotations. Some time ago, however, I showed[2] that a straightforward application of the virial theorem to the great cluster of nebulae in Coma leads to an average nebular mass four hundred times greater than the one mentioned, that is, $M_N' = 4 \times 10^{11} M_\odot$. This result has recently been verified by an investigation of the Virgo cluster.[3] Observations on the deflection of light around nebulae may provide the most direct determination of nebular masses and clear up the above-mentioned discrepancy.

Dark matter mapped (blue) in Bullet Cluster by gravitational lensing. Hot x-ray gas (red) is bulk of normal matter.



Overview of Evidence for Dark Matter (II)

- Vera Rubin and Kent Ford published first paper on rotation of Andromeda galaxy in 1970 indicating rotation curve falling slower than expected from Keplerian motion.
- In 1980 Rubin, Ford and Thunnard publish rotational properties of 21 Sc spiral galaxies showing unequivocal evidence of dark matter dominance of galaxies



THE ASTROPHYSICAL JOURNAL, **238**:471–487, 1980 June 1

ROTATIONAL PROPERTIES OF 21 Sc GALAXIES WITH A LARGE RANGE OF LUMINOSITIES AND RADII, FROM NGC 4605 ($R = 4$ kpc) TO UGC 2885 ($R = 122$ kpc)

VERA C. RUBIN,[1,2] W. KENT FORD, JR.,[1] AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1979 October 11; accepted 1979 November 29

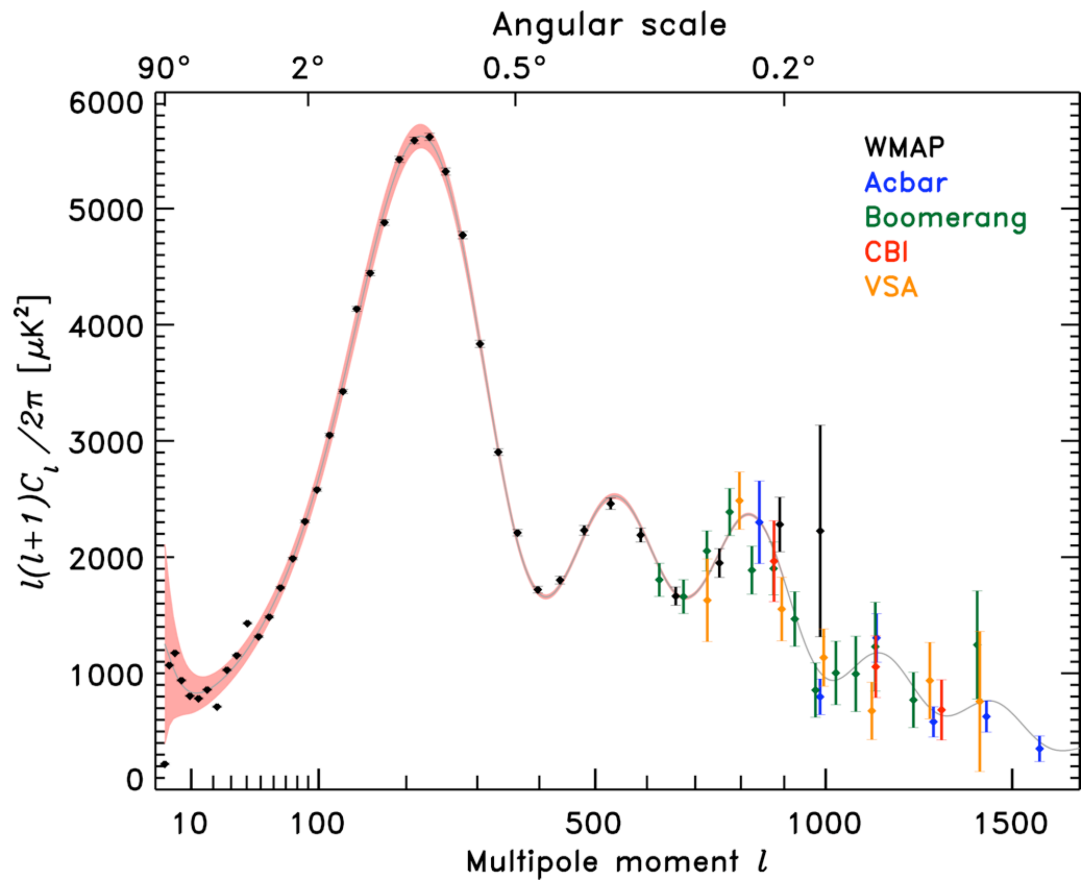
VIII. DISCUSSION AND CONCLUSIONS

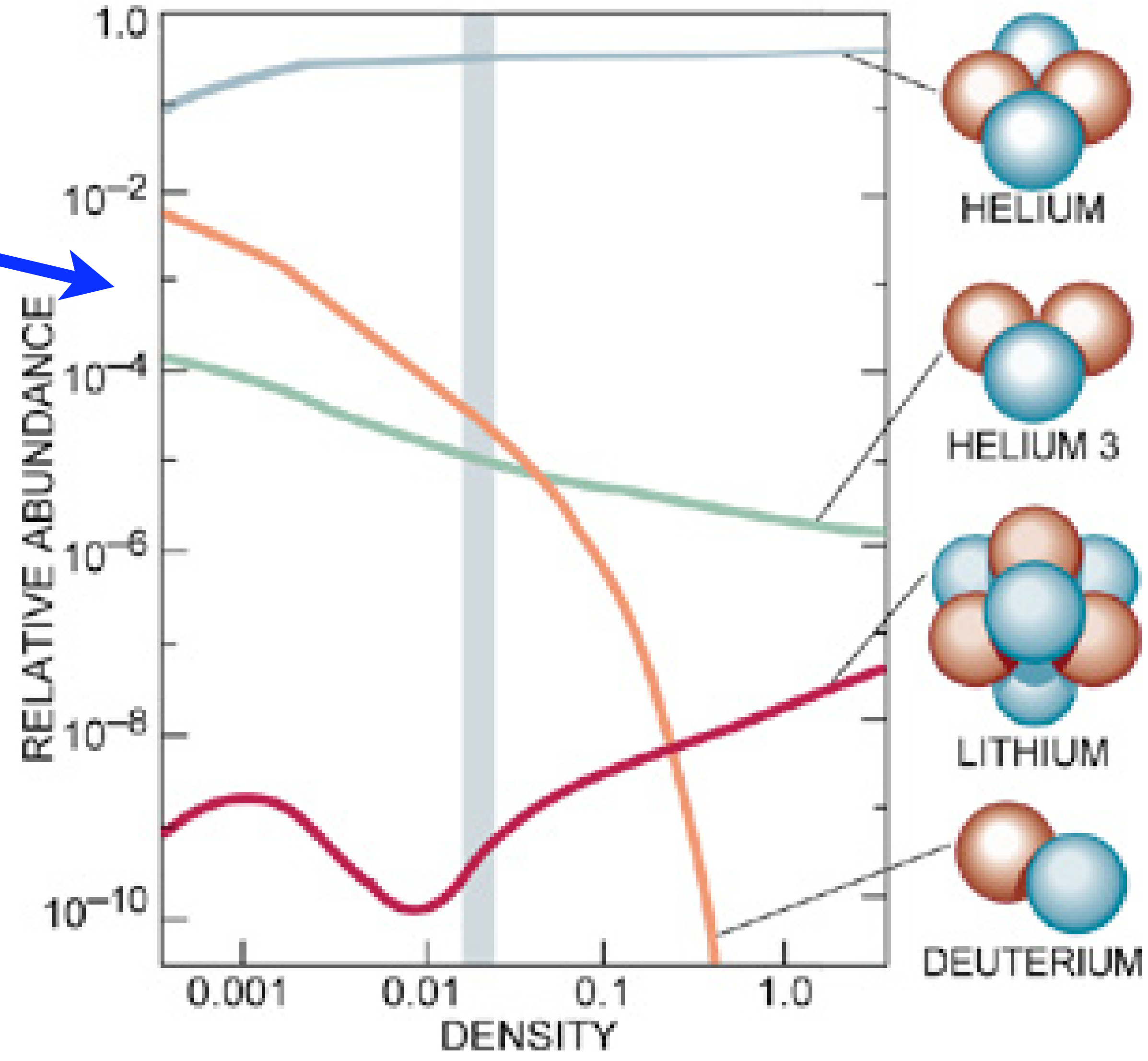
We have obtained spectra and determined rotation curves to the faint outer limits of 21 Sc galaxies of high inclination. The galaxies span a range in luminosity from 3×10^9 to $2 \times 10^{11}\ L_\odot$, a range in mass from 10^{10} to $2 \times 10^{12}\ M_\odot$, and a range in radius from 4 to 122 kpc. In general, velocities are obtained over 83% of the optical image (defined by 25 mag arcsec^{-2}), a greater distance than previously observed. The major conclusions are intended to apply only to Sc galaxies.

1. Most galaxies exhibit rising rotational velocities at the last measured velocity; only for the very largest galaxies are the rotation curves flat. Thus the smallest Sc's (i.e., lowest luminosity) exhibit the same lack of a Keplerian velocity decrease at large R as do the high-luminosity spirals. This form for the rotation curves implies that the mass is not centrally condensed, but that significant mass is located at large R. The integral mass is increasing at least as fast as R. The mass is not converging to a limiting mass at the edge of the optical image. The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.

Overview of Evidence for Dark Matter (III)

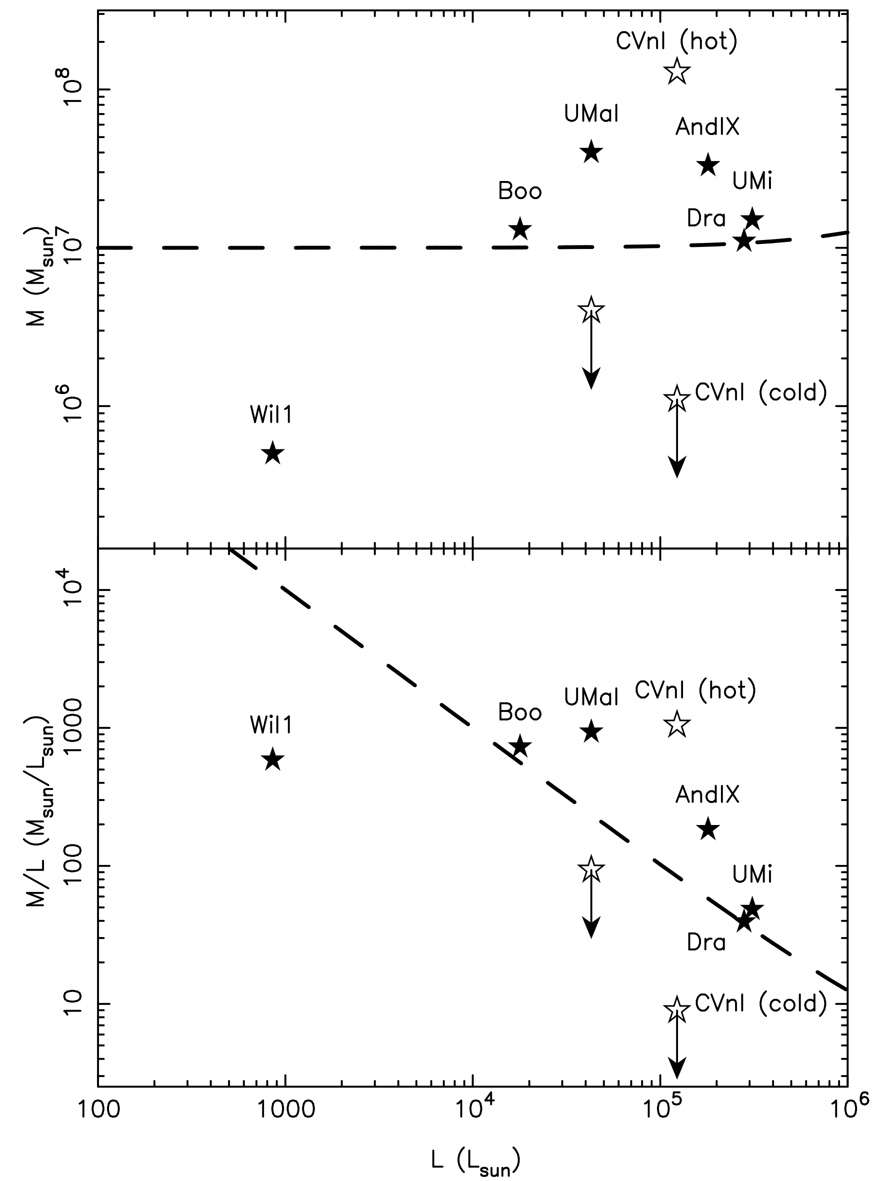
- Measurements of CMB multipole moments and fits to same give (+SN Ia + BAO)
  $\Omega_{baryon}h^2 \approx 0.0227 \rightarrow \Omega_{baryon} = 0.0456$
  $\Omega_{matter}h^2 \approx 0.136 \rightarrow \Omega_{matter} = 0.274$
  $h \approx 0.705$
- Inferred D/H ratio agrees well with BBN





Why Look for Dark Matter in Dwarf Spheroidal Galaxies?

- Stars in dSph galaxies have large velocity dispersions which can indicate
  a) Large Mass/Light ratio ⇨ possible dark matter concentrations
  b) Tidal disruption of galaxy by Milky Way
- Central velocity dispersion has been shown to be generally good indicator of mass
- Earlier data indicated that possibly all dSphs embedded in DM halo of >~$10^7 M_\odot$ indep. of luminous mass
- Low intrinsic (non-DM) γ-ray production
- Willman 1 may be least massive dwarf galaxy found to date (~few ×$10^5 M_\odot$)
  - new class of dwarf residing in less massive DM halo?
  - tidally stripped by Milky Way and once more massive?



N.F. Martin *et al.*, arXiv 0705.4622v1 (2007)

Particle Physics — Astrophysics

$$\frac{d\phi(E,\vec{\psi},\Delta\Omega)}{dE} = \left[\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN(E,m_\chi)}{dE}\right] J(\vec{\psi},\Delta\Omega)$$

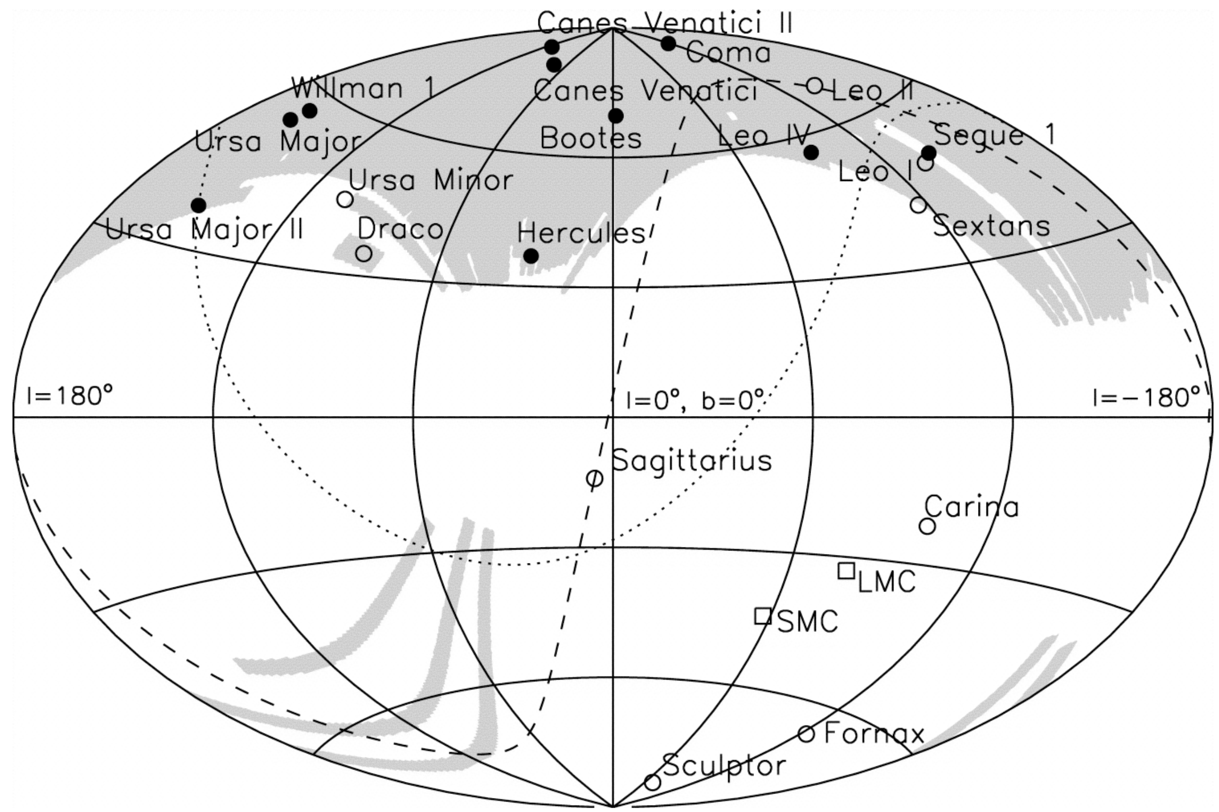
Line of Sight Integral over Source Region

$$J(\vec{\psi},\Delta\Omega) = \left(\frac{1}{\rho_c^2 R_H}\right)\int_{\Delta\Omega} d\Omega \int \rho(\vec{\psi},\Omega,s)^2 ds$$

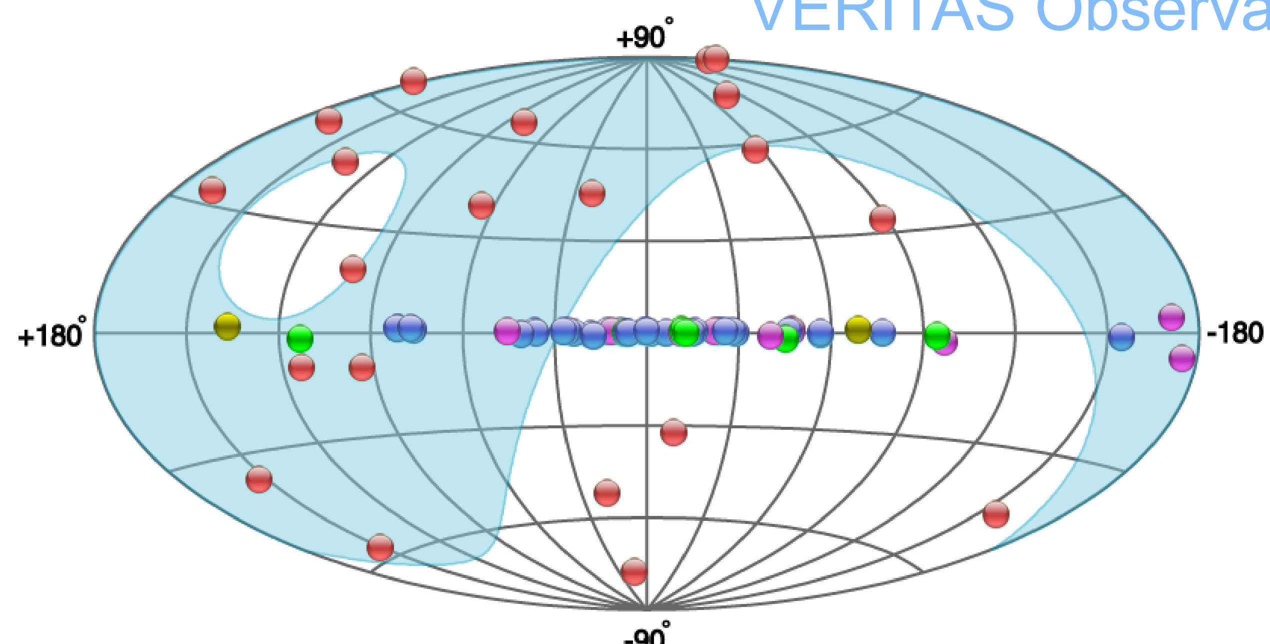
New Dwarfs Discovered by SDSS

Name	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	2005
Willman I	2005
Ursa Major II	2006
Bootes	2006
Canes Venatici I	2006
Canes Venatici II	2006
Coma	2006
Segue I	2006
Leo IV	2006
Hercules	2006
Leo T	2007
Bootes II	2007

VERITAS Targets

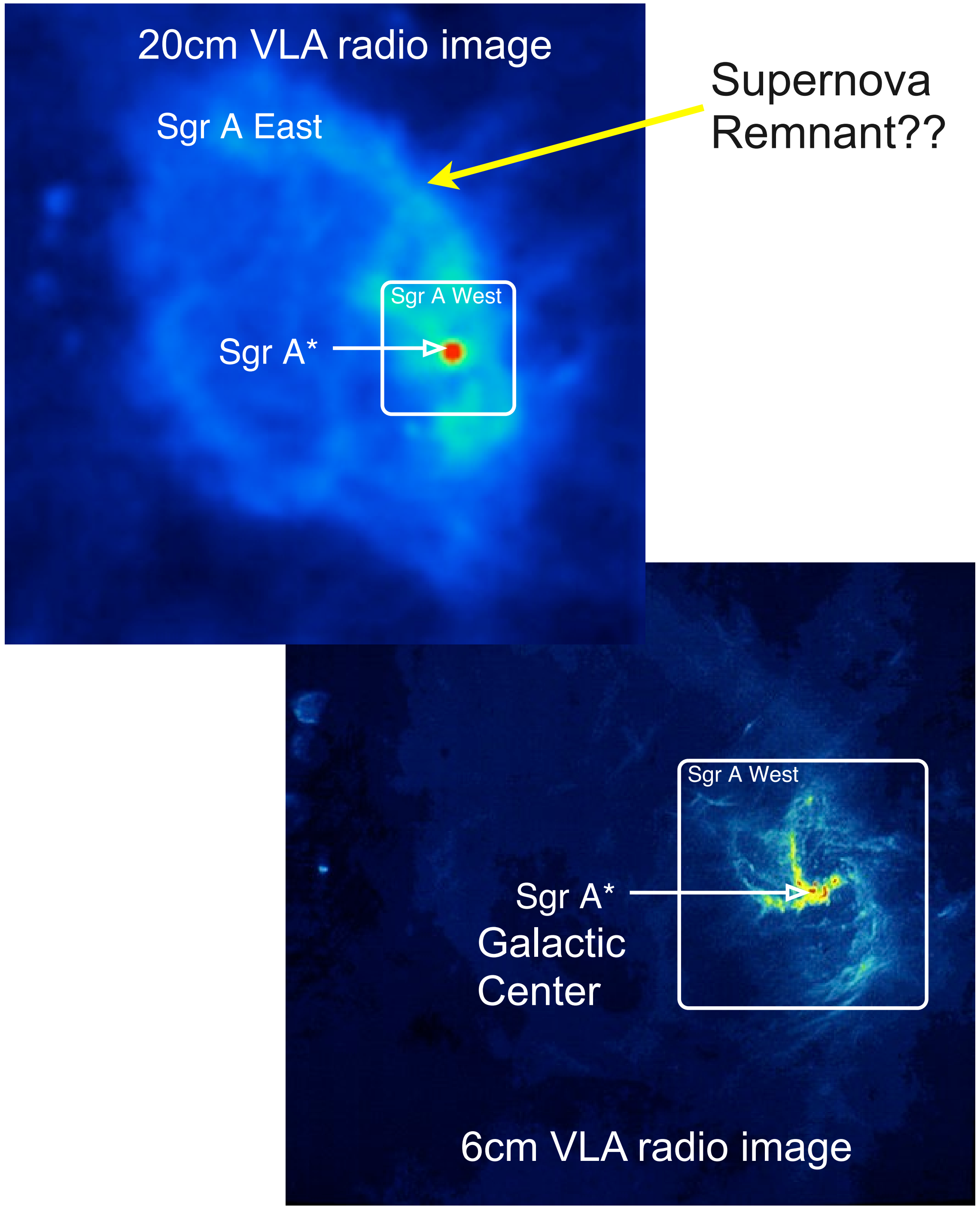


VERITAS Observability

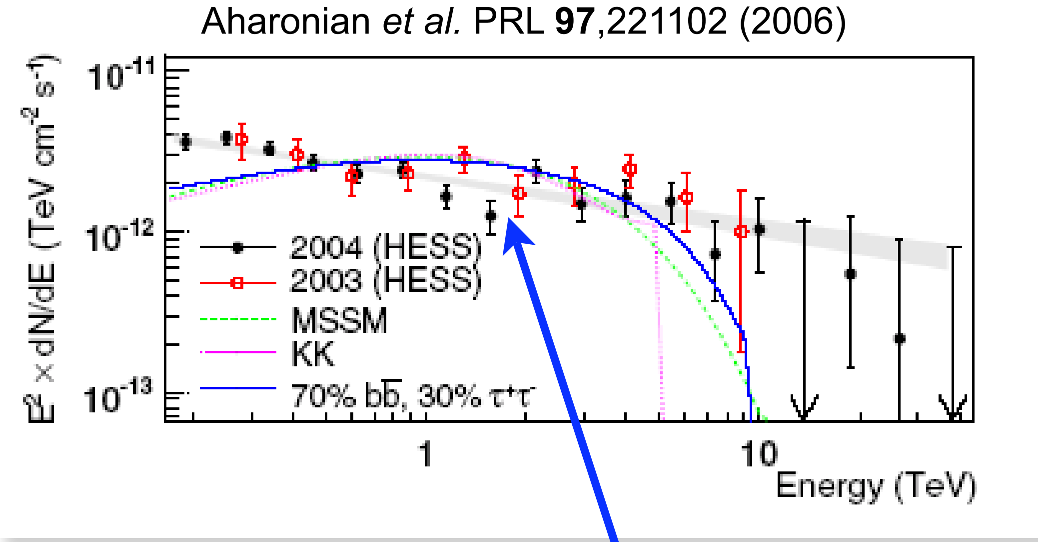


from TeVCat: http://tevcat.uchicago.edu/

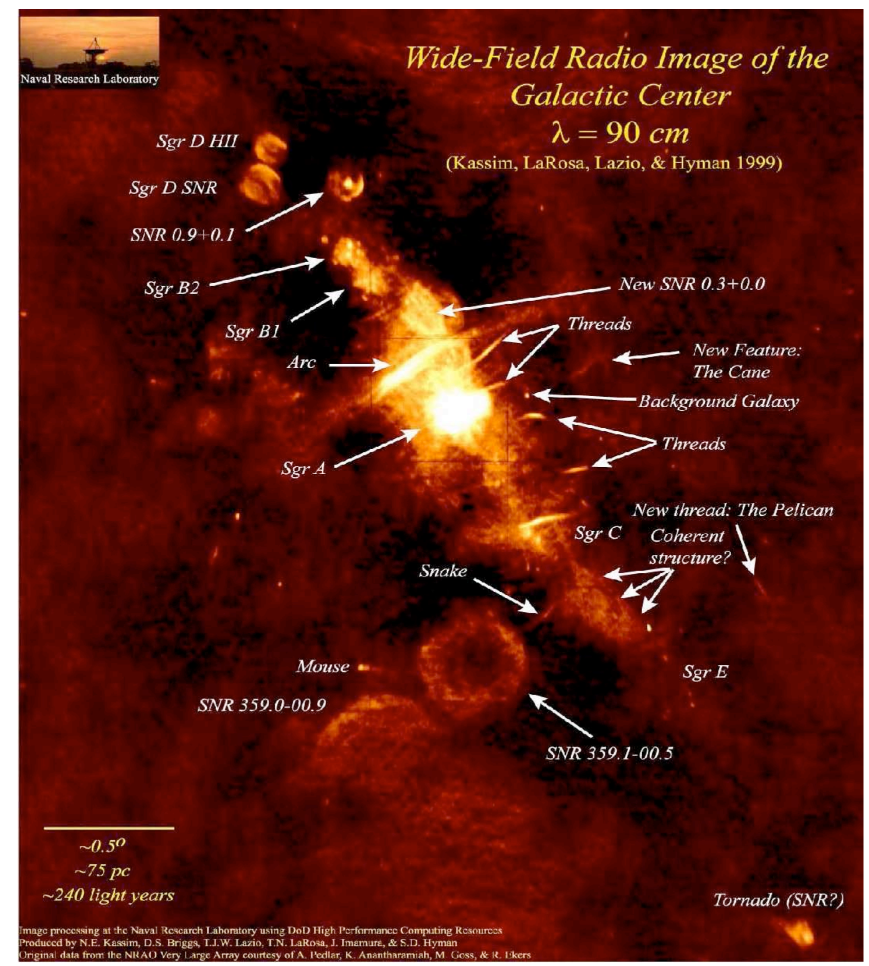
Observation of Galactic Center



Supernova
Remnant??



Data have power law dependence with no cutoff
Bulk of γ-ray emission must have non-Dark Matter origin



Not a good target for VERITAS: visible only in June at elev. ~30°

VERITAS Status & Overview (1)

- Smithsonian Astrophysical Observatory
- Purdue University
- Iowa State University
- Washington University in St. Louis
- University of Chicago
- University of Utah
- University of California, Los Angeles
- McGill University, Montreal
- University College Dublin
- University of Leeds
- Adler Planetarium
- Argonne National Laboratory
- Barnard College
- dePauw University
- Bartol Research Institute/ University of Delaware
- Grinnell College
- University of California, Santa Cruz
- University of Iowa
- University of Massachusetts
- Cork Institute of Technology
- Galway Mayo Institute of Technology
- National University of Ireland Galway

- ~25 Associate Members

VERITAS Array complete and operating in 4 telescope mode since April, 2007

VERITAS Overview & Status (2): Physical Location

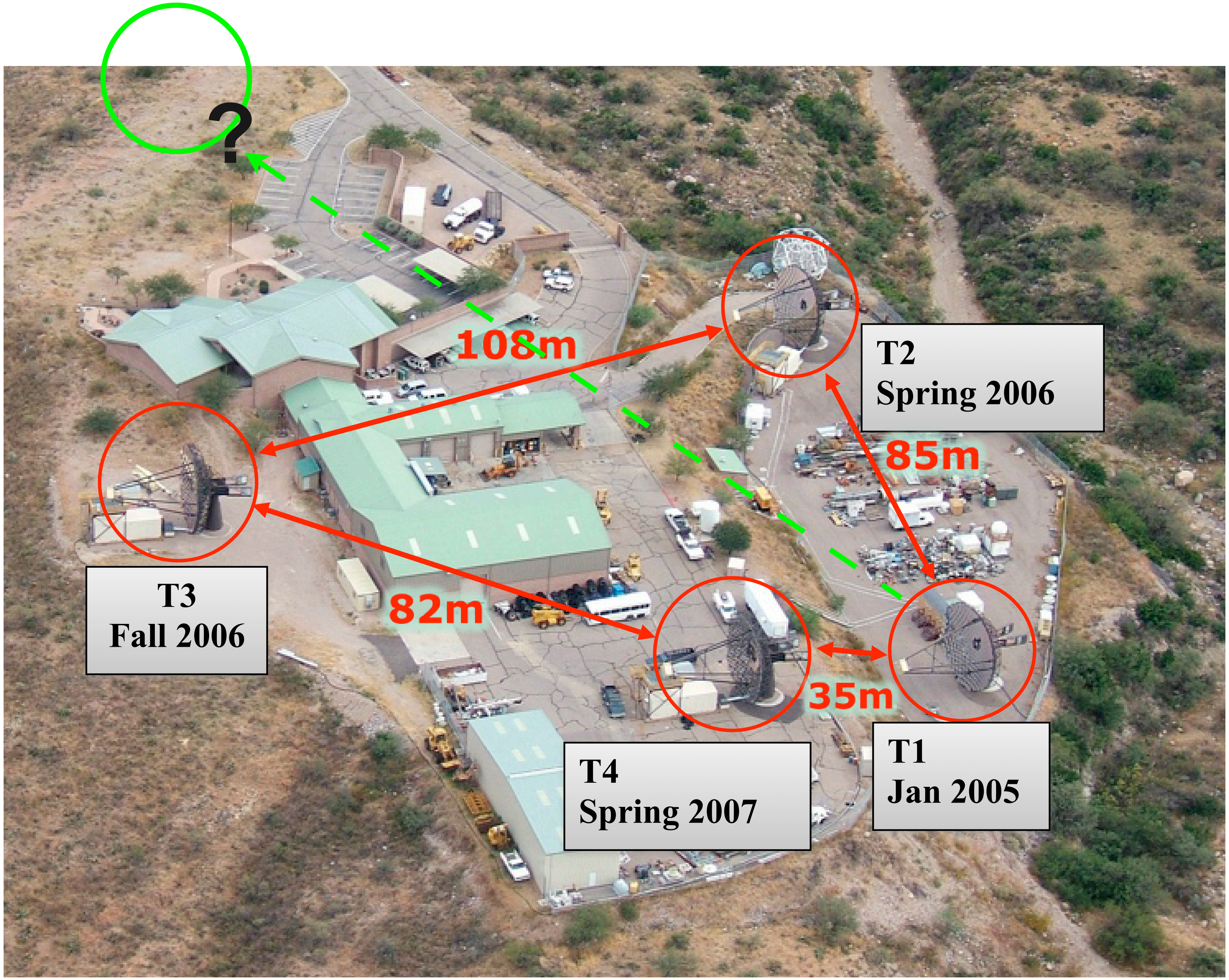
Discussing movement of T1 to new location to provide more useful separation

Implementation of routine moonlight observing has added substantially more observing time (>~25%), e.g.

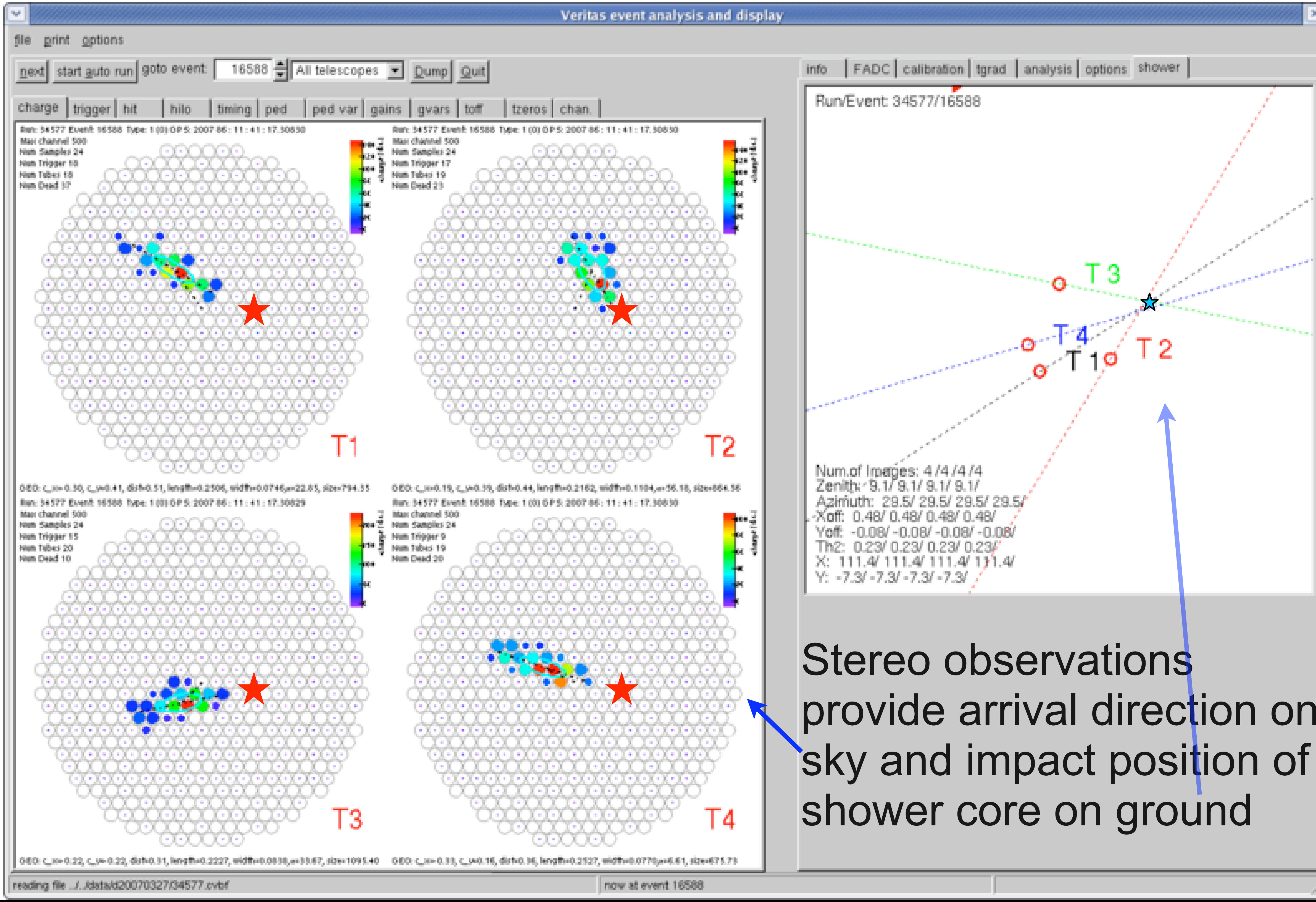
91 observation hours in Nov/Dec dark run including 22 hrs. moonlight data. Requires separate handling in analysis due to brighter Night Sky Background light

Useful for blazar monitoring.

In addition, to planned observing program, have ToOs: GRB alerts, flaring AGN

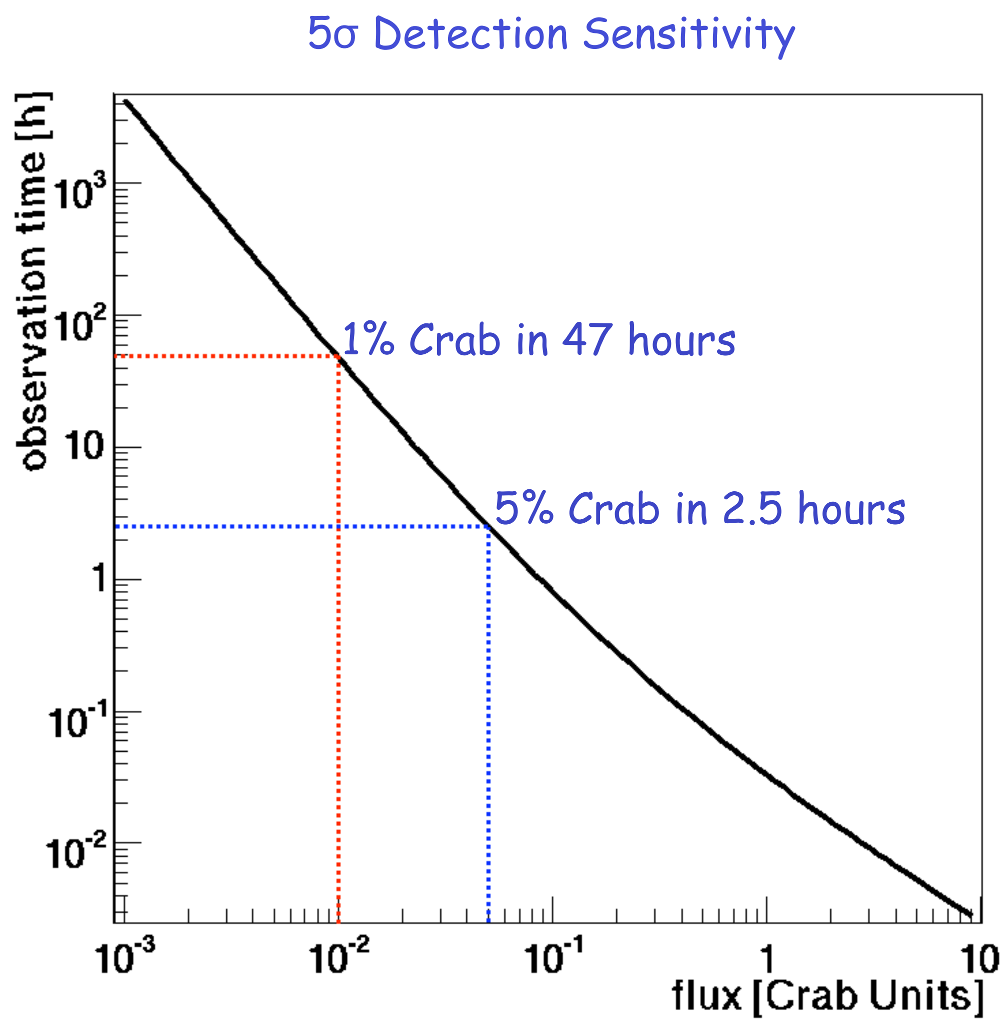


VERITAS Overview & Status (3): Stereo Observation



Stereo observations provide arrival direction on sky and impact position of shower core on ground

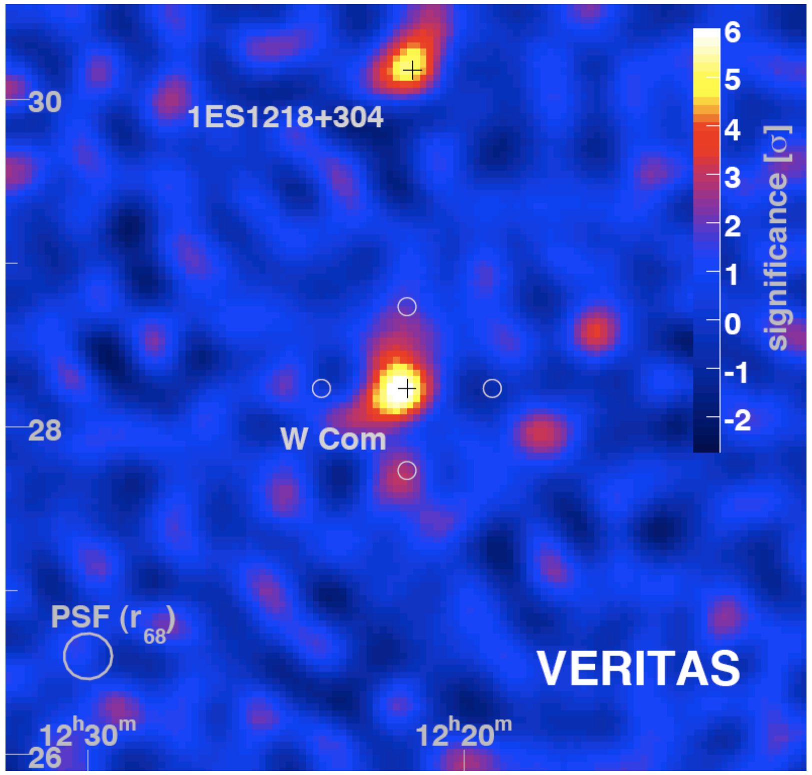
VERITAS Overview & Status (4): Sensitivity

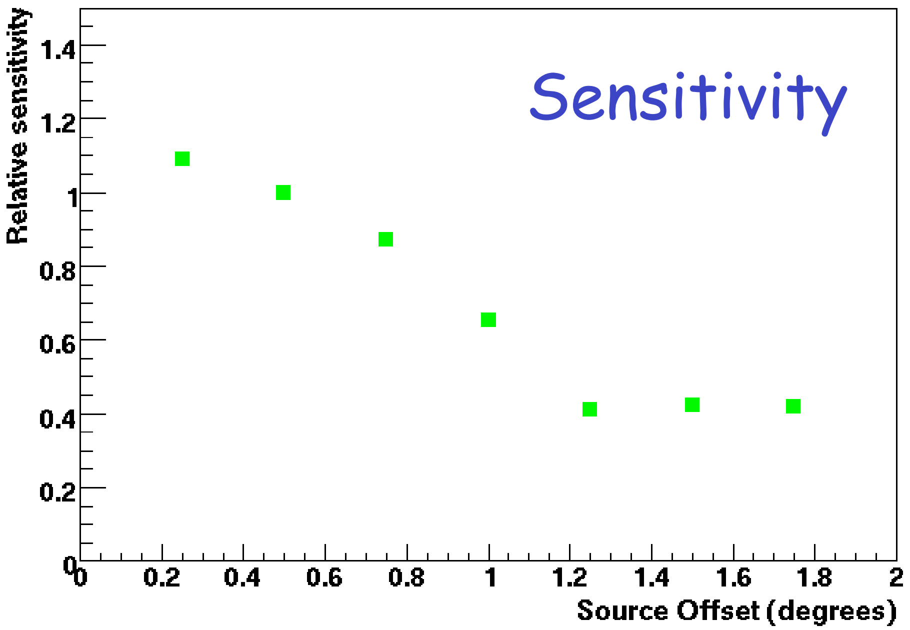


- Measured sensitivity to the Crab Nebula at high elevation (>65°)
- HESS ~1% Crab in 25 hours
- MAGIC ~2% Crab in 50 hours

Off-axis sensitivity

Observation of two VHE γ-ray Blazar sources in same FOV

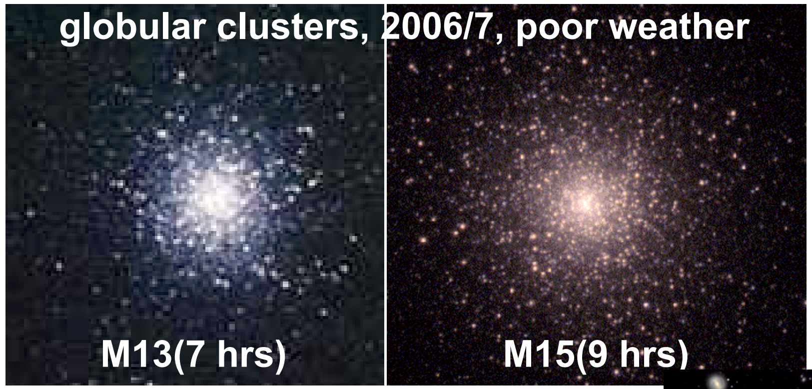


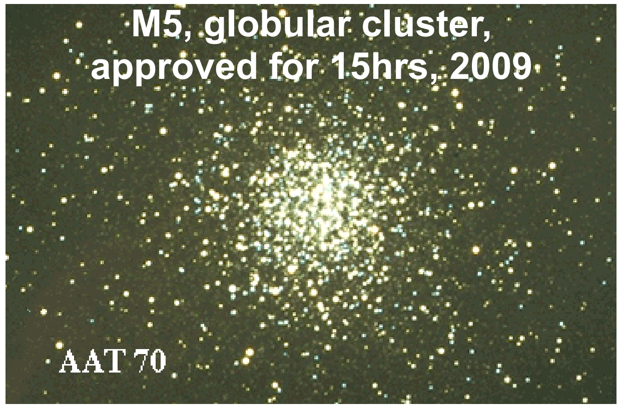


Physical camera radius = 1.75°

VERITAS Dark Matter Key Science Project

- Dark Matter search is one of four VERITAS Key Science Projects that receive an unreviewed time allocation beyond proposals to the Time Allocation Committee (TAC). We are in second year of key science project allocations
  - Sky Survey of Cygnus region
  - Supernovae Remnants/Plerions (Pulsar Wind Nebulae)
  - Blazars
  - Dark Matter
- Dark Matter search carried out by Dark Matter Science Working Group which administers KSP, other Dark Matter proposals, analysis, and planning (Karen Byrum, Deputy Leader).
  - Since nature of DM unknown, target a variety of object types: galaxy clusters, local large galaxies, globular clusters, and dwarf spheroidal galaxies (dSph).
  - Observation Program

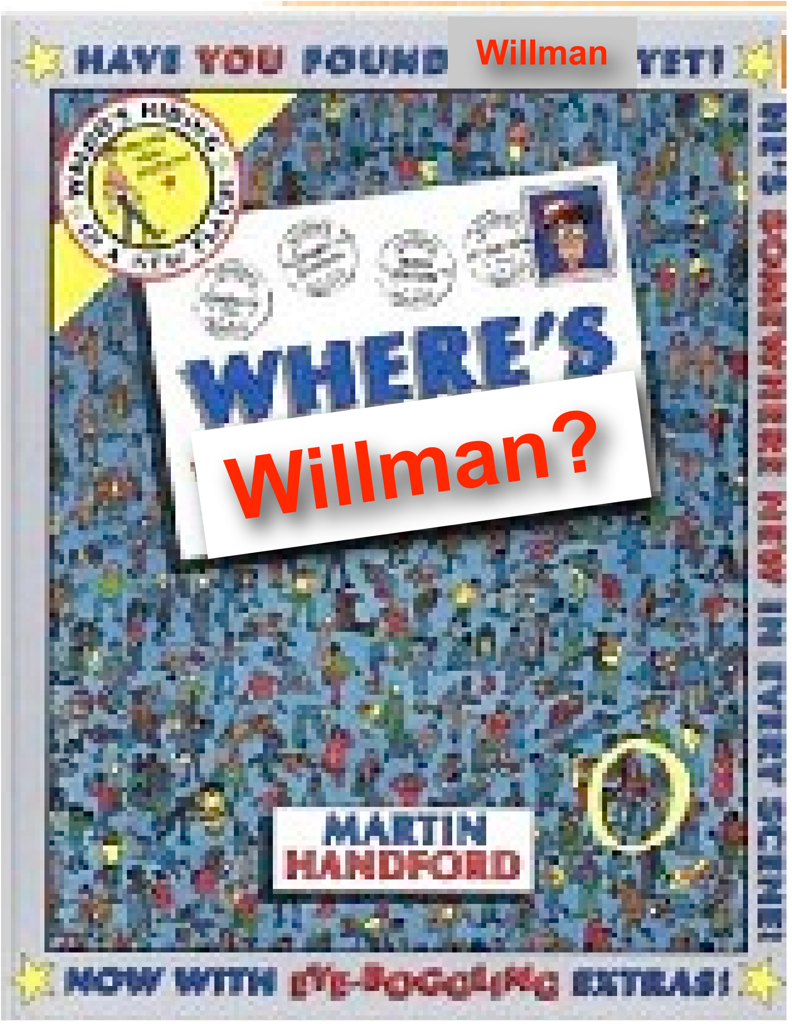


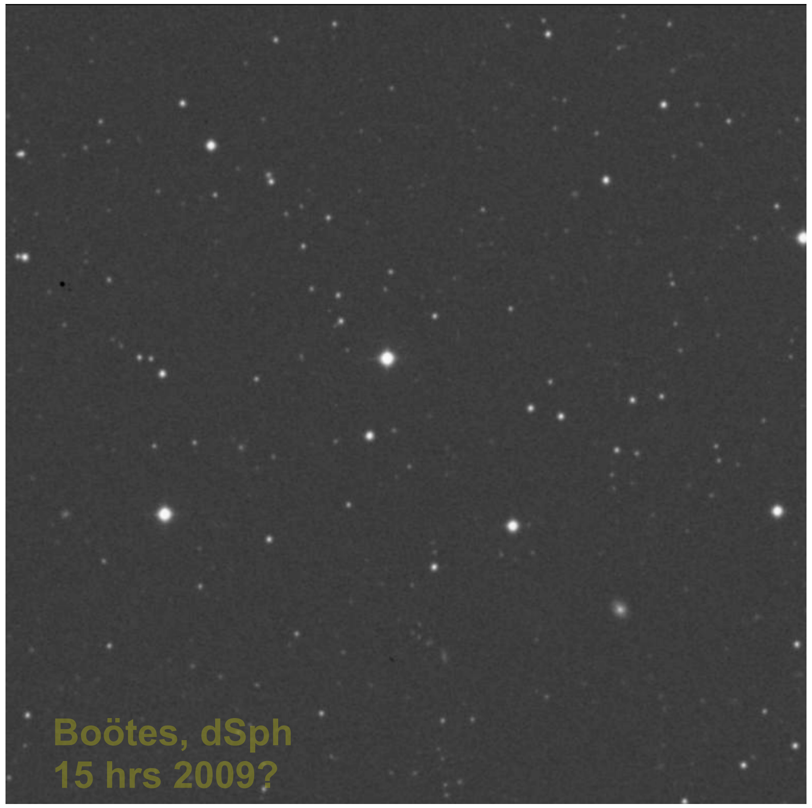


So how about the dwarfs?...

The Dwarf Spheroidals

or Why There's Dark Matter Out There





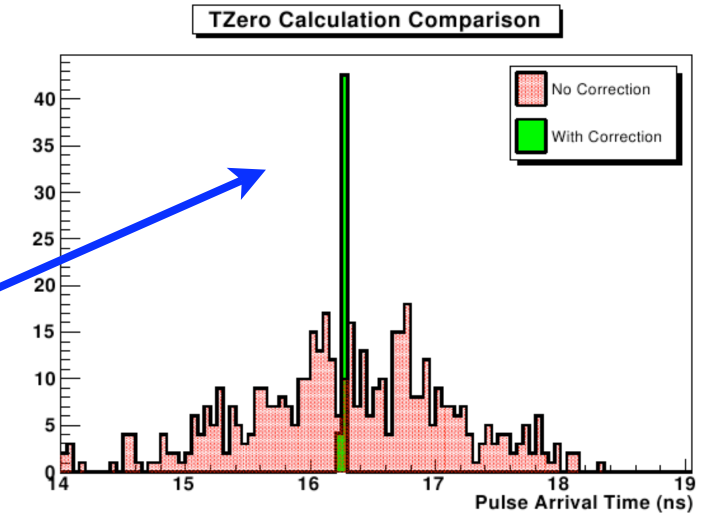
Hoping for both SEGUE and Boötes in 2009. Time allocated for 1.

VERITAS Data Analysis Stream

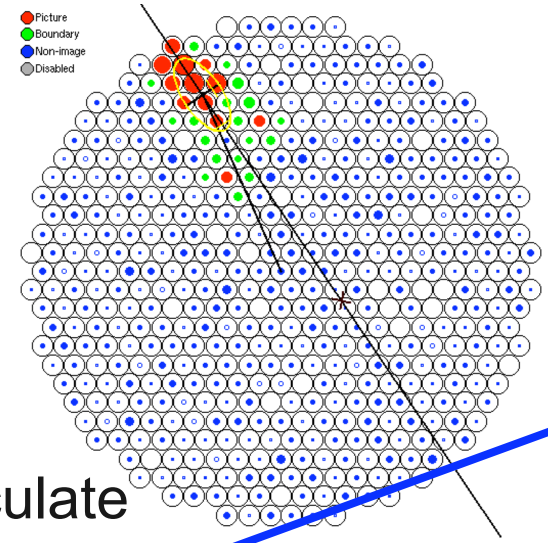
- Analysis accomplished through several competing packages:
  - VERITAS Gamma-ray Analysis Suite (VEGAS)
    - *Chosen standard analysis package*
    - *Very easy to use with wide variety of options*
    - *Had initial problems and bugs that prevented spectral analysis, but is now mature reliable suite of analysis*
  - EventDisplay
    - *original display and analysis program*
    - *still widely used as primary and secondary analysis*
    - *avoided many of initial problems of VEGAS (due to smaller developer group?)*
  - ChiLA (Chicago/L.A. analysis)
    - *Combines simulation and analysis packages*
    - *Pretty much used only by UCLA group*
    - *Secondary analysis done for Dwarf Galaxy data and primary simulation for dark matter search*

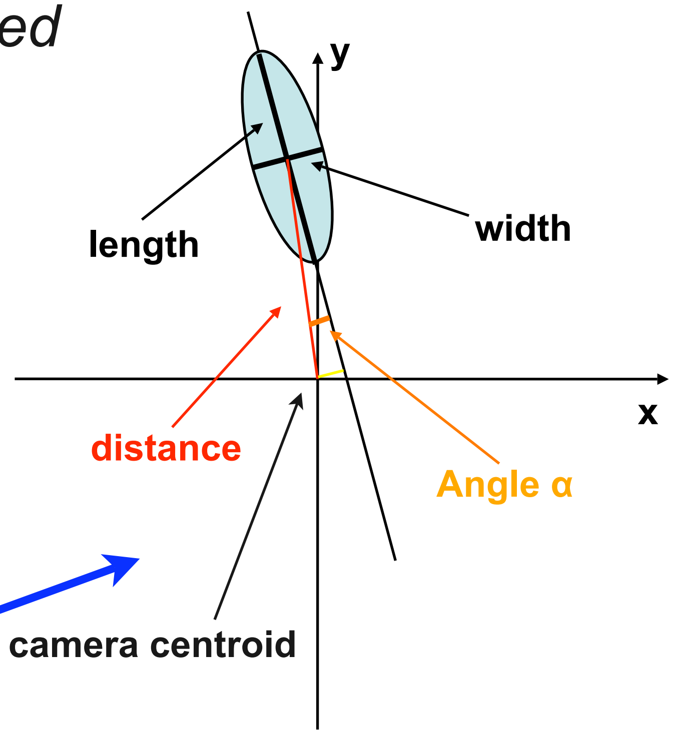
VERITAS Data Analysis Stream -- VEGAS

- Analysis Suite consists of six separate stages with dedicated executables plus visualization application and dozens of ROOT macros to perform analysis tasks
  - Based on ROOT for data model and graphical interface
  - **Stage 1:** Calibration analysis
    - *Applied both to observational data and separate dedicated laser run data*
    - *Time dependent pedestal calculation*
    - *Laser run: gain equalization & time offset for each pixel*



  - **Stage 2/3:** Calibration application & image parametrization
    - *Stage 2 & 3 combined in upgraded VEGAS to save time and reduce file size*
    - *Time dependent pedestals subtracted, pixels gain corrected*
    - *Pixel cleaning*
      (5σ above ped for "picture"; 2.5σ for "boundary")

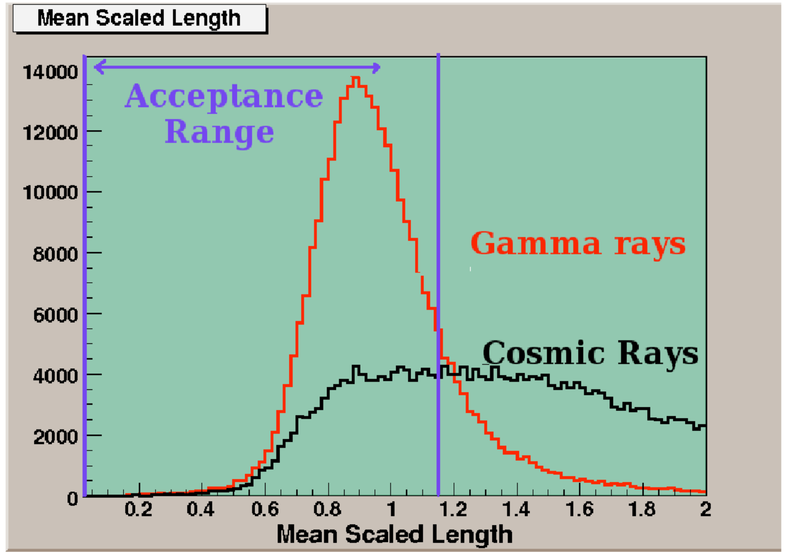




    - Second moment analysis to calculate elliptical (Hillas) parameters of image

VERITAS Data Analysis Stream -- VEGAS (2)

- VEGAS Stages (cont.)
  - **Stage 4:** Array level shower stereo reconstruction
    - *Apply cuts on Hillas parameters to eliminate Night Sky Background, hadronic showers, and events near camera FOV edge*
    - *Calculate image angular position in sky and impact parameter on ground, i.e. trajectory of shower*
    - *Use image parameters to estimate energy from simulation lookup table*
    - *Calculate array level parameters, e.g.*
      - Mean Scaled Width -- Ratio Width to expected width from simulation as function of size and impact parameter of shower; averaged over *n* telescopes
      - Mean Scaled Length -- same for length parameter
      - Θ^2 -- squared angular distance of image from assumed source position
  - **Stage 5:** Gamma-ray selection
    - *Application of cuts to data to select gamma-ray sample*
  - **Stage 6:** Results extraction; many options including
    - *Calculation of number signal and background events*
    - *Estimation of signal significance*
    - *Calculation of mean effective area*
    - *Spectral analysis*



Dwarf Galaxy Observation Analysis: Signal and Background Estimation

- "Standard" analysis of data from IACT observations estimates:
  - N_{ON} ≡ # counts in defined signal(test) region
  - N_{OFF} ≡ # counts in defined backgrd region
- Excess (or deficit) counts and significance derived:
  - $N_{Excess} = N_{ON} - \alpha N_{OFF}$
  - Significance: (assuming all backgrd. in ON region)

$$S = \sqrt{-2 \ln \lambda} = \sqrt{2} \left\{ N_{\rm on} \ln \left[\frac{1+\alpha}{\alpha} \left(\frac{N_{\rm on}}{N_{\rm on} + N_{\rm off}} \right) \right] + N_{\rm off} \ln \left[(1+\alpha) \left(\frac{N_{\rm off}}{N_{\rm on} + N_{\rm off}} \right) \right] \right\}^{1/2}$$

ref: T-P. Li & Y-Q. Ma, ApJ, **272**, 317(1983), Eqn. 17

  - α ≡ normalization to correct for differences in signal and bkgd regions
    typically is ratio of area of signal to bkgd region, but can vary over FOV
  - λ ≡ likelihood ratio statistic
    $\sqrt{-2\ln\lambda}$ → absolute value of n(0,1) distribution
- Challenge is to define suitable background region that gives high statistical precision without introducing excessive systematic uncertainties.
  - Several methods used, with varying advantages/disadvantages

excellent ref: D. Berge, S. Funk, J. Hinton, A&A, **466**, 1219(2007)

Background Estimation Methods

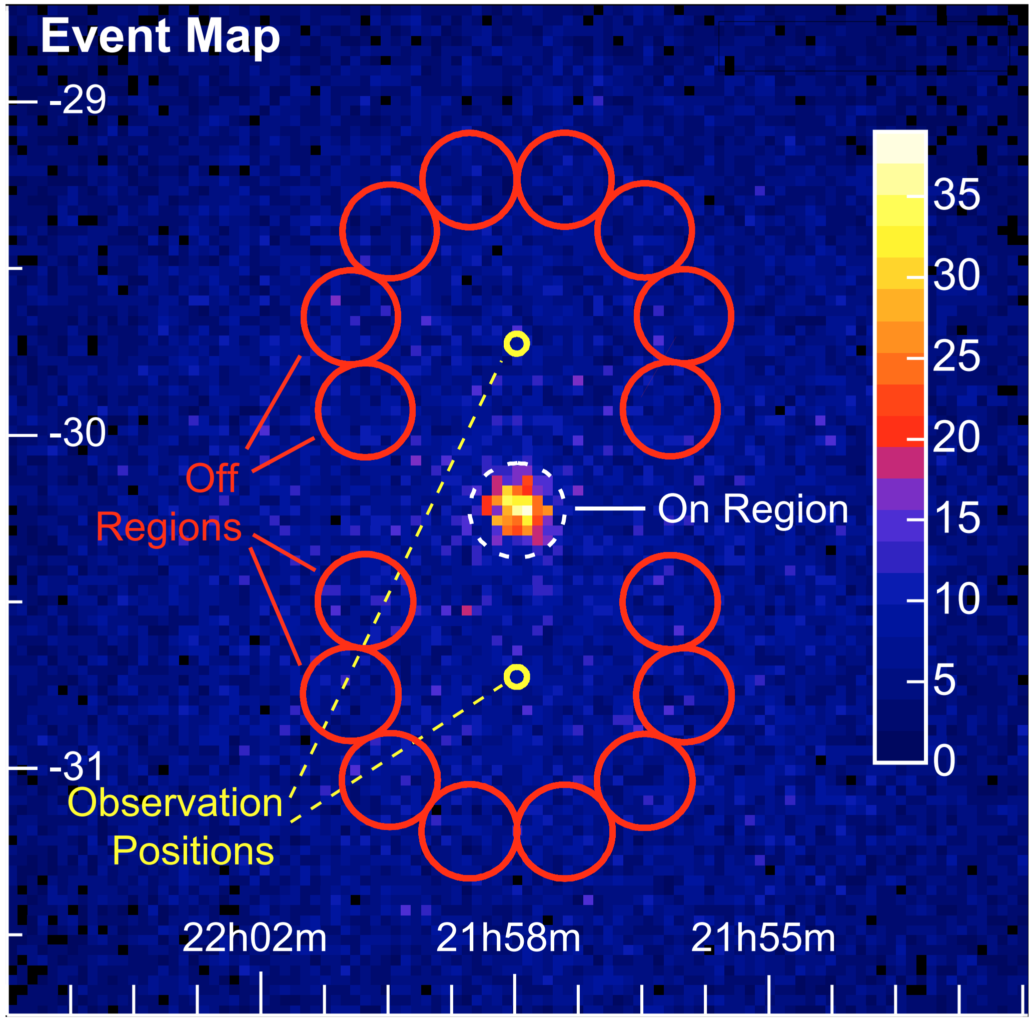
- ON/OFF Separate Runs
  - Initial method for imaging Cherenkov telescopes; developed for single telescope systems
  - ON and OFF runs taken in pairs with OFF run covering same region of sky separated in Right Ascension from ON by time difference of runs.
  - Removes variations in acceptance across field of view
  - Only assumes acceptance not dependent on RA.
    - *Good assumption unless significant differences in celestial environments, e.g. bright stars in FOV for one region*
    - *Environmental differences can be corrected by "padding", adding random noise to events in region with lower sky backgrd*
  - Low statistics and guarantee half the data have no signal.
- Modified ON/OFF: FOV Background
  - Accumulate data from many observations giving no γ-ray signal over large range of zenith angles.
  - Gives large statistics background estimate over FOV for ON observations
- Template Method
  - Use ON region but select events failing γ-ray selections
  - Useful for extended sources
- Methods using signal and background regions in same field of view:
  - Reflected regions (Wobble)
  - Ring background

} Generally best for source detection

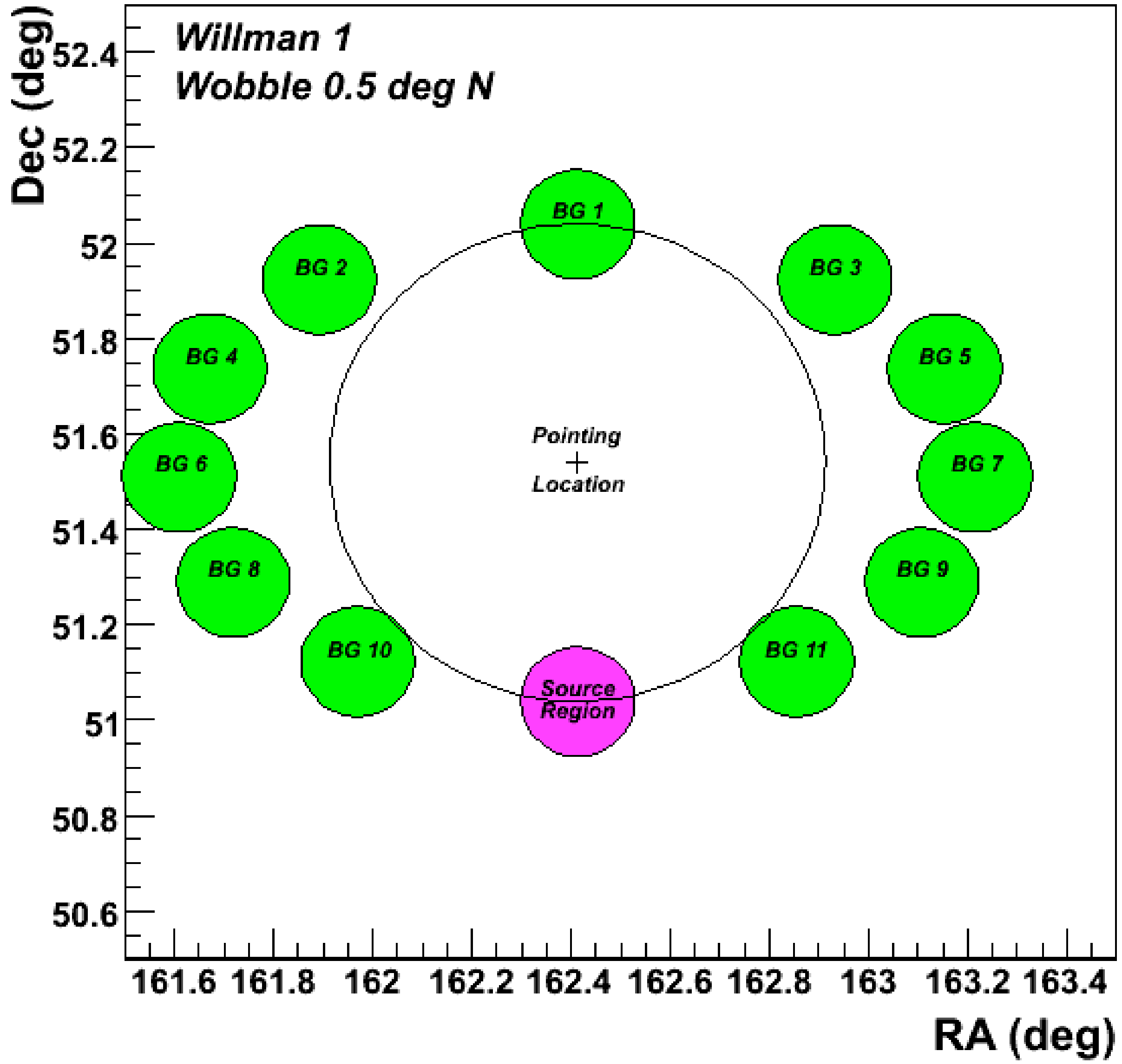
Reflected Region Background Estimation (Wobble Bkgd)

Generally used to provide an overall estimate of (non)significance of a possible source (1 number)
This can then be used for overall flux or flux limit

HESS observation of PKS 2155-304



from D. Berge, S. Funk, J. Hinton (fig. 4)

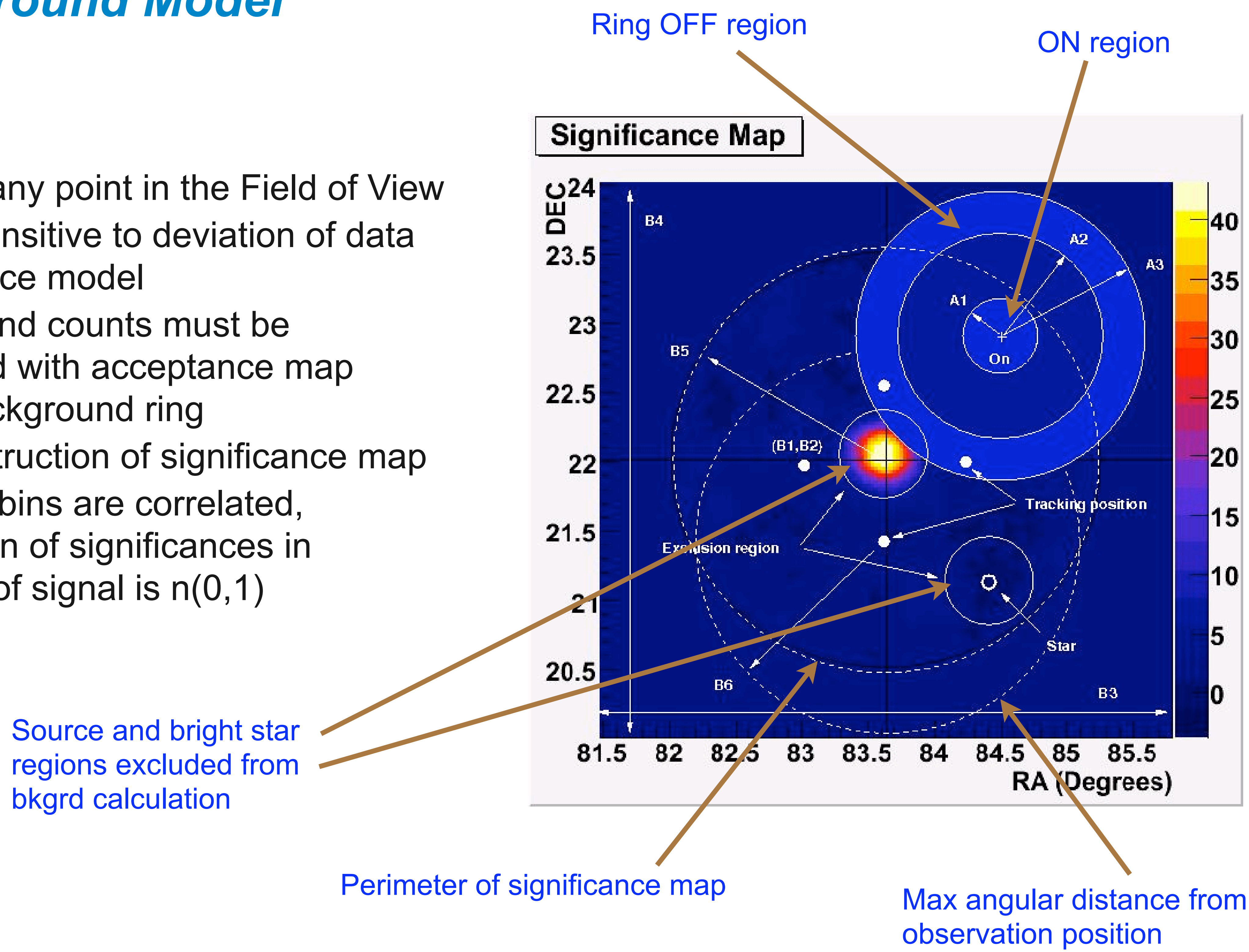


Reflected region background in practice:

- Declination distorts RA position of background regions
- Regions are determined in camera coordinates

Ring Background Model

- Applicable to any point in the Field of View
- Generally insensitive to deviation of data from acceptance model
  - Background counts must be convolved with acceptance map within background ring
- Used for construction of significance map
  - Although bins are correlated, distribution of significances in absence of signal is n(0,1)



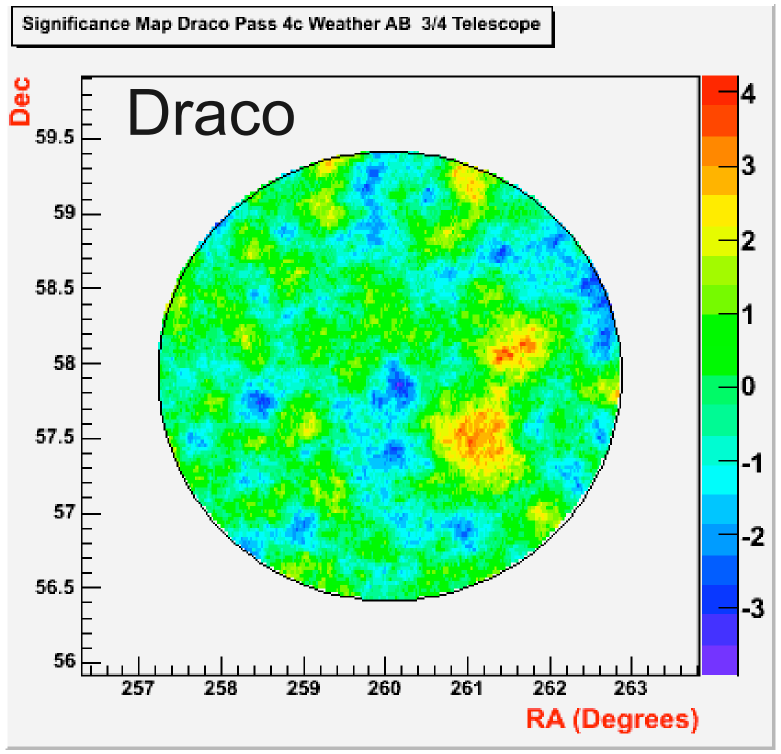
Results of Wobble Analyses

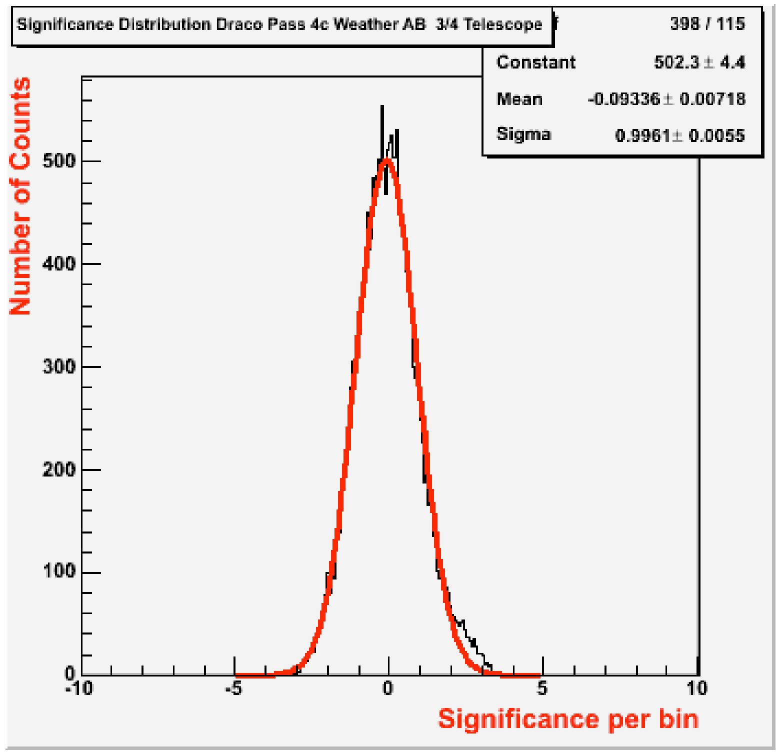
Source	ON	OFF	Significance
Draco	305	3667	-1.511
Ursa Minor	250	3084	-1.772
Willman 1	326	3602	-0.077

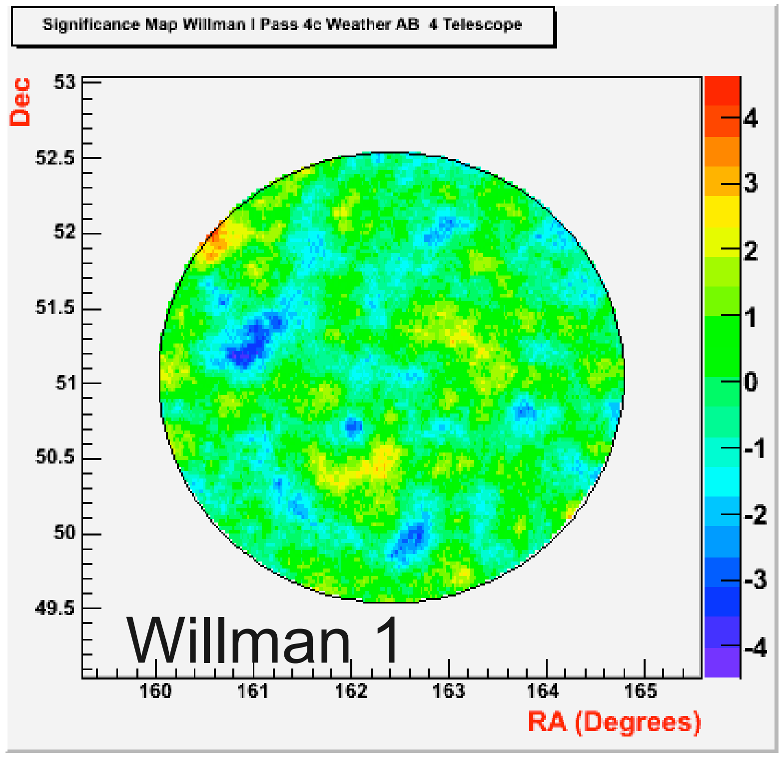
Preliminary

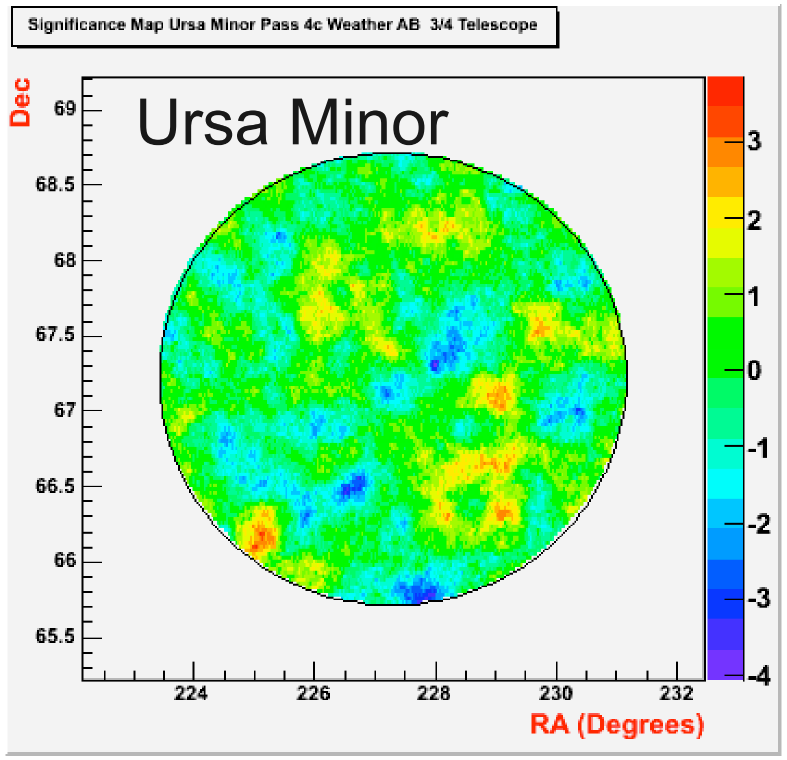
OFF/ON area = 11/1 → $\alpha = 0.09091$

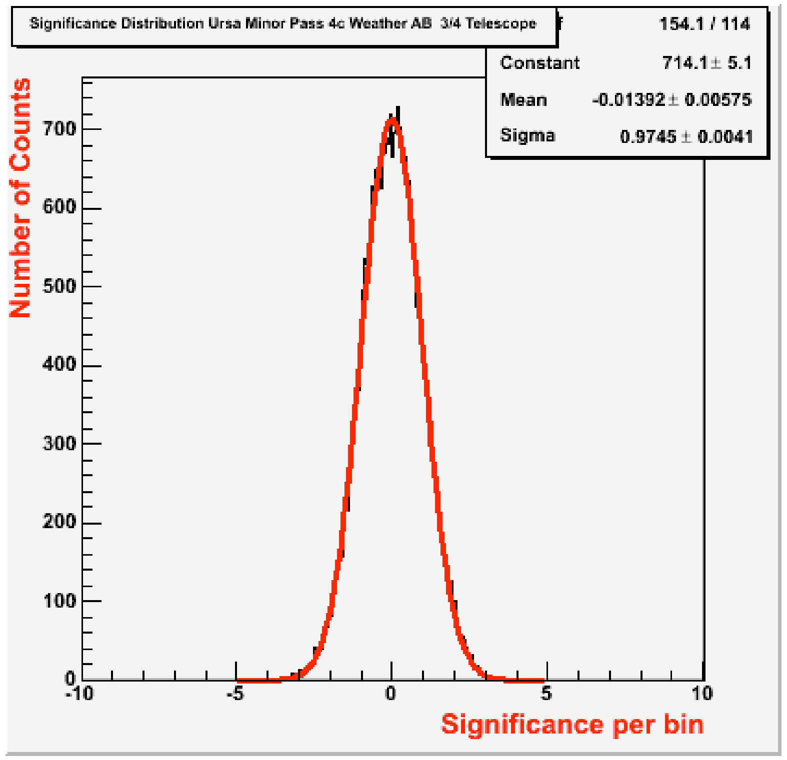
Significance Maps of Dwarf Galaxy Regions

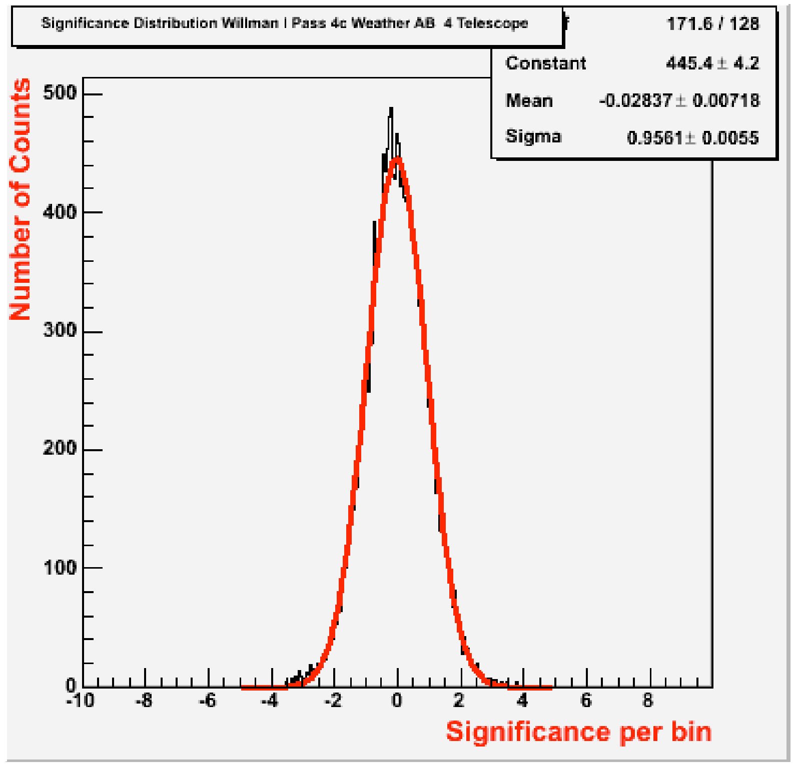












Construction of Flux Limits

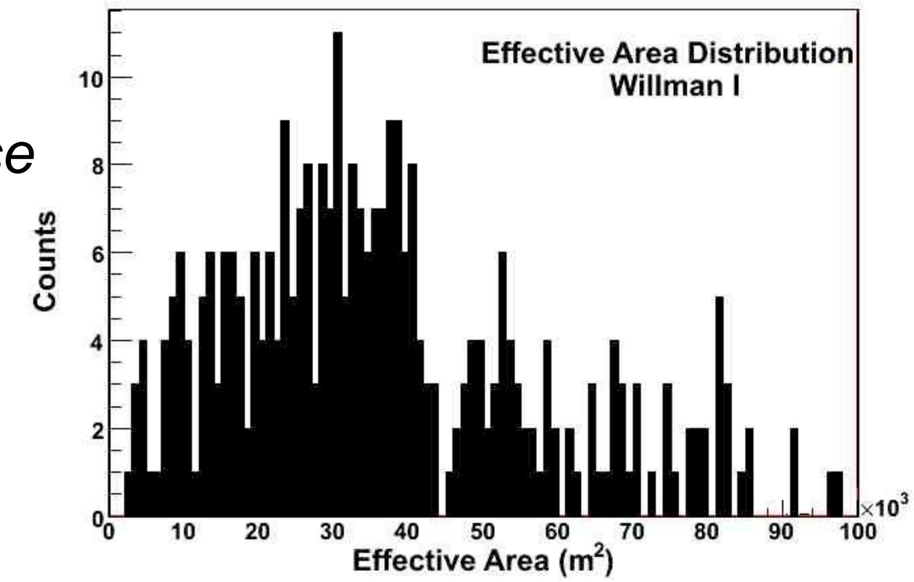
- Use Rolke *et al.* Profile Likelihood method [ref. NIM A**551** (2005) 493]
  - Test hypothesis, $H_0(\mu_0,b_0)$ where signal, μ_0, is given; b_0 maximizes likelihood given μ_0
    vs.
    alternative, $H_1(\mu_1,b_1)$ where μ_1, b_1 maximize likelihood
    - $\mu \equiv$ # signal events $b \equiv$ # background events
    - $x \equiv$ total events in signal region
    - $y \equiv$ total events in background region

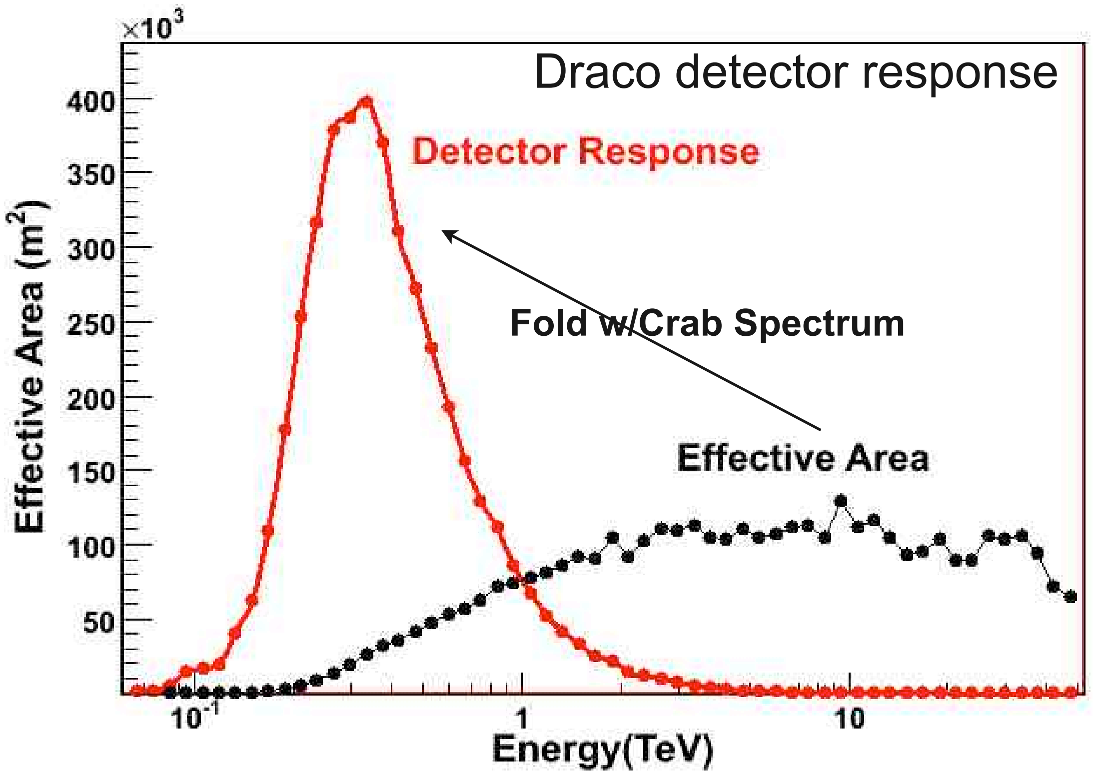
    } $\tau \equiv$ background region size/signal region size $= 1/\alpha$
  - Similar to Feldman-Cousins, but background is unknown and treated as nuisance parameter
  - Assume signal and background event counts are Poisson distributed
    - $\mu_1 = x - (y/\tau)$ $b_1 = y/\tau$
    - $b_0 = \{[(x+y) - \mu_0(1+\tau)] + ([(x+y) - \mu_0(1+\tau)]2 + 4(1+\tau)\mu_0 y)^{1/2}\}\ /\ 2(1+\tau)$
    - $\lambda(\mu_0 \mid x,y) = \mathcal{L}(\mu_0,b_0 \mid x,y)\ /\ \mathcal{L}(\mu_1,b_1 \mid x,y)$
      - $\mathcal{L}(\mu,b \mid x,y) = [(\mu+b)^x/x!]\ e^{-(\mu+b)}\ [(\tau b)^y/y!]\ e^{-\tau b}$

$$-2\mathrm{Ln}\ \lambda(\mu_0 \mid x,y) \text{ is } \chi^2(1)$$

Physical Flux Limits

- Useful flux unit: counts cm^{-2} s^{-1} above some energy threshold
  - requires estimating effective area of telescope
    - *Calculated on event-by-event basis using effective area vs. energy, zenith angle, azimuth, and noise*
    - *Average effective area of all ON events*
  - Need to define energy threshold
    - *No precise energy that defines threshold*
    - *Usual definition is characterization of "detector response"*
      - Convolve effective area with (assumed) spectral energy distribution; typically use Crab spectrum scaled to some assumed flux as percentage of Crab
      - For dwarf analysis, use 3% Crab with Flux $\propto E^{-2.5}$
      - Energy Threshold defined as energy at peak of Detector Response





Dwarf Galaxy Flux Limits

Source	Counts 95% c.l.	Effective Area (m^2)	Energy Threshold (GeV)	95% c.l. Flux Limit ($cm^{-2}\ s^{-1}$)
Draco	8.70	44,228	340	2.97×10^{-13} (~0.29%Crab)
Ursa Minor	3.34	50,185	440	9.78×10^{-14} (~0.14%Crab)
Willman 1	36.7	37,118	250	2.01×10^{-12} (~1.3%Crab)

Preliminary

Older Analysis Comparison to WIMP Models

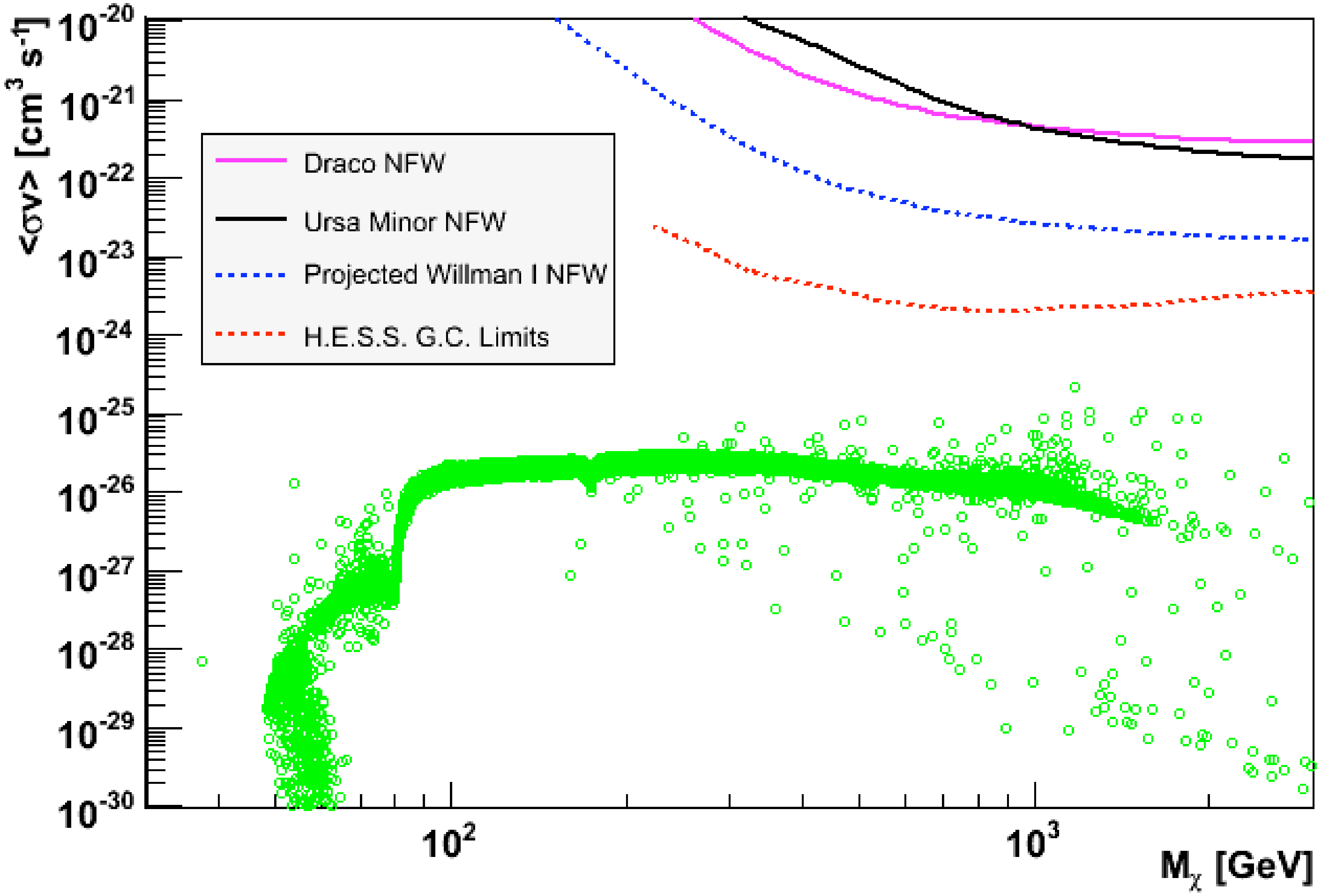
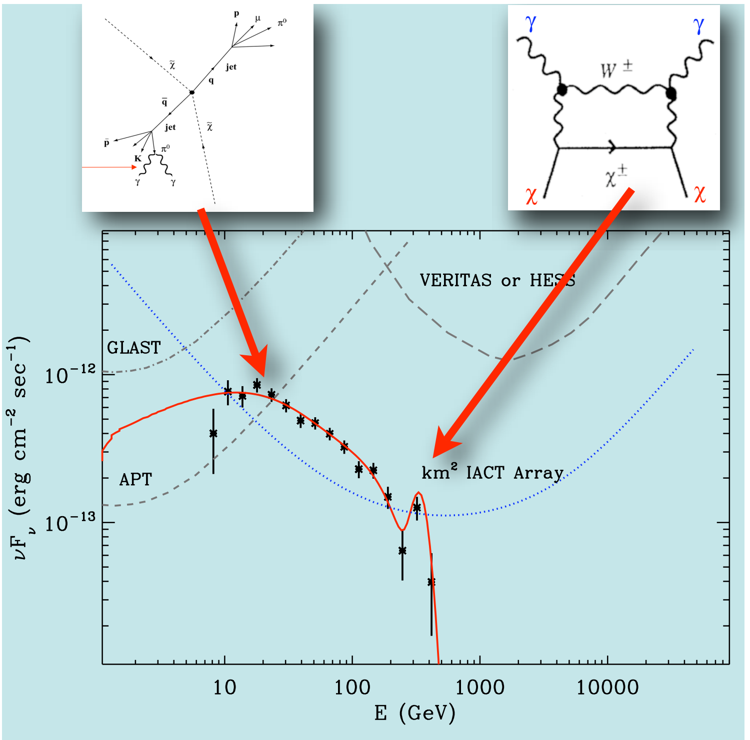


figure by Matthew Wood, UCLA, Jan. 2008

The Future

- VERITAS will observe at least one dwarf galaxy in Spring, 2009 (SEGUE 1 or Boötes)
  - Approved for 15 hours
  - Hope to persuade collaboration and TAC to include both
  - Expect that some dark matter targets will continue to be part of the VERITAS observational program
  - Follow-up unidentified VHE gamma-ray sources from Fermi/GLAST
    - *Not necessarily dark matter halo candidates, but those may be among the mix!*



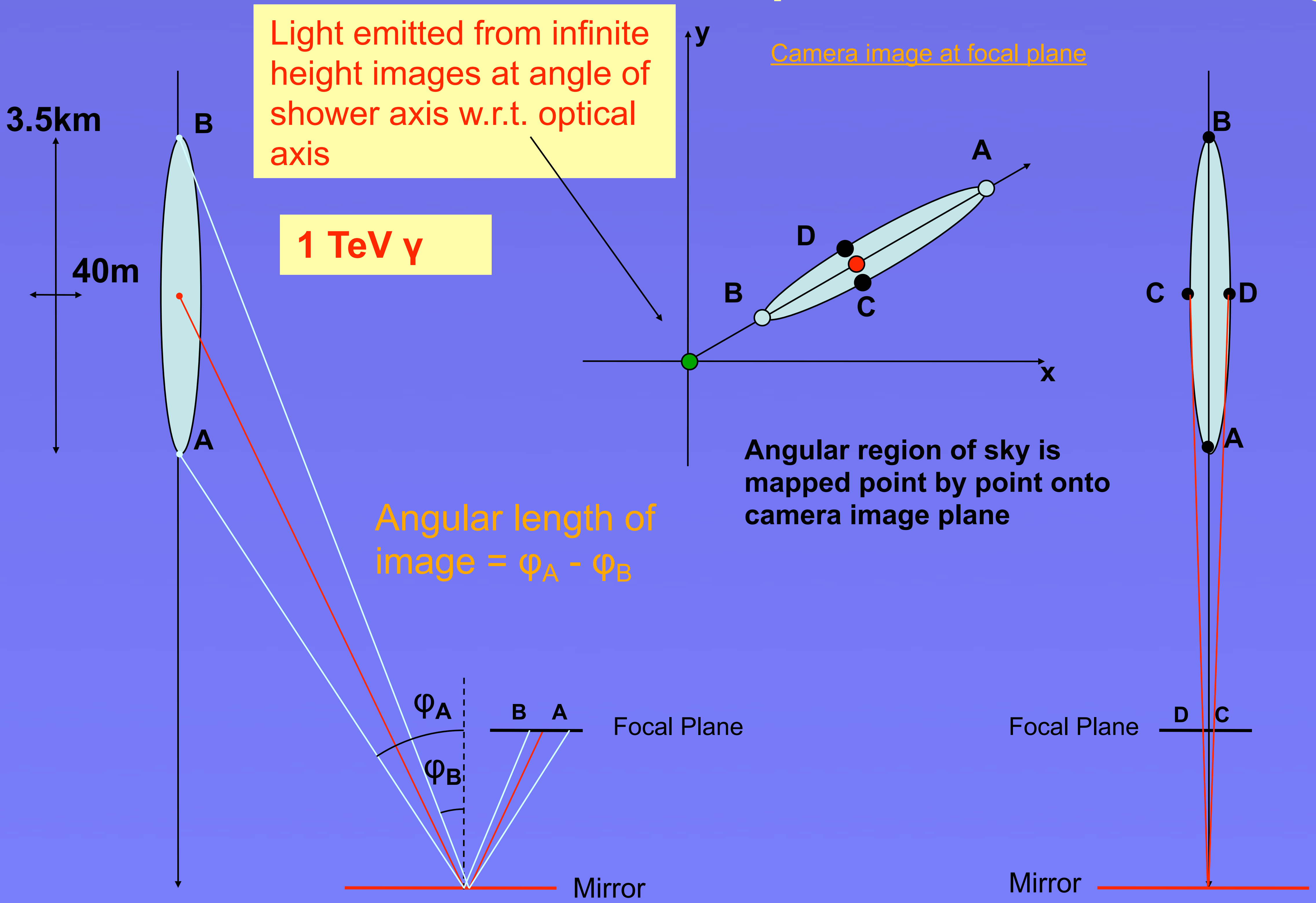
- Two groups proposing next generation VHE γ-ray IACTs
  - Cherenkov Telescope Array (CTA)
    - *mainly European institutions*
    - *appear to have good support from planning/funding agencies*
    - *n.b. Vic Guarino doing design work on 12m Davies-Cotton candidate for CTA*
  - Advanced Gamma-ray Imaging System (AGIS)
    - *mainly U.S. with collaborators from Mexico, Argentina, Germany*
    - *Argonne VERITAS group involved in several areas*
      - Fast topological trigger system (Gary D., Karen B., Andy S. plus Frank Krennrich at Iowa State
      - Schwarzschild-Couder two mirror telescope OSS design (Vic G., Karen B., Bob W.)
      - Photodetector development (SiPM and/or MAPMT; Gary D, Bob W.)

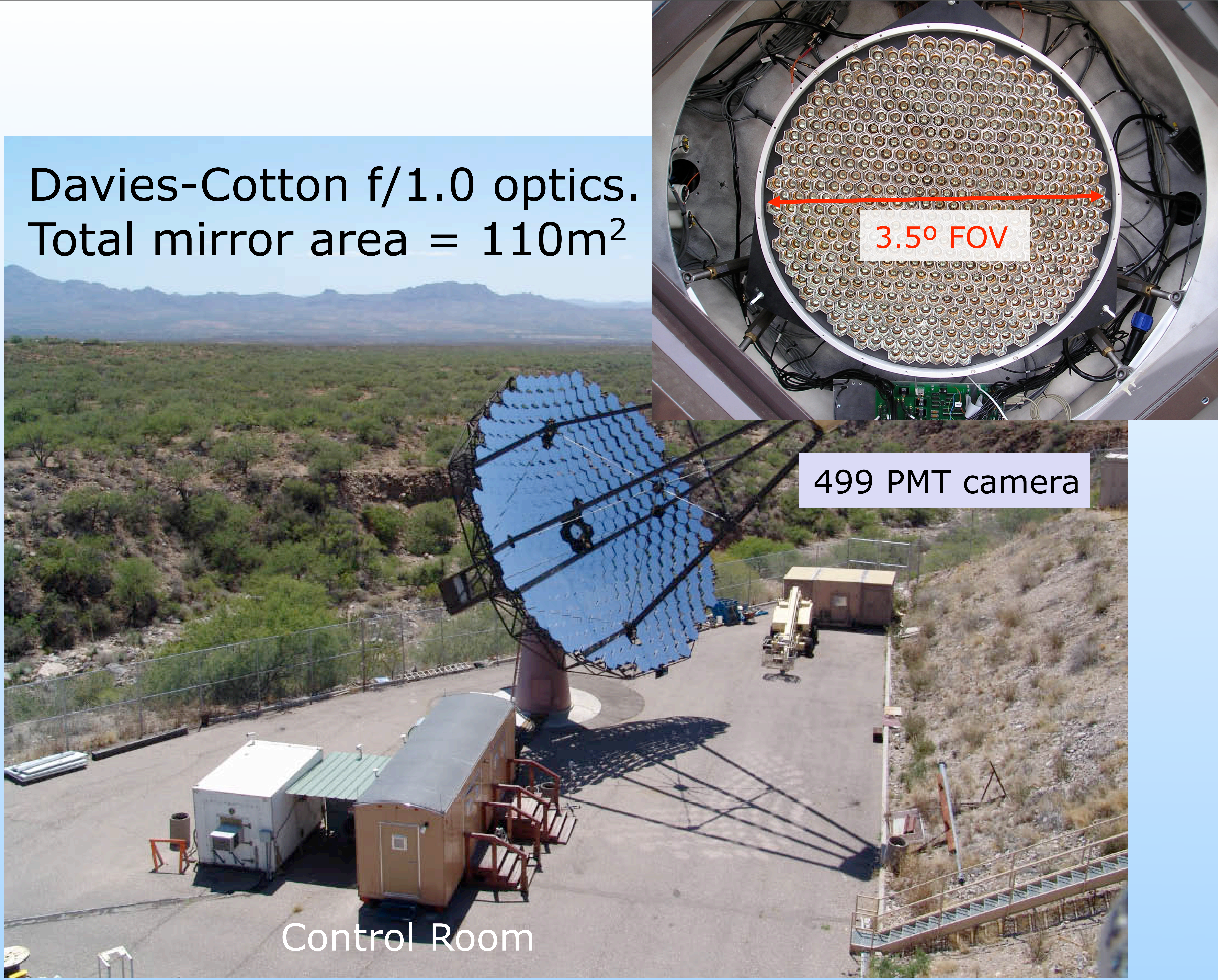
Summary

- Dwarf spheroidal galaxies may be most Dark Matter dominated objects
  - lack of recent star formation and low luminous mass suppresses known astrophysical γ-ray backgrounds
  - Mass/Light ratios ~ few hundred or greater are inferred
- VERITAS, HESS, MAGIC (and previously Whipple 10m) have all targeted dSph's to search unsuccessfully for a VHE γ-ray signal
  - Unless there is a significant boost factor from central clumping in these galaxies, present generation telescopes may be one or two orders of magnitude from sensitivity to see a WIMP-like signal
- Future array such as CTA or AGIS could address model elimination or signal detection in a statistically significant manner
- Fermi/GLAST with its ability to view entire sky could provide interesting targets for follow-up by IACTs now and for future arrays.
- Indications of excess high energy electrons/positrons observed by ATIC & PAMELA have interesting implications for follow-up by IACTs

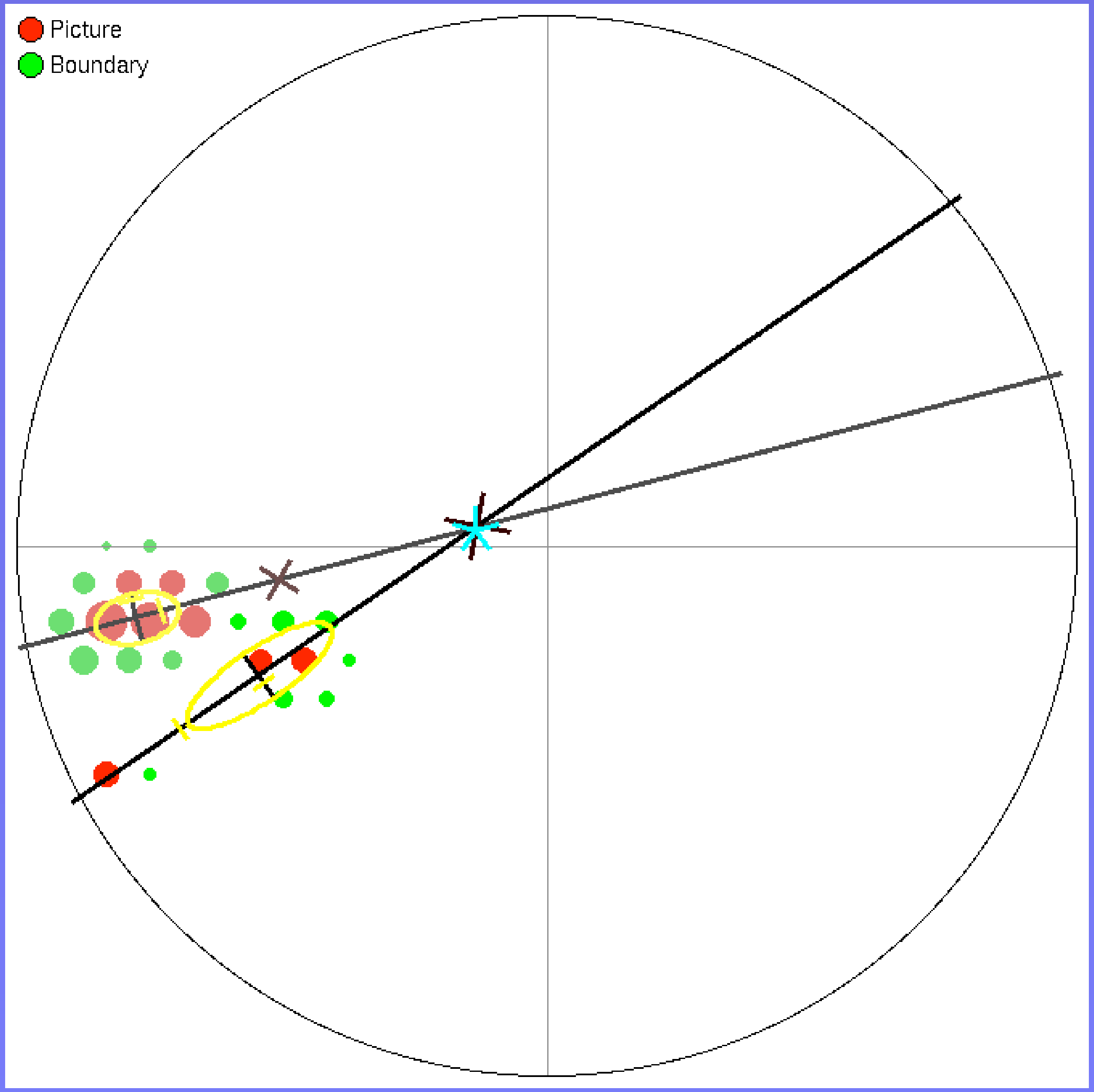
Backup Slides

Cherenkov Telescope Basics - Imaging

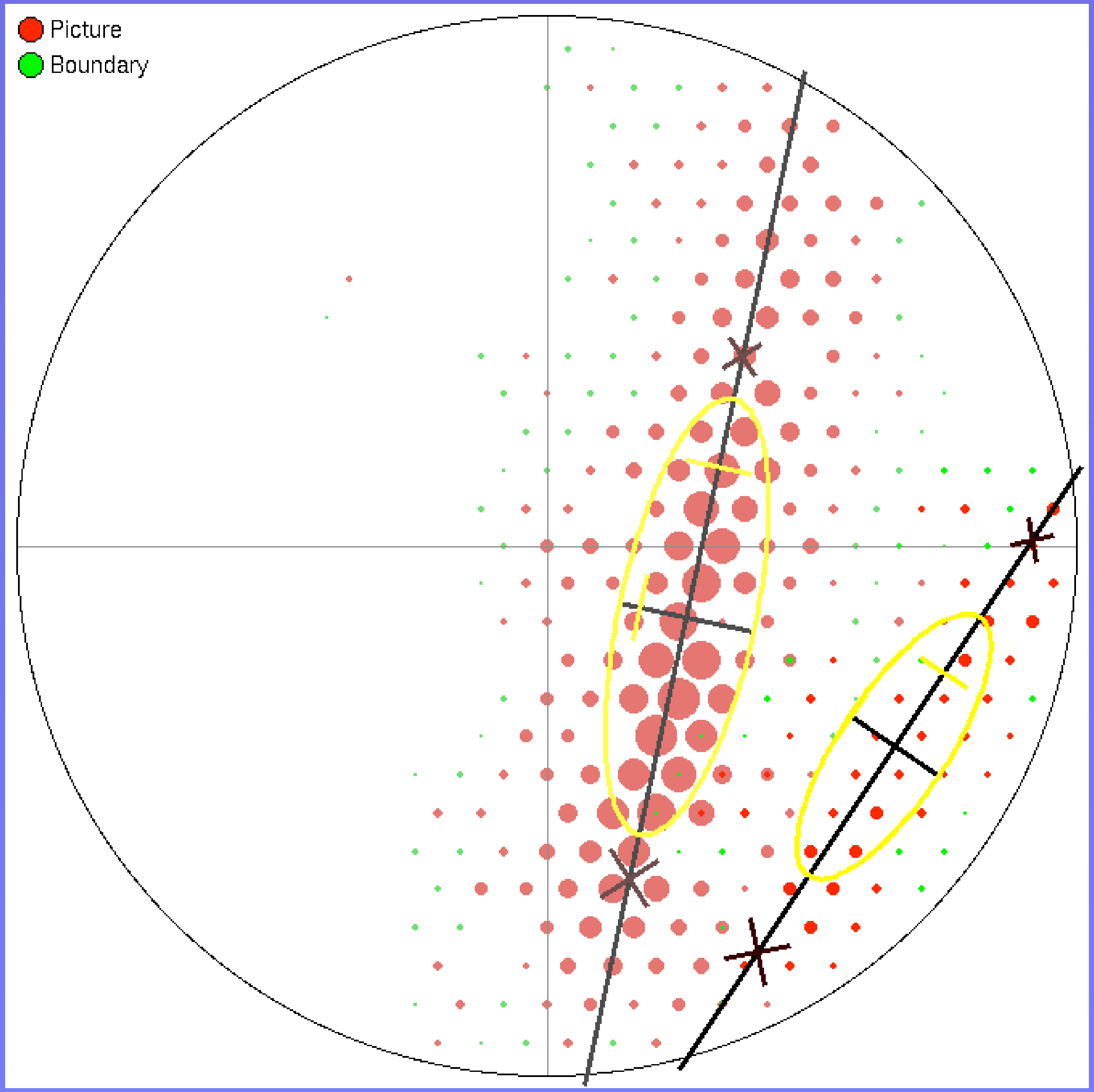



Davies-Cotton f/1.0 optics.
Total mirror area = 110m^2
3.5º FOV
499 PMT camera
Control Room

Stereo Shower Reconstructions



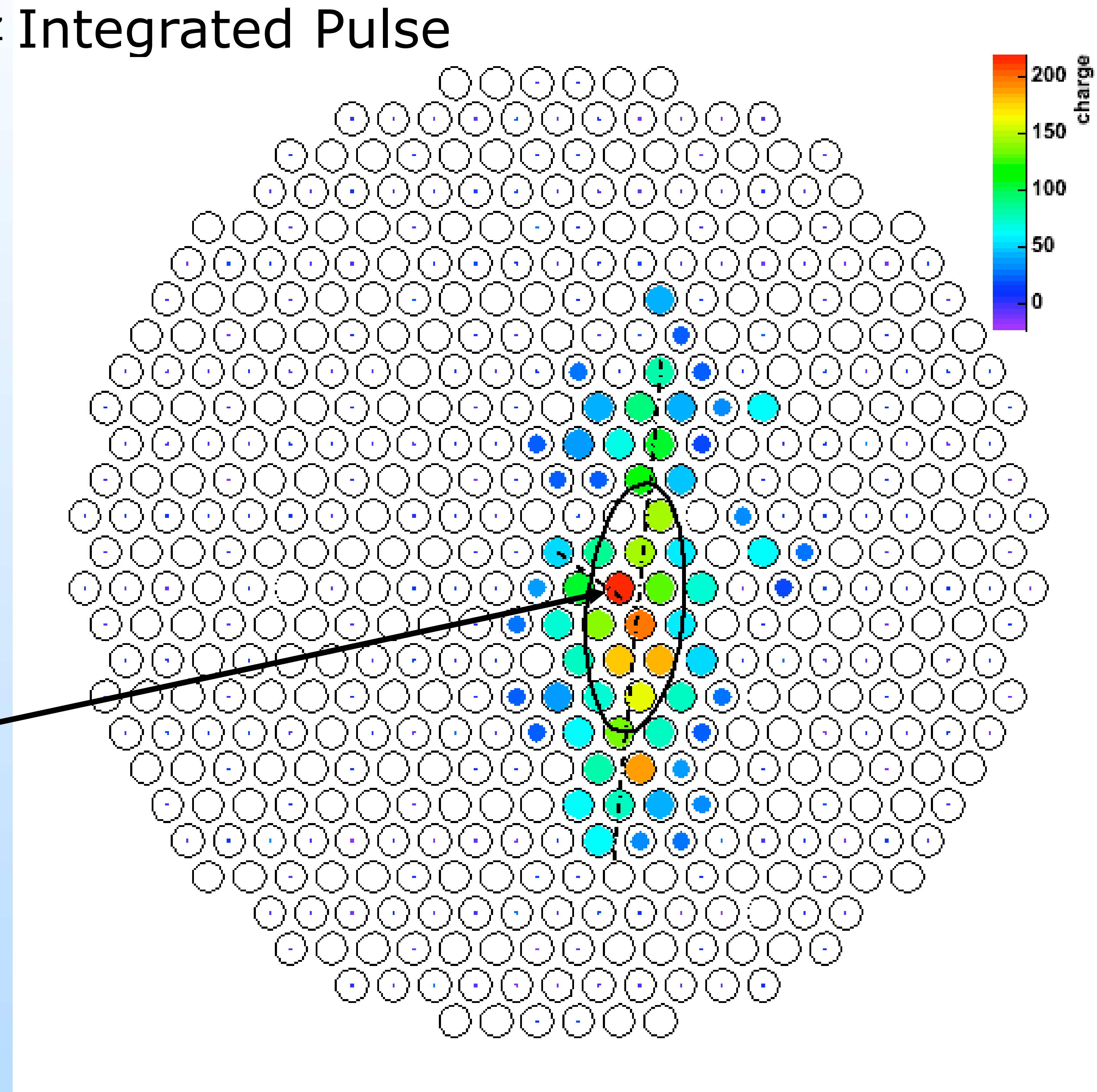
Stereo image projected onto the sky with origin within camera FOV

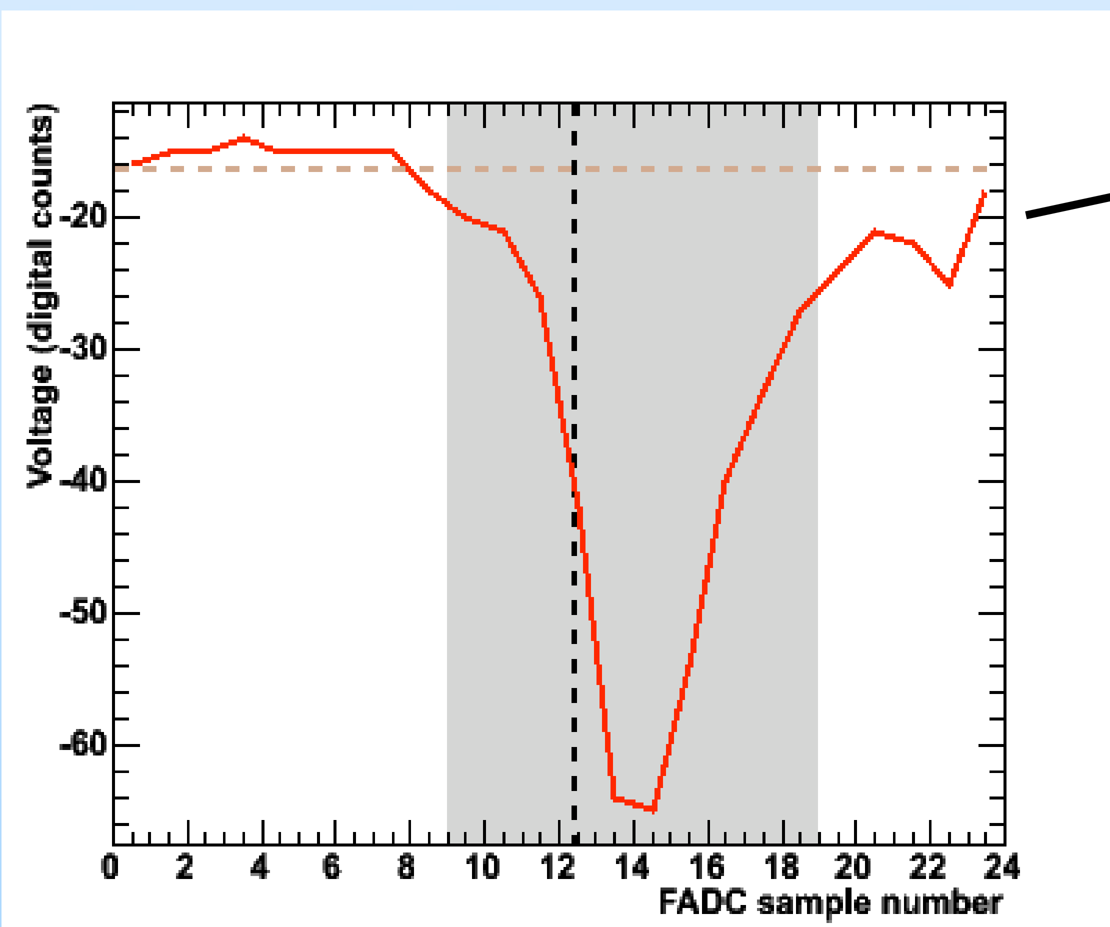


Stereo image of large shower originating outside FOV

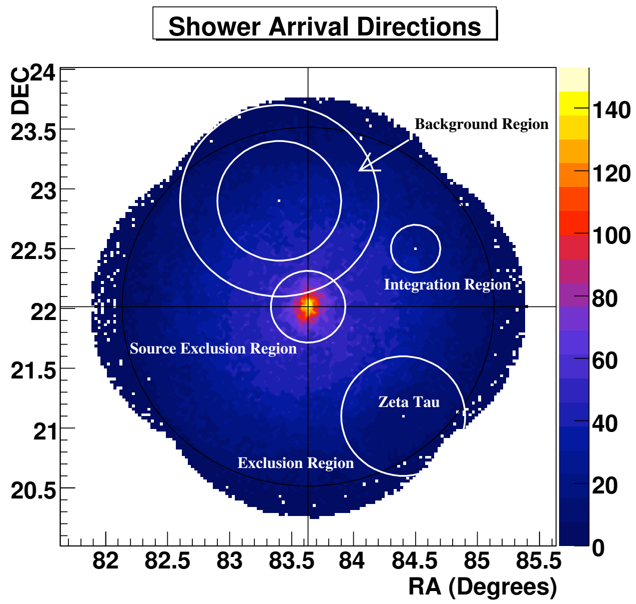
Data Acquisition

- PMT signals digitised with 500MHz sampling FADCs
- Data rates
  - 24 samples/channel
  - 13.5 kb/event/Tel @ 250 Hz
  - **15 Gb/hour !**
  - 15 Tb/year

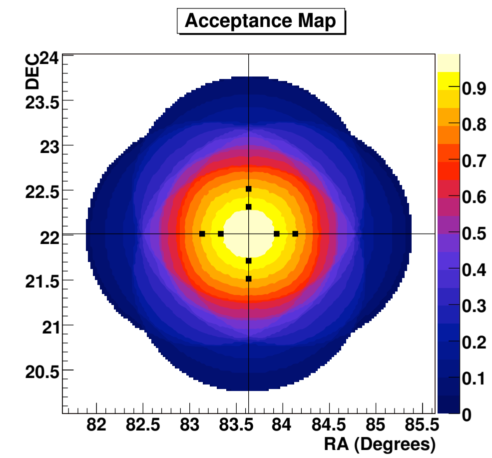




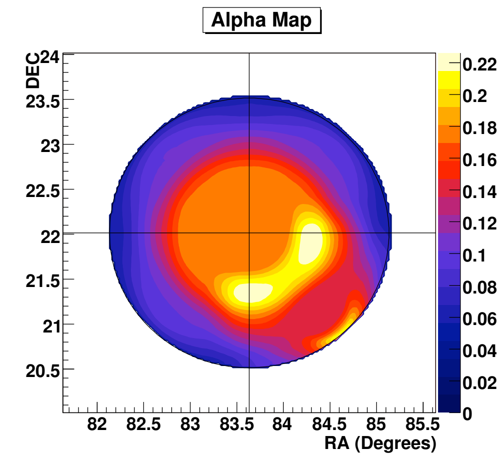
Example of 2-d Maps for Crab Nebula



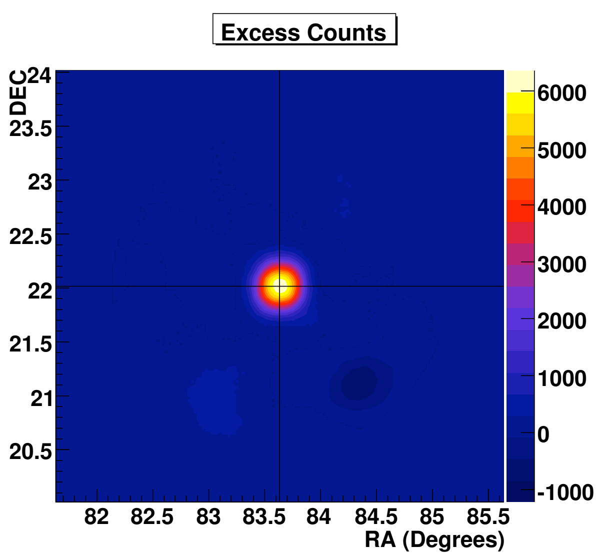
Ring bkgd for Crab Nebula



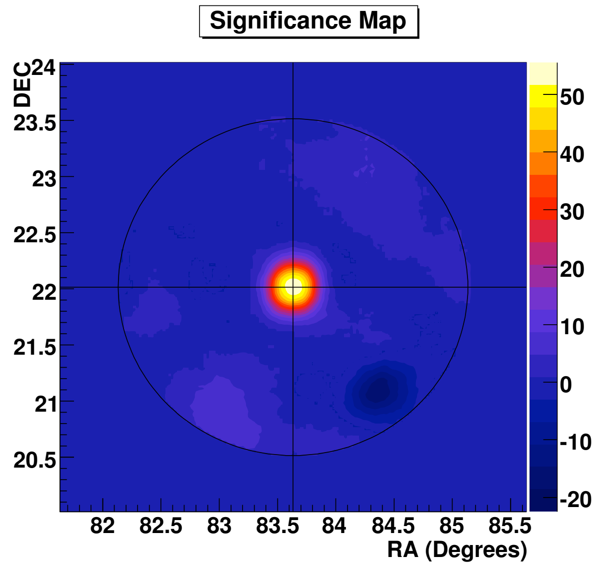
Acceptance map
at each grid point

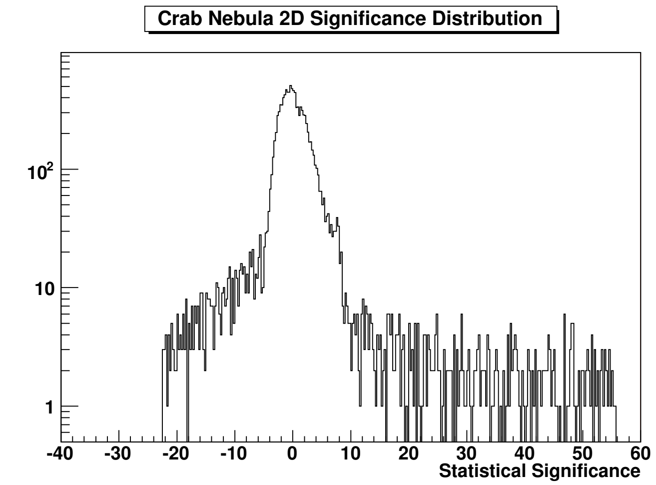


Signal acc./Bkgd acc. map



$N_{\gamma} = N_{ON} - \alpha N_{OFF}$

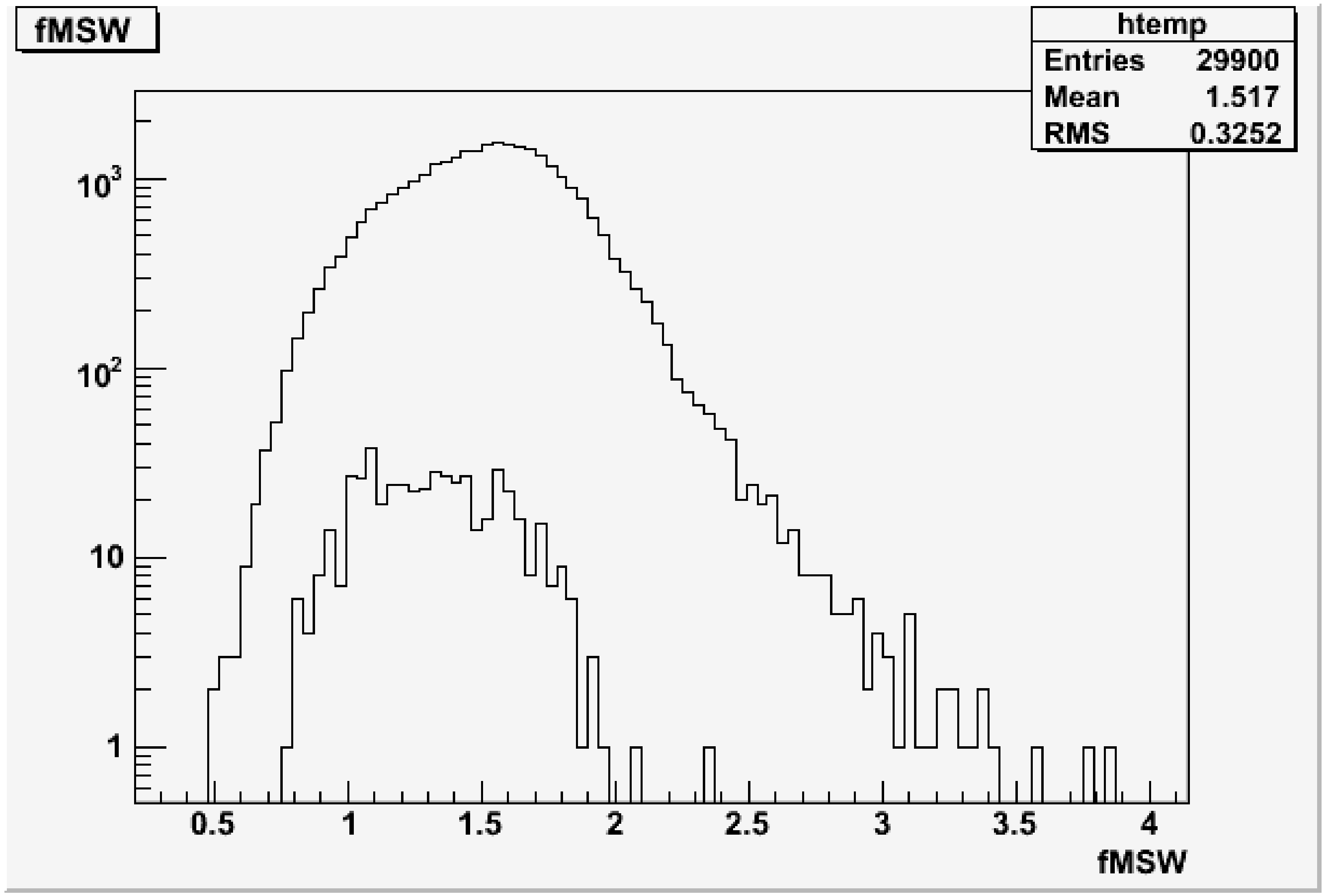




Significance dist. for each point in map at left.
high side tail is from Crab
low side tail is from excluded star bias

from thesis of Peter Cogan

Mean Scaled Width Plots -- Willman 1



MSL: 0.05-1.36 & $\Theta^2 < 0.2$