Argonne NATIONAL LABORATORY

... for a brighter future

A New High-Speed Pattern Recognition Trigger for Ground-Based Telescope Arrays used in Gamma Ray Astronomy

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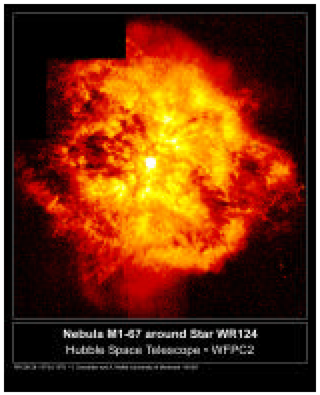
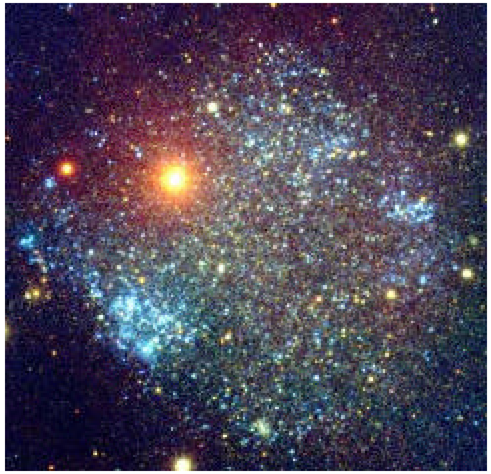
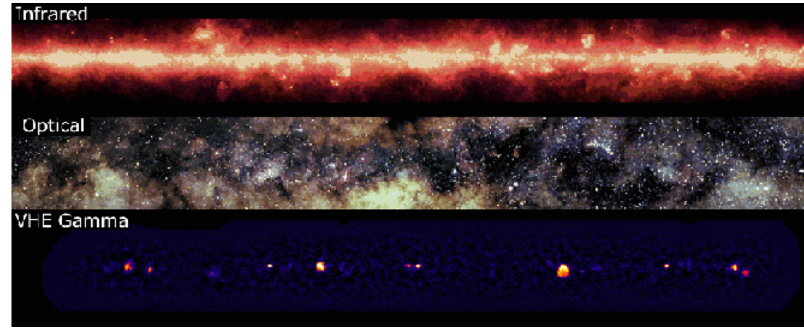
Very High Energy Gamma Ray Science



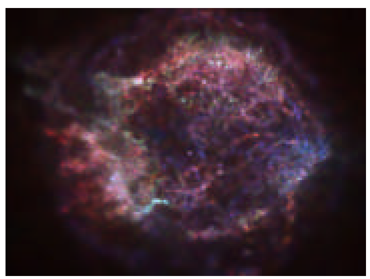
Gamma Ray Bursts



Indirect detection of Dark Matter

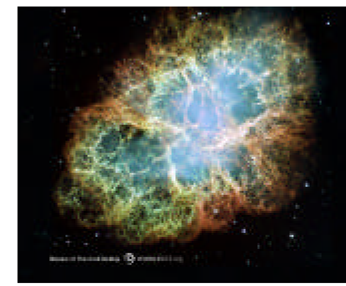


Search for New Sources/Phenomena



Supernova Remnants

Active Galactic Nuclei



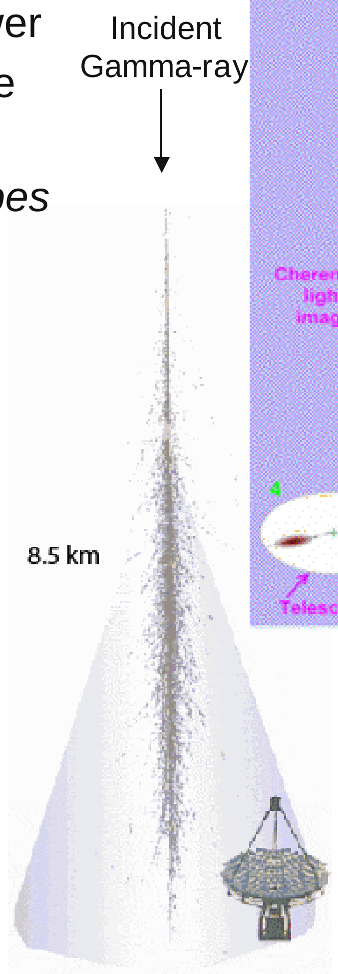
Pulsars and Pulsar Wind Nebulae

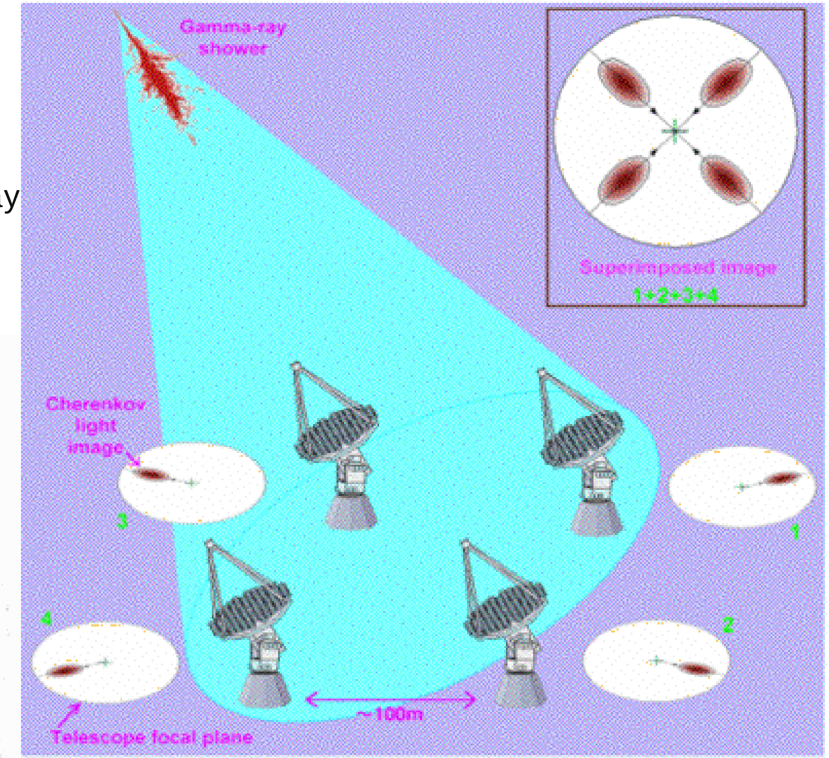
- ⇨ ***Rich scientific program***
- ⇨ ***Exploring the Universe out to Redshifts of 1-2 via 10 GeV – 100 TeV Gamma-rays***
- ⇨ ***Technique: Observe showers in upper atmosphere from incident gamma-rays using ground-based telescope arrays***

Slide courtesy of Bob Wagner, Argonne

The Imaging Air Cherenkov Telescope Technique

- **Detection**
  - Gamma-rays strike upper atmosphere and create a shower
  - Light pattern is imaged onto the camera of a telescope
    - *typically photo-multiplier tubes*
- **Telescope arrays**
  - Improve Angular Resolution
  - Improve Energy Resolution
  - Reduce Backgrounds
  - Eliminate Muons
  - Improve Stability



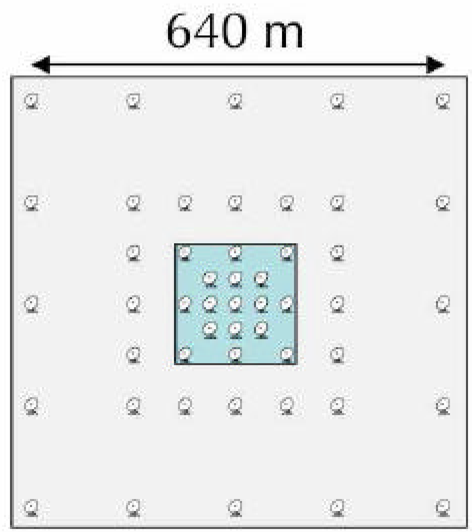


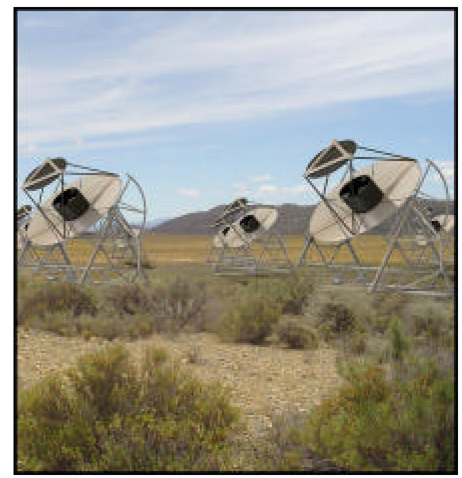
Graphics & Pictures Courtesy of VERITAS

Ground-Based Gamma-Ray Telescope Arrays

- **Current Generation**
  - 2 - 5 telescopes
  - VERITAS, HESS, MAGIC, CANGAROO…

- **Next Generation**
  - ~50 – 100 telescopes
  - AGIS, CTA
  - Goals:
    - *increase Field of View*
    - *increase sensitivity*
    - *increase pointing accuracy*
    - *observe more distant objects*





Conceptual Rendering of AGIS

⇨ ***We are designing for the Next Generation, but will prove concept with VERITAS***

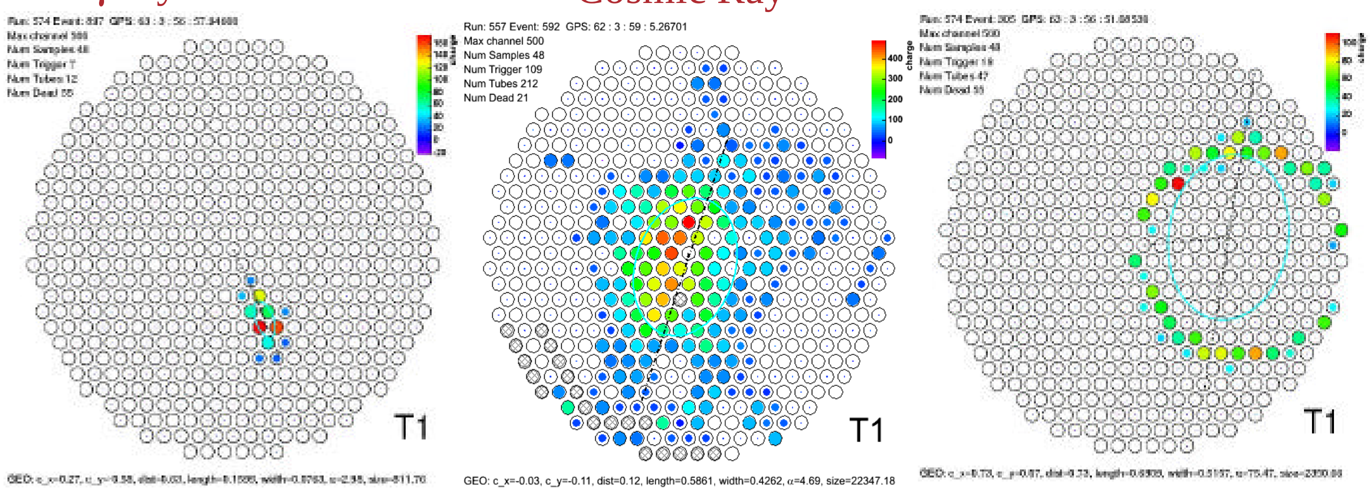
Motivation for High-Speed Trigger

- **Signal of Interest:** Gamma-ray Showers
- **Background Signals:**
  - Muons
  - Cosmic Rays
    - *Protons, nuclei*
  - Night Sky Background (NSB)
    - *Mostly single photons*
    - *Singles rate: 1-10 MHz / pixel depending on threshold → 0.5 – 5 GHz -rate per camera*

- **Signatures**
  - Gamma-rays look very different from background events
    - *Singles are isolated hits without neighbors*
    - *Hadronic showers have larger lateral and longitudinal spread compared to gamma-ray showers*
    - *Muons are rings*

⇨ ***Signals of interest have unique pattern…***

γ-ray Candidate | Cosmic Ray | Muon



VERITAS Telescope 1 Images Courtesy of Liz Hayes & VERITAS

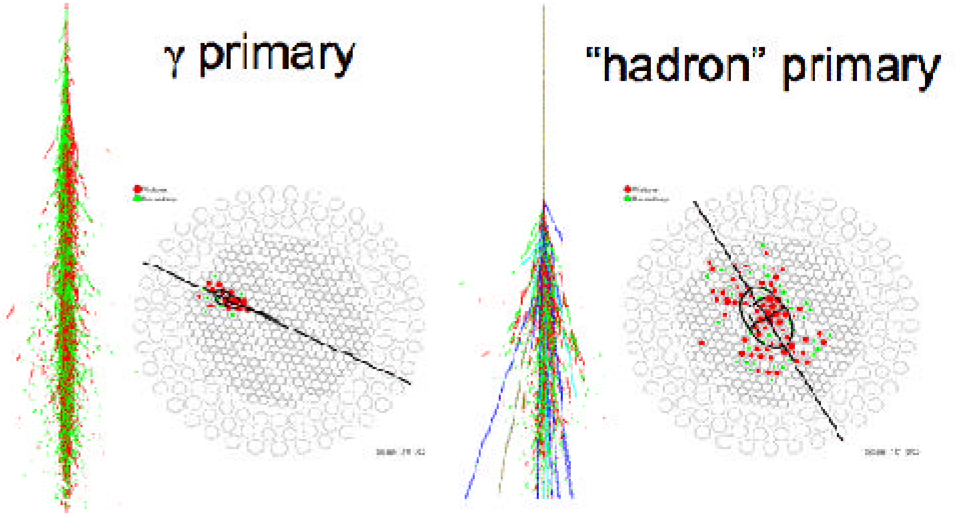
Motivation for High-Speed Trigger 2

- **Signatures with array**
  - Using array of telescopes, have additional capability to distinguish signals of interest
    - *Calculate 1st moment → major axis of ellipse*
    - *Look for intersection of axes → **Paralactic Displacement***
      - Convergence: Event of interest
      - Divergence: Background event

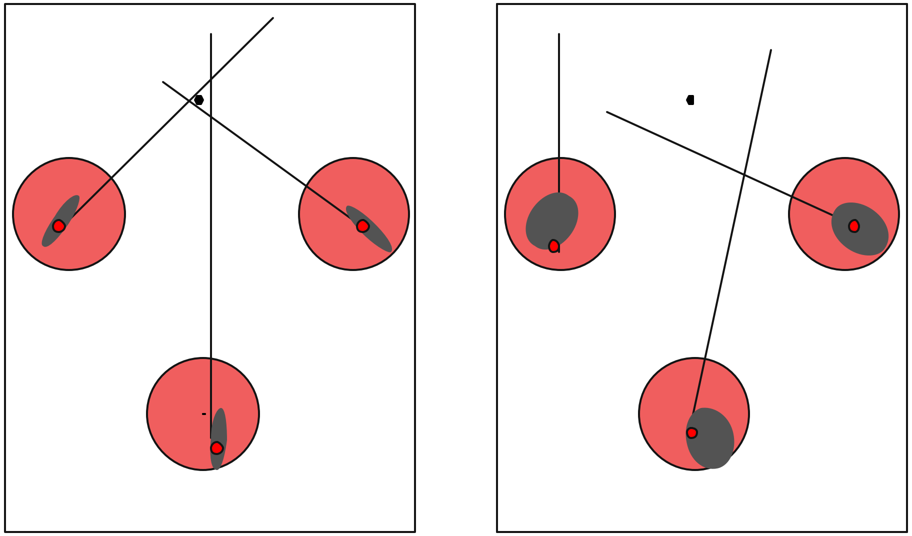
⇨ ***Goals:***

⇨ ***Differentiate these patterns in real time using information from entire array***

⇨ ***Lower the L1 threshold***
  - ⇨ ***Observe objects farther away***
  - ⇨ ***But, have higher background rates***



Graphic Courtesy of VERITAS



Method of Parallactic Displacement

Parallactic Displacement

- **Method**
  - Calculate 1st moment of images in each telescope

    $\Sigma x_i \quad \Sigma y_i \quad N_{HIT}$
  - Convert to Polar Coordinates, & form vectors

    $\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}$

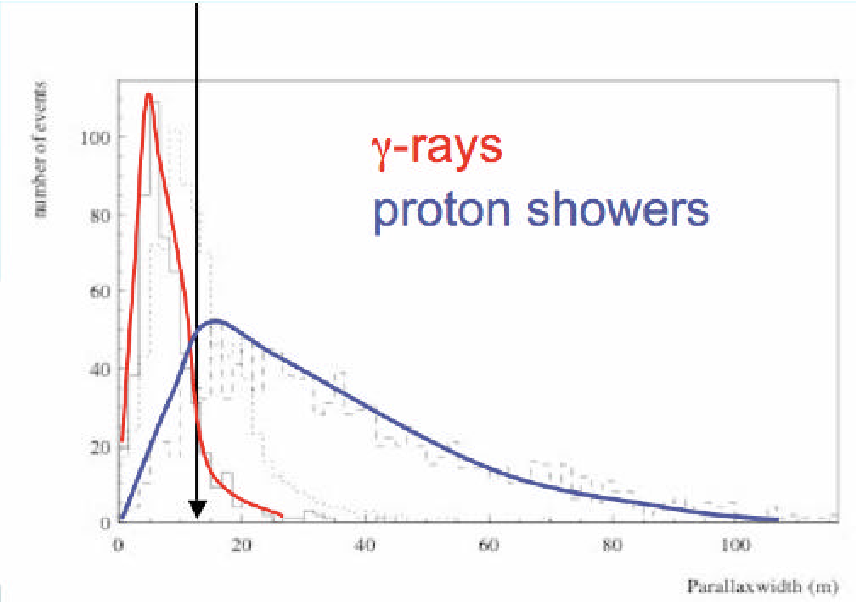
    $\phi = \arcsin(\bar{y} / \bar{r})$
  - Calculate Parallaxwidth:

$$Parallaxwidth \approx \sqrt{\frac{\sum_{i=1}^{n}(\vec{r}_i - <\vec{r}>)^2}{n}}$$

$$\vec{r}_i = \text{location of intersection point } i$$

$$<\vec{r}> = \text{averaged core location}$$

  - Calculate 2nd Moments
    - $s_{xx}^2 \quad s_{yy}^2 \quad s_{xy}^2$
    - *Evaluates "Goodness" of Fit



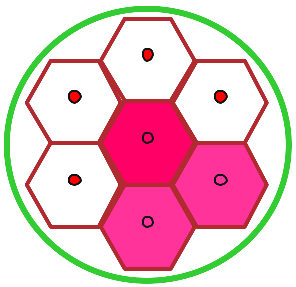
Monte Carlo simulation of g / hadron separation capabilities using parallactic displacement. Simulation used array of (19) 10-meter telescopes spaced 60 meters apart.

⇨ ***Reject 90% of cosmic rays while retaining 90% of gamma-rays***

Overview of Approach

- Receive ***discriminated hits*** (Level 1 Trigger) of each pixel in a camera from the FEE
- Form time window, & collect hits
- Process hits that have "3-fold neighbor coincidence"
  → Mostly rejects singles
- Calculate 1st & 2nd moments of images in each camera
- Use stereo view from multiple telescopes to project image back into the sky
- Identify γ-ray images by tight correlation of projection
  → Parallactic Displacement
- Do this with no dead time

⇨ ***Neighbor logic must run at 400 MHz***

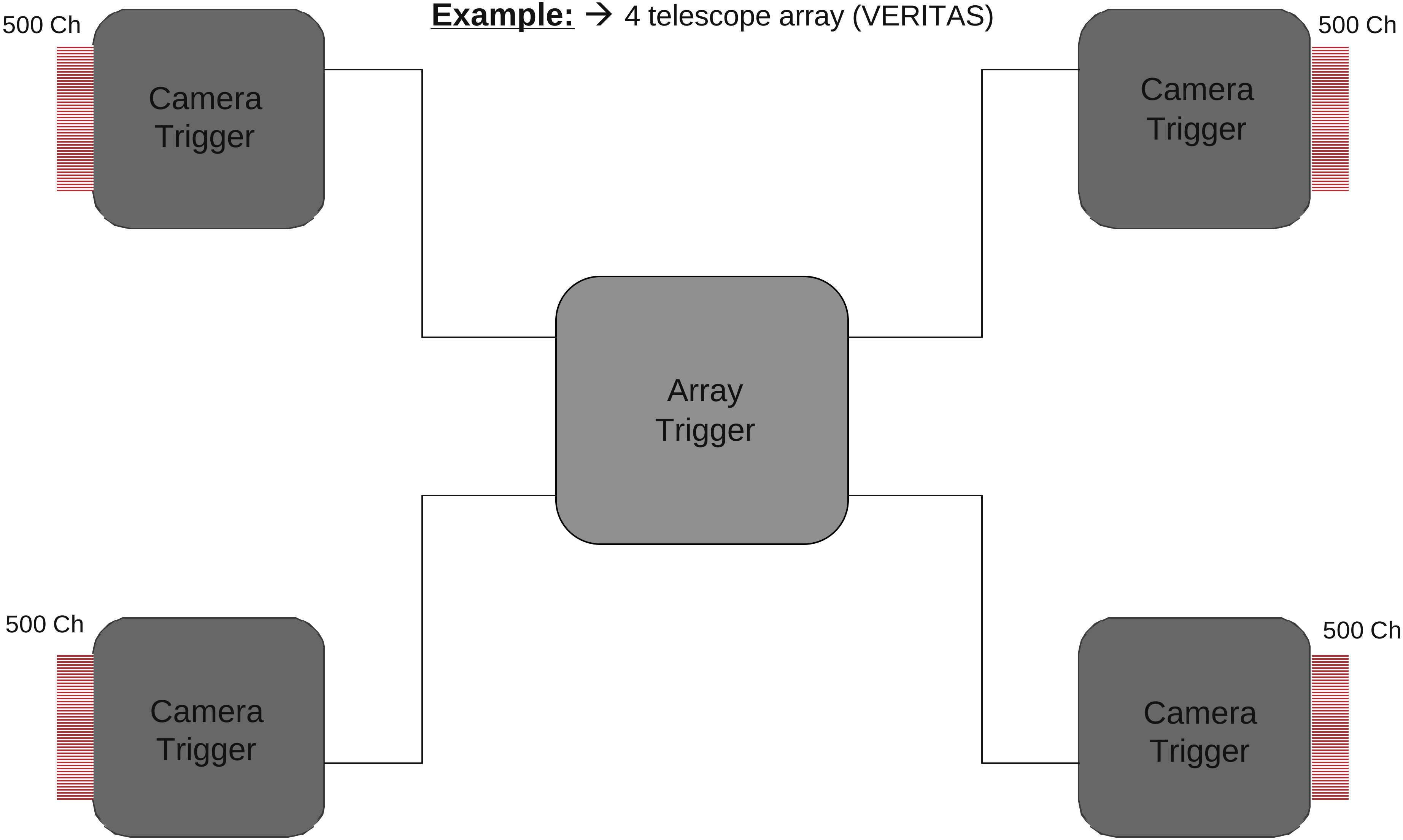


3-Fold Neighbor Coincidence,
7-pixel cell,
Formed around
primary pixel

→ List Of Hits + Time Stamp → X,Y Of Hits → 1st & 2nd Moments → Polar Coord. → Parallax Width

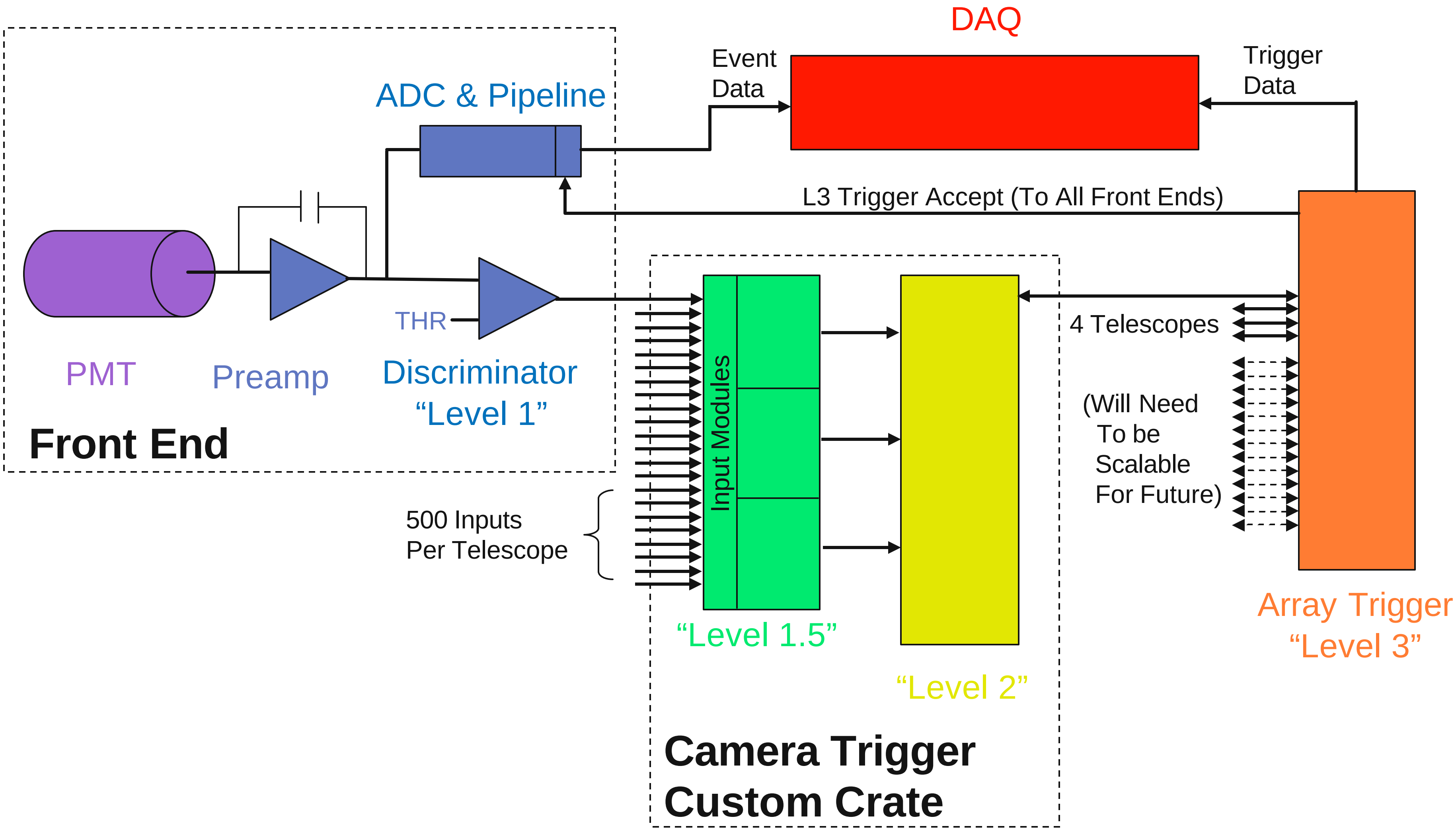
System Concept

Example: → 4 telescope array (VERITAS)



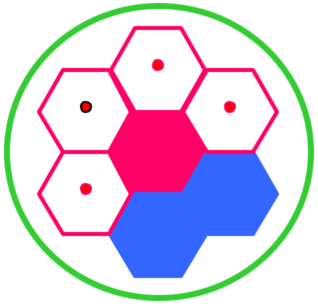
System Concept 2

- Multi-Level Trigger System

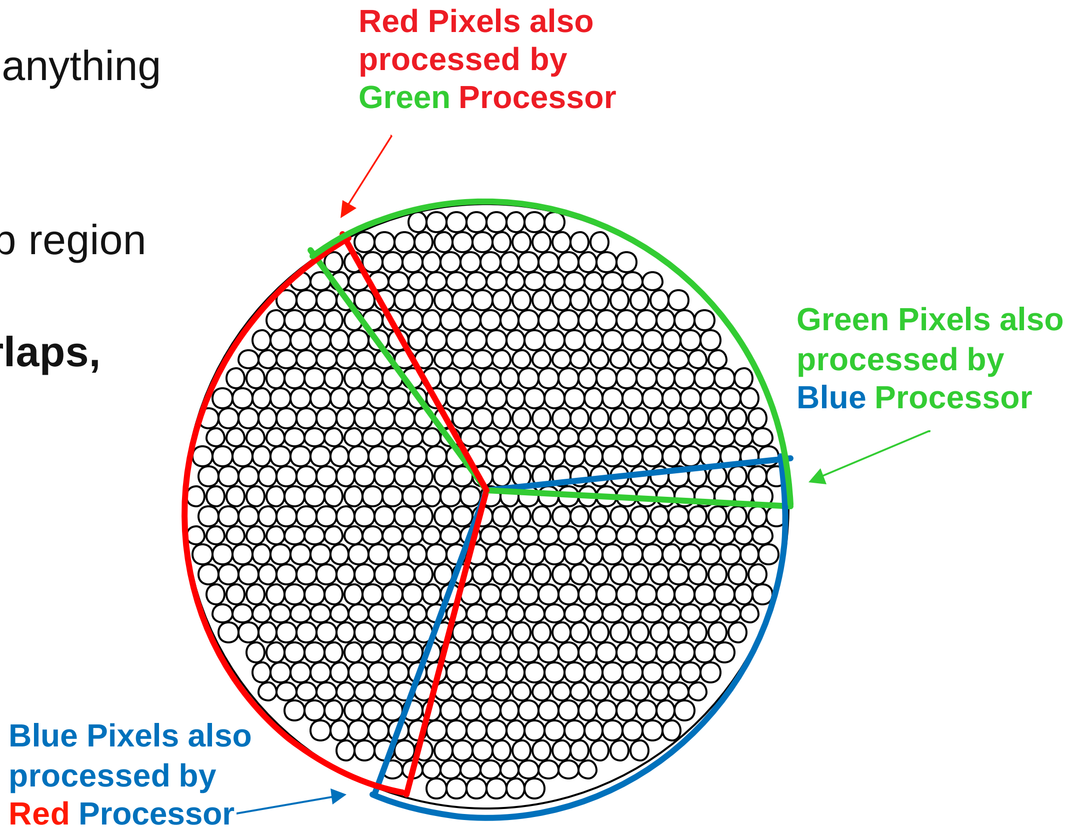


Physical Connection Strategy

- **Divide 499 channel camera into 3 regions** ⇨ ***Design for VERITAS***
  - ~166 pixels per region
- **Overlapping Radial Regions**
  - Required if don't want to miss anything with 3-fold logic
  - ~13 pixels per overlap region
  - Each region contains 1 overlap region → overlaps not counted twice
- **Each region, along with the overlaps, is processed separately**



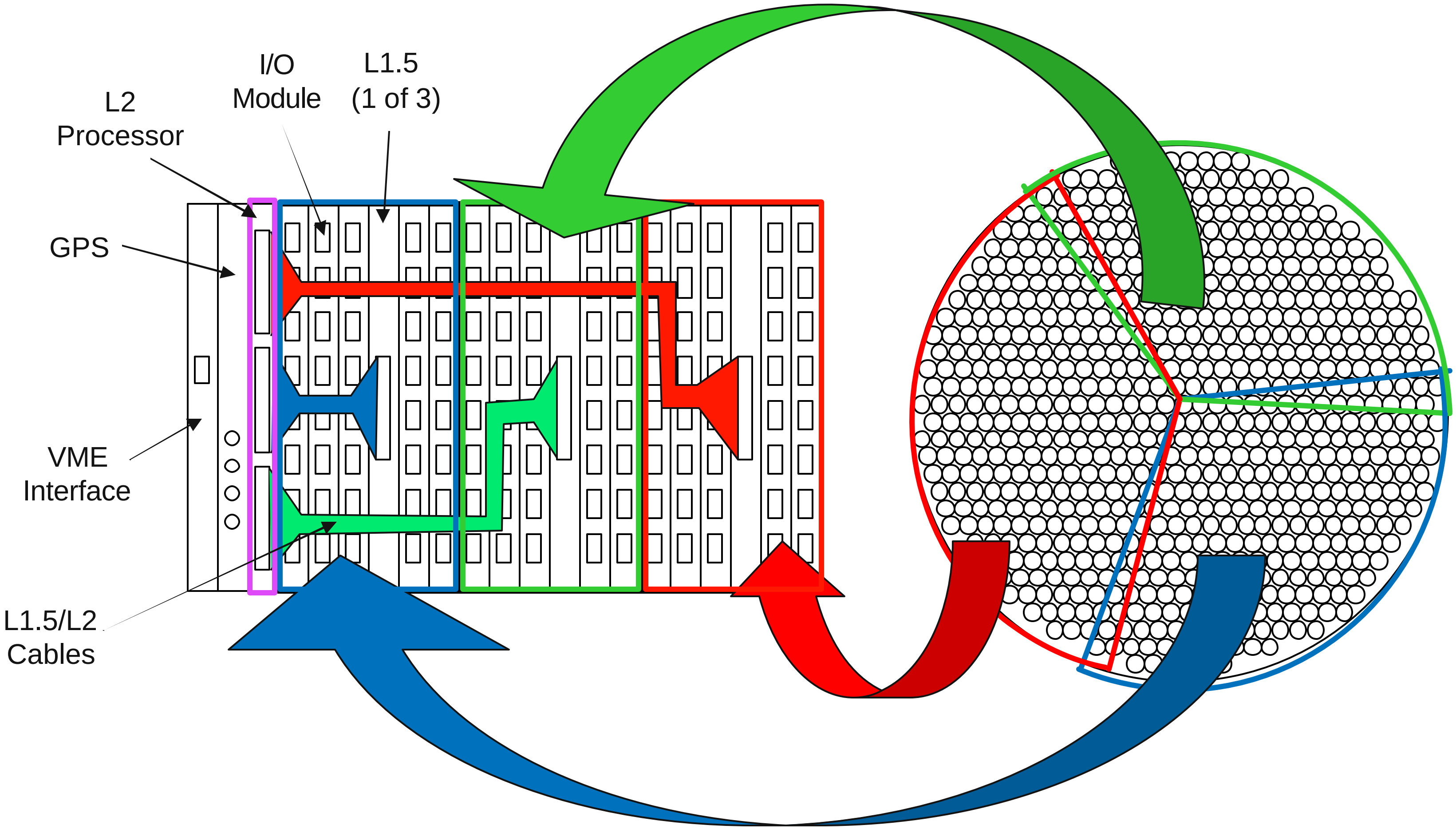
3-Fold Coincidence
For Overlap



499 Channel Camera

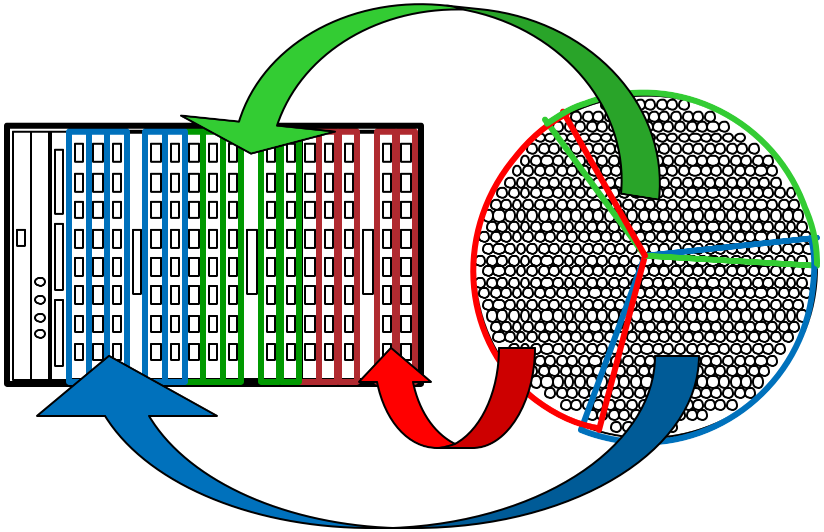
Physical Connection Strategy 2

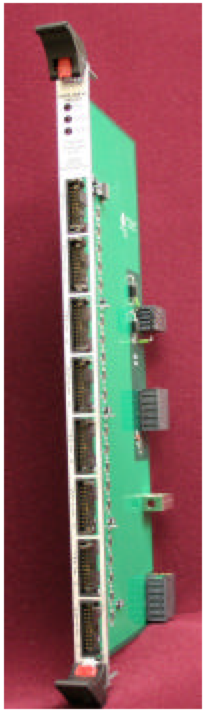
- **Camera trigger processing is done in custom 9U Crate**
  - Each region processed separately → Neighbor Logic + Timestamps
  - Hit list from all regions fed to single L2 Processor → Moment calculations

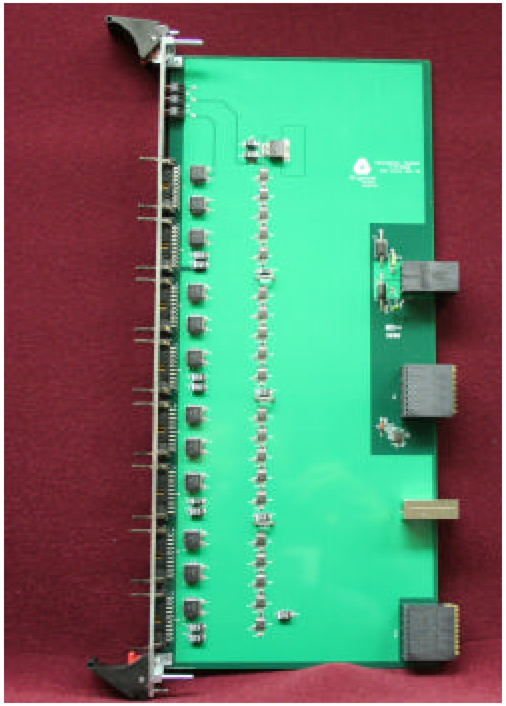


Description of Components

- **I/O Module**
  - Receives differential ECL signals from FEE – 10 pair Twist-N-Flat (VERITAS)
  - Translates to LVDS
  - ⇨ ***100 ohm, impedance controlled***
  - Copied to 2 connectors for routing onto custom backplane: primary & overlaps
    - *All signals copied,*
      but only subset are used
      → *<u>Specific routing on backplane</u>*
  - "Output" of "I/O" for use in VERITAS so that new system can coexist with current system → I/O Module "spies" on L1 signals







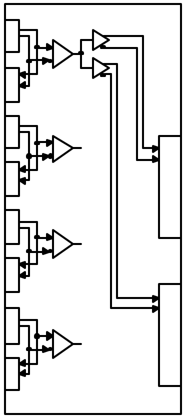
From L1 Trigger →

To existing L2 Trigger ←

For VERITAS

ECL-to-TTL Translators
Motorola MC10H125FN

TTL-to-LVDS Translators
Maxim MAX9123ESE

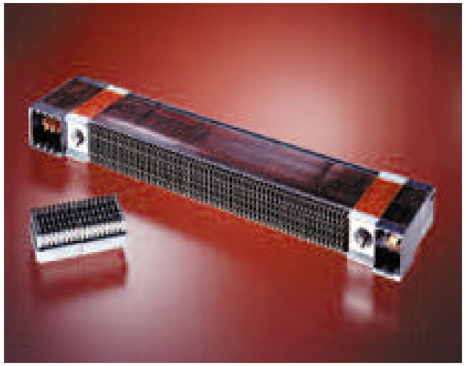


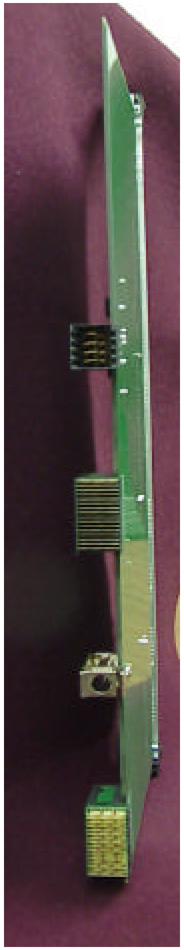
Description of Components

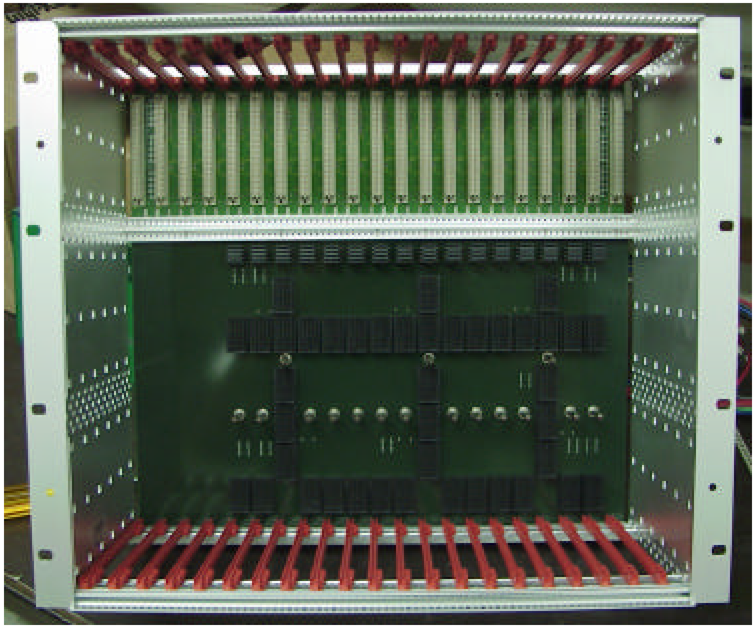
- **Backplane**
  - 9U in size
    - *J1 is standard VME for slow control & diagnostics*
    - *J2 is used for point-to-point routing of L1 signals from I/O Modules to a particular L1.5 Processor*
    - *J3 is used for point-to-point routing of L1 signals in overlap regions*

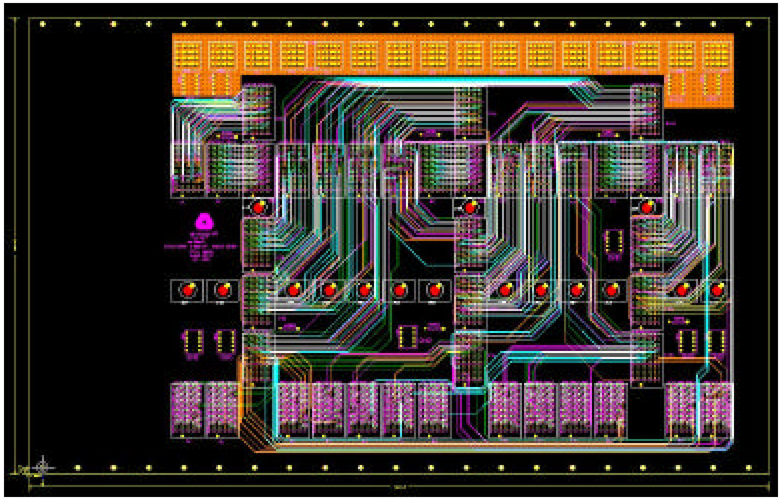
  ⇨ ***100 ohm, Impedance-controlled***
  - Uses Multi-GIG Connectors from Tyco
    - *Capable of ~3-10 Gbps*

    ⇨ ***ATCA***









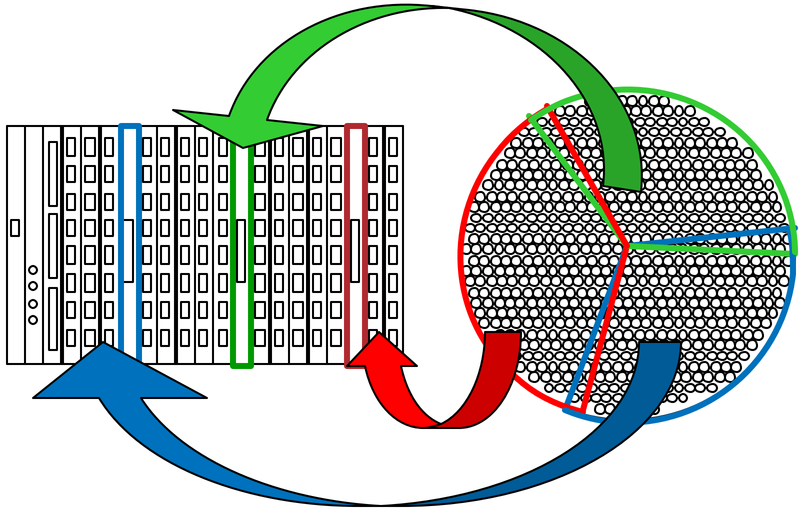
10-Layer Circuit Board Layout of Backplane

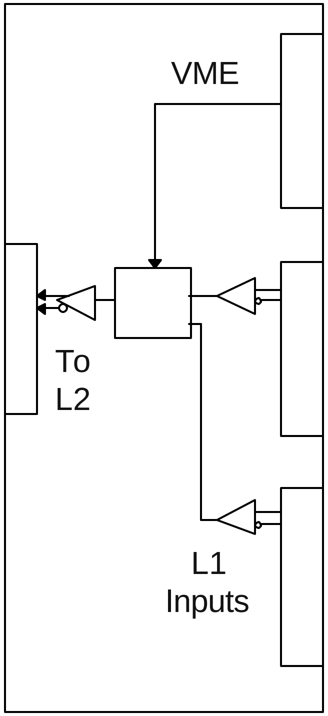
Description of Components

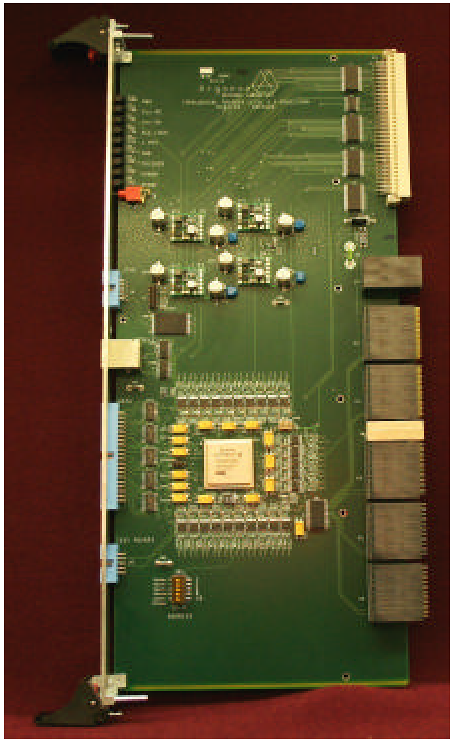
- **L1.5 Processor**
  - One L1.5 Processor per region
  - Receive signals from I/O Cards
  - Skew adjust for input signals
  - Form (programmable) time window
  - Perform neighbor logic

    ⇨ ***Runs at 400 MHz***
  - Throw away duplicate addresses
  - Timestamp hits passing 3-fold coincidence

  ⇨ ***Output :***
  Timestamp + pixel addresses
  - Send data to L2 Processor
    - *LVDS, 16-bit data, Twist-N-Flat, via front panel connection*
  - Has VME interface & diagnostics
    - *Input signal skew adjust*
    - *Disable any input*
    - *Test pattern state machine*
  - All cards are identical, 3 per crate

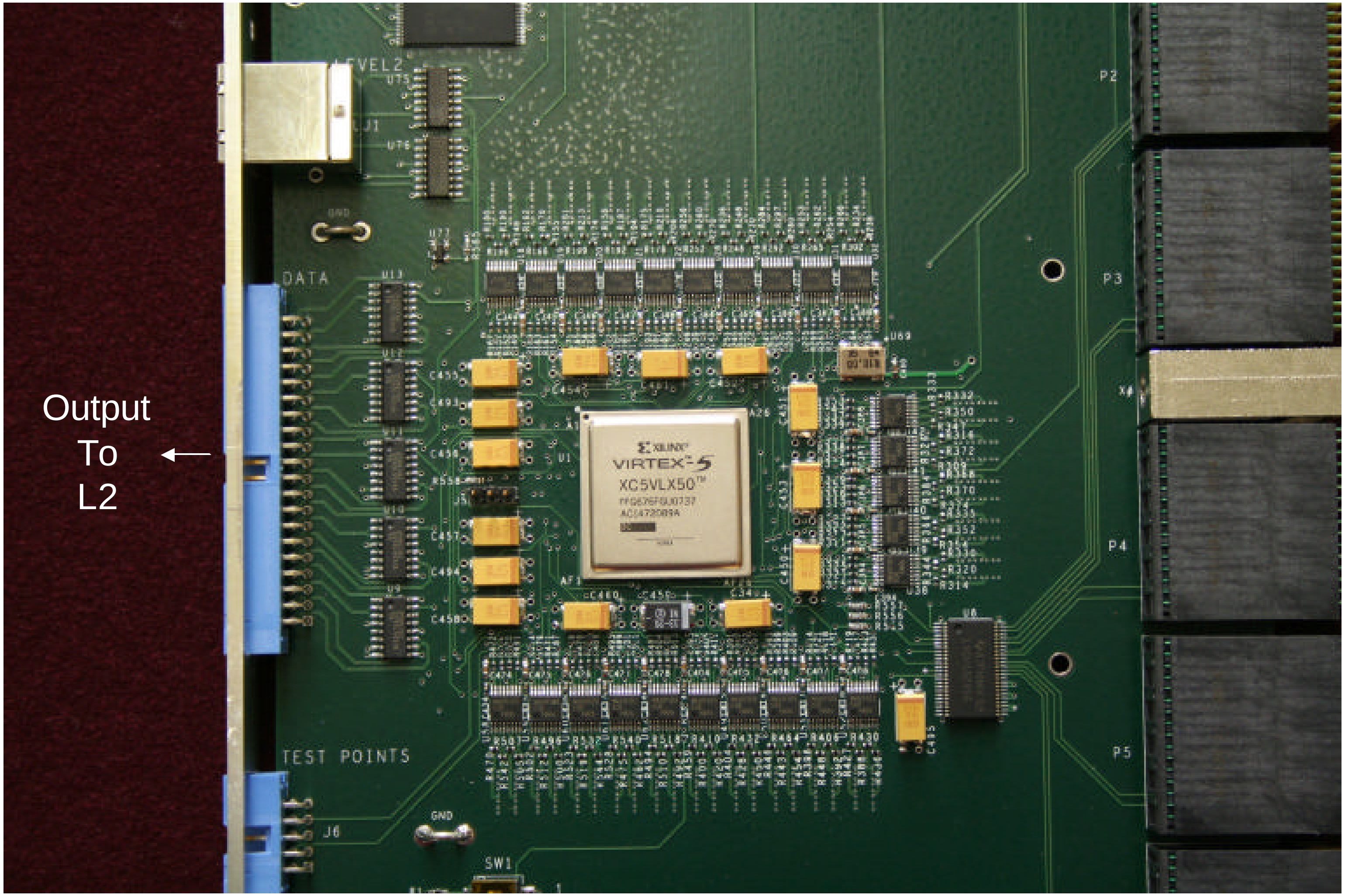






Description of Components

- **L1.5 (Cont.)**

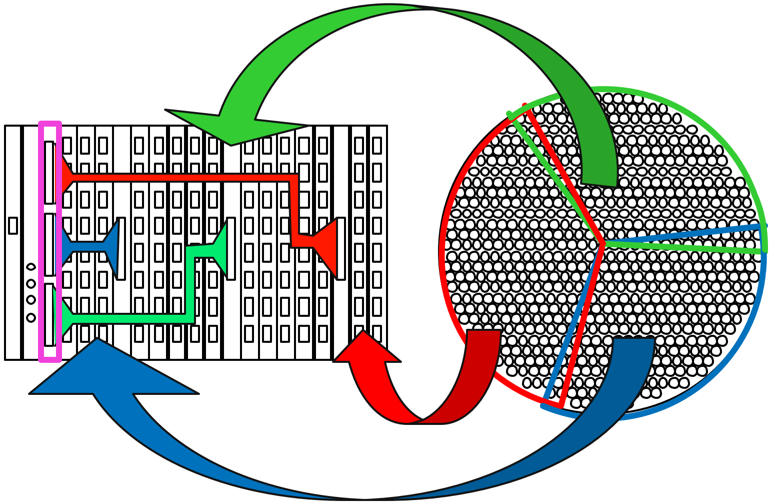


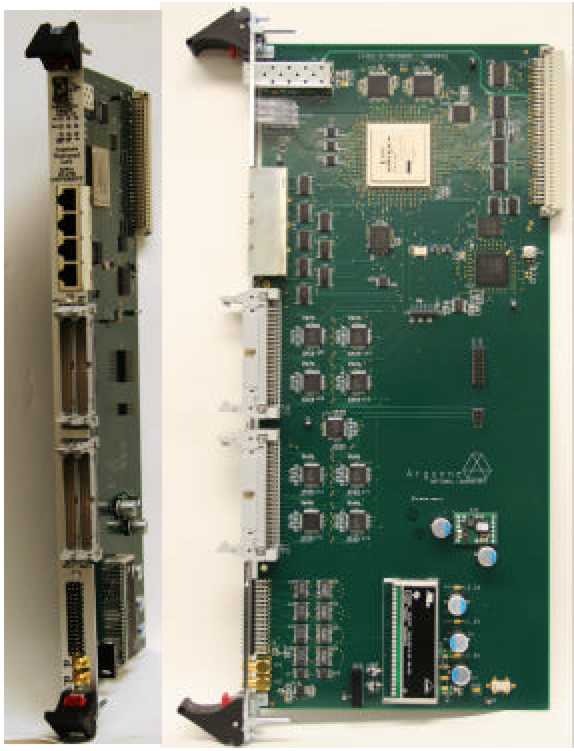
L1 Signals
← From
Backplane

⇨ *One of the fastest FPGAs <u>currently</u> in existence …*

Description of Components

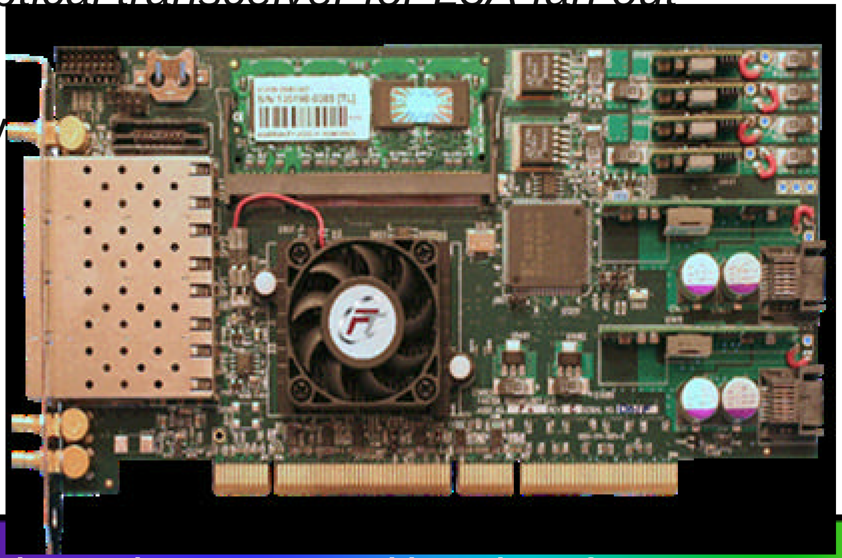
- **Level 2 Processor**
  - One L2 Processor per crate
  - Receives data from L1.5 Processors
  - Performs calculations on all pixels received from L1.5 Processors
  - Calculate:
    n, Sx, Sy, Sx^2, Sy^2, Sxy
  - Send data & timestamp to L3 Processor
    - *Currently RJ45 twisted pair*
    - *Next: optical fiber link*
    - *Ultimately: wireless*
  - Other features:
    - *Clock tree* ⇨ ***System Timing is important…***
      - provides timing fan out for L1.5
      - Can use on-board crystal oscillator, external GPS, or L3 source
    - *R/W comm. w/L3*
    - *Error reporting / recovery*
    - *VME access*
    - *Diagnostics*





Description of Components

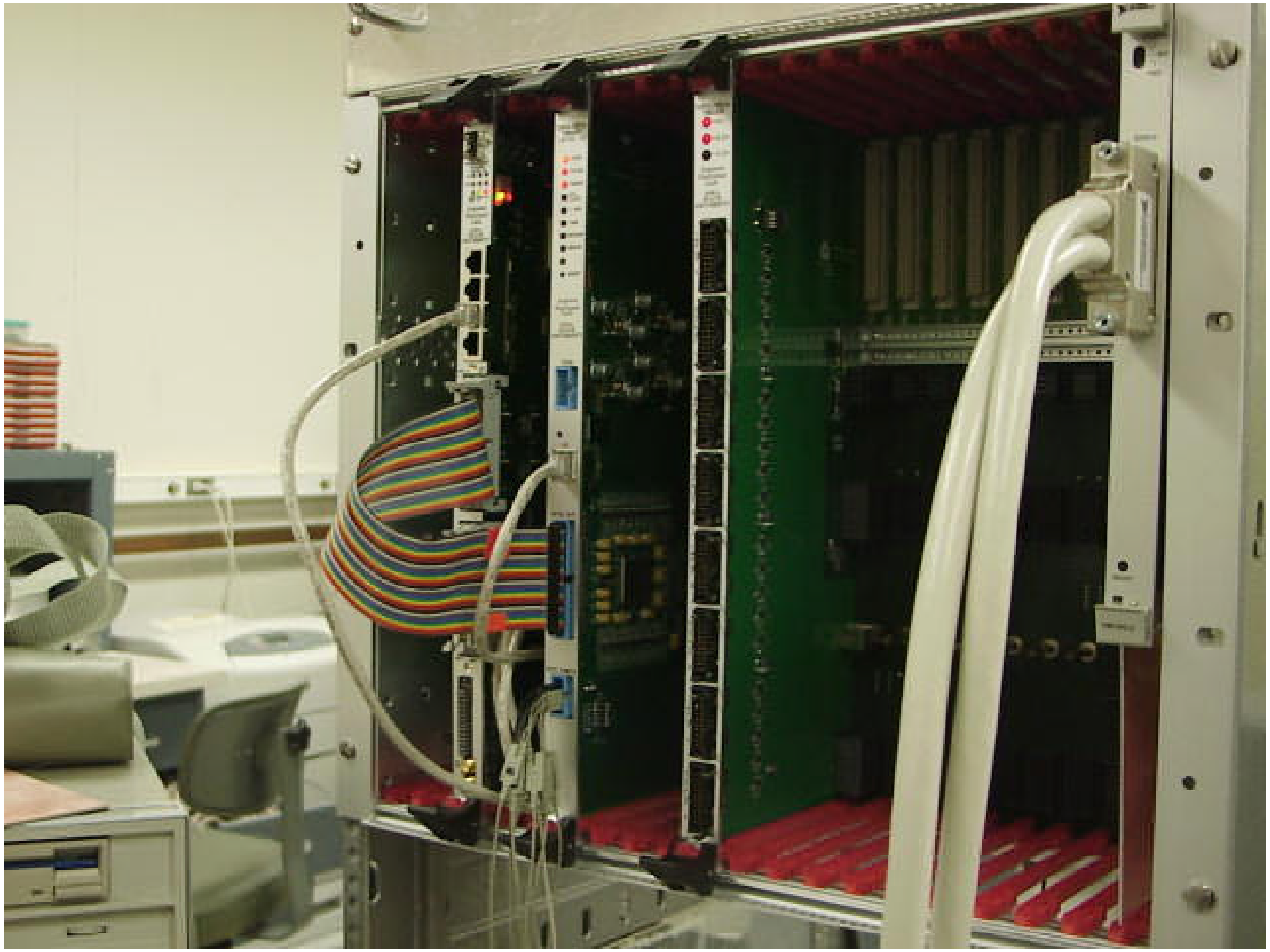
- **Level 3 Processor**
  - Receives 1st & 2nd moments from each L2 Crate, along with timestamps
  - Calculate Parallaxwidth, produces L3 Accept when criteria met
  - Uses timestamps to calculate hold-off time
  - Send L3 Accept to front ends at correct time
- **Current plan for VERITAS implementation**
  - Using PCI Card from Faster Technology
    - *Processes 4 data streams*
    - *Virtex 4 FPGA, programmable, with I/O cores*
    - *Use SFP optical transceiver for L3A fan out*
- **For the future**
  - Scalable array
  - Wireless
  - Hub…



Faster Technology
P6 PCI FPGA Card

Test Stands

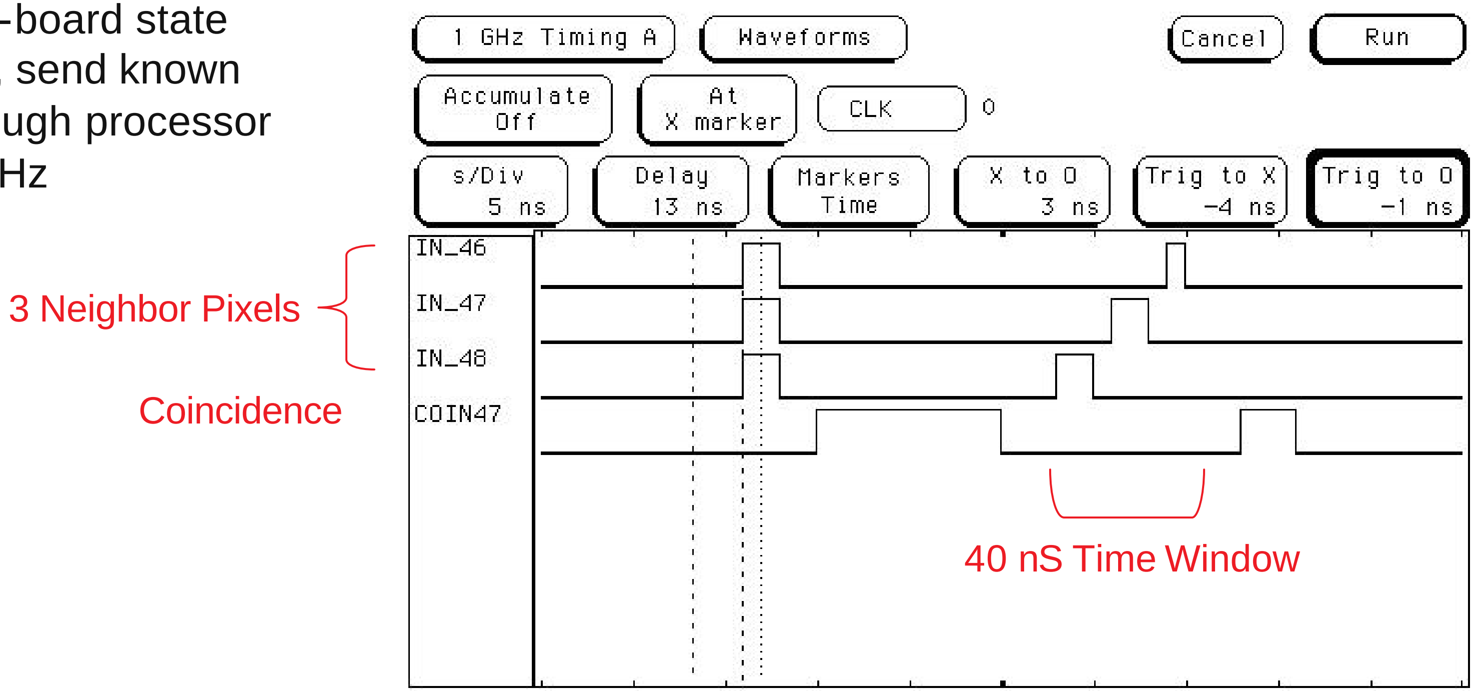
- Currently at Argonne, Similar at Iowa State



First Results

- Test of Backplane
  - Signal transmission integrity is excellent!!! (Sorry, no picture…)
- Test of L1.5
  - Using on-board state machine, send known data through processor at 400 MHz

Capture from Logic Analyzer



⇨ ***L1.5 Neighbor Logic works at speed!!!***

Summary

- We have designed a fast pattern recognition trigger for use in ground-based gamma-ray telescope arrays
  - Well advanced in system design
    - *Prototypes in hand*
    - *Testing under way*
- Next Steps
  - Complete debugging of prototypes
  - Assemble boards to service (1) 500-channel telescope
  - Test at VERITAS
- Future
  - Work on L3 architecture → scalable, wireless communication
  - Possible proposal for upgrade to VERITAS
  - Develop technology for future telescope array → AGIS