VERITAS Analysis: Concepts and Practices in IACTs

Jon Dumm

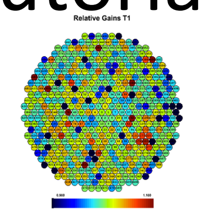
UMD – Fermi, VERITAS, HAWC Workshop

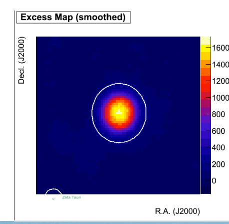
Feb 11, 2014

Credits: Gernot Maier, Ben Zitzer

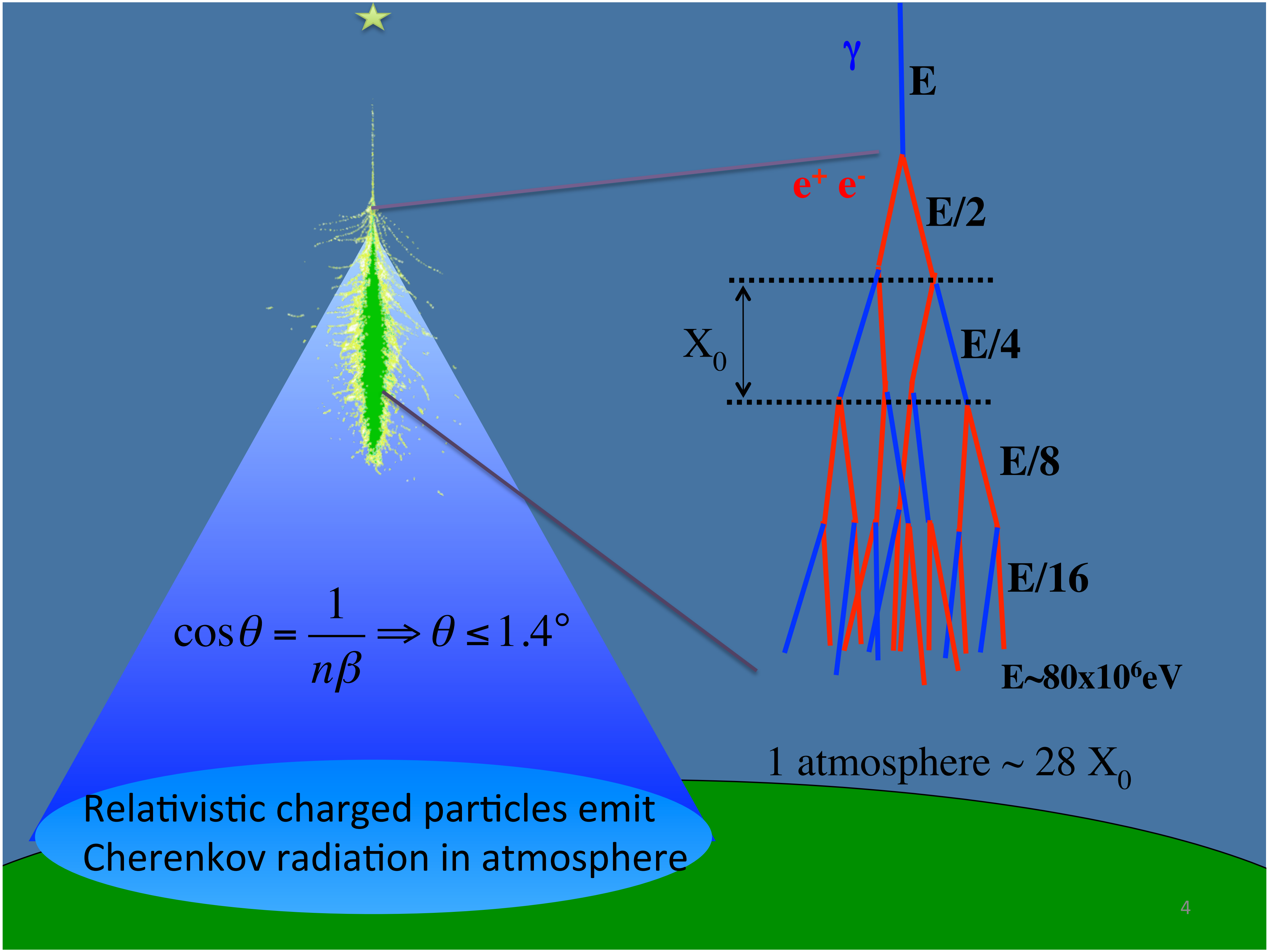
Goals

- Introduce VERITAS analysis packages
  - Cover concepts of 'standard' IACT analysis
- Hands-on analysis tutorials
  - Examining events
  - Creating skymaps

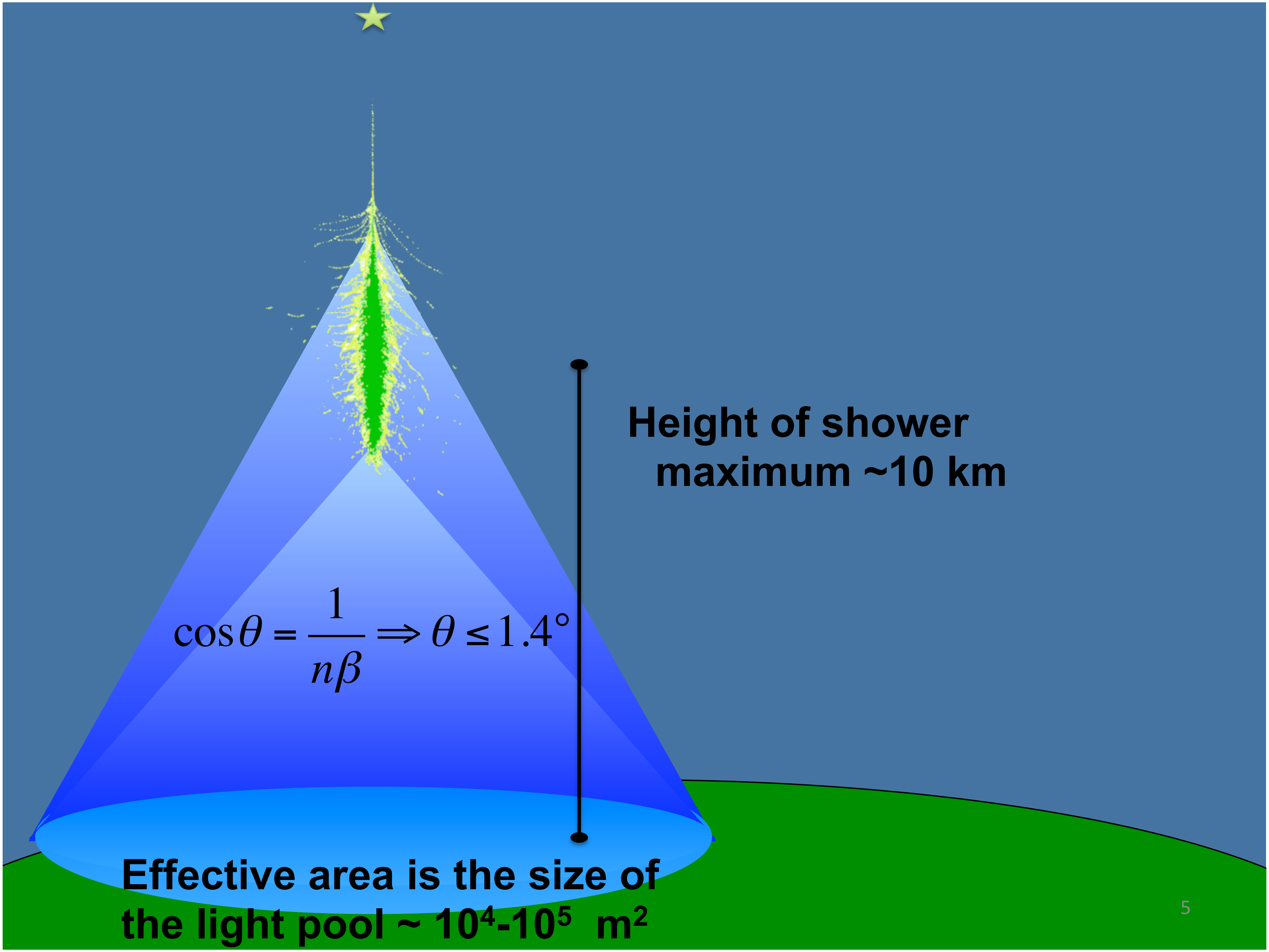


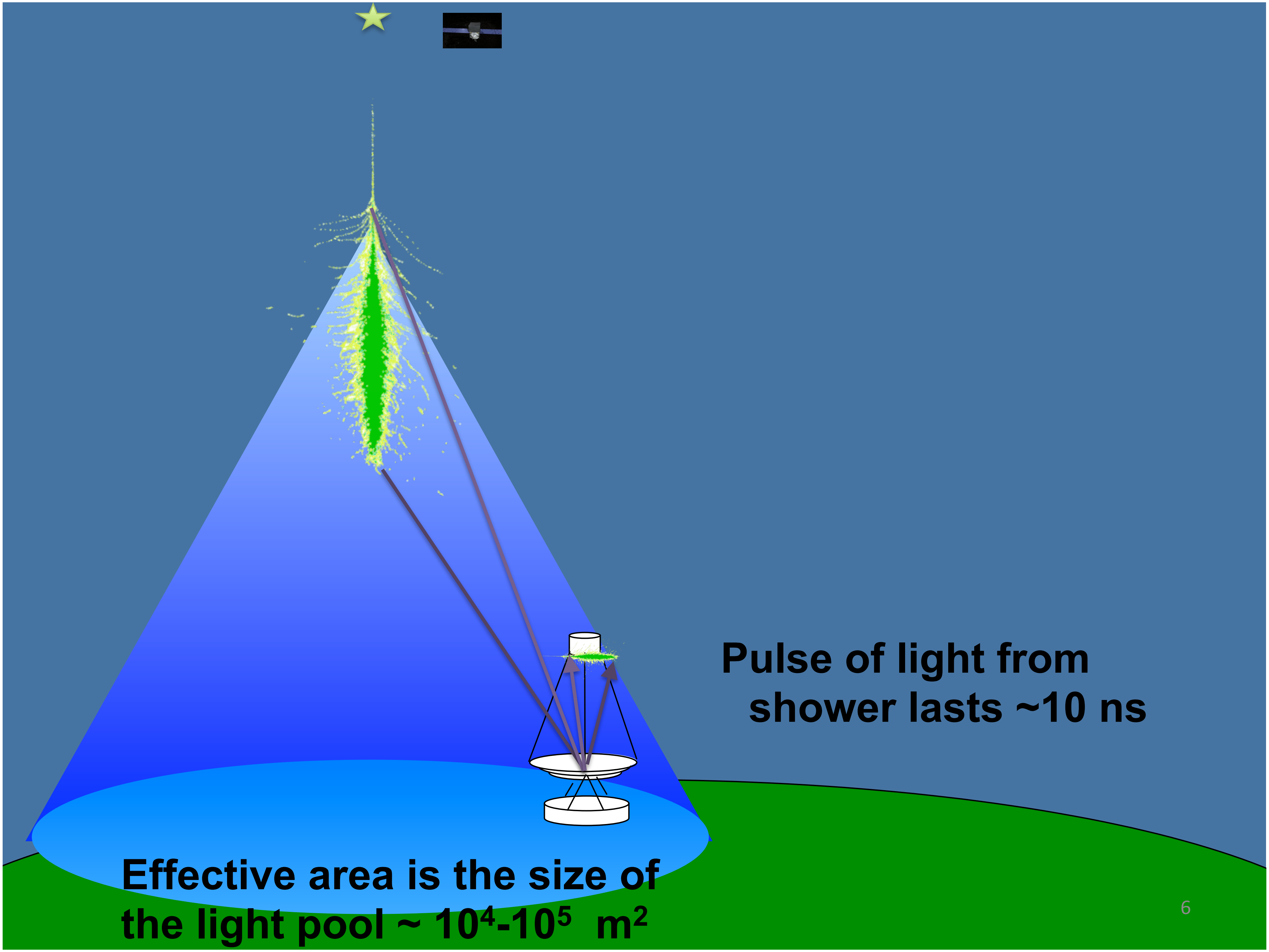


Basics of IACT Technique



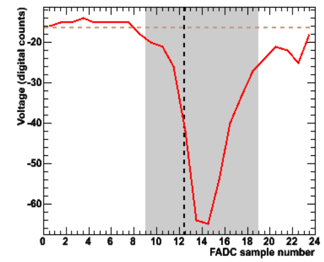
γ
E
$e^+ e^-$
E/2
X_0
E/4
E/8
E/16
$E \sim 80 \times 10^6 eV$
$$\cos\theta = \frac{1}{n\beta} \Rightarrow \theta \leq 1.4°$$
1 atmosphere ~ 28 X_0
Relativistic charged particles emit
Cherenkov radiation in atmosphere


Height of shower
maximum ~10 km
$\cos\theta = \frac{1}{n\beta} \Rightarrow \theta \leq 1.4°$
Effective area is the size of
the light pool ~ 10^4-10^5 m^2

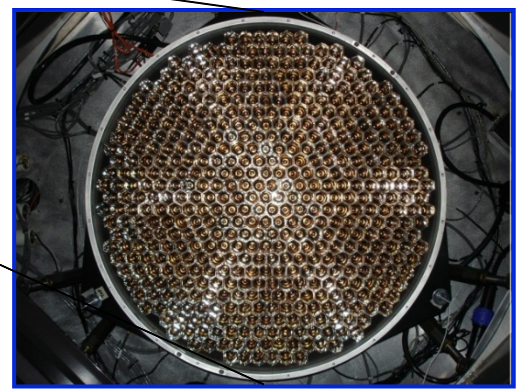

Pulse of light from
shower lasts ~10 ns
Effective area is the size of
the light pool ~ 10^4-10^5 m^2

VERITAS Components

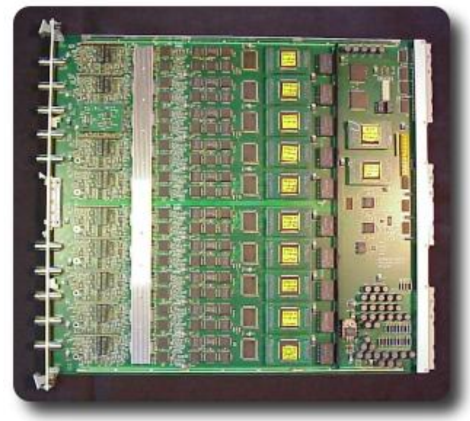
PMT Assembly



FADC Board & Trace



Camera (x 4)
499 PMTs, 3.5° FOV

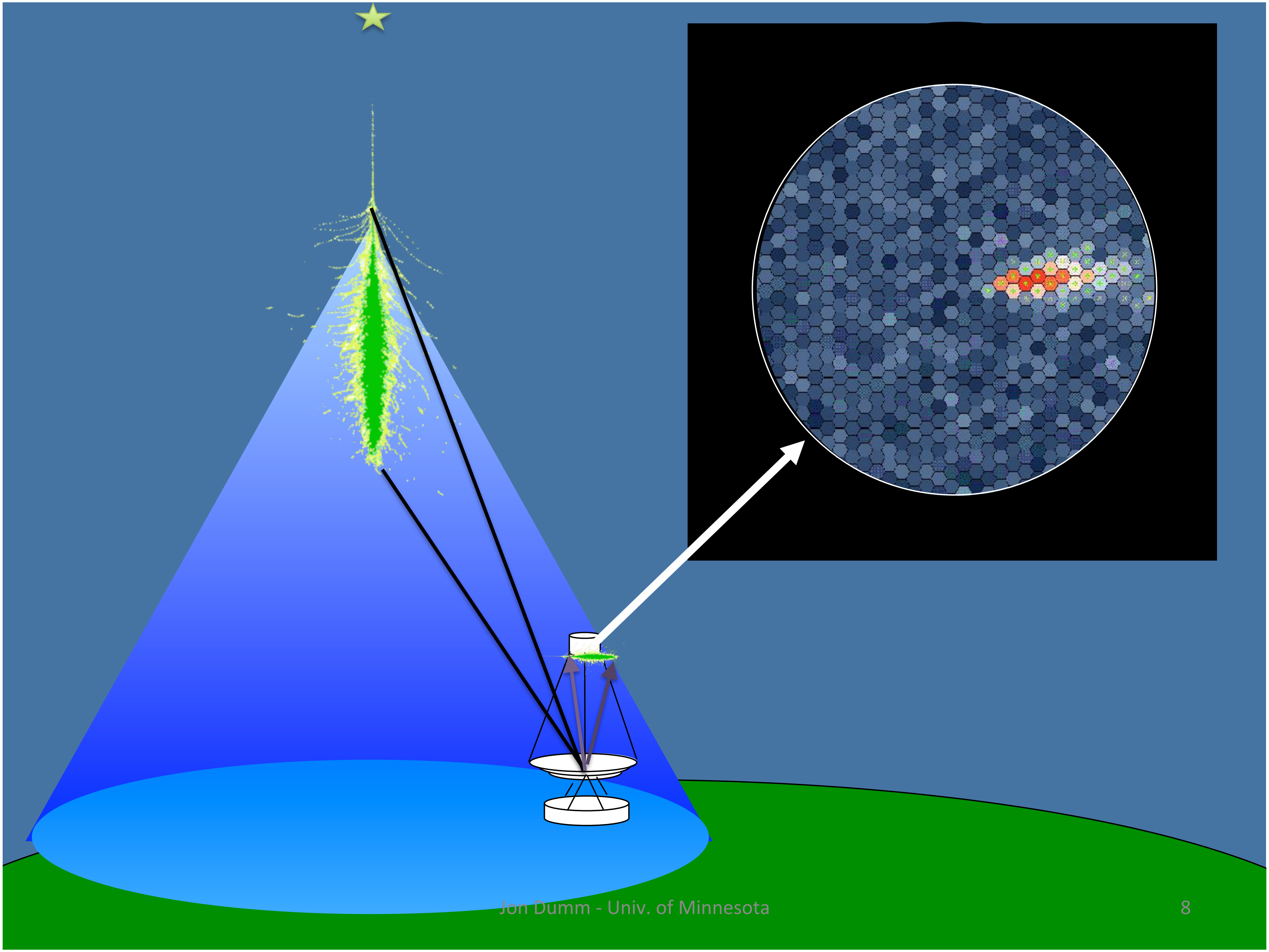


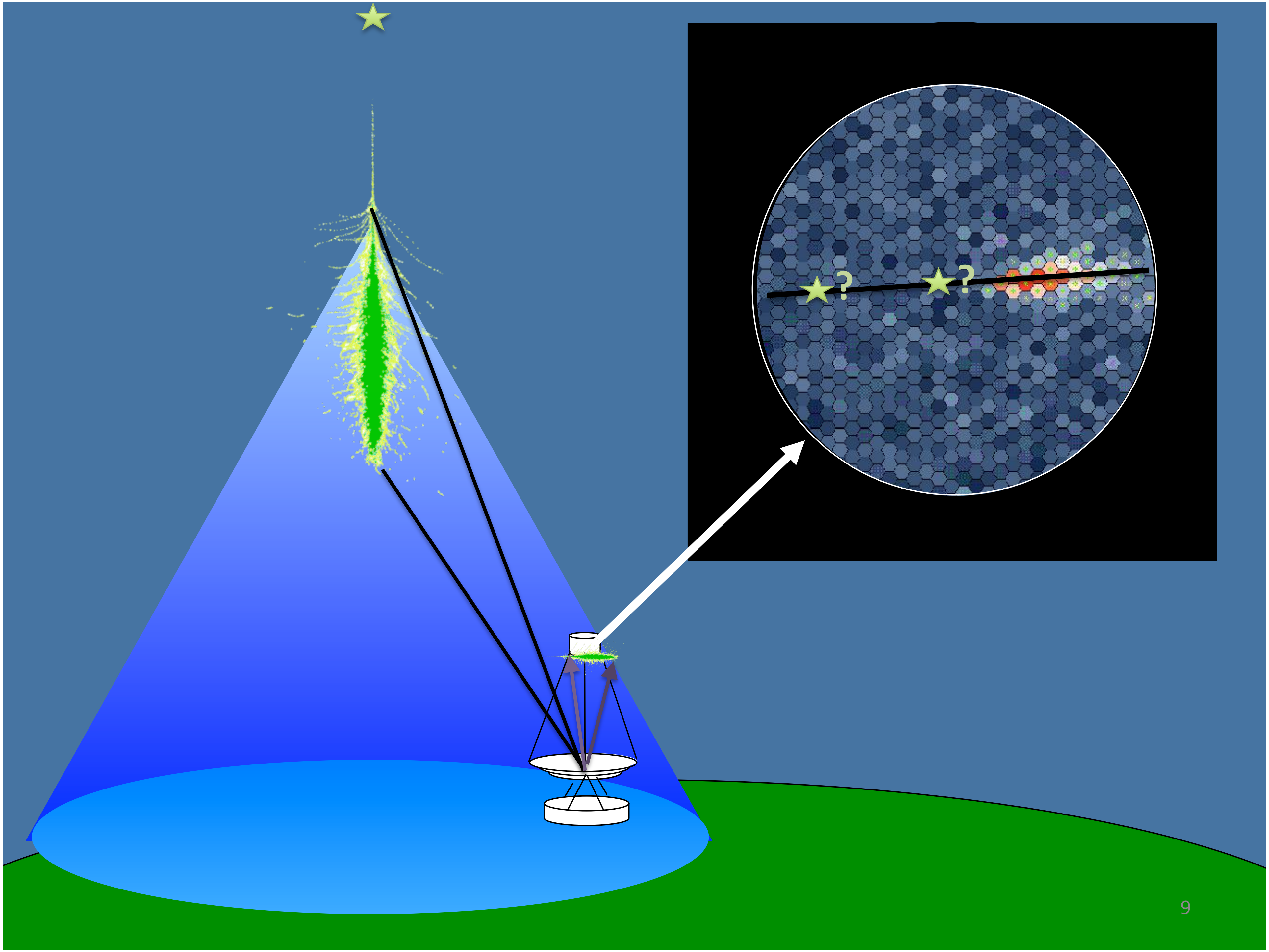
Telescope (x 4)
12-m diameter Davies-Cotton
f/1.0, 110 m^2 area

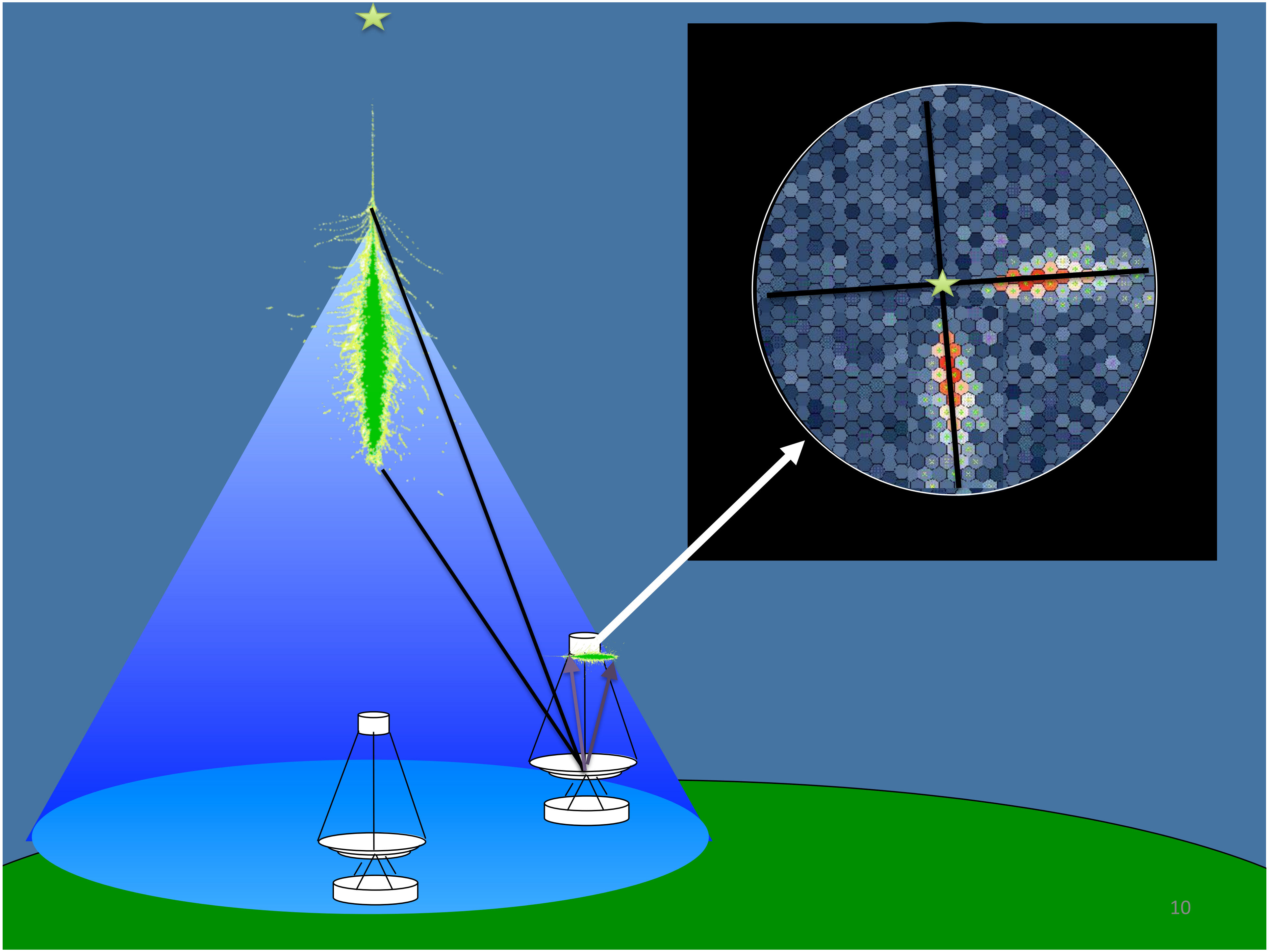
Mirror Facets (x 350 x 4)
Reflectivity ~ 88%
(Recoated every 2 years)

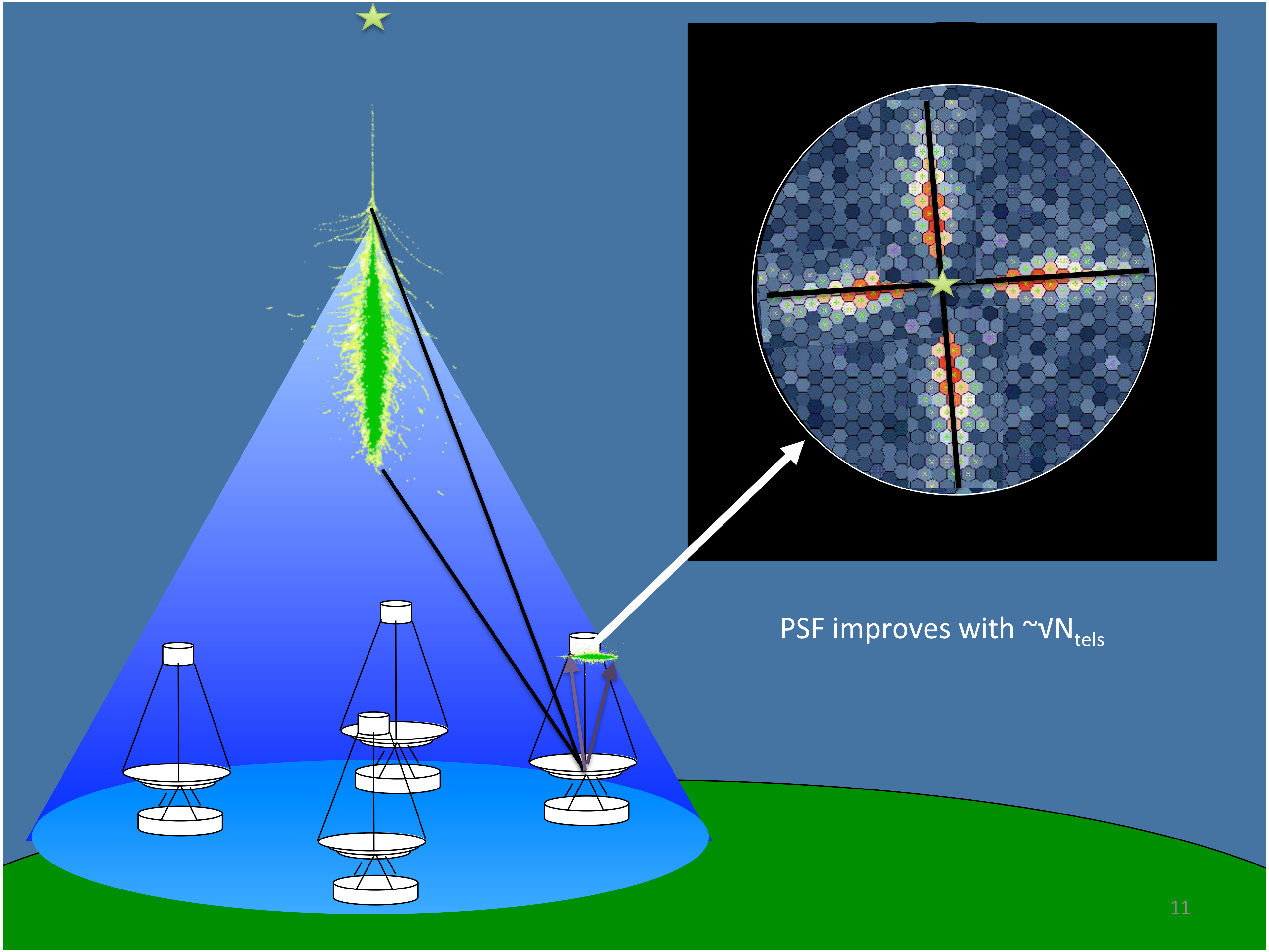
FADC Readout
500 Msps, dual-gain

3-Level Trigger
Pixel, Telescope, Array
Deadtime ~15% @ 400 Hz



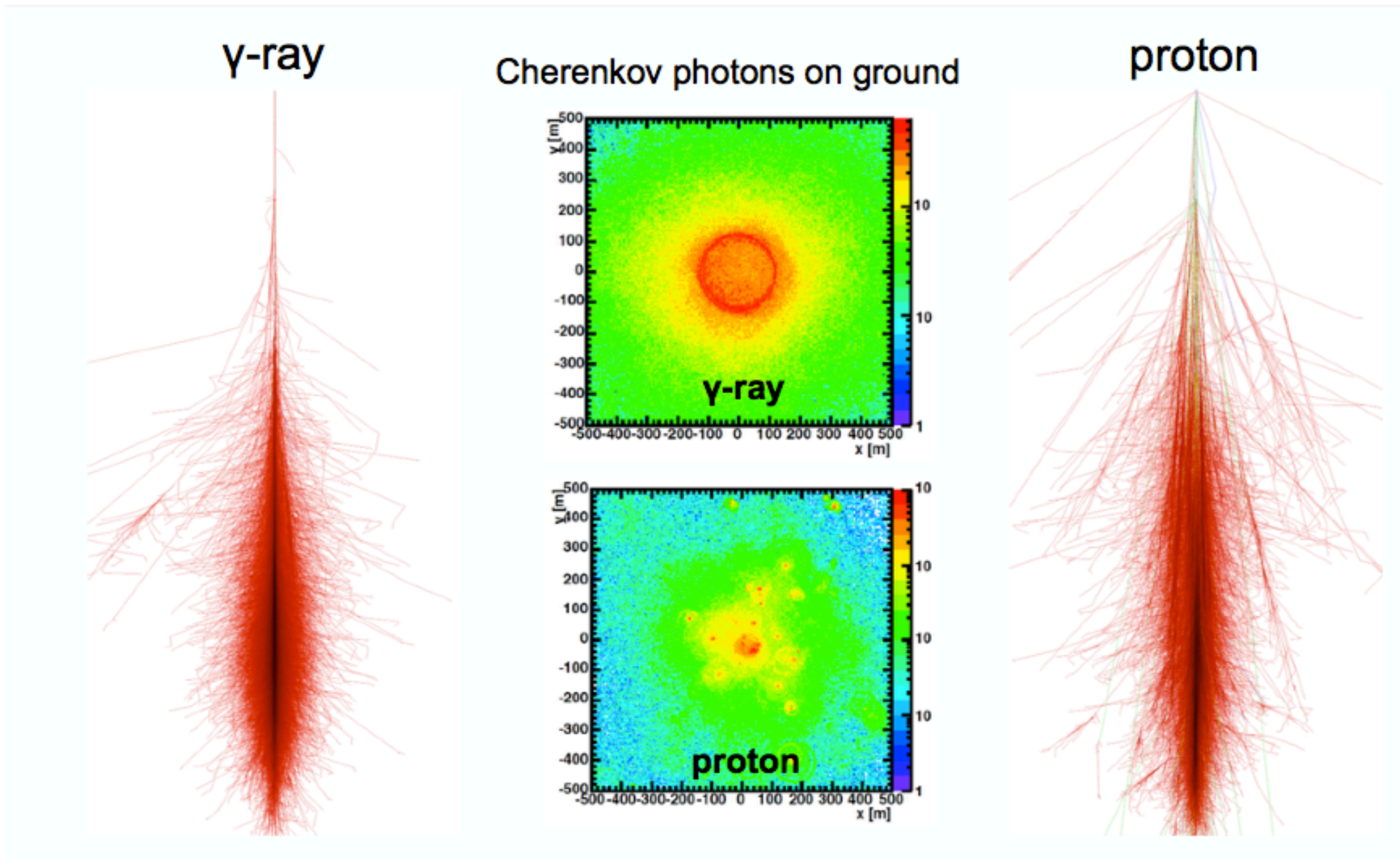




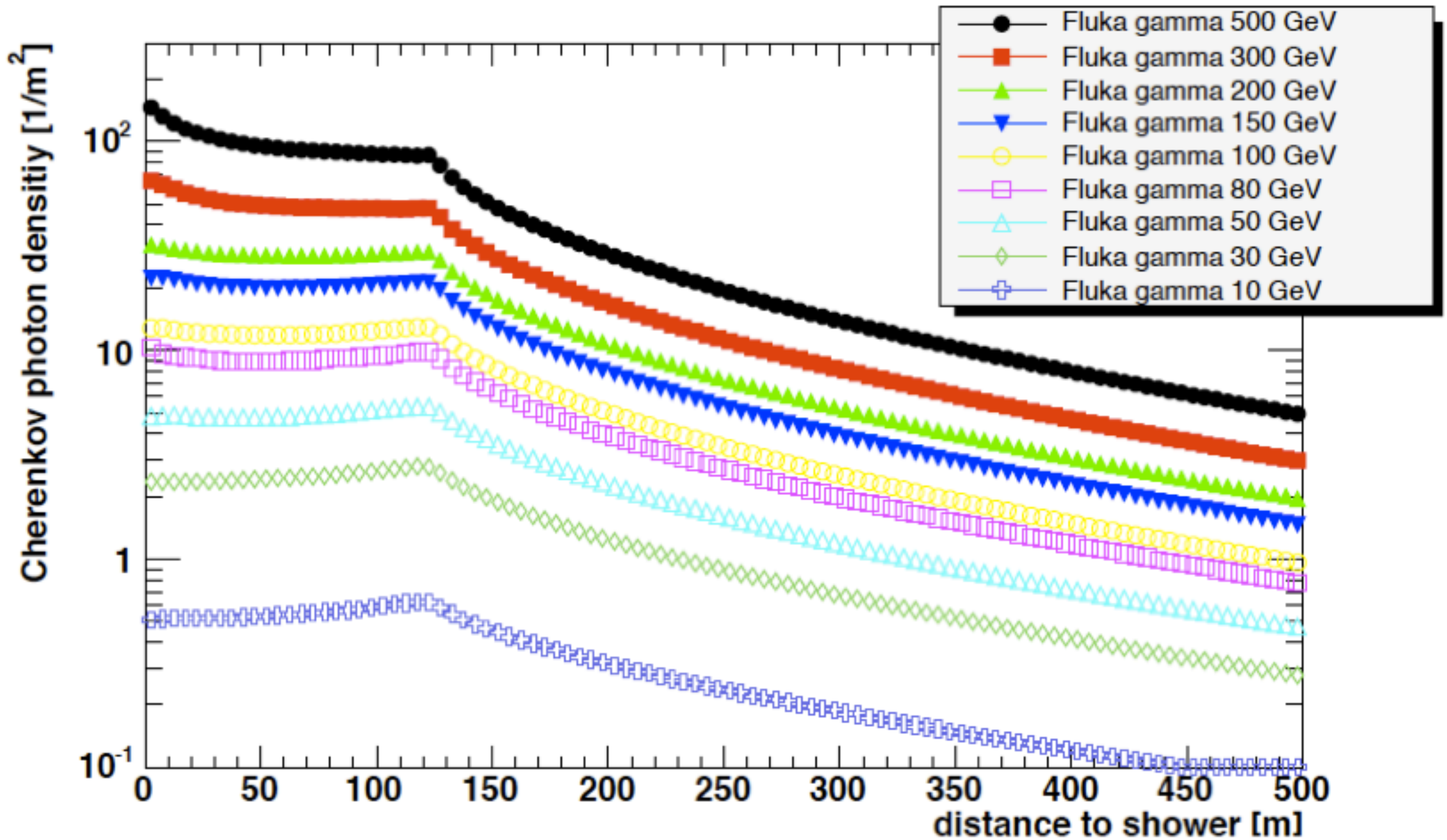


PSF improves with ~√N_{tels}

Simulated Showers

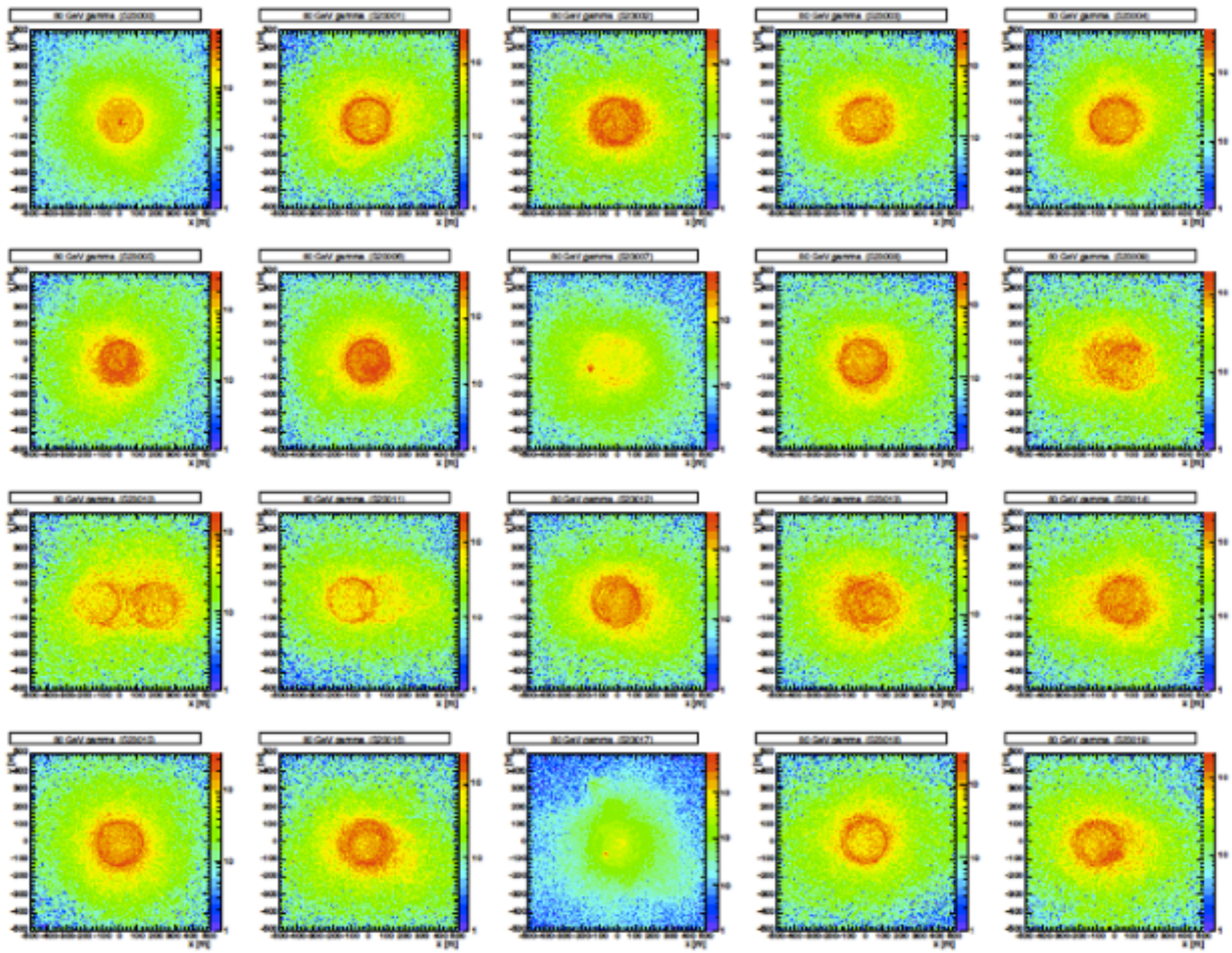


Simulated Showers



Simulated Showers

randomly selected showers with 80 GeV primary photon energy



Offline Analysis Packages

- Two parallel analysis packages
  - **VEGAS** – VERITAS Gamma-ray Analysis Suite
  - **ED** – eventdisplay (Gernot Maier)
    - (but it does more than the name suggests, includes CTA)

- Independent development over ~8 year period

Revision **1.1** - (view) (download) (annotate) - [select for diffs]
Tue Jul 12 14:19:08 2005 UTC (8 years, 6 months ago) by *pcogan*
Branch: **MAIN**

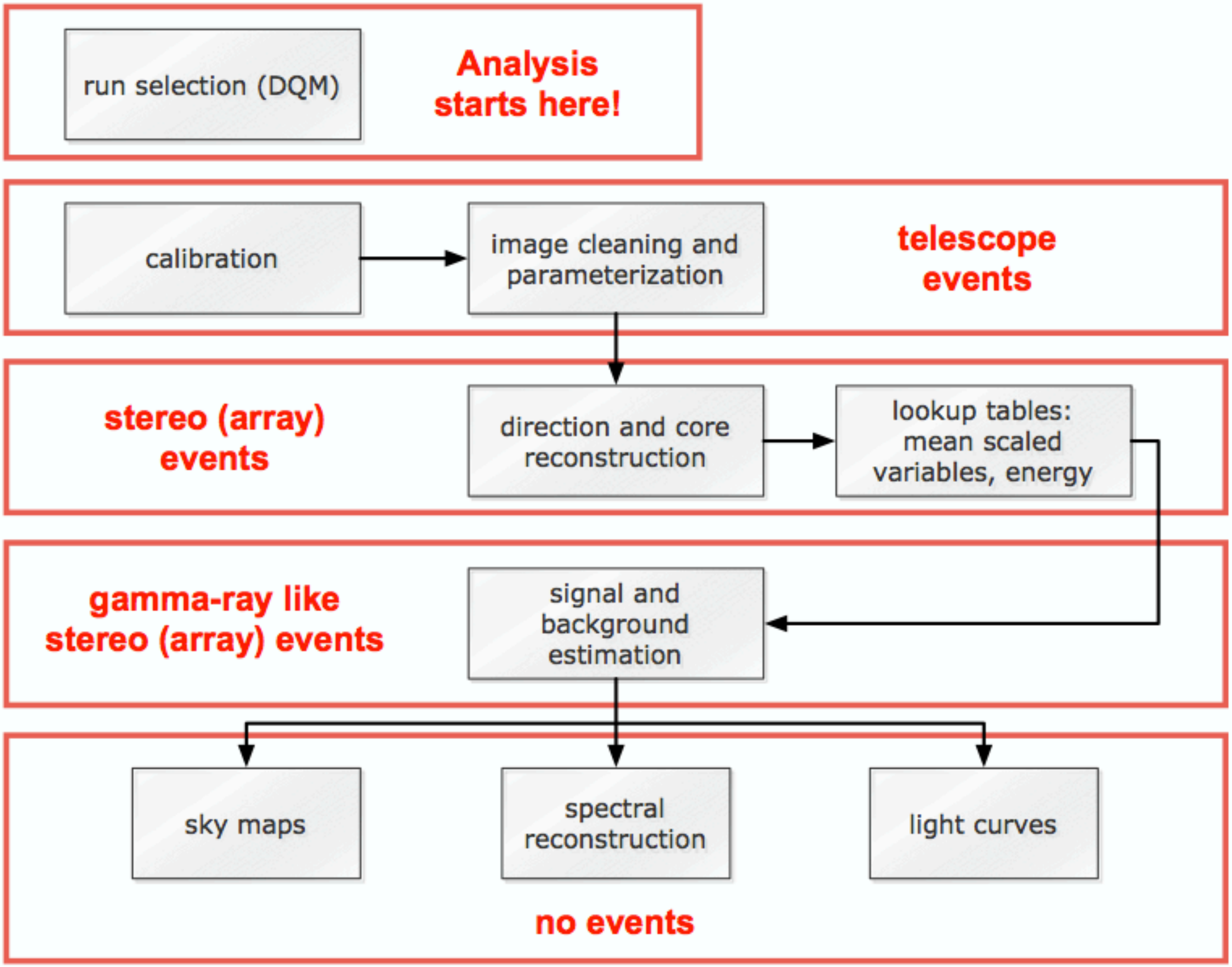
```
Added some new files
```

- All published results duplicated in independent secondary analyses

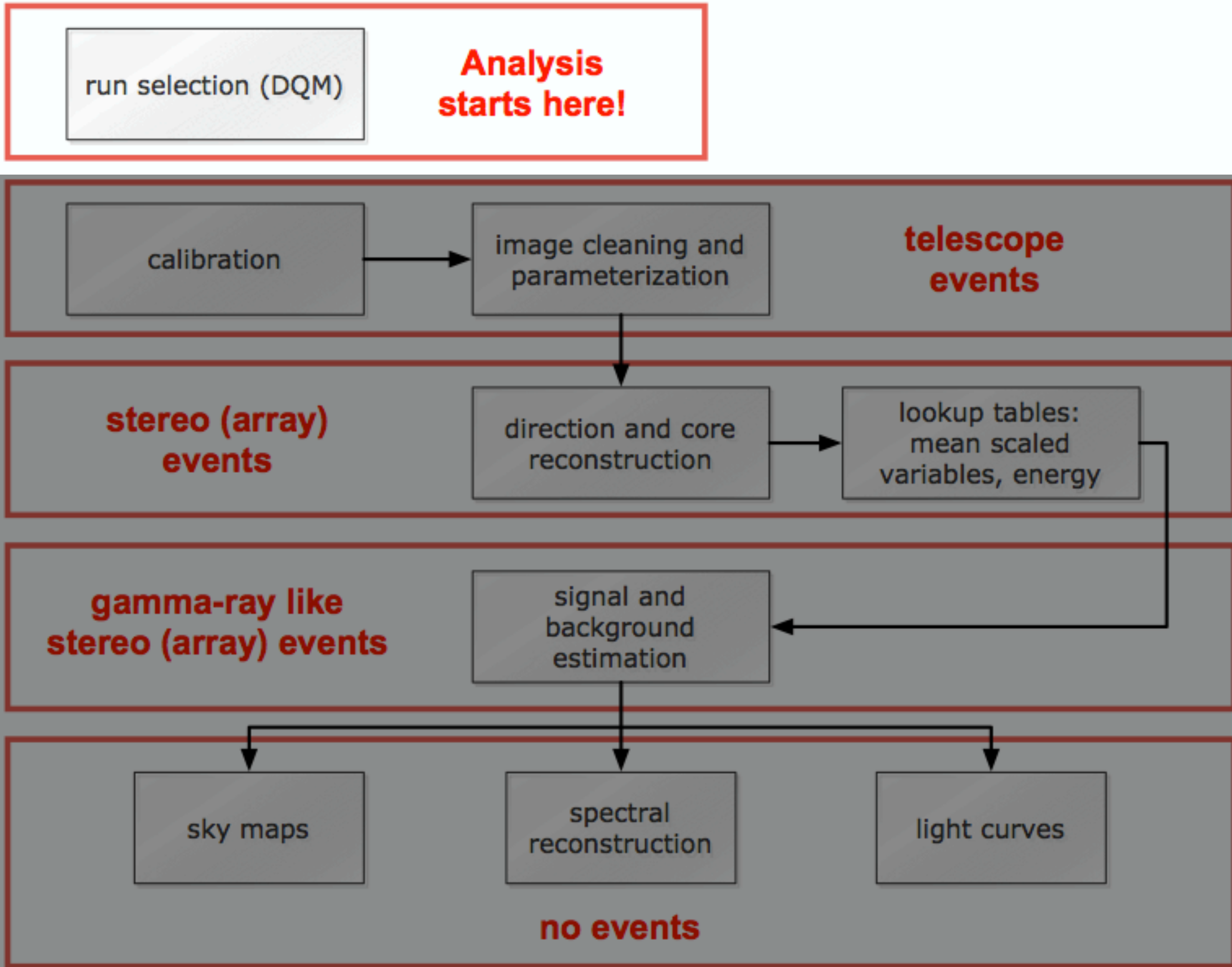
Design Philosophy

- Both written in C++, heavily dependent on ROOT
- Modular: processing in stages
- Flexible
  - Lots of options, alternative algorithms
  - File format is quite rigid, however
- Most point-source analysis standardized
  - Automated analyses can be trusted ~90% of the time
  - More about non-point source analysis tomorrow

Analysis Overview



Analysis Overview



Log Sheet Generator

VERITAS Run Log Generator

The LogGen page on GammaWiki includes a User Manual.

Nightly ELog (Date Search)

Choose Today (UT) or select a date and click Submit :

Today Year: 2014 Month: February Day: 01 Submit Reset

Run Search

Specify run id to bring up log entry :

Run ID : Search Reset

~1000 hours of dark time/year to sift through
~+300 hours of moon time w/ increased threshold
(10-15% duty cycle)

Targeted Search

Specify search criteria and click 'Search'.

Source name options :

- Start typing and press ‹right-arrow› to complete a name from the list or click to select.
  - List of sources updates automatically on page reload.
  - (688 sources have successful data runs; list is up-to-date.)
- **New!** Use the 'as prefix' checkbox to list, for example, all GRB data in one search.
- Use source name wildcard 'any' to find any type of run at all.
- **New!** More search wildcards for calibration/engineering data: check the drop-down list.
- Click here for Andrew McCann's tool to build run lists based on telescope pointings.

Source Name :	Crab (as prefix ☐) OR select from this list: Crab
Observing Mode :	Any
Begin Date :	Year: 2011 Month: 12 Day: 01
End Date :	Year: 2011 Month: 12 Day: 31
Weather :	○ ≥A ◉ ≥B ○ ≥C ○ All/any weather conditions
Elevation :	Lower: 0 Upper: 90
Required Telescopes :	☐ T1 AND ☐ T2 AND ☐ T3 AND ☐ T4
Data Category :	☑ Regular AND ☐ Filter AND ☐ Reduced HV
Number of telescopes :	at least 0 at most 4
Online Status :	Any (including Aborted)
Offline Status :	Any
Offline Status Reason :	Any
Offline Data Category :	Any
Usable duration (mins) :	at least 0
Offline Light-level :	Any

Search Reset

Interfaces with DB to generate a run list – essentially a MySQL query wrapper around user search criteria

Log Sheet Generator

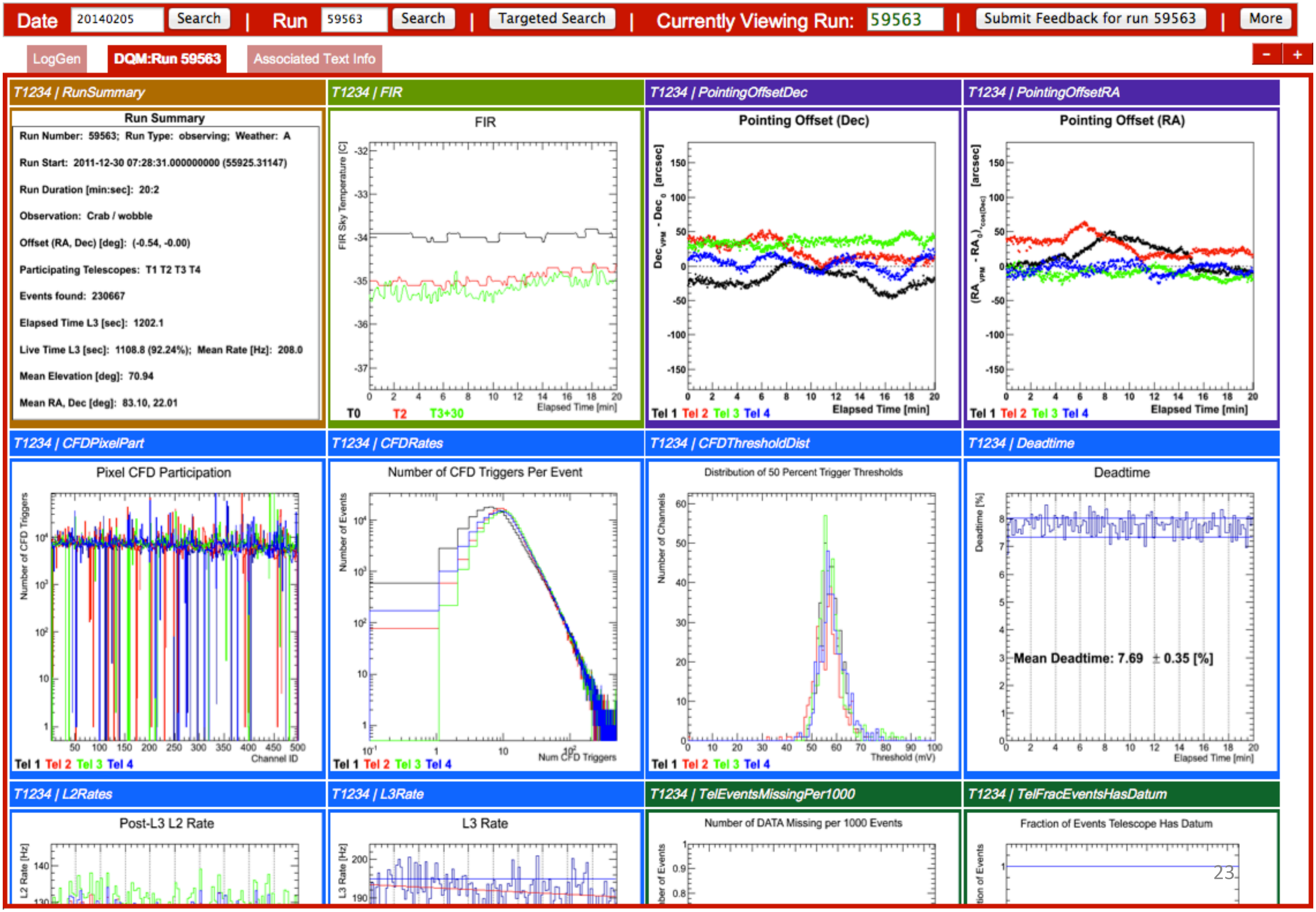
DATE	RUN	SOURCE	CALIB	UTC	DUR	USE	MODE	SKY	'T1'-FIR CRMS	T3-FIR CRMS	EL	AZ	Hz	TEL	NSB	FLG	CMT
20111215	59183	Crab	1234/$_2$	03:54	20	0	0.5N	B	0.1 (A)	0.2	45	89	37	^{2}/1234	1.8 (d)	X(m):¡	1 a
20111215	59186	Crab	1234/$_2$	05:07	20	0	0.5S	B	0.2 (B)	0.2	60	102	52	^{2}/1234	1.4 (l)	X(m):¡	2
20111215	59191	Crab	1234/$_2$	05:56	20	0	0.5E	B	0.1 (A)	0.3	70	113	29	^{2}/1234	2.2 (l)	X(m):¡	3
20111215	59192	Crab	1234/$_2$	06:26	20	0	0.5W	B	0.1 (A)	0.3	76	131	34	^{2}/1234	2.5 (l)	X(m):¡	4
20111215	59193	Crab	1234/$_2$	06:47	20	0	0.5W	B	0.1 (A)	0.2	79	149	31	^{2}/1234	2.7 (l)	X(m):¡	5
20111215	59194	Crab	1234/$_2$	07:08	20	0	0.5N	B	0.1 (A)	0.2	81	171	30	^{2}/1234	2.9 (l)	X(m):¡	6
20111215	59195	Crab	1234/$_2$	07:30	10	0	0.5S	B	0.1 (A)	0.1	80	194	30	^{2}/1234	3.1 (l)	X(m):¡	7
20111216	59228	Crab	1234/$_1$	06:42	20	20	0.5N	A	0.1 (A)	0.2	79	144	63	^{2}/1234	3.7 (l)	<:s	8
20111226	59410	Crab	1234/$_1$	06:18	20	20	0.5S	A	0.1 (A)	0.2	79	163	197	^{2}/1234	5.6 (d)	<:s	b
20111227	59451	Crab	1234/$_1$	08:08	20	20	0.5S	A-	0.1 (A)	0.2	65	253	194	^{2}/1234	5.8 (d)	<:s	
20111227	59452	Crab	1234/$_1$	08:29	20	20	0.5E	A-	0.1 (A)	0.2	62	258	190	^{2}/1234	5.9 (d)	<:s	9
20111229	59521	Crab	1234/$_1$	05:41	20	20	0.5W	A	0.1 (A)	0.3	77	138	194	^{2}/1234	5.3 (d)	<:s	
20111229	59522	Crab	1234/$_1$	06:01	20	20	0.5N	A	0.1 (A)	0.2	80	155	194	^{2}/1234	5.2 (d)	<:s	
20111229	59523	Crab	1234/$_1$	06:23	20	20	0.5S	A	0.1 (A)	0.2	80	186	198	^{2}/1234	5.3 (d)	<:s	
20111230	59562	Crab	1234/$_1$	07:08	20	20	0.5E	A	0.2 (B)	0.3	75	233	196	^{2}/1234	5.3 (d)	<:s	
20111230	59563	Crab	1234/$_1$	07:29	20	20	0.5W	A	0.2 (B)	0.1	71	246	192	^{2}/1234	5.5	<:s	
					19.4						72.4		116.3			MEANS	
	16				310	180										TOTALS	

Run number and link to CHILA diagnostics plots.

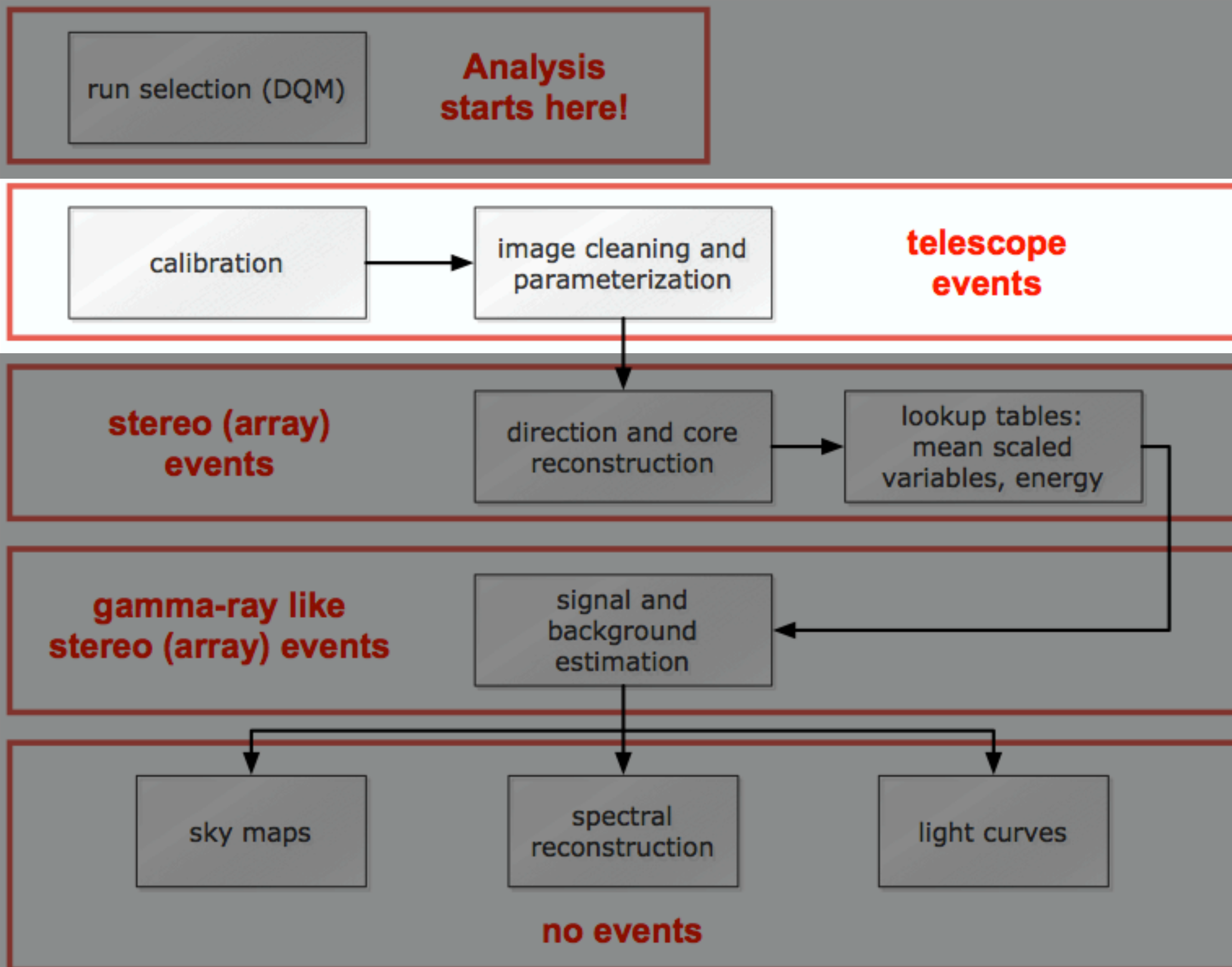
All the most important information on one page. More details on DQM page.

Data Quality Monitoring

- ‘Standardized’ run selection
  – Every collaborator takes part in DQM shifts
- Web interface provides many low-level plots for determining data quality
  – Generally performed by noon following day
  – Allows for fast turnaround in fixing problems
- A good starting place for runlist
  – Different analyses may have different quality requirements

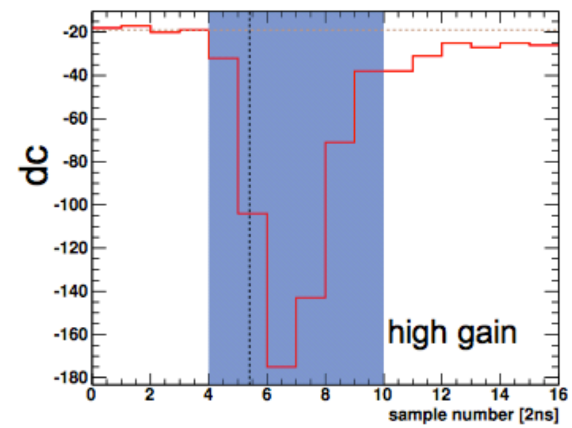

Date 20140205 Search | Run 59563 Search | Targeted Search | Currently Viewing Run: 59563 | Submit Feedback for run 59563 | More
LogGen
DQM:Run 59563
Associated Text Info
T1234 | RunSummary
Run Summary
Run Number: 59563; Run Type: observing; Weather: A
Run Start: 2011-12-30 07:28:31.000000000 (55925.31147)
Run Duration [min:sec]: 20:2
Observation: Crab / wobble
Offset (RA, Dec) [deg]: (-0.54, -0.00)
Participating Telescopes: T1 T2 T3 T4
Events found: 230667
Elapsed Time L3 [sec]: 1202.1
Live Time L3 [sec]: 1108.8 (92.24%); Mean Rate [Hz]: 208.0
Mean Elevation [deg]: 70.94
Mean RA, Dec [deg]: 83.10, 22.01
T1234 | FIR
FIR
FIR Sky Temperature [C]
Elapsed Time [min]
T0 T2 T3+30
T1234 | PointingOffsetDec
Pointing Offset (Dec)
Elapsed Time [min]
Tel 1 Tel 2 Tel 3 Tel 4
T1234 | PointingOffsetRA
Pointing Offset (RA)
Elapsed Time [min]
Tel 1 Tel 2 Tel 3 Tel 4
T1234 | CFDPixelPart
Pixel CFD Participation
Number of CFD Triggers
Channel ID
Tel 1 Tel 2 Tel 3 Tel 4
T1234 | CFDRates
Number of CFD Triggers Per Event
Number of Events
Num CFD Triggers
Tel 1 Tel 2 Tel 3 Tel 4
T1234 | CFDThresholdDist
Distribution of 50 Percent Trigger Thresholds
Number of Channels
Threshold (mV)
Tel 1 Tel 2 Tel 3 Tel 4
T1234 | Deadtime
Deadtime
Deadtime [%]
Mean Deadtime: 7.69 ± 0.35 [%]
Elapsed Time [min]
T1234 | L2Rates
Post-L3 L2 Rate
L2 Rate [Hz]
T1234 | L3Rate
L3 Rate
L3 Rate [Hz]
T1234 | TelEventsMissingPer1000
Number of DATA Missing per 1000 Events
T1234 | TelFracEventsHasDatum
Fraction of Events Telescope Has Datum

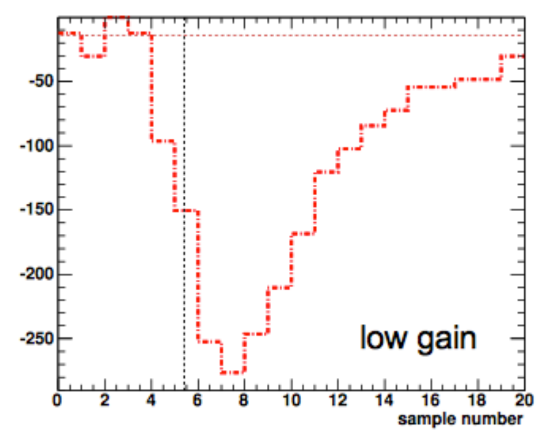
Analysis Overview



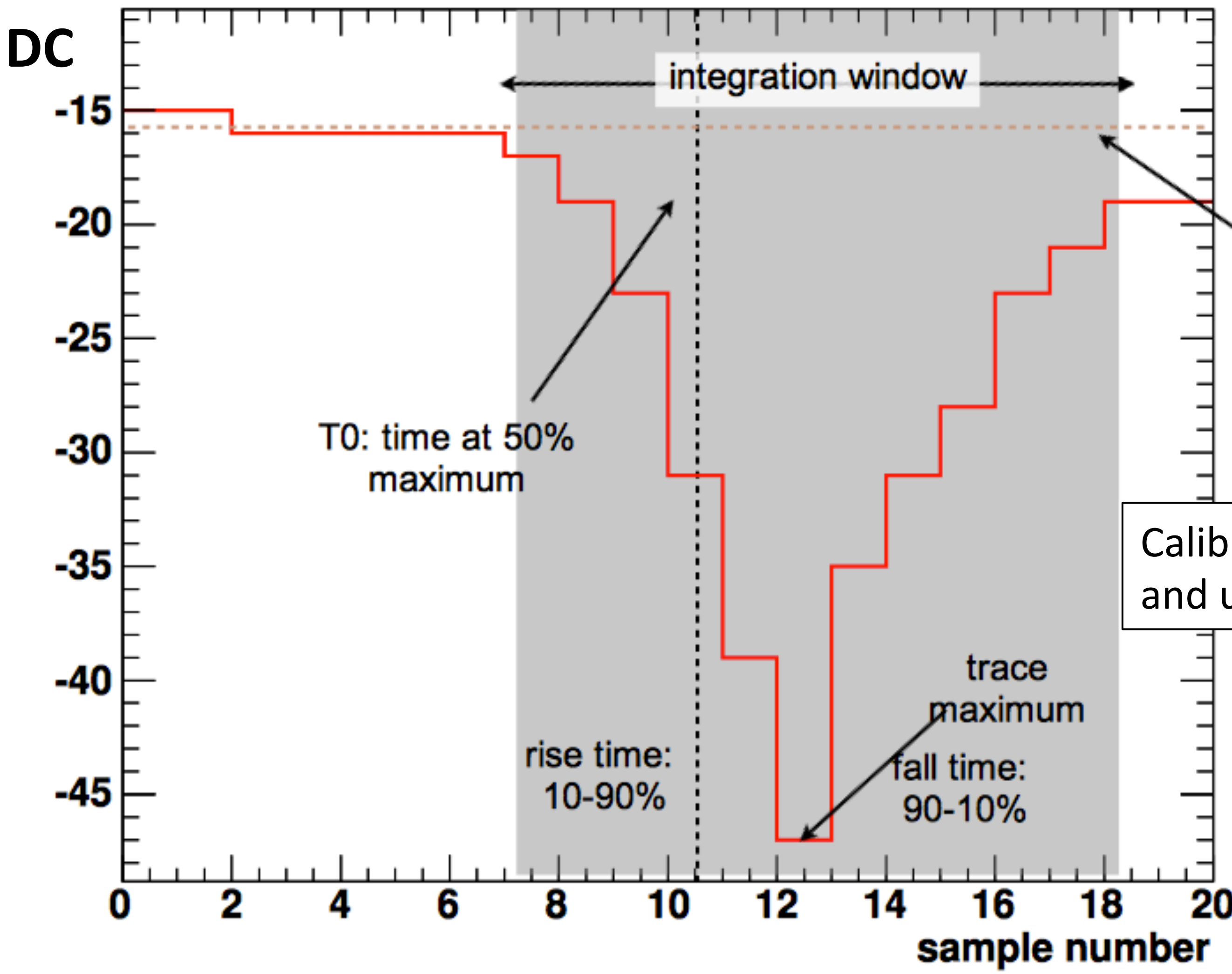
Calibration

per dark run	**single pe calibration runs**	dc/pe ratio	
per dark run	**hilo calibration runs**	low-gain pedestal calculation	high/low ratio
per night	**flasher (laser)**	relative gain calibration	relative time calibration
per run	**data run**	high-gain pedestal calculation	average pulse arrival time calculation





FADC Trace

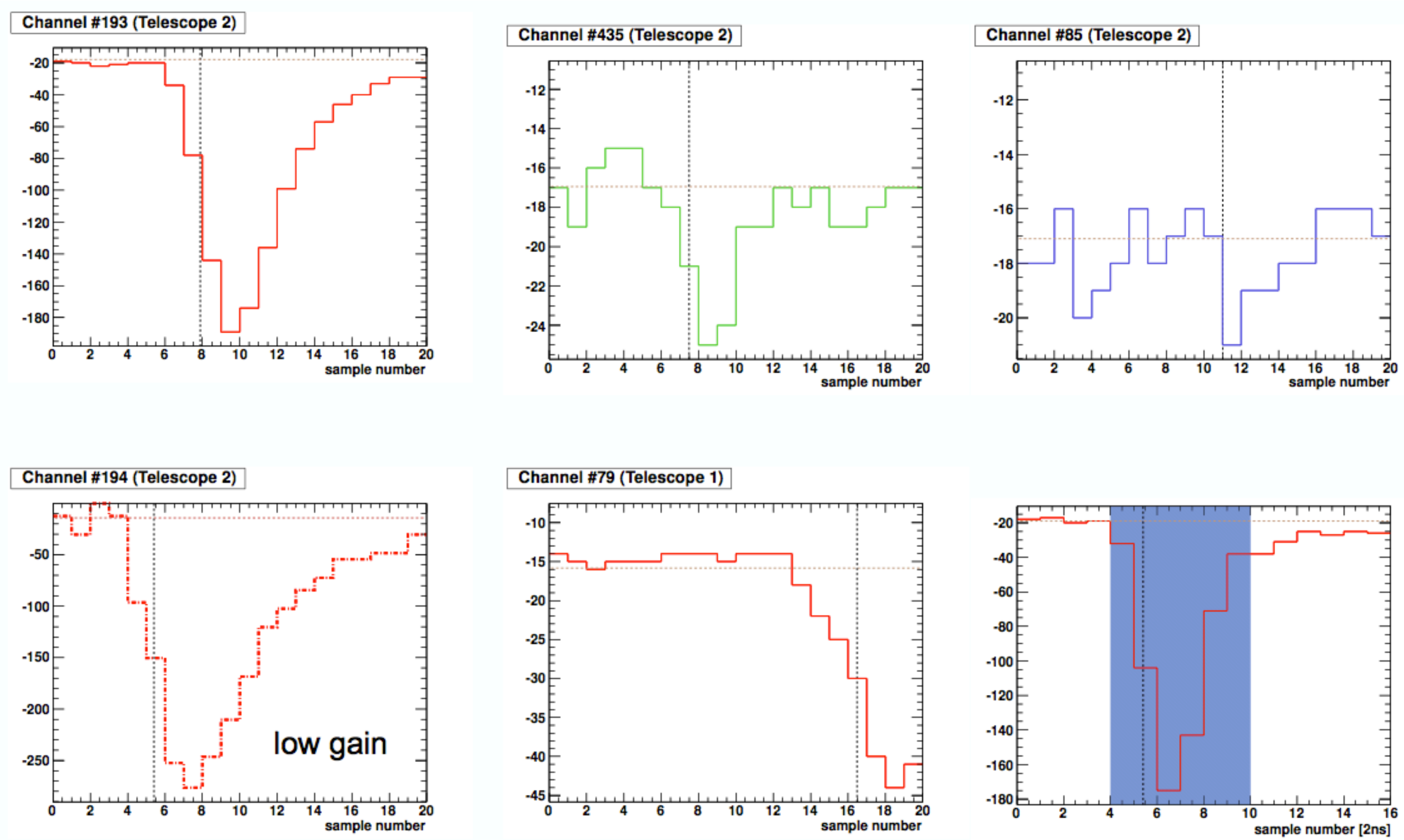


Digitization of PMT Output: Fundamental data element of VERITAS

Calibrate left-to-right (timing) and up-to-down (gain and peds)

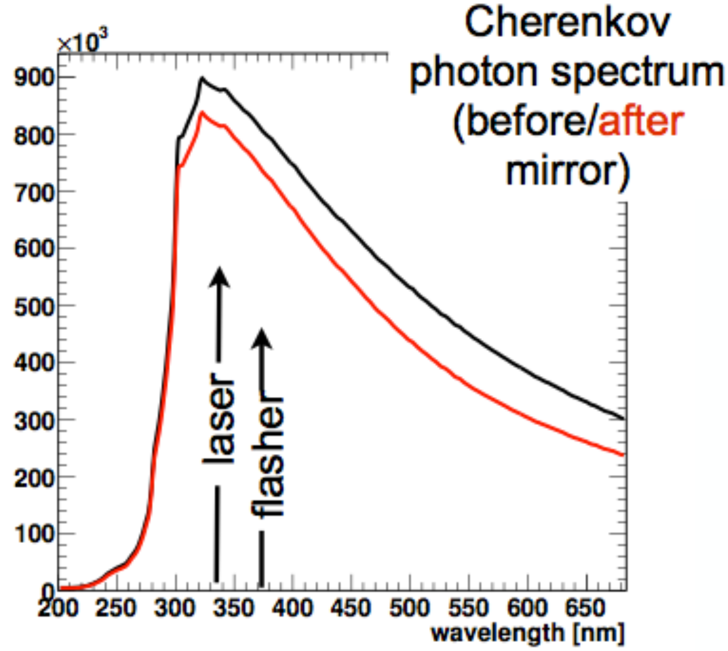
(1 sample = 2 ns)

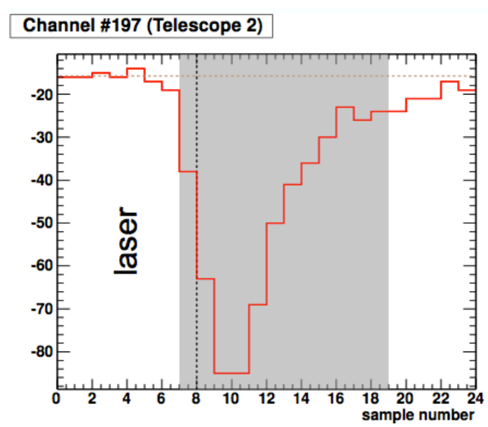
FADC Traces

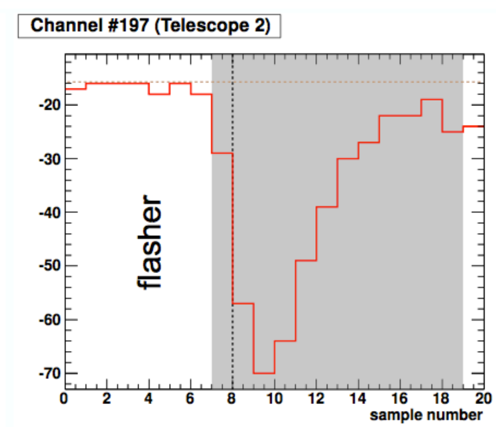

Channel #193 (Telescope 2)
sample number
Channel #435 (Telescope 2)
sample number
Channel #85 (Telescope 2)
sample number
Channel #194 (Telescope 2)
low gain
sample number
Channel #79 (Telescope 1)
sample number
sample number [2ns]

Flasher/Laser Calib Runs

- Purpose: provide photon pulses that are time-coincident and uniformly bright across camera
- <2009: Nitrogen laser @ 330 nm
  - 5 min runs at 10 Hz
- >2009: 7 LED flasher @ 370 nm
  - 2 min runs at 300 Hz



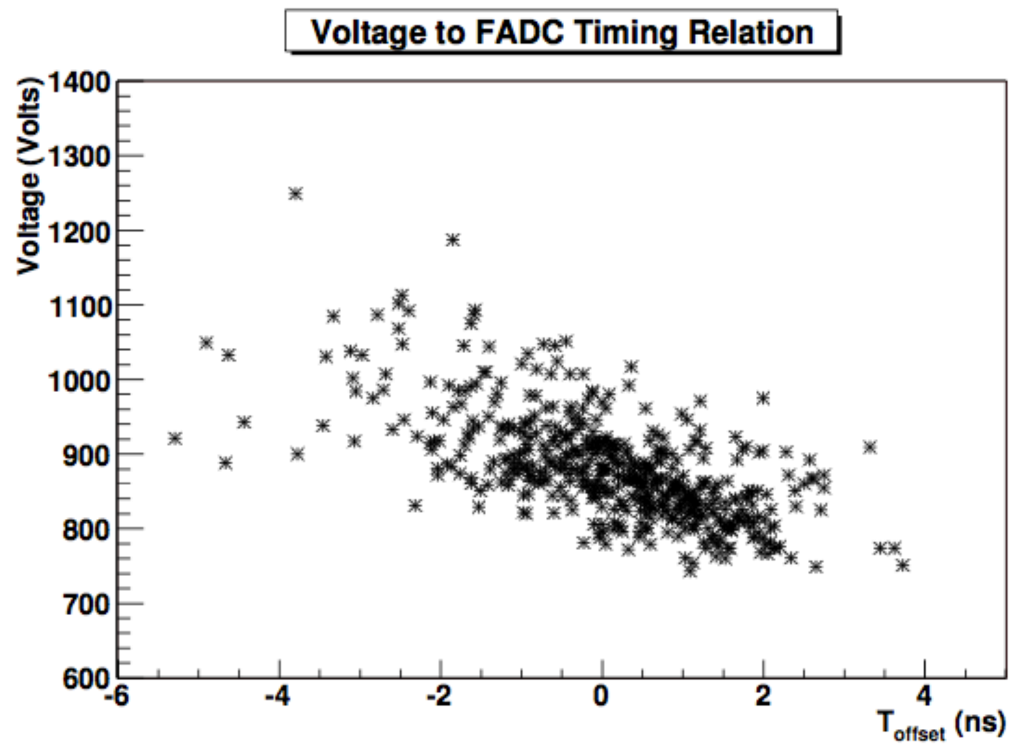




Relative Timing

- Flasher/Laser provides time-coincident light to all PMTs
- Remaining time differences must be related to PMT/ electronics
- We change our HV routinely for moon

PMT HV vs Timing delay

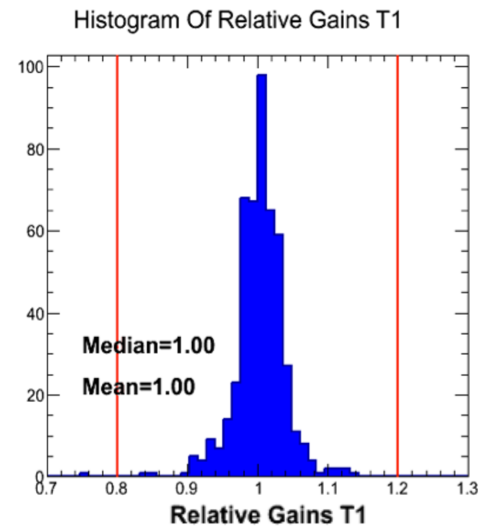


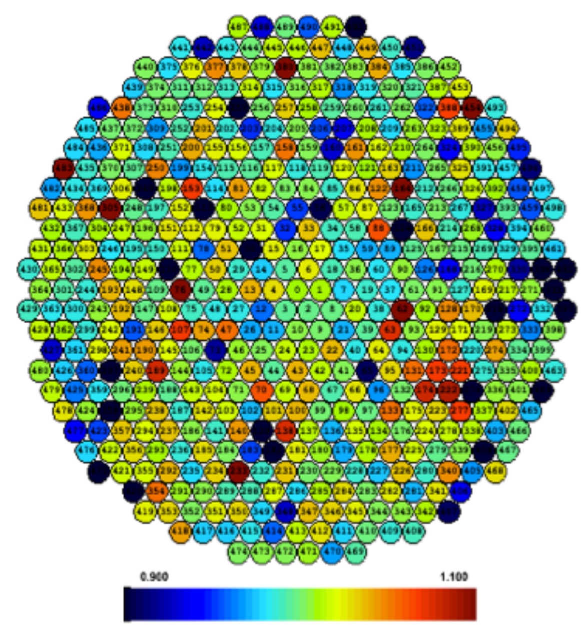
Relative Gain

- Basic idea: In a flasher event, compare the charge seen in a single pixel to the average over the whole camera

- Simplest 'laser' method
  - Histogram Q_i /<Q> of high-gain chans,
  - Get the mean -> rel gain
  - Get the RMS -> rel gain var

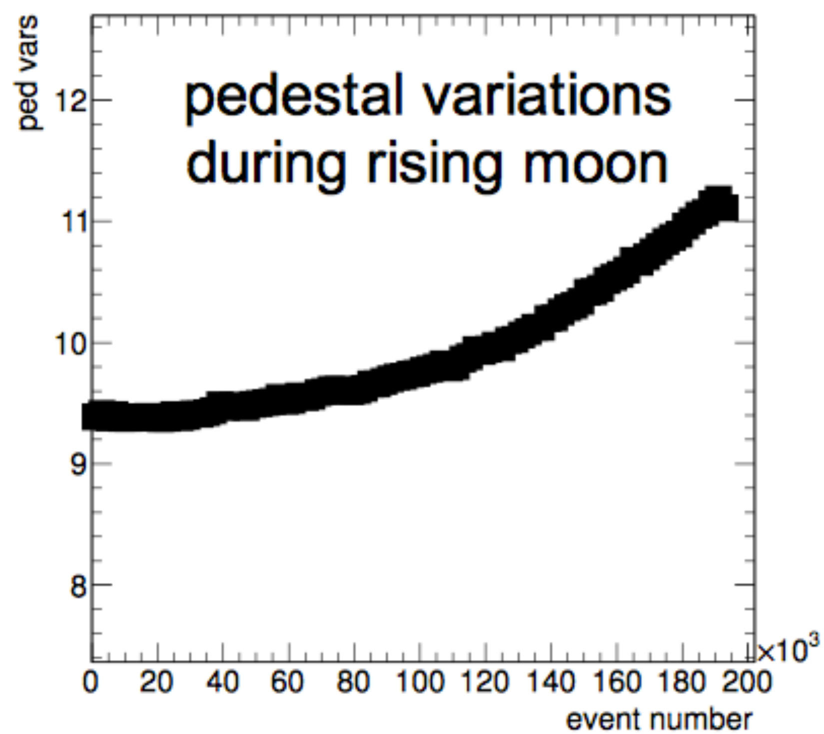
- Advanced 'flasher' method
  - Fill 2D Profile with Q_i vs <Q>
  - Fit with line, slope is rel gain



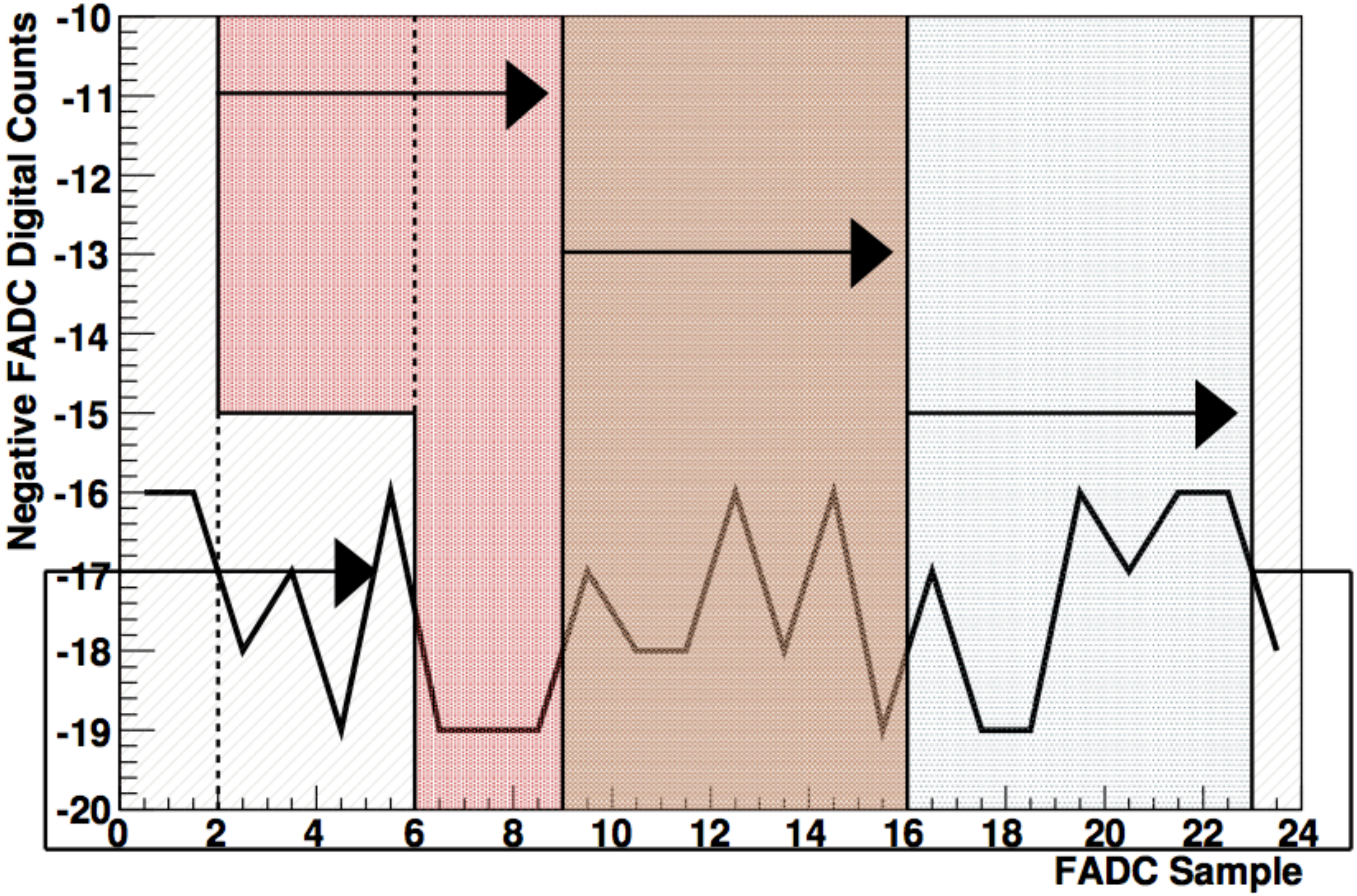


Pedestals

- During the data run itself, ‘pedestal’ events are triggered at a rate of 3 Hz
- We inject a pedestal (DC offset from 0) into the trace so we can characterize + and - fluctuations
- Ped and Ped Variance (*pedvar*) are calculated in 3-min time slices
  - Pedvar depends on NSB

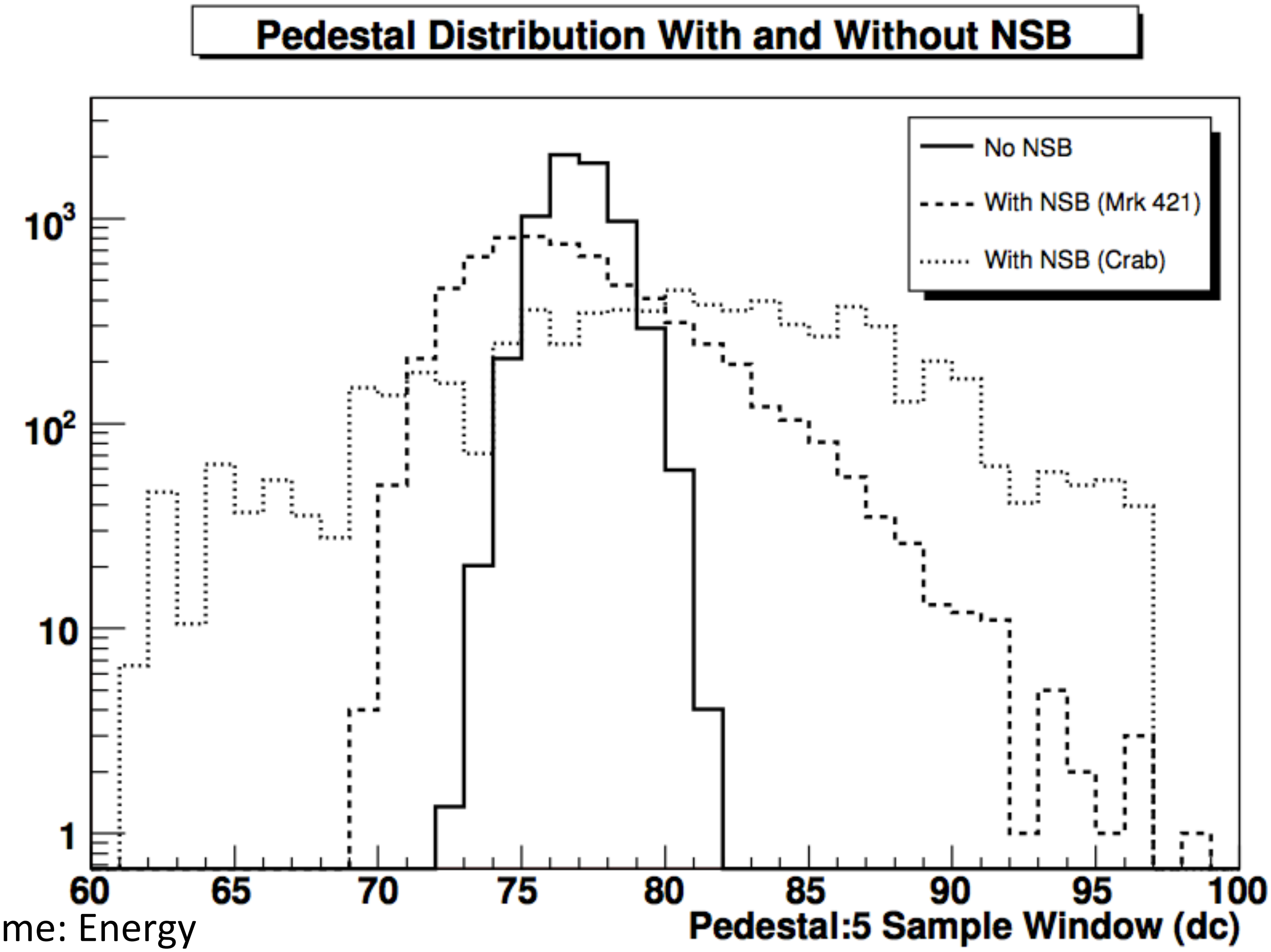


Pedestals



Negative FADC Digital Counts
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
0
2
4
6
8
10
12
14
16
18
20
22
24
FADC Sample

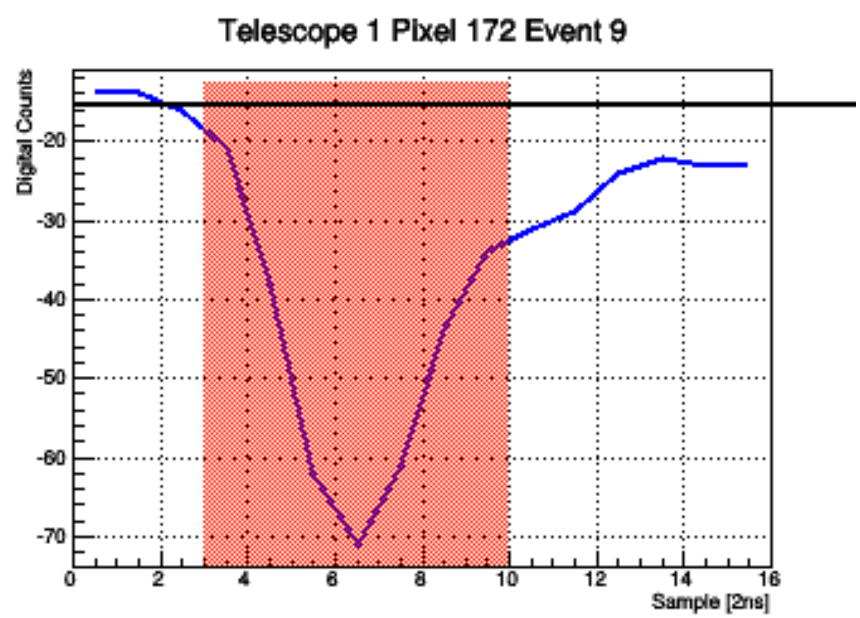
Pedestals



Take home: Energy threshold depends on field

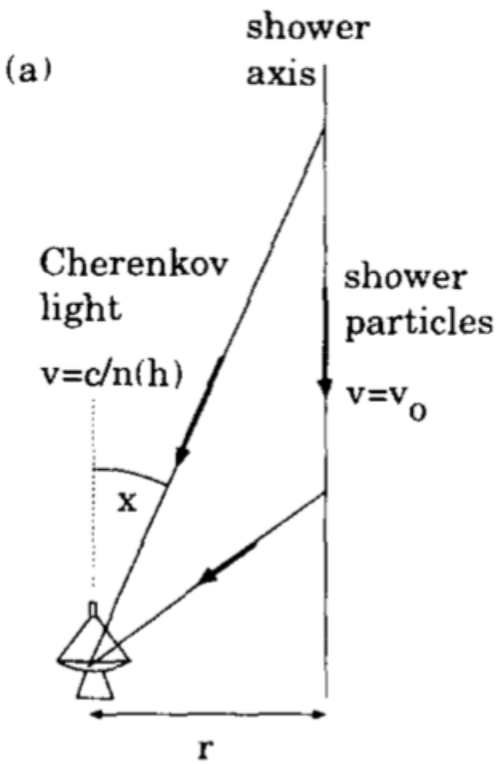
FADC Trace Integration

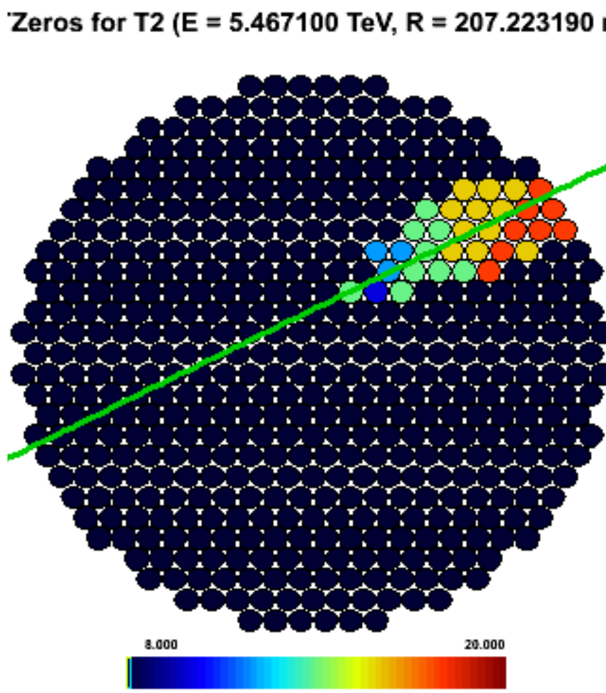
- Use duration which maximizes S/N
  - 7 samples fixed duration in VEGAS
  - ED expands to entire trace for low gain traces
- Strategies for window placement
  - Static window
  - Dynamic window
    - i.e. Double-pass

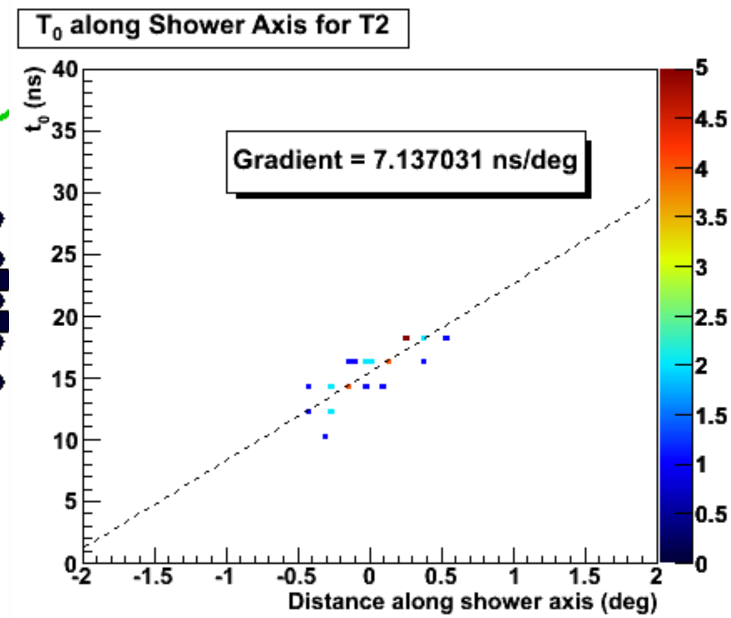


Double Pass Placement

- Fit photon arrival times along first-pass shower axis
- Use time gradient to place FADC integration window



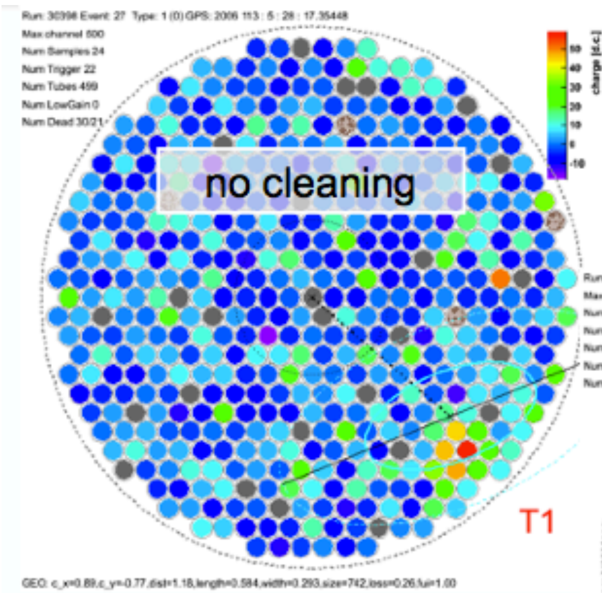


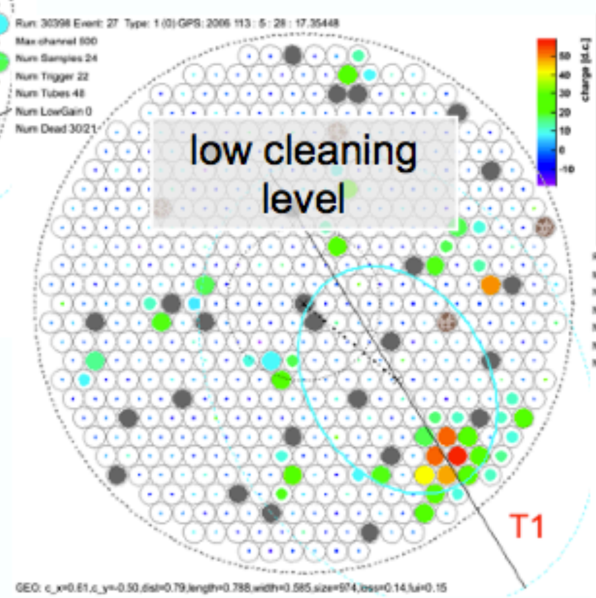


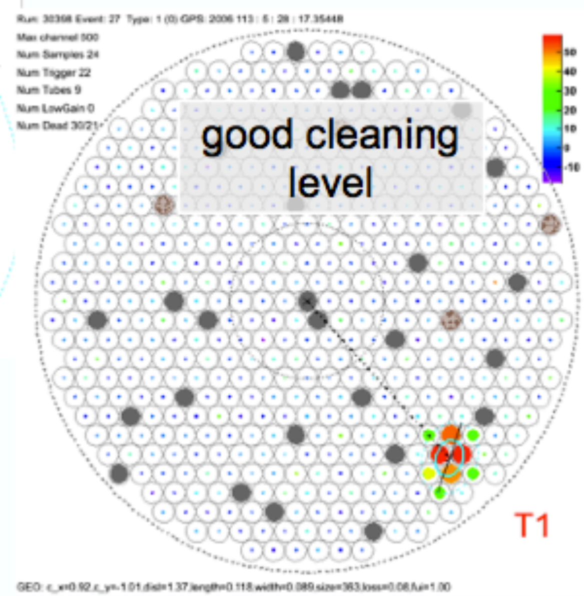
- Window placement determined from neighboring pixels – no bias

Image Cleaning

remove pixel with low signal/noise ratios (taking into account expected noise and time evolution of signal)







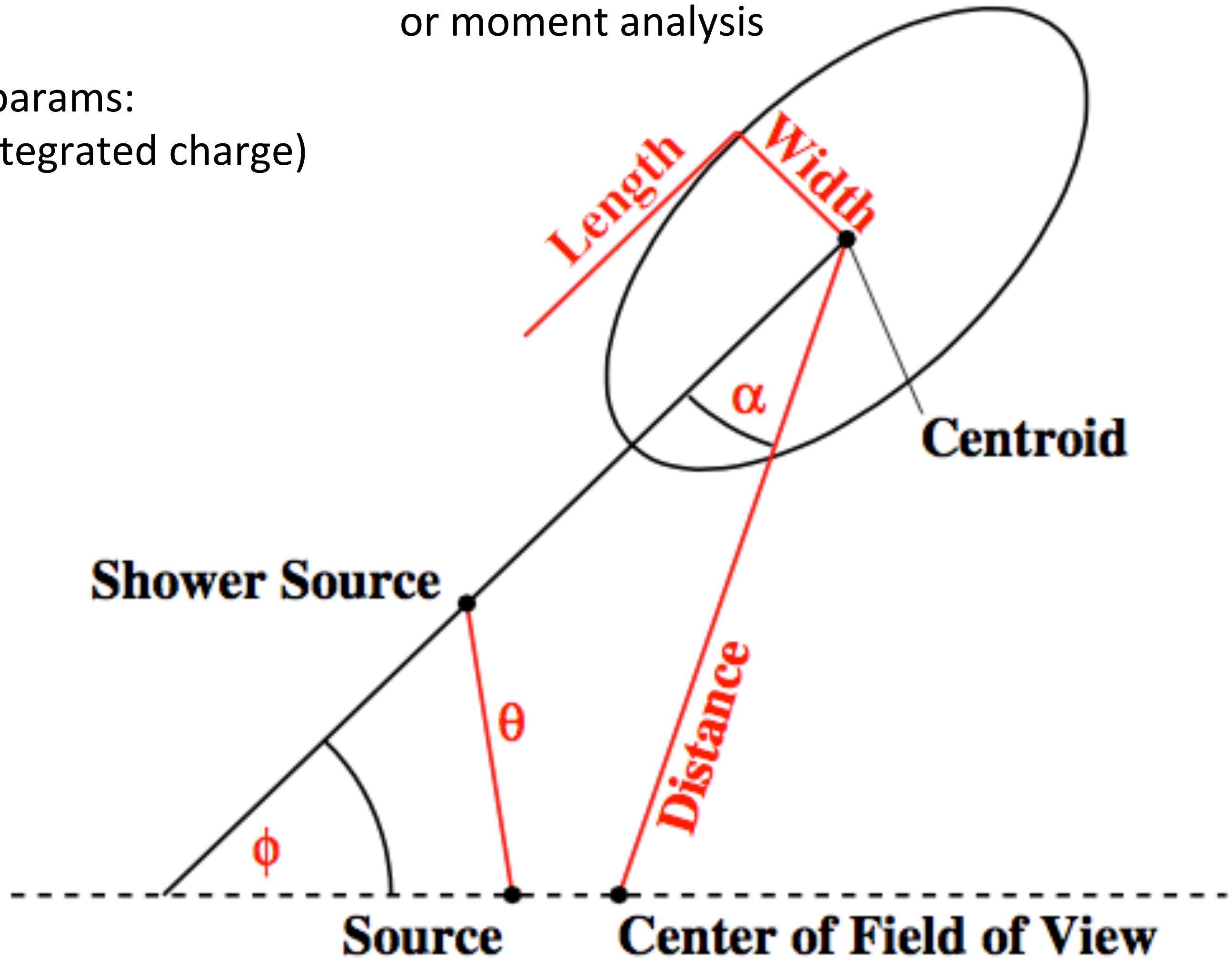
several cleaning methods:
- fixed cleaning levels
- variable cleaning levels
- time cleaning

two-level cleaning: remove pixels where neighbors have no signal

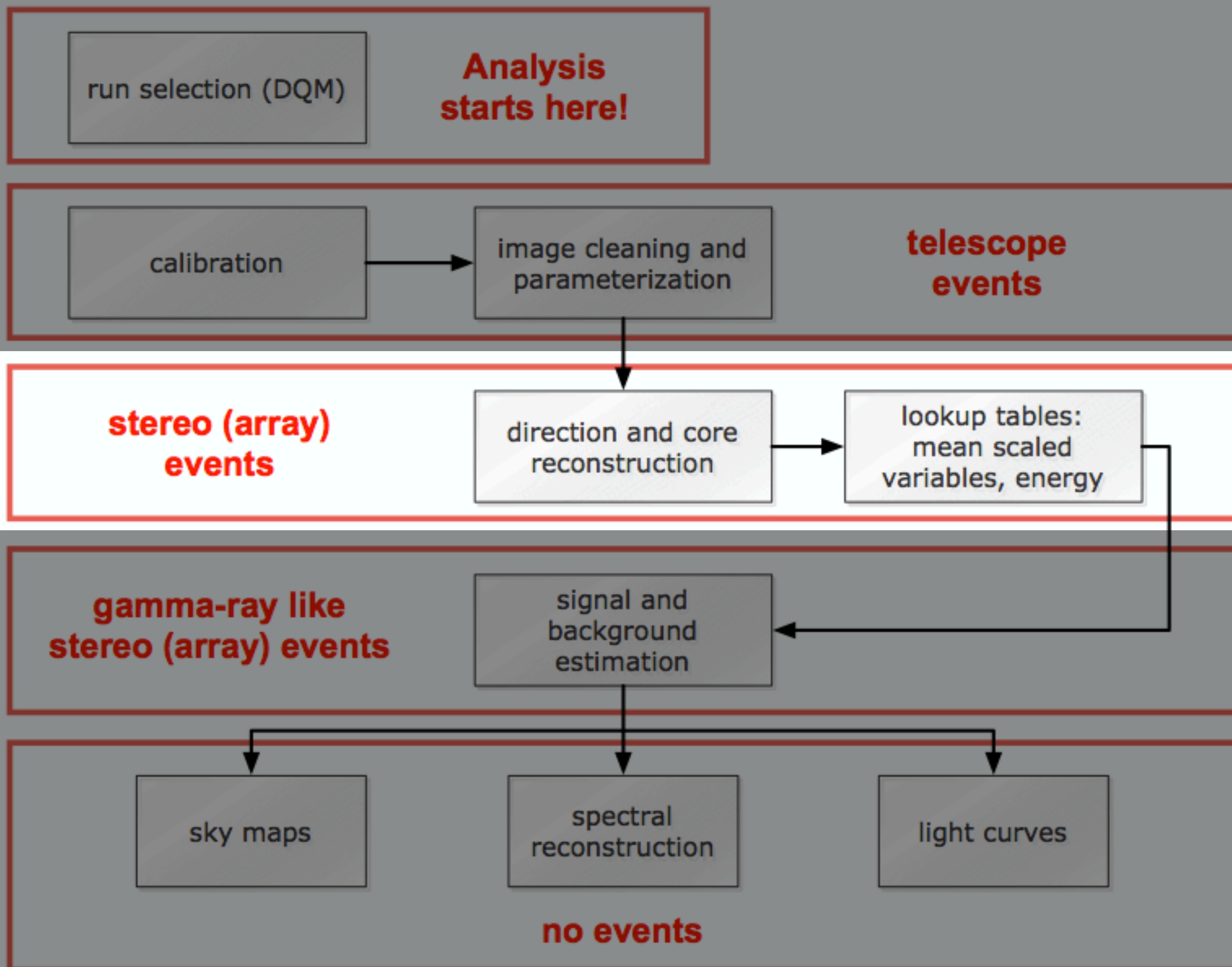
Hillas Parameters

a.k.a Principle Component Analysis
or moment analysis

Notable params:
Size (integrated charge)
Length
Width
Dist

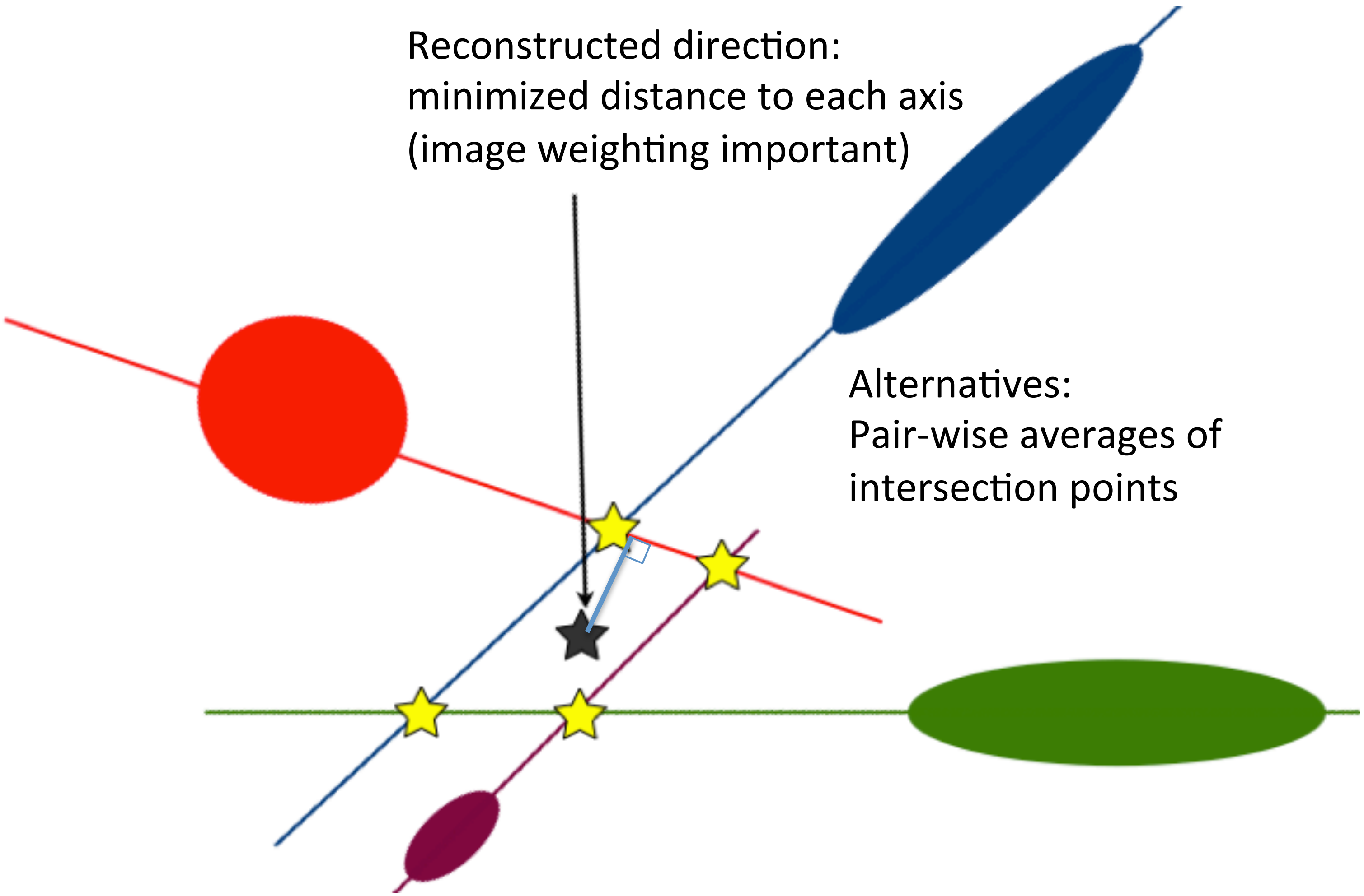


Analysis Overview



Direction Reconstruction

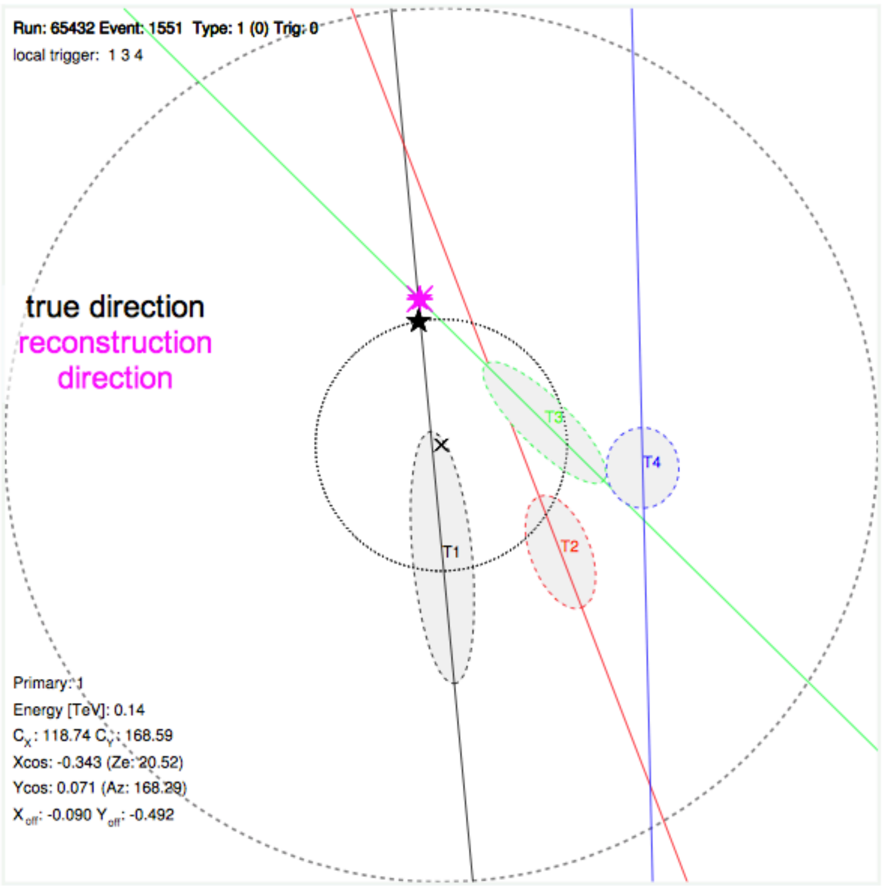
Reconstructed direction:
minimized distance to each axis
(image weighting important)



Alternatives:
Pair-wise averages of
intersection points

Direction Reconstruction

- Crucial to decide which telescopes are worth considering



- Telescope-level cuts apply
- E.g. Soft cuts:

```
DistanceUpper 0/1.43
SizeLower 0/200
NTubesMin 0/5
```

- Format is “Tel/Value” with Tel=0 applying to all tels

Tel events are cut from recon

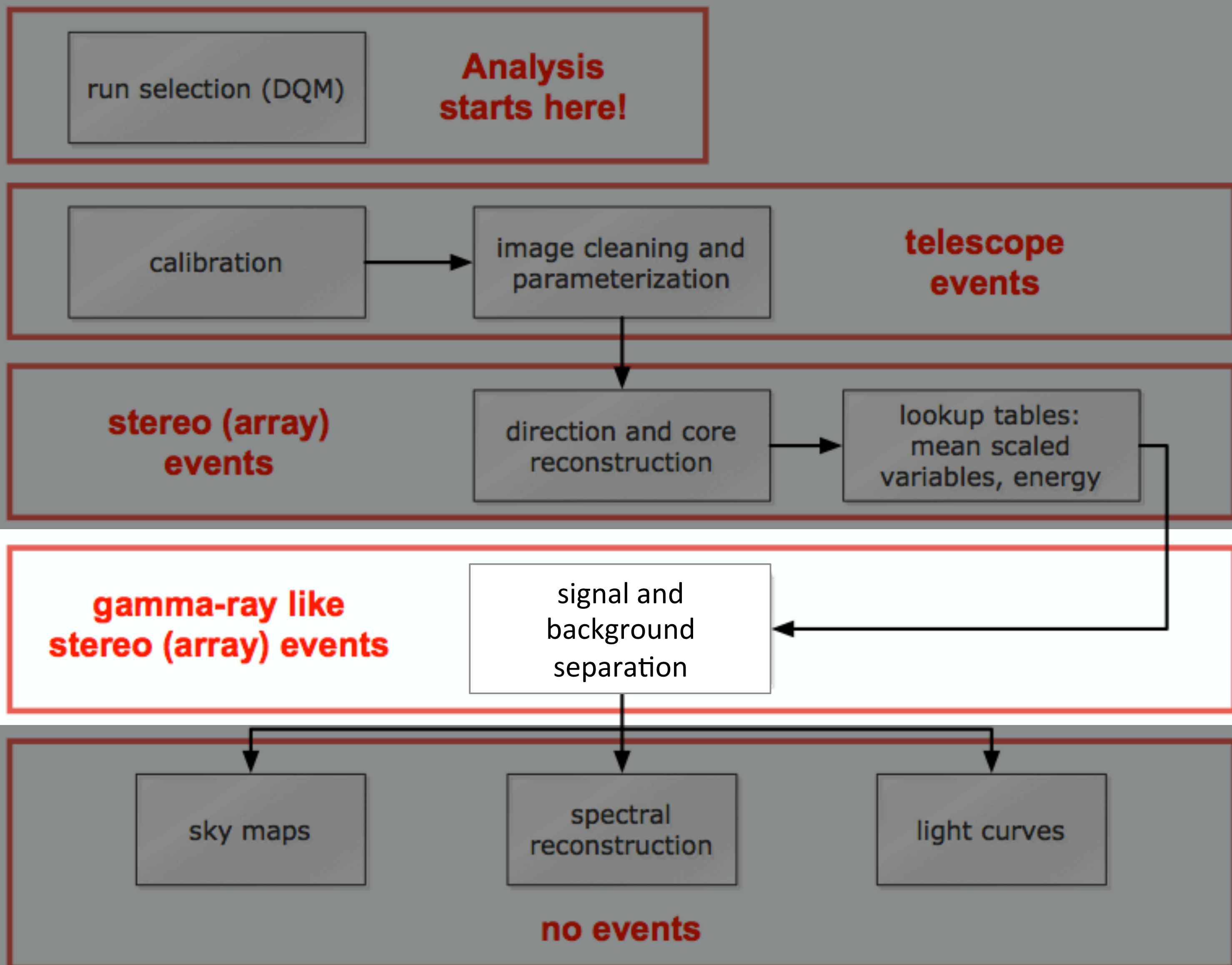
vaDisplay Exercise

- Use vaDisplay to examine VERITAS events:

```
]$ cd /home/fermi
]$ source veritasinit.csh
]$ cd VERITAS
Look at flasher run:
]$ vaDisplay CrabAnalysis-calib/59534.root
Look at data run:
]$ vaDisplay CrabAnalysis-calib/59521.root
```

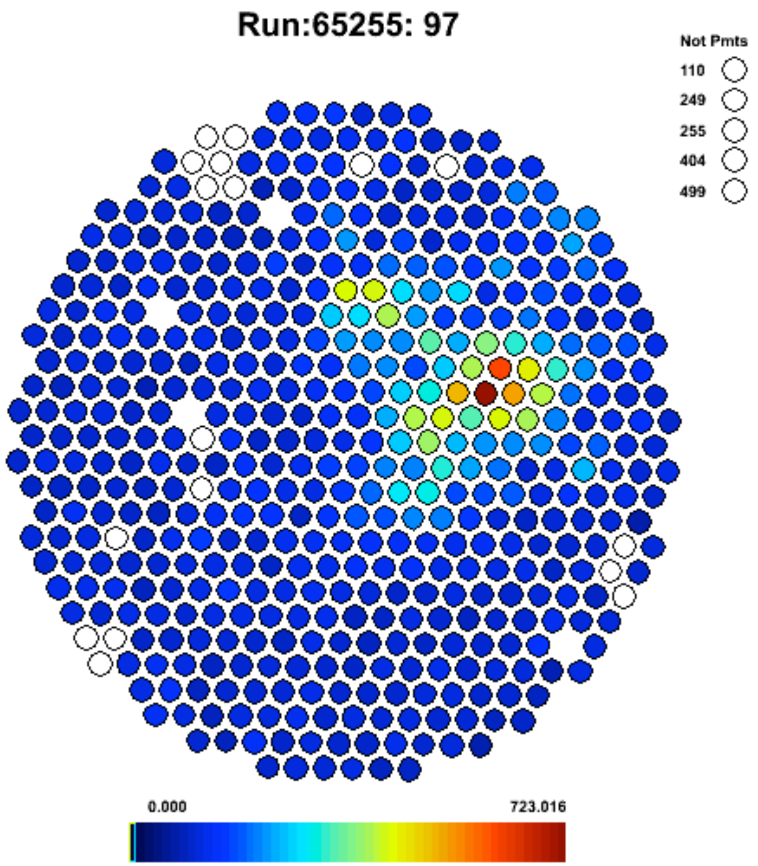
- Flasher scavenger hunt:
  - What is pattern of # of LEDs flashed?
    - Hint: H.fSize is integrated light in image. Ignore first few events and look for pattern.
  - What charge threshold actives Low-gain switch?
    - Hint: As #LEDs ramps up, pixels fluctuating up will switch first. Use Display Mode “HiLo” to identify channels that have switched to lower gain. T1 flasher too dim! Look at Display Control: T2 Image.
  - Is the Hillas parameterization of a flasher event what you expected?
    - Hint: Use “Display Hillas Fit”
- Data scavenger hunt:
  - Find a muon ring (at least a partial one).
    - Hint: Turn on Display Control: “All-Images” and Cleanup: “eventDisplay”
  - Find a BIG CR or gamma. Did it land inside the array?
    - Hint: Display Mode “Ground” Shows core reconstruction location on ground

Analysis Overview

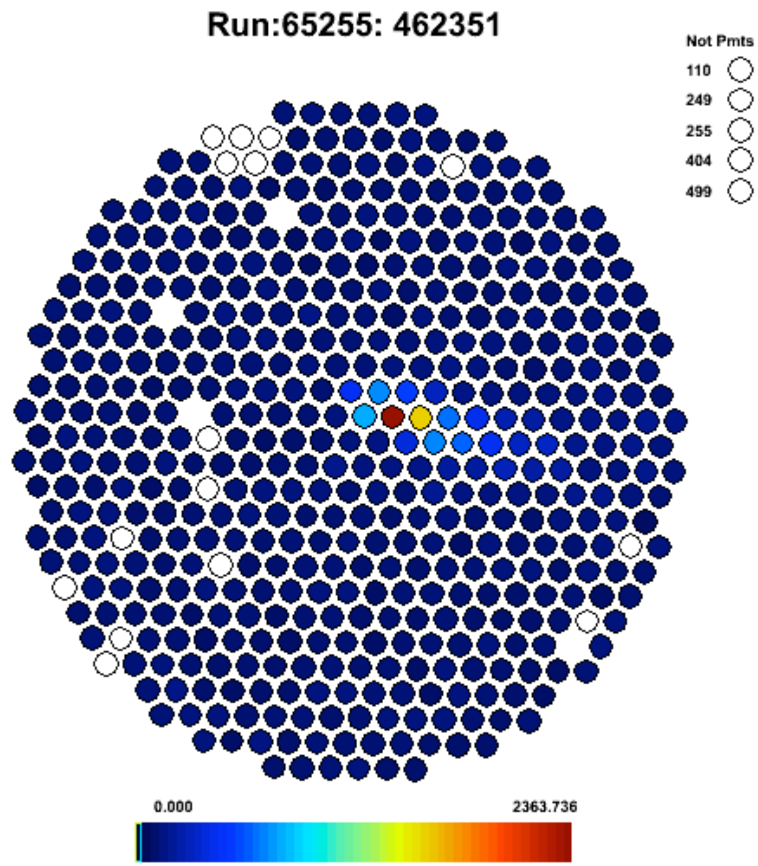


Gamma/Hadron Separation

Cosmic Ray

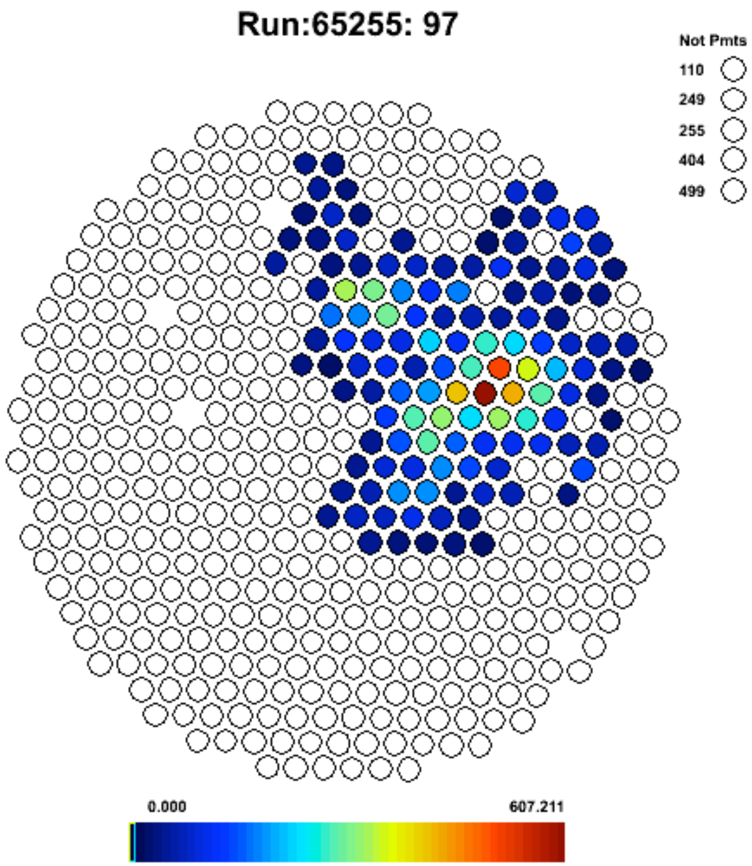


Gamma Ray

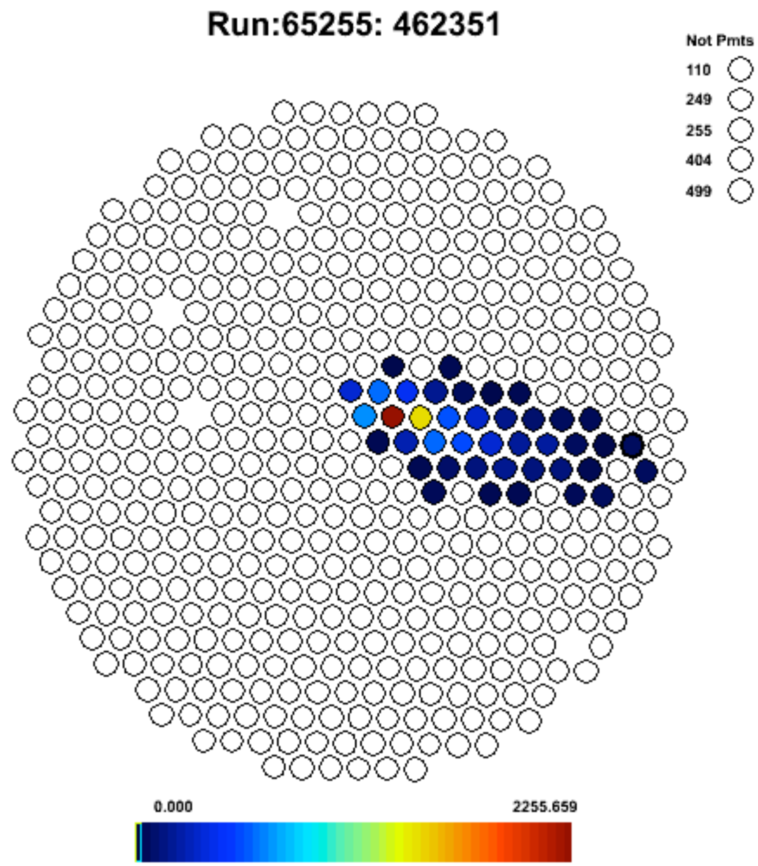


Gamma/Hadron Separation

Cosmic Ray

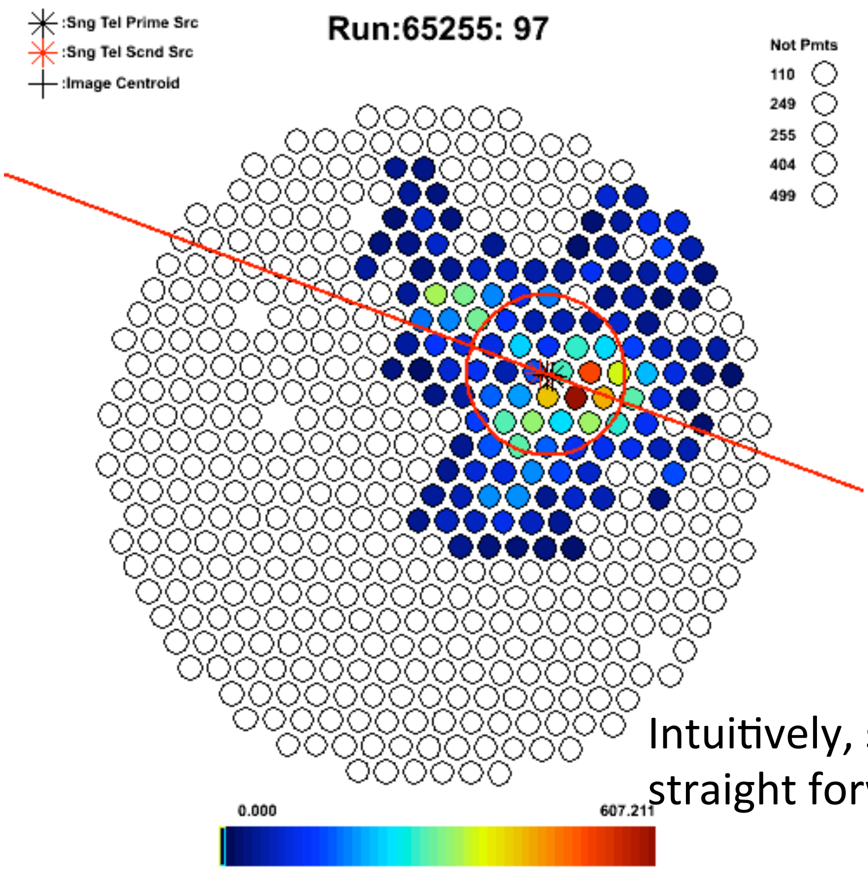


Gamma Ray

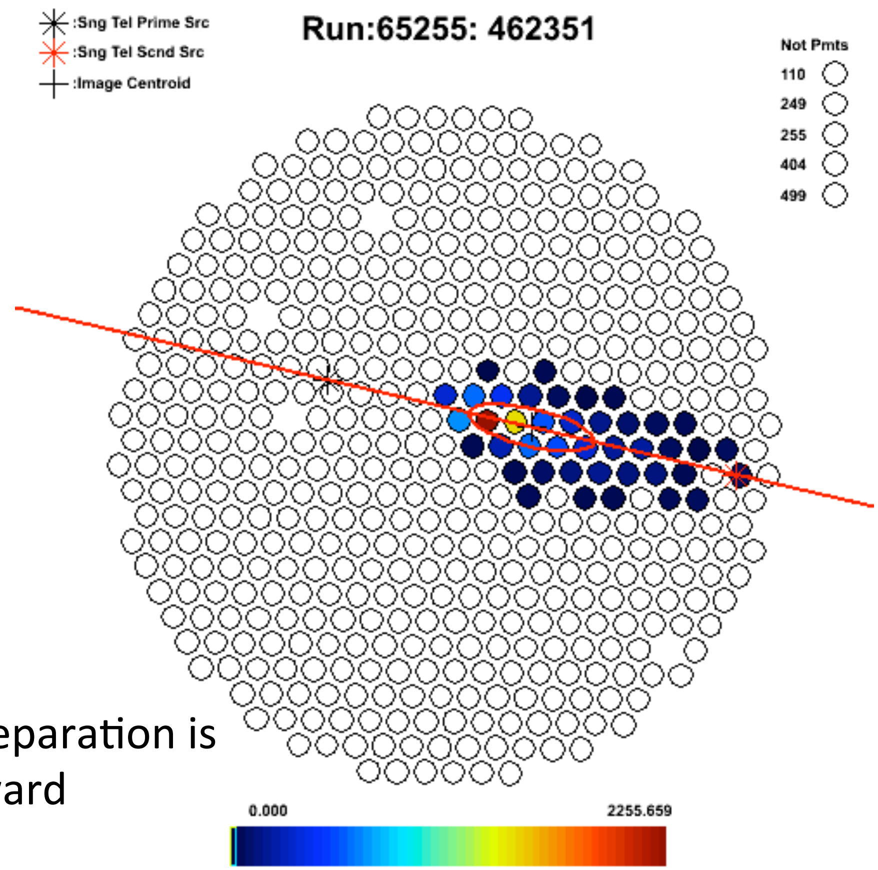


Gamma/Hadron Separation

Cosmic Ray



Gamma Ray



Intuitively, separation is straight forward

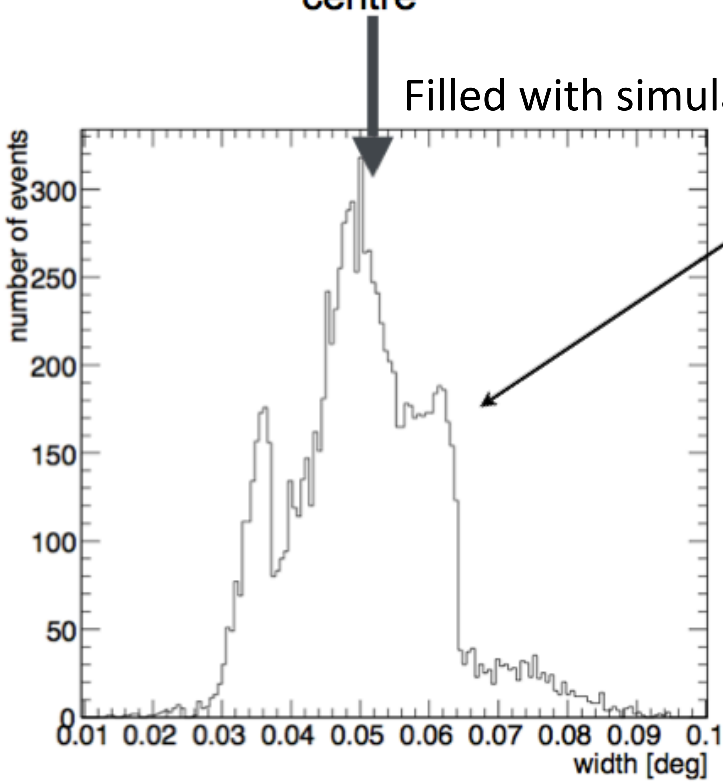
In practice, width etc. depend on geometry and amount of light

→ Lookup tables

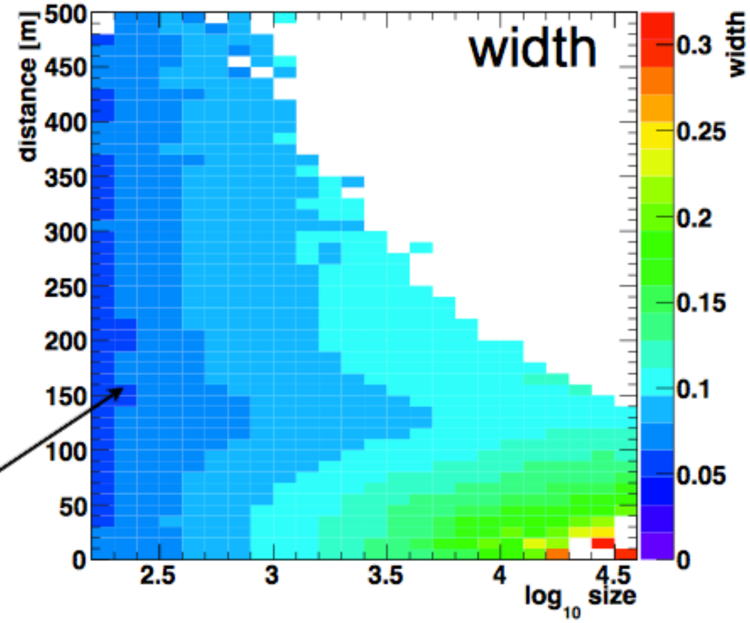
Lookups

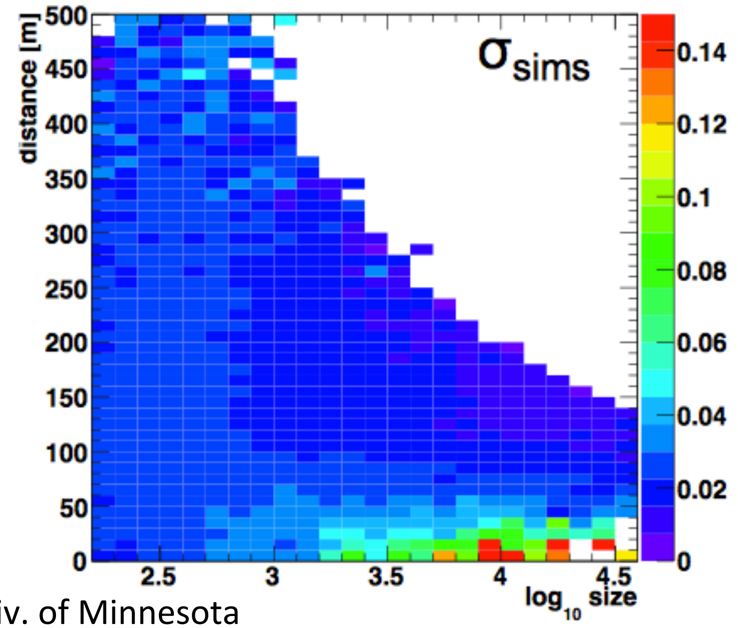
width distribution for a given size, distance, zenith and azimuth angle, noise level and offset from the camera centre

Filled with simulations



"typical" or average width

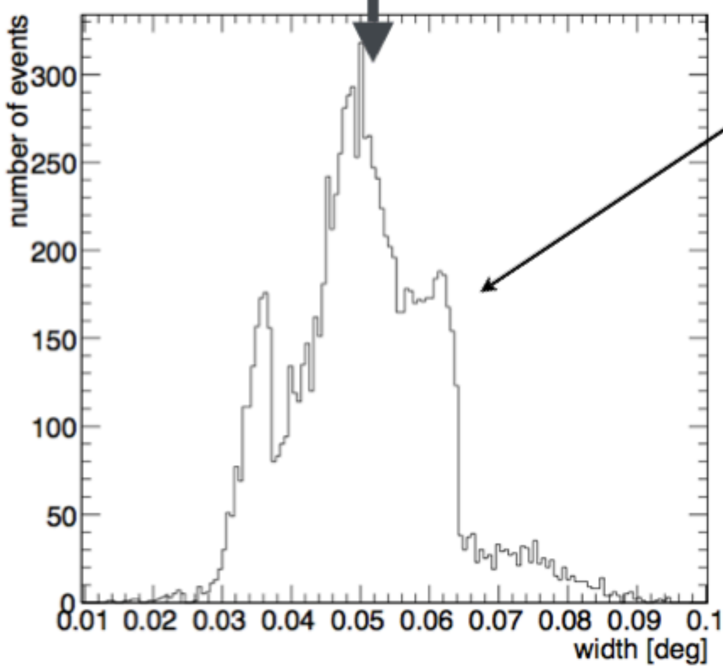


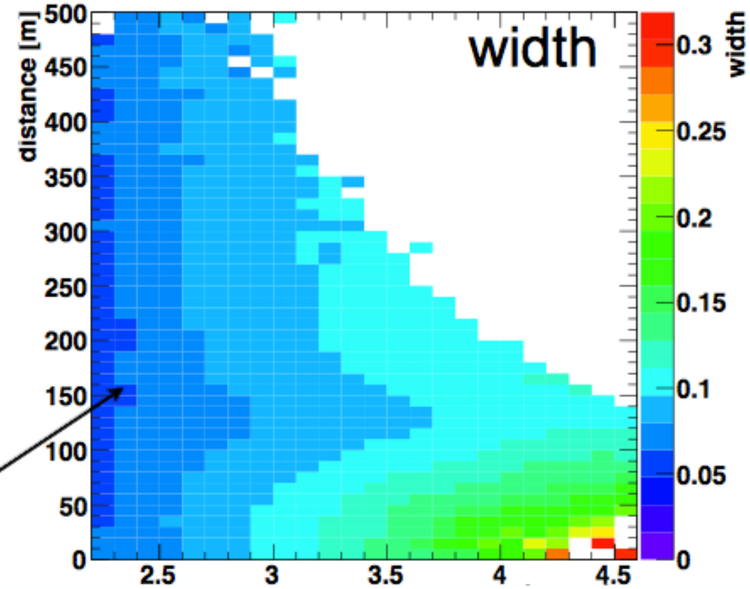


Lookups

width distribution for a given size, distance, zenith and azimuth angle, noise level and offset from the camera centre

Filled with simulations



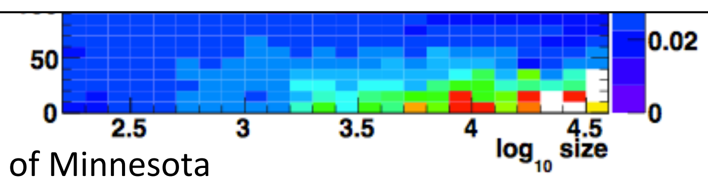


mean scaled width

$$\text{MSW} = \frac{1}{N_{images}}\left[\sum_{i}^{N_{images}} \frac{width_i}{w_{MC}(R,s,\Theta)}\right]$$

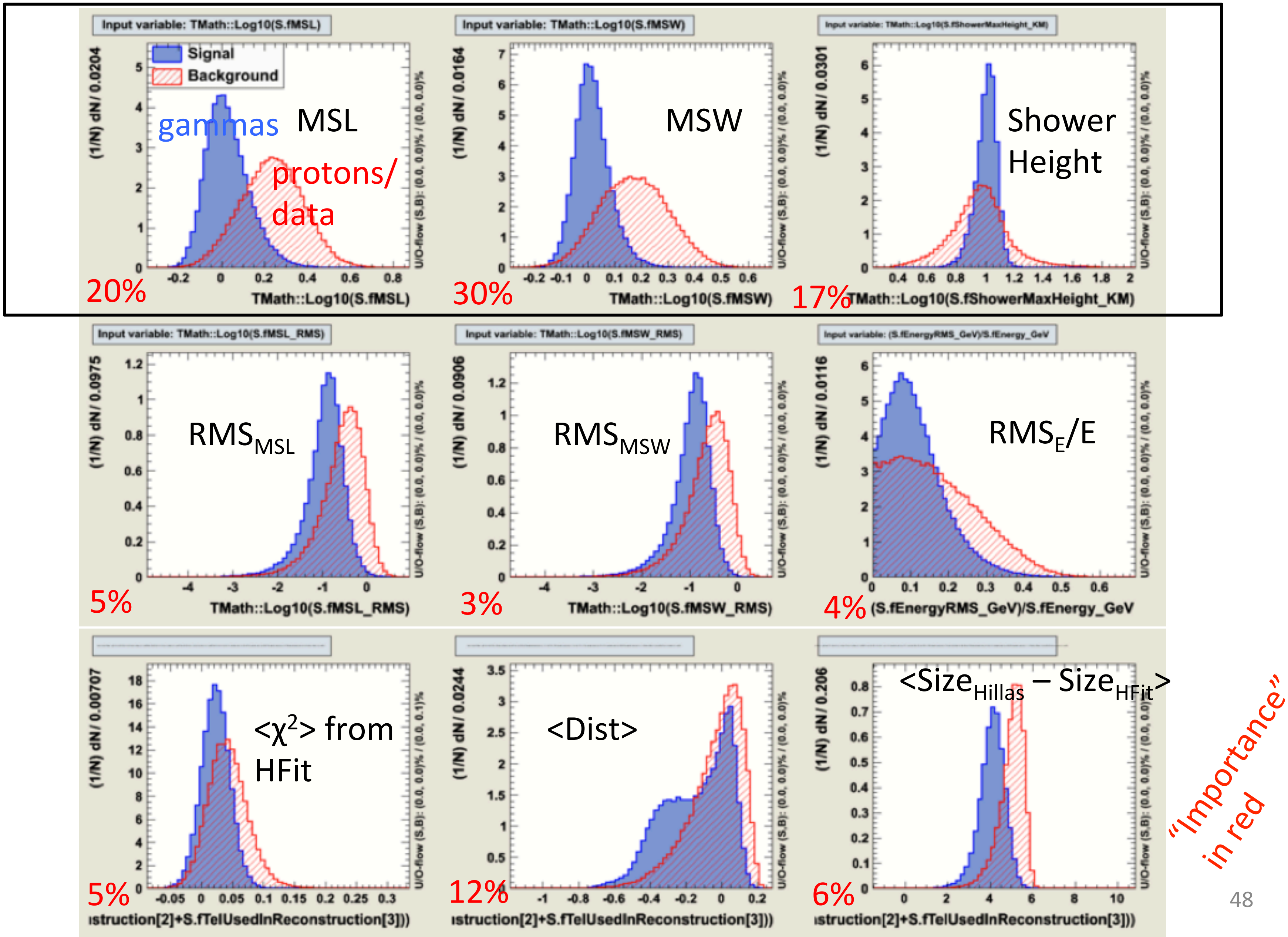
(same for length)

Think of 'mean-scaled' quantities as "wrt a typical gamma-ray shower"

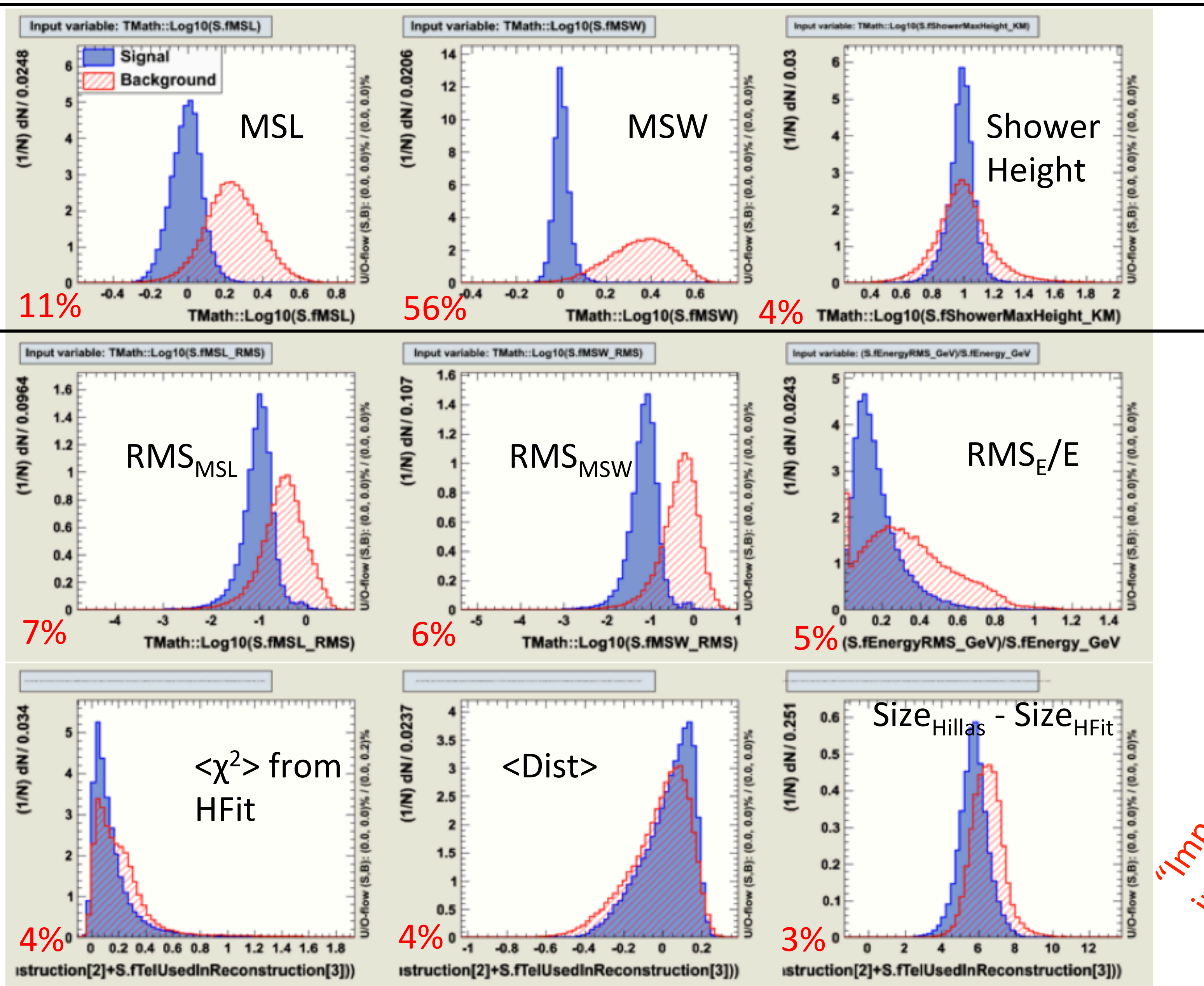


Same concept used for energy reconstruction

Useful Parameters, <320 GeV

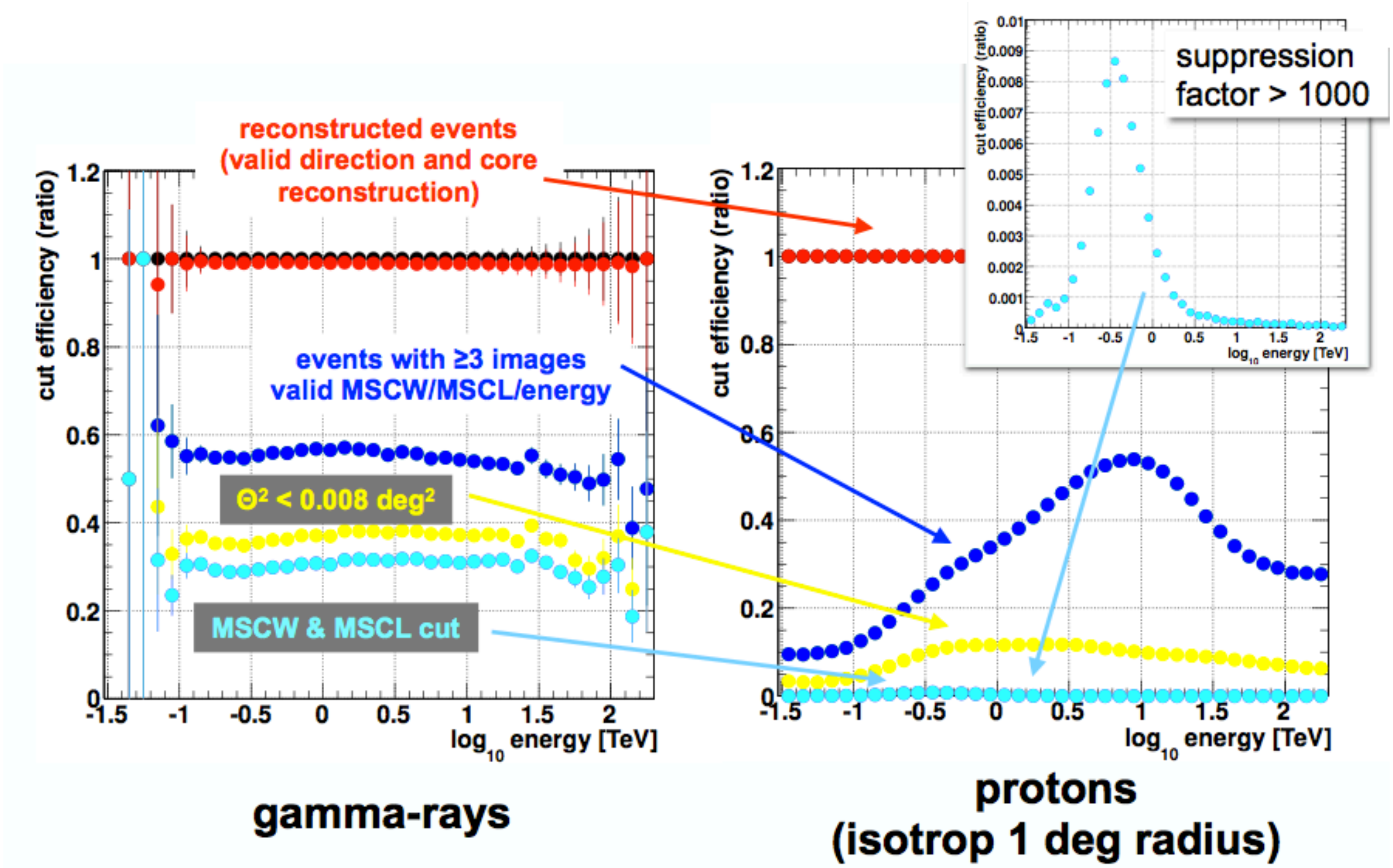


Useful Parameters, > 1 TeV



"Importance" in red

Gamma/Hadron Separation



Browsing Gamma-like Events

List of gamma-like events is natural jumping off point for joint analysis!

```
]$ cd ~/VERITAS/CrabAnalysis
]$ root
[0] TFile *file = new TFile("59521.stage5.root");
// Ignore warnings
[1] TBrowser tb;
// Navigate: ROOT files -> 59521.stage5.root -> SelectedEvents
[2]  ShowerEventsTree->Draw("fTheta2_Deg2>>h(40,0,0.4)")
```

The essential quantities are:

fDirection[RA/Dec]_J2000_Rad and fEnergy_GeV

How to Run Everything

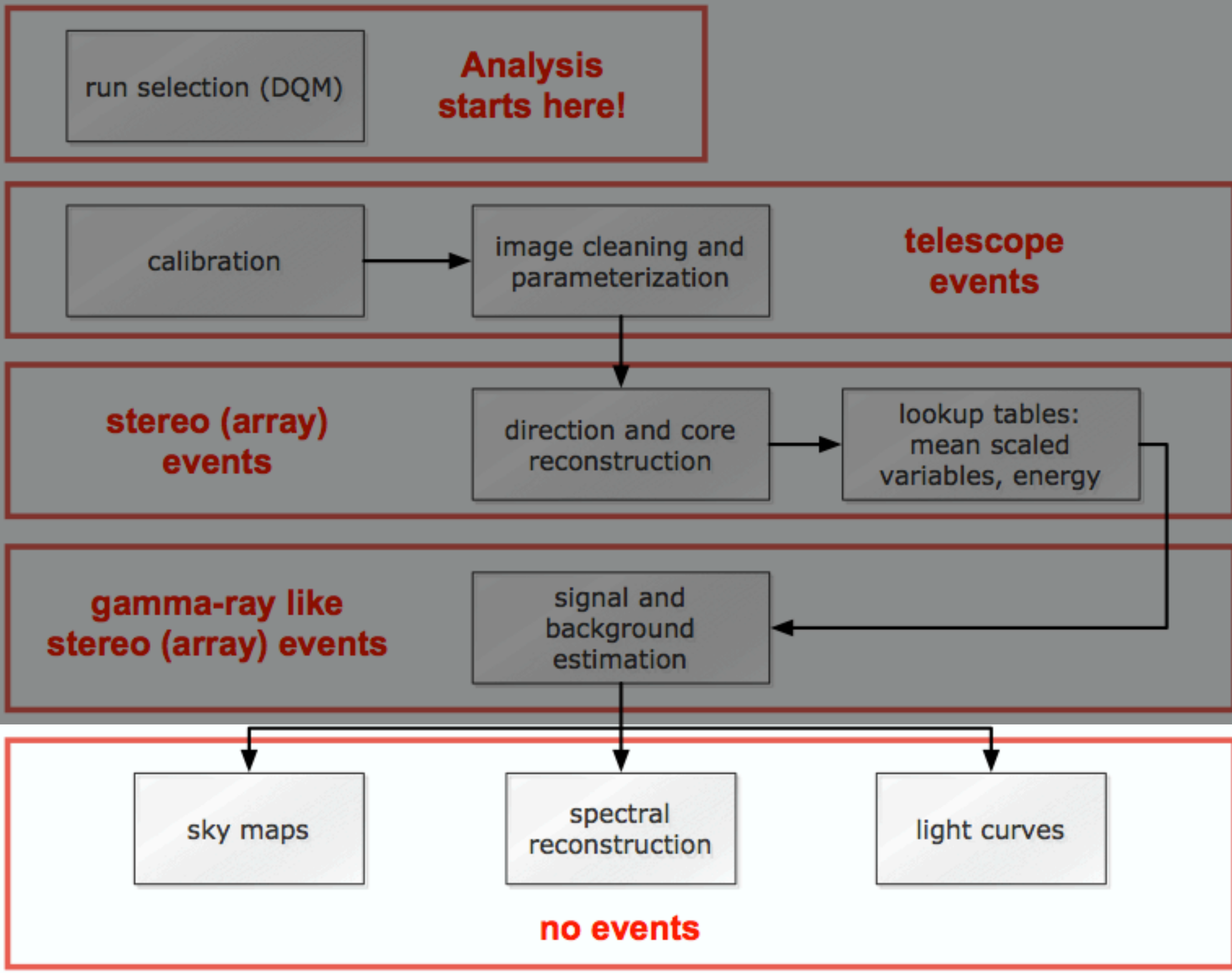
- Simple bash script to run a VERITAS analysis

```
]$ cd /home/fermi
]$ cd VERITAS
]$ less vegas-vanilla.sh
```

- Decision points:
  - Tel Size cut in **stage4**
  - MSW/L and ShowerHeight cuts in **stage5**

Soft, medium, hard, loose options standardized.
Today we are running a **soft** analysis

Analysis Overview

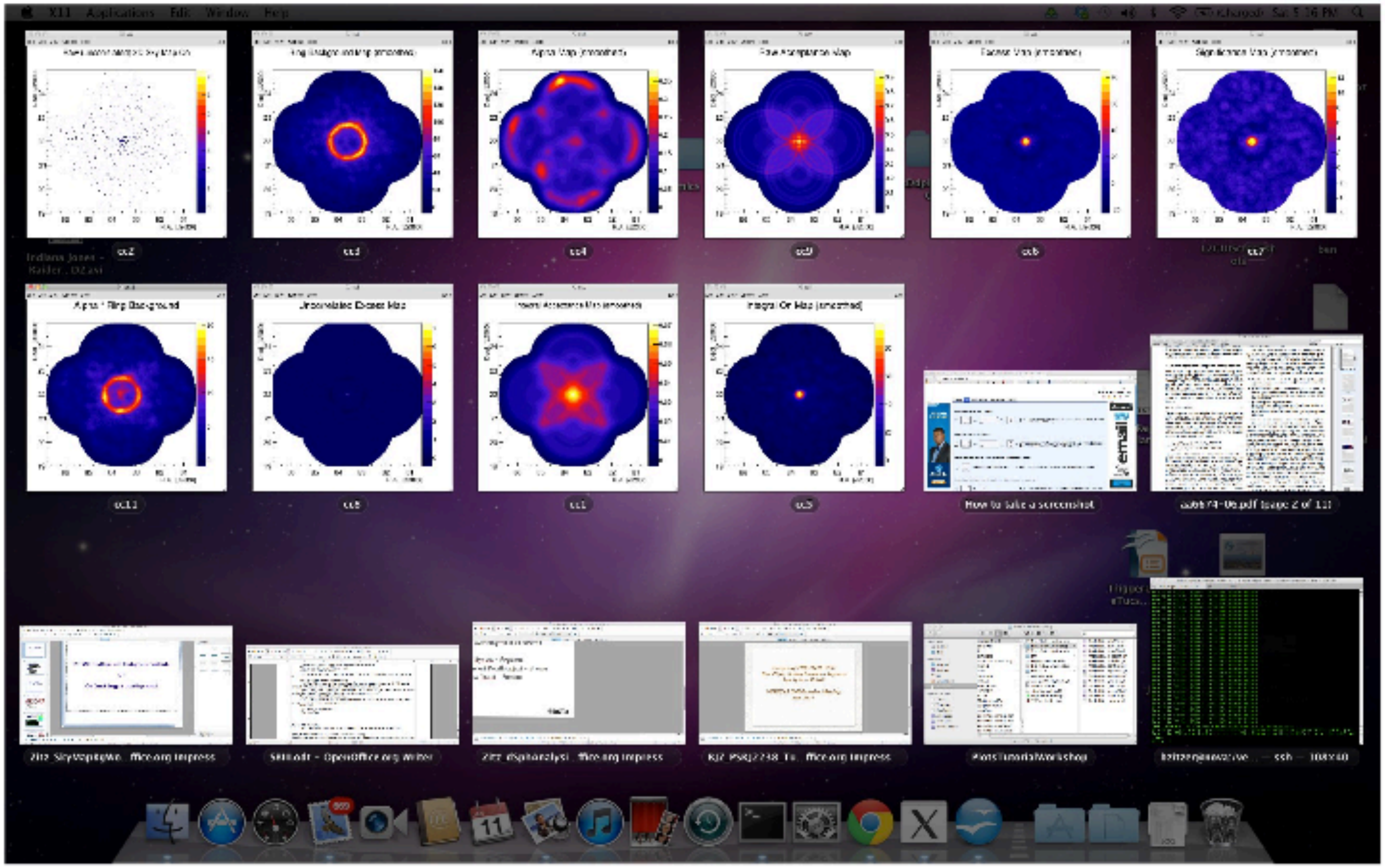


Results Extractor

- Running the final stage is the most user-configurable:

```
]$ cd /home/fermi
]$ source veritasinit.csh
]$ cd VERITAS

]$ less stage6.sh
]$ ./stage6.sh
```



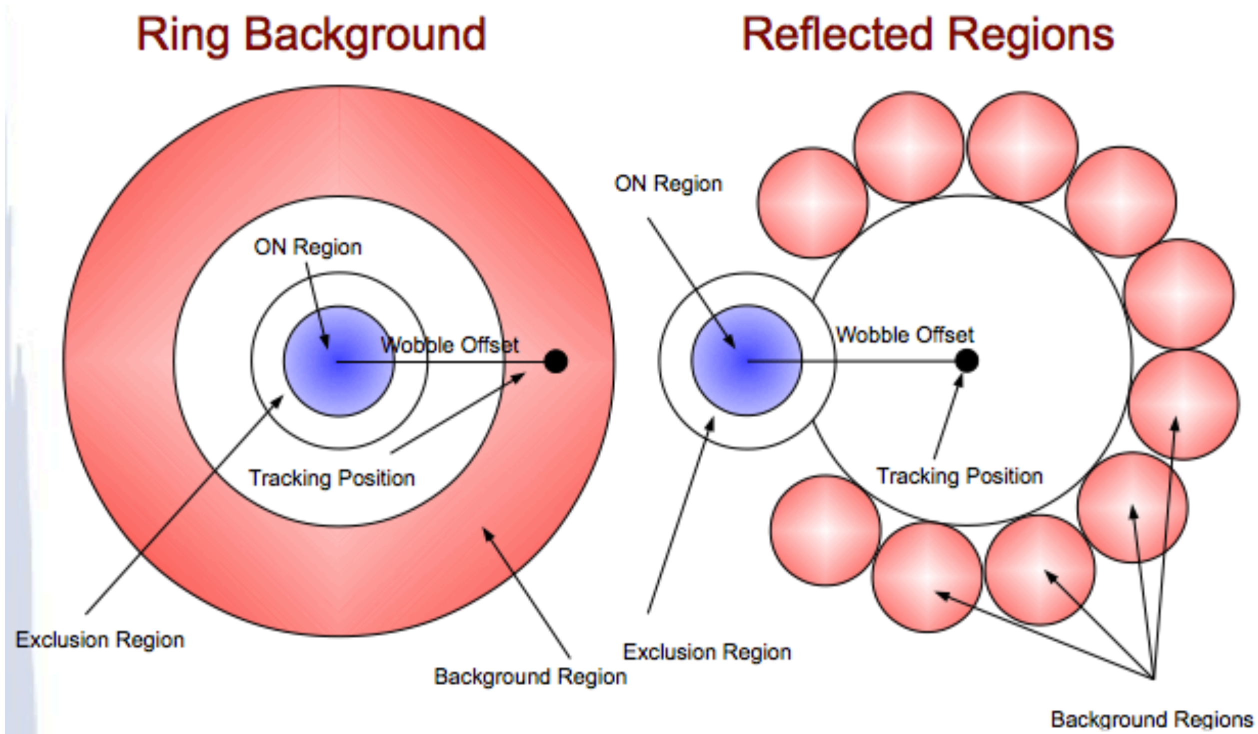
"VEGAS SkyMaps and Background Methods"
Or:
"Oh Crap! Stage 6 Just Exploded!"

Ben Zitzer – 1/14/14

Background Estimation

- Even after gamma/hadron separation cuts, we still have hadronic contamination
  - These are the CRs that look like gammas
  - Need to estimate contamination and subtract
- Two main background estimation methods
  - Ring Background Method (RBM)
  - Reflected Region (aka Wobble)
  - (Time very useful for pulsars)

Background Methods



RBM: Use annulus around source

+**Pros**: Lots of statistics, great for skymaps/extended sources

-**Cons**: Not good for spectra, requires acceptance correction

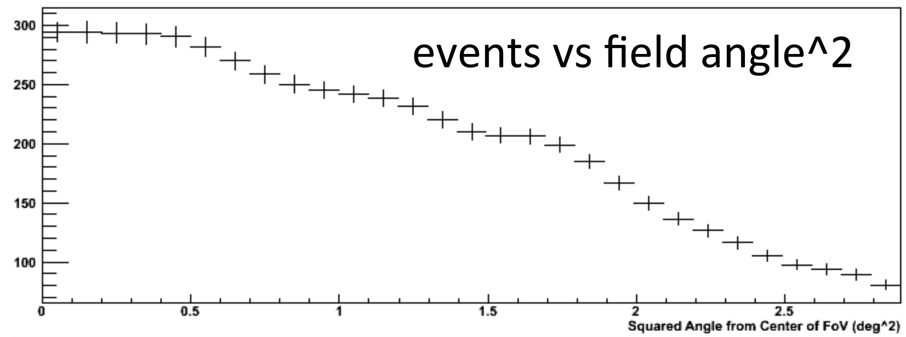
Reflected Regions: Uses ON-shaped regions reflected about tracking position

+**Pros**: Uniform acceptance, great for spectra

-**Cons**: Less background statistics

Acceptance

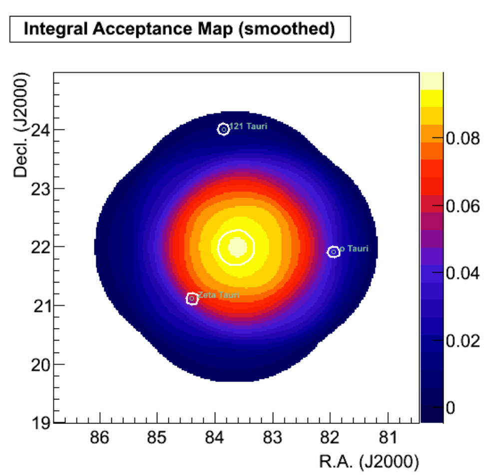
- The probability of accepting a gamma-ray-like event at a position in the field of view

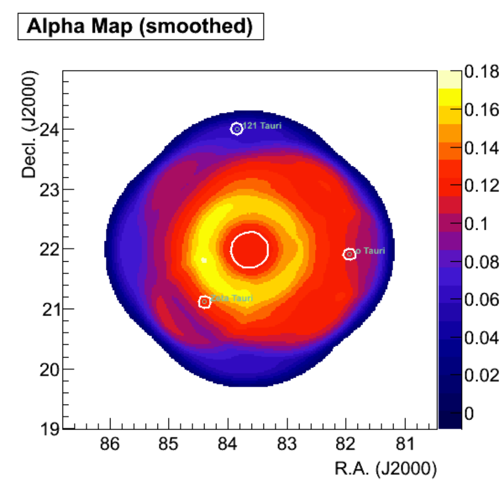


- Alpha: ratio of ON/OFF integral acceptance

$$\alpha = \frac{\int_{on} A^{\gamma}_{on}(\psi_x, \psi_y, \phi_z, E, t)\, d\psi_x\, d\psi_y\, d\phi_z\, dE\, dt}{\int_{off} A^{\gamma}_{off}(\psi_x, \psi_y, \phi_z, E, t)\, d\psi_x\, d\psi_y\, d\phi_z\, dE\, dt}$$

- Both radially symmetric around tracking position





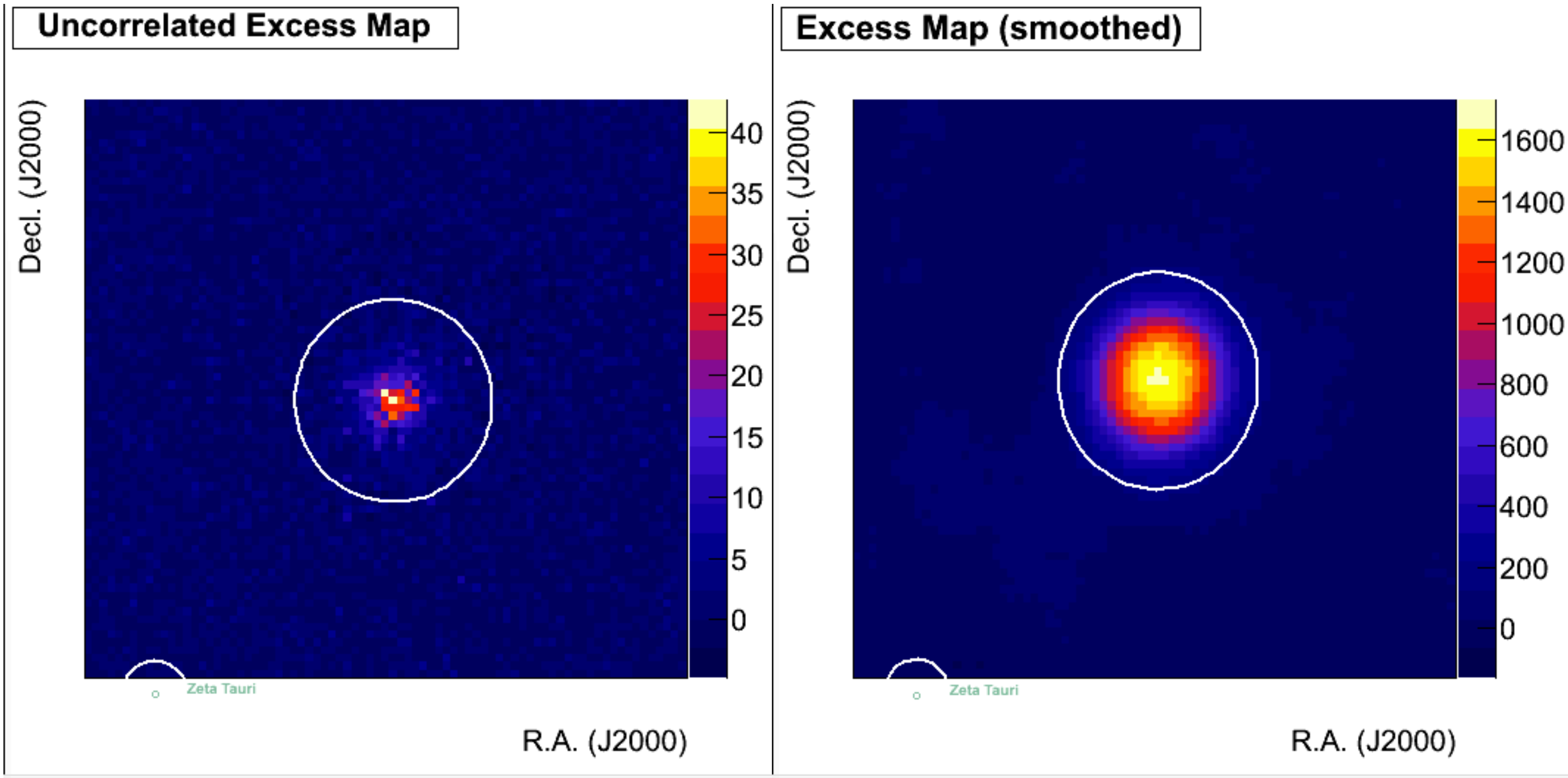
Significance and Detection

- Significance calc from Li&Ma 1983
  - Binned likelihood ratio test:

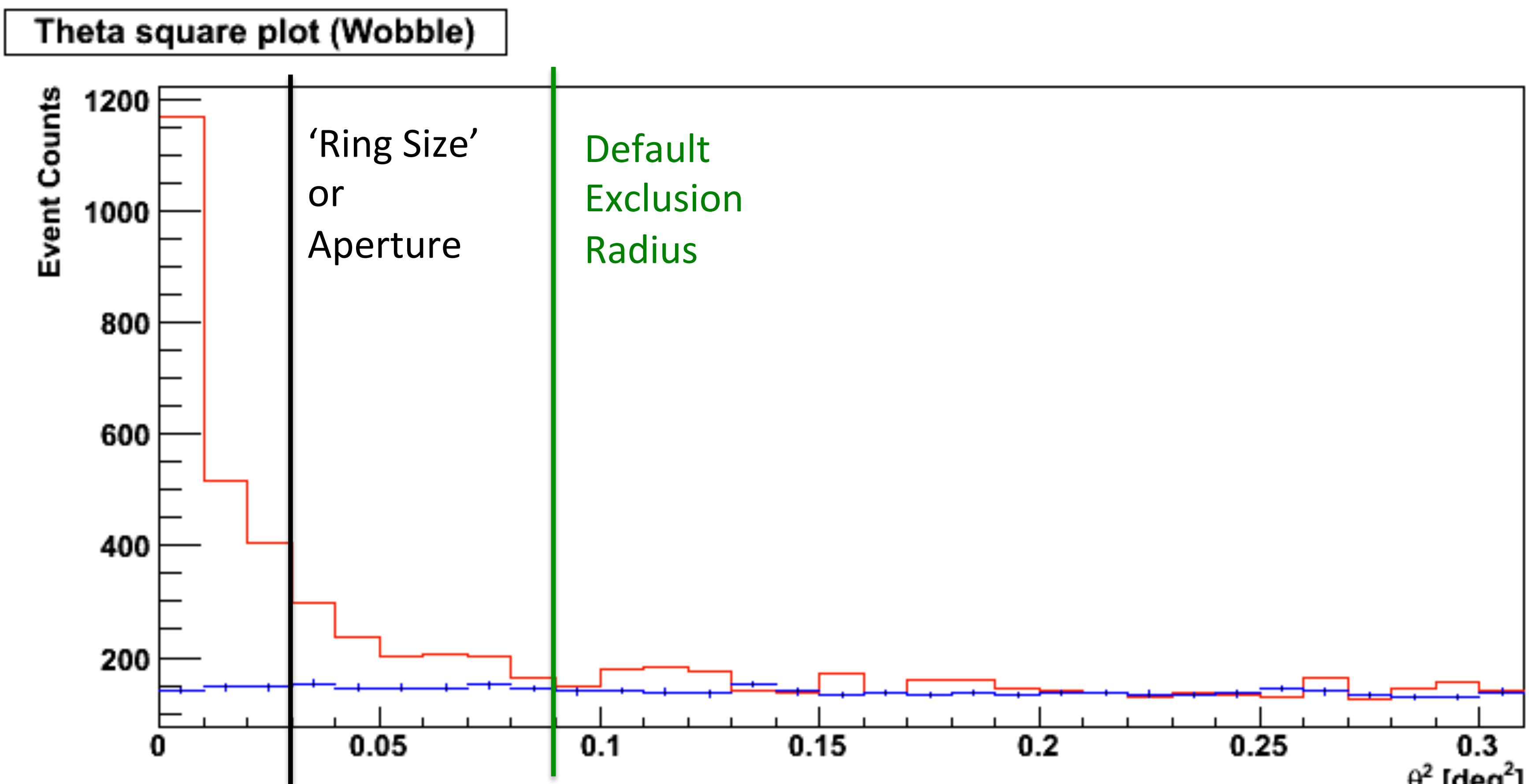
$$S = \sqrt{2}\left(N_{on}\ln\left(\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right) + N_{off}\ln\left((1+\alpha)\frac{N_{off}}{N_{off}+N_{on}}\right)\right)^{1/2}$$

- 5 σ required for claim of detection
  - After taking into account the Look Elsewhere Effect (i.e. trials)

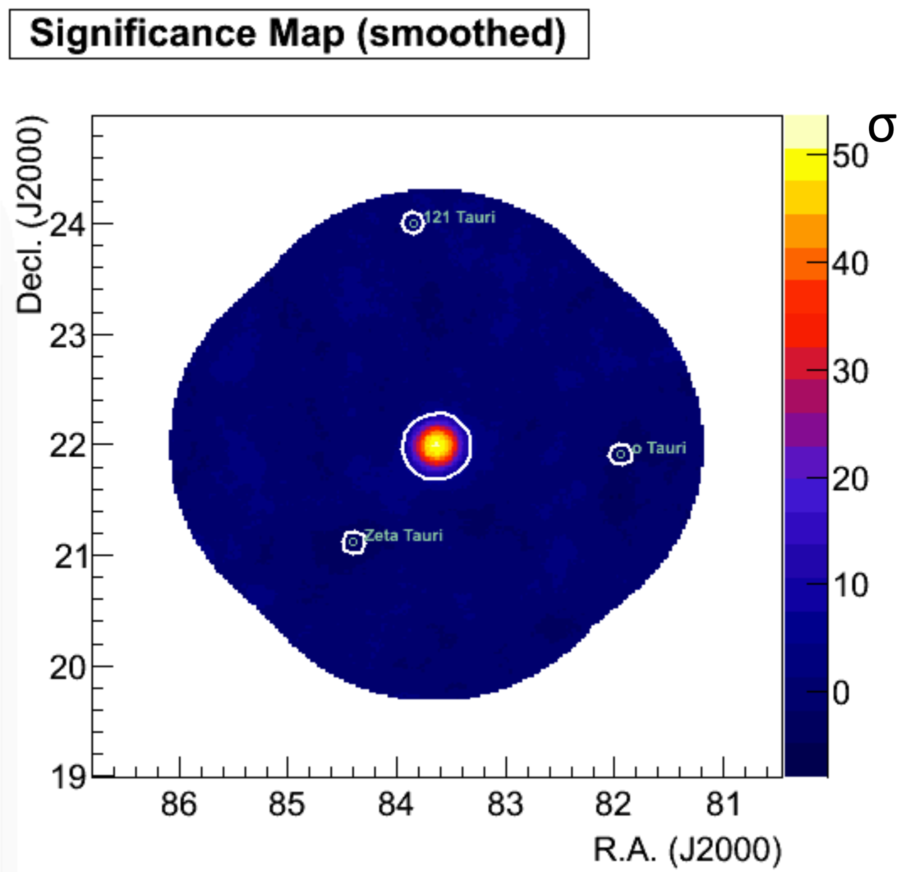
Smoothing Using Circ Aperture

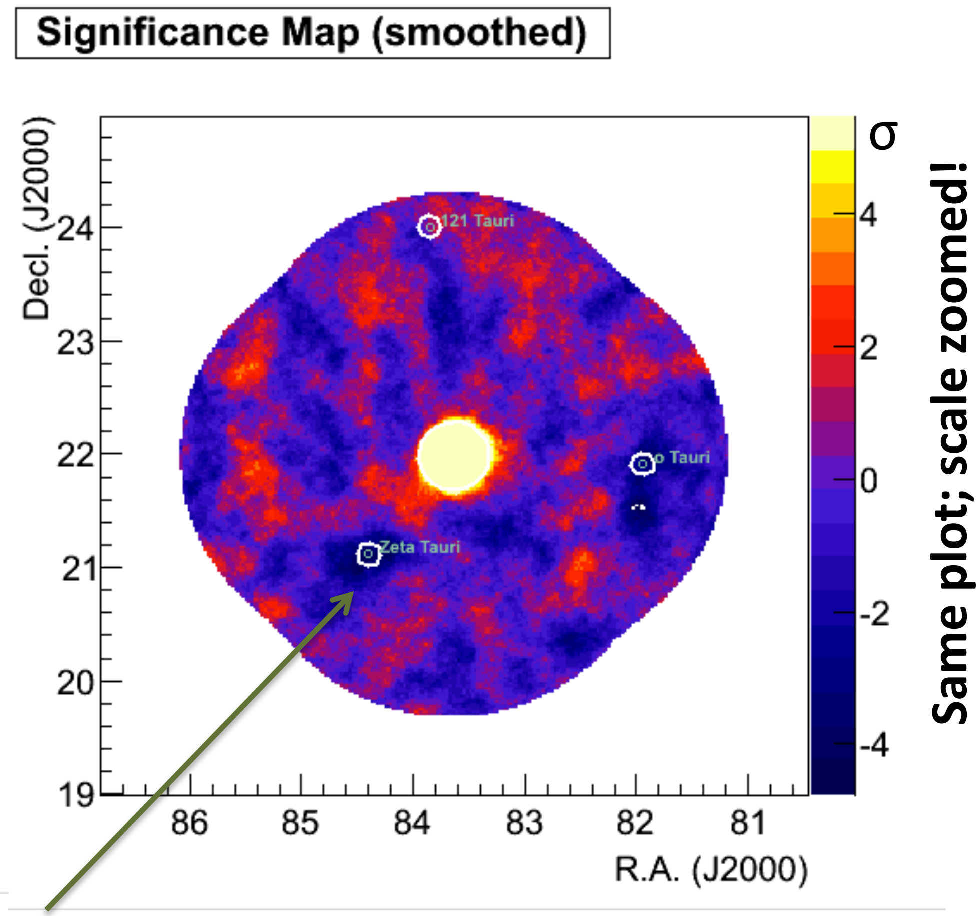


Theta^2 Plot (PSF)



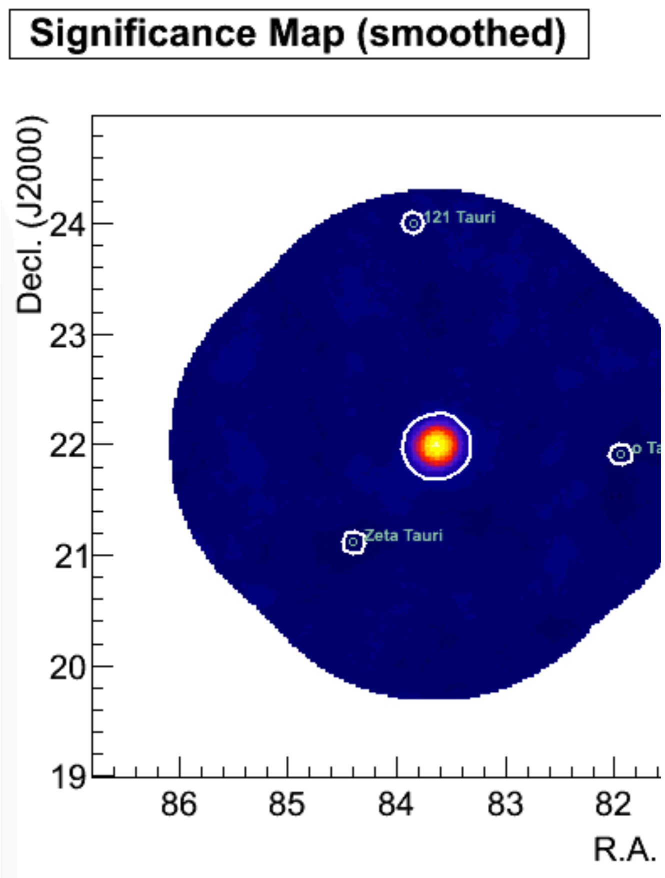
Significance Distribution

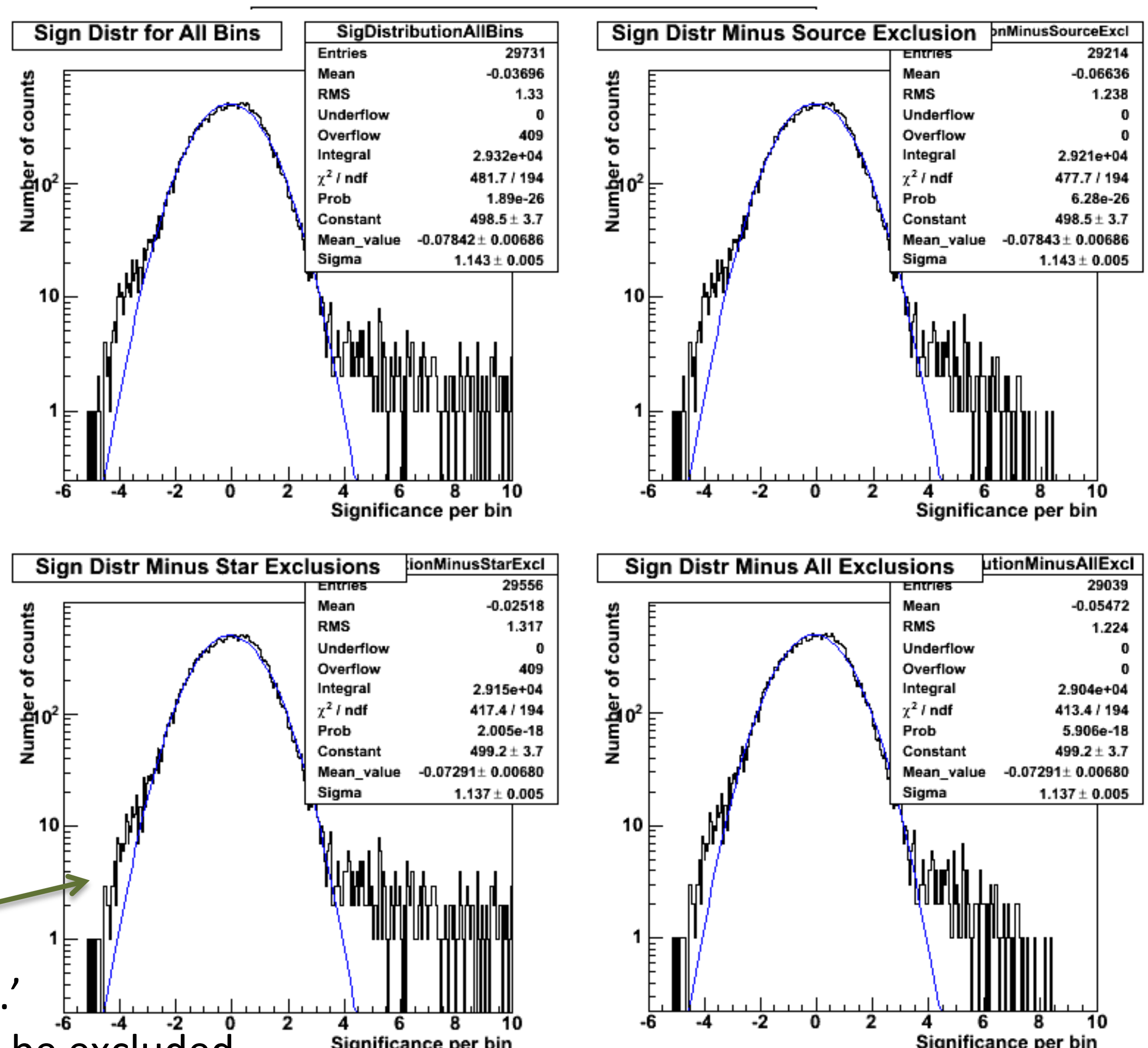




This is a 'soft' analysis:
Size>200 susceptible to 'star bias.'
Negative sig. near stars needs to be excluded.

Significance Distribution





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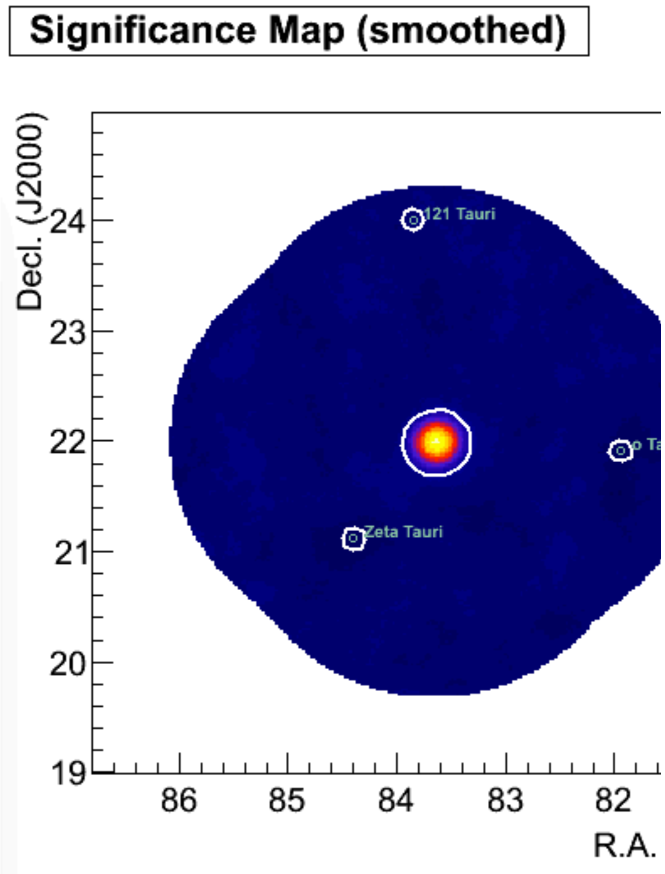
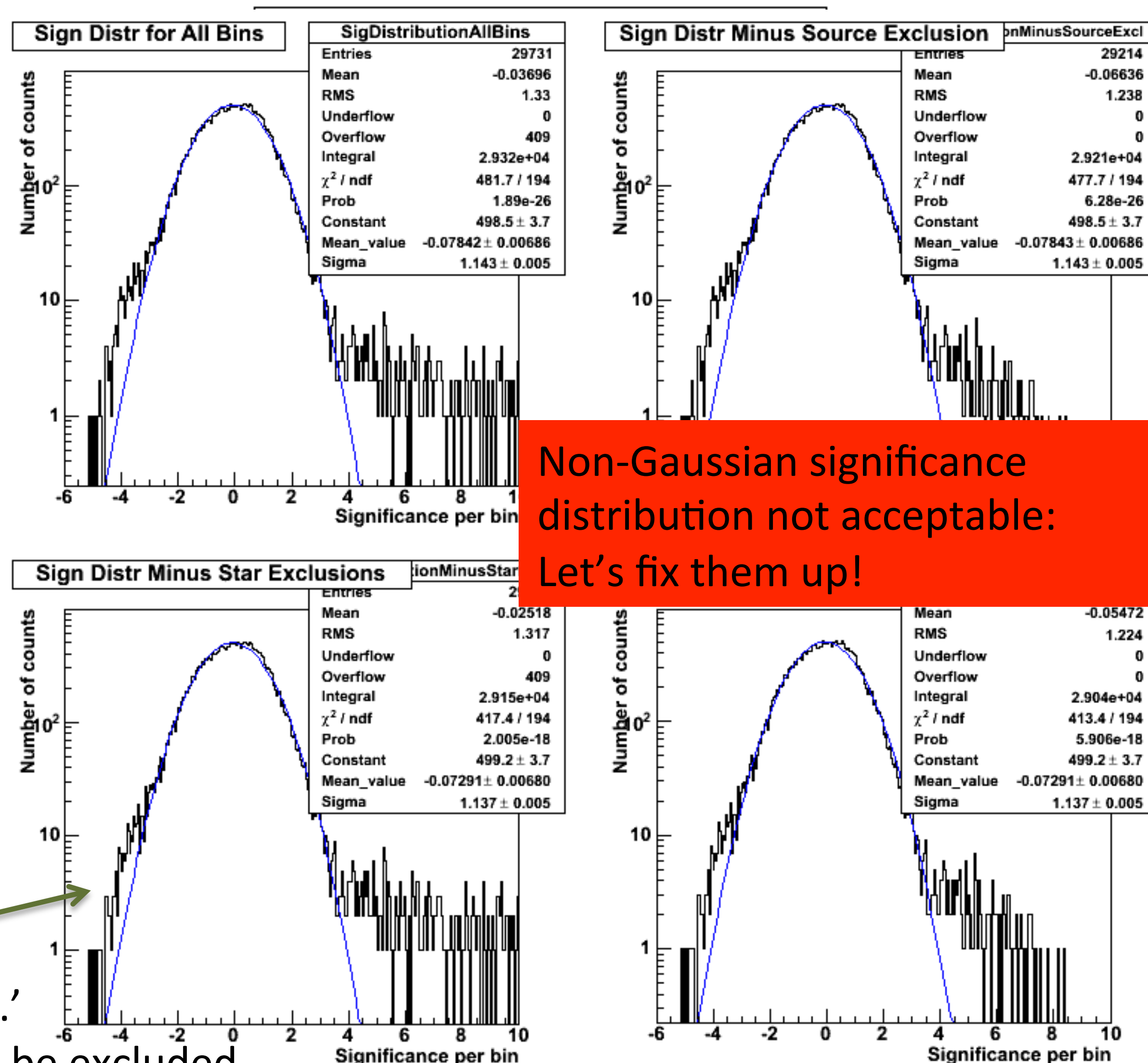
Negative sig. near stars needs to be excluded.

Significance Distribution





Non-Gaussian significance distribution not acceptable: Let's fix them up!

This is a 'soft' analysis:
Size>200 susceptible to 'star bias.'
Negative sig. near stars needs to be excluded.

Techniques to Fix Sky Map

- Most important stage6 options in stage6.sh:

```
-S6A_SourceExclusionRadius=0.3
-S6A_StarExclusionBMagLimit=5
-S6A_StarExclusionRadius=0.1
```

← Increase for bright sources
← Increase to exclude dimmer stars
← Increase if star bias large

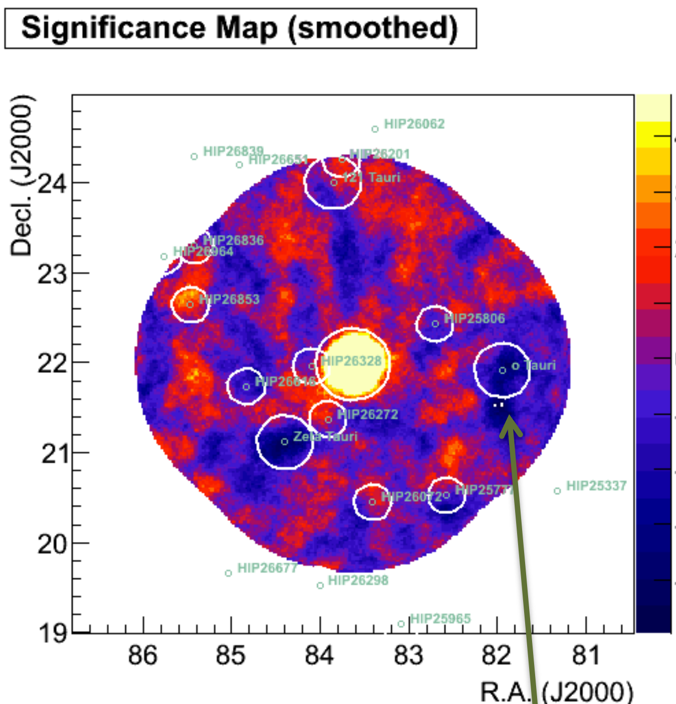
- For full help text on each option:

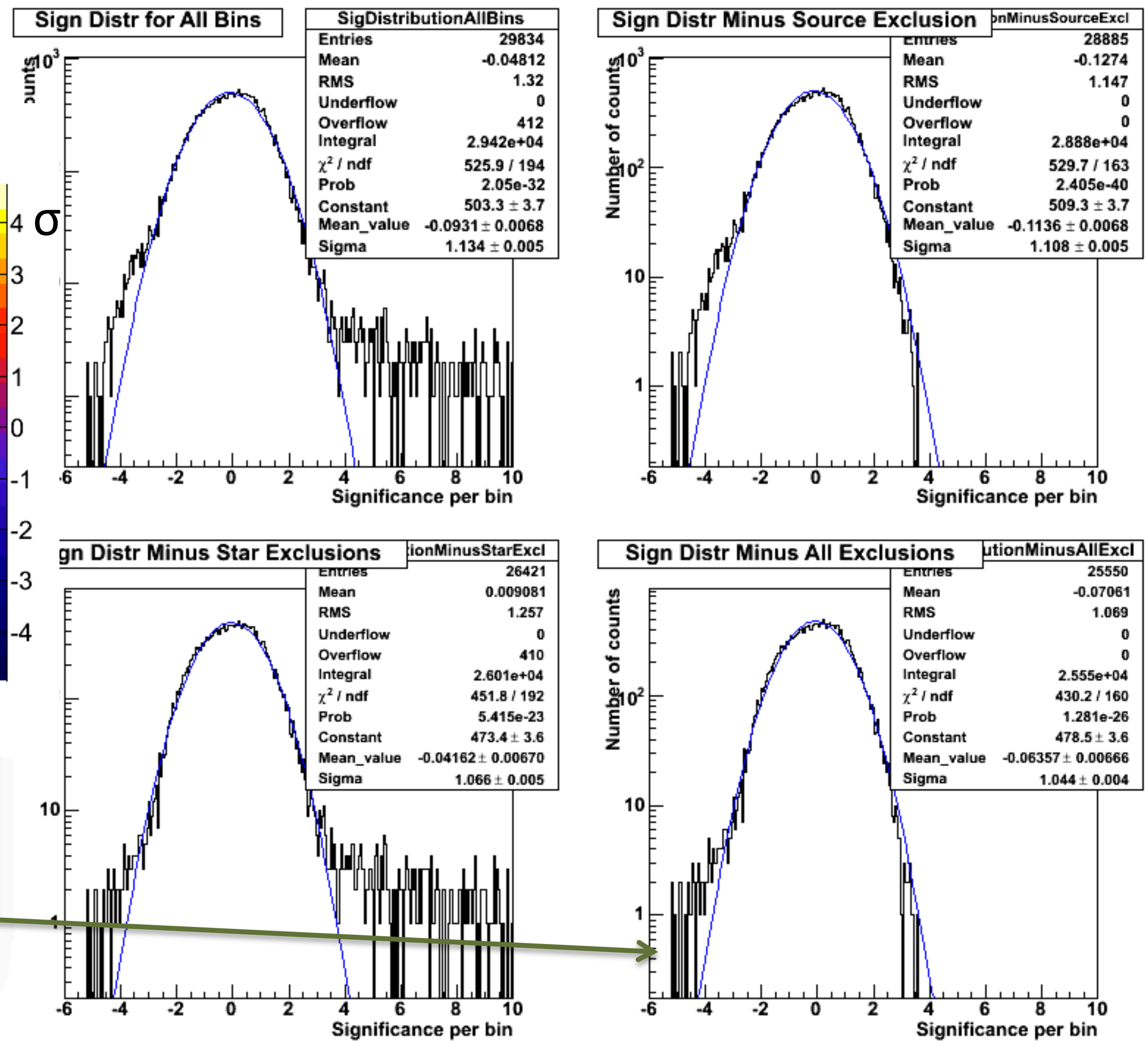
```
vaStage6 -help=full | less
```

- Rerun the stage6.sh wrapper with tweaked options to clean up background estimates

```
nano stage6.sh
./stage6.sh
```

Significance Distribution





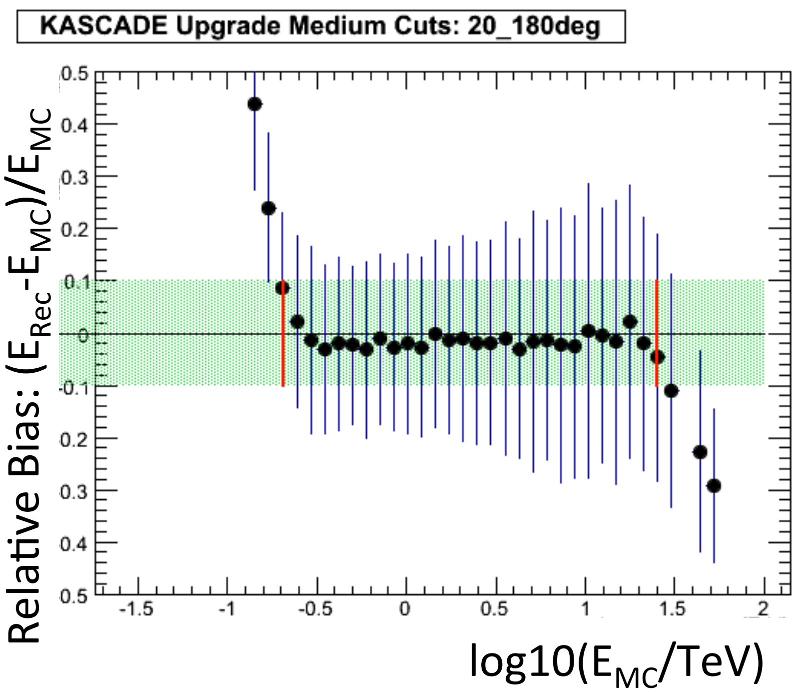
check out:

.stage6.sh.answerkey

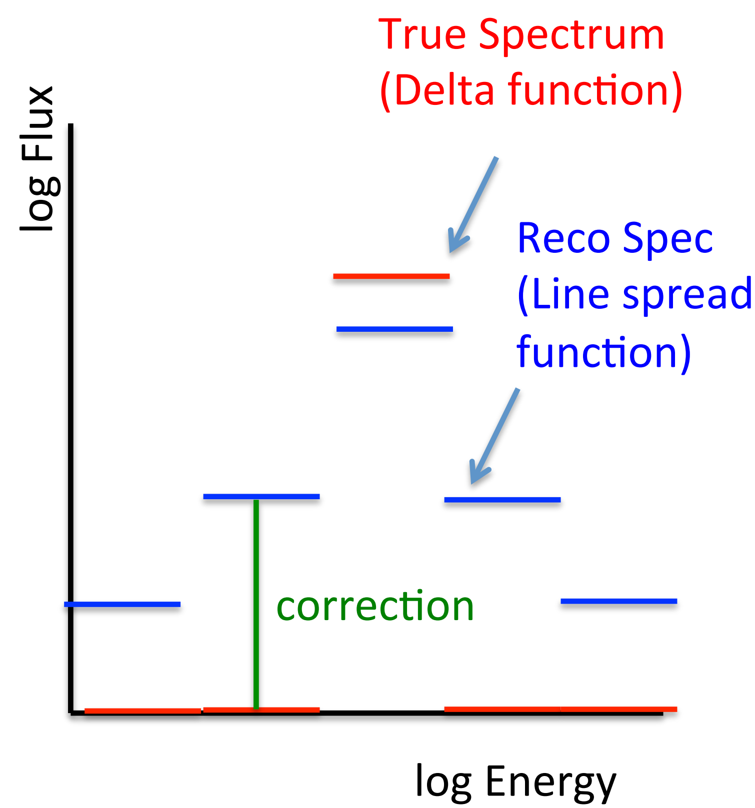
Still some more cleanup could be done – few dim stars

Spectral Reconstruction

- Why is it difficult?
  - non-zero Energy resolution:



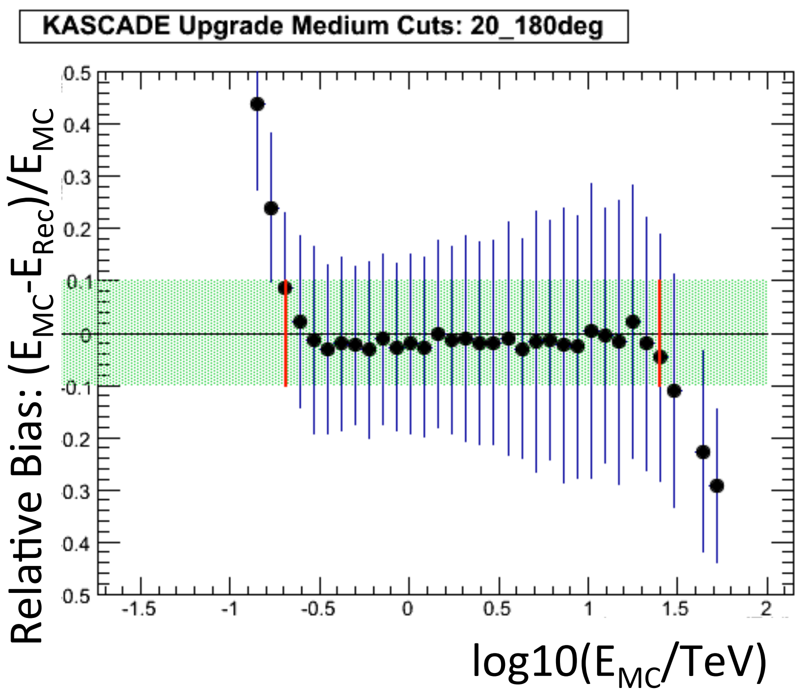
Energy Resolution Curve



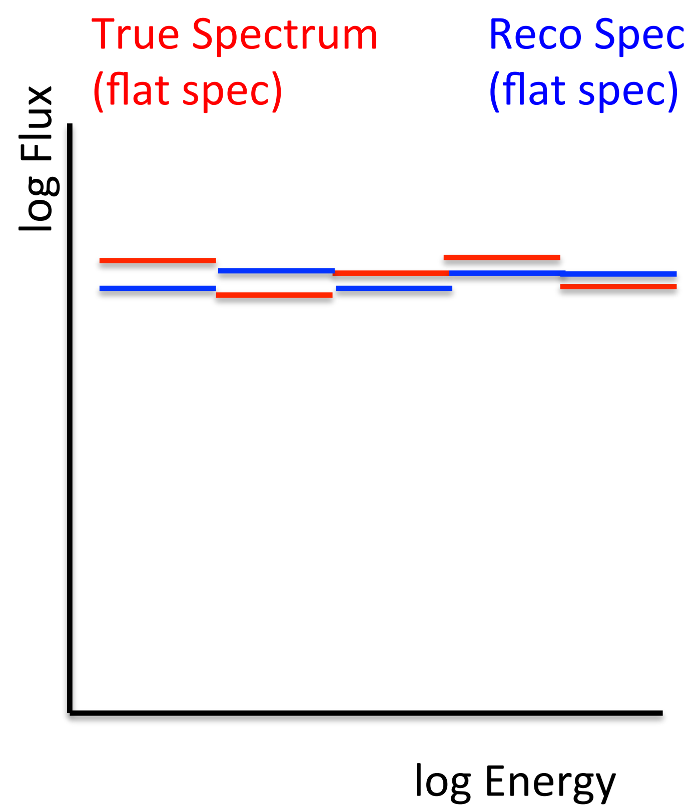
If you know true spectrum and energy resolution, one can subtract off 'cross talk' to obtain true flux

Spectral Reconstruction

- Why is it difficult?
  - non-zero Energy resolution:



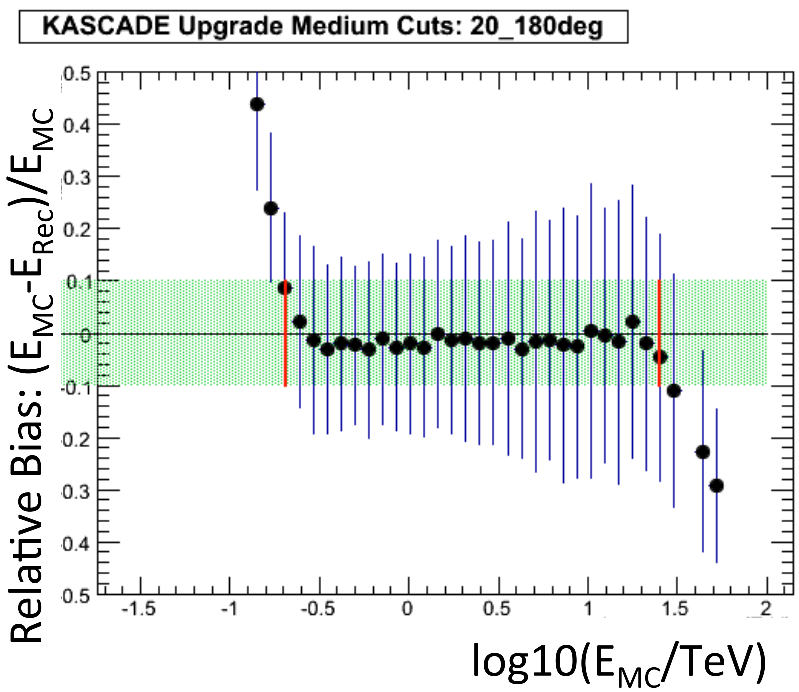
Energy Resolution Curve



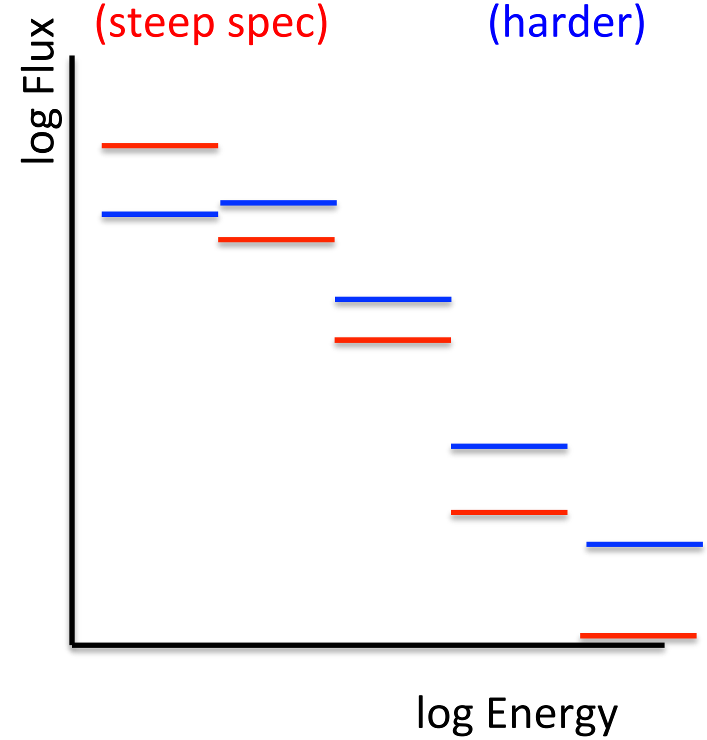
Only small corrections for flat spectra

Spectral Reconstruction

- Why is it difficult?
  - non-zero Energy resolution:



Energy Resolution Curve



Larger corrections for steep spectra

Spectral Reconstruction

number of observed events in energy bin E_j

gamma-ray source spectrum

"Modified" Effective Area

detector uptime

$$N_{obs}(E_j^{rec}) = \int_{t_0}^{t_1} dt \int_0^{\infty} dE \frac{dN_\gamma}{dE\,dA\,dt} A_0 \times p(E_j^{rec}|E) \times \epsilon(t)$$

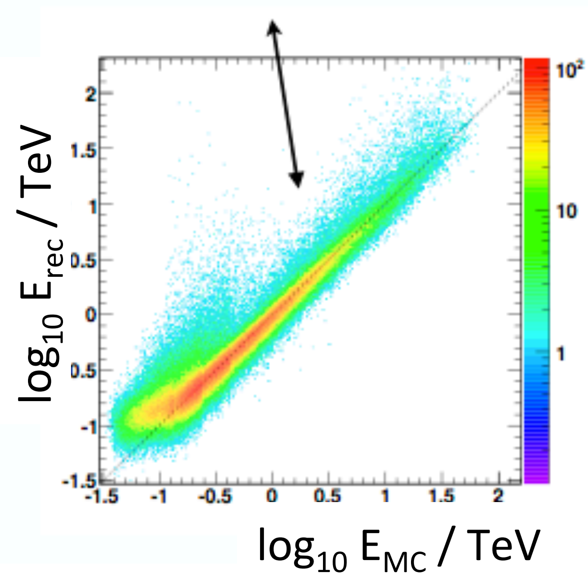
observing interval

probability of measuring E^{rec}

Goal is to reconstructed the gamma-ray source spectrum: invert this integral

Bin correction method as rudimentary unfolding

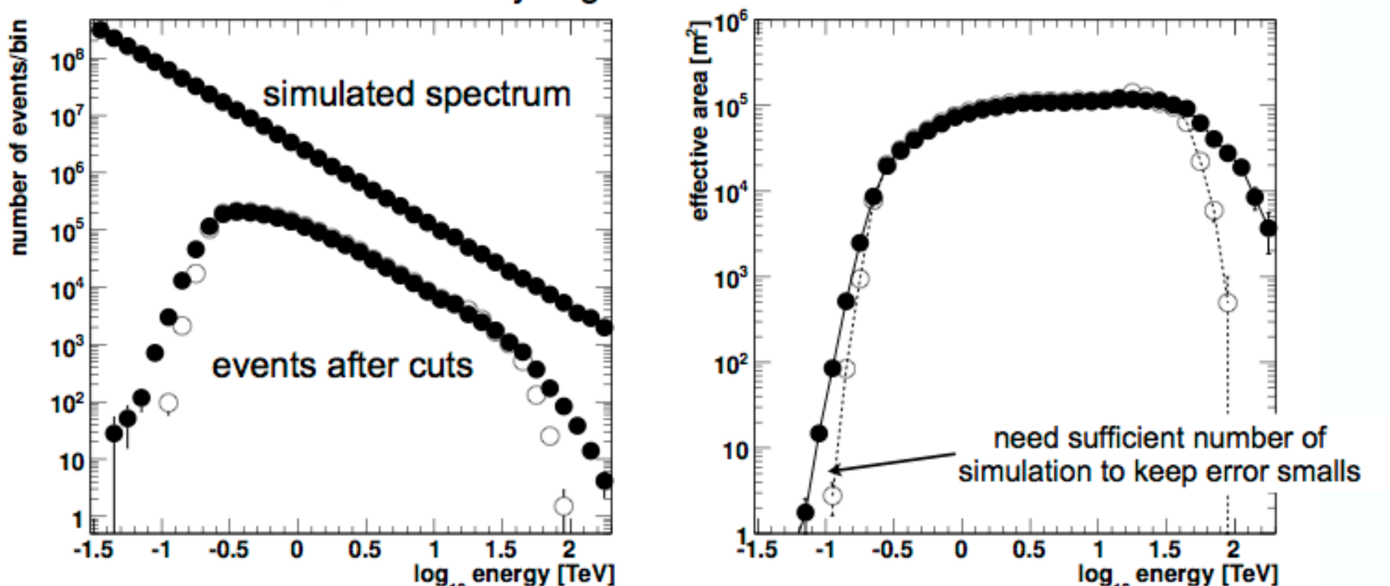
G.Mohanty et al, Astroparticle Physics 9, 15 (1998)
J.Albert et al, NIM A 583, 494 (2007)
Many textbooks, e.g. Cowan: Statistical Data Analysis, Oxford (1998)



Effective Area

$$A(E) = A_0\left(\frac{\text{number passing selection at } E}{\text{number simulated at } E}\right)$$

A_0: sufficiently large throw area of MC events



Filled circles: True Energy
Open circles: Reco Energy -> Modified Eff Area

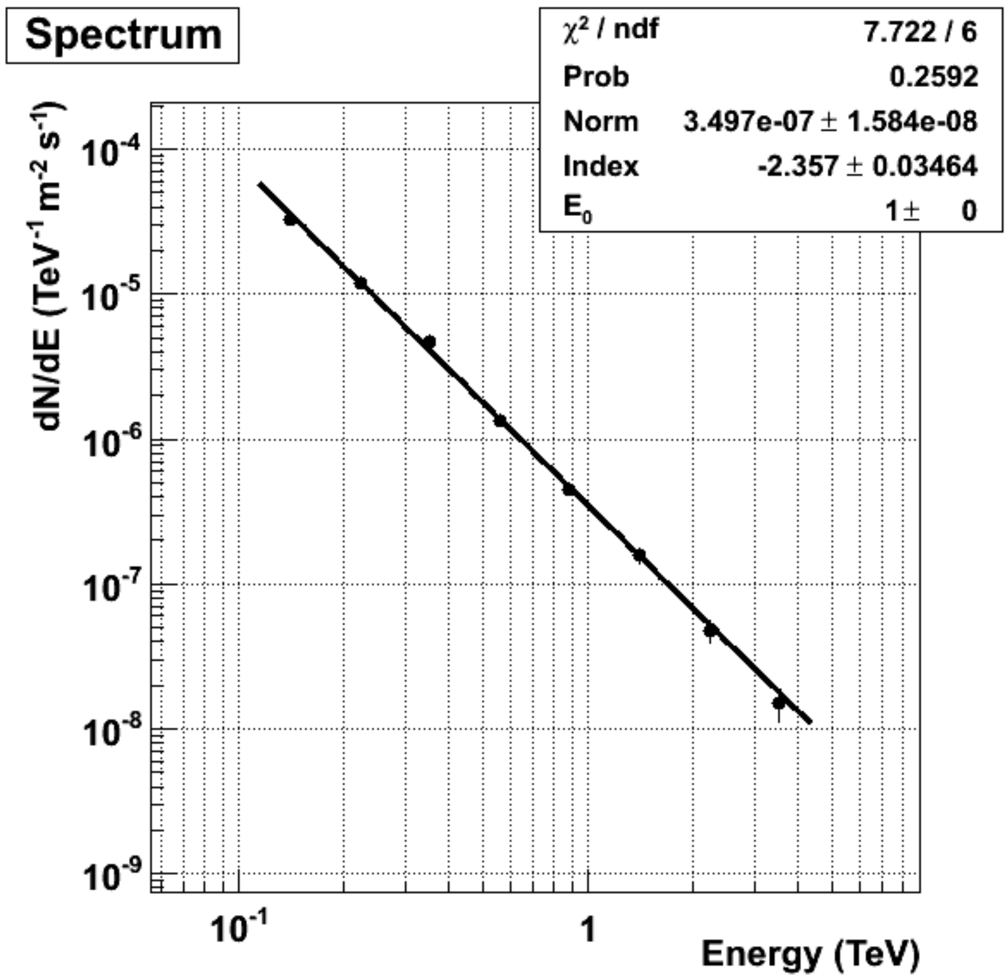
Correction Method

- Inverting our integral eqn to solve for flux:

$$\frac{dF_i}{dE} = (T\,\Delta E_i)^{-1} \cdot \left(\sum_{j=0}^{N_{\mathrm{on}}} (A_{\mathrm{reco}_j})^{-1} - \alpha \sum_{k=0}^{N_{\mathrm{off}}} (A_{\mathrm{reco}_k})^{-1} \right)$$

- Mod. Eff. Area (A_{reco}) depends on true spectrum
  - Results biased towards hypothesis spectrum
  - Iterate (by hand) until results look like hypothesis
    - Trivial for power laws
- Variance scales like bin cross-talk squared
  - Keep bins larger than energy resolution

Final Remarks on Spectra



- Energy threshold determined by:
  - Max differential counts
  - Max rel. uncertainty in Eff Area
  - Max energy bias
- Bin requirements by default:
  - 2 σ in VEGAS; 3 σ in ED
  - >=5 excess counts
- Thresholding possibly biases end points of spectra

Conclusions

- VERITAS has two mature standard analysis packages
  - Interested in VERITAS data? Need to partner with VERITAS member
  - Exploring more public tools
    - Expansion of existing internal tools (nextday analysis)

- Lots of improvements compared to what I showed today are in the pipeline
  - Image/shower template fitting
  - Machine learning event selection (BDTs)
  - Spectral unfolding techniques
  - Unbinned maximum likelihood source fitting