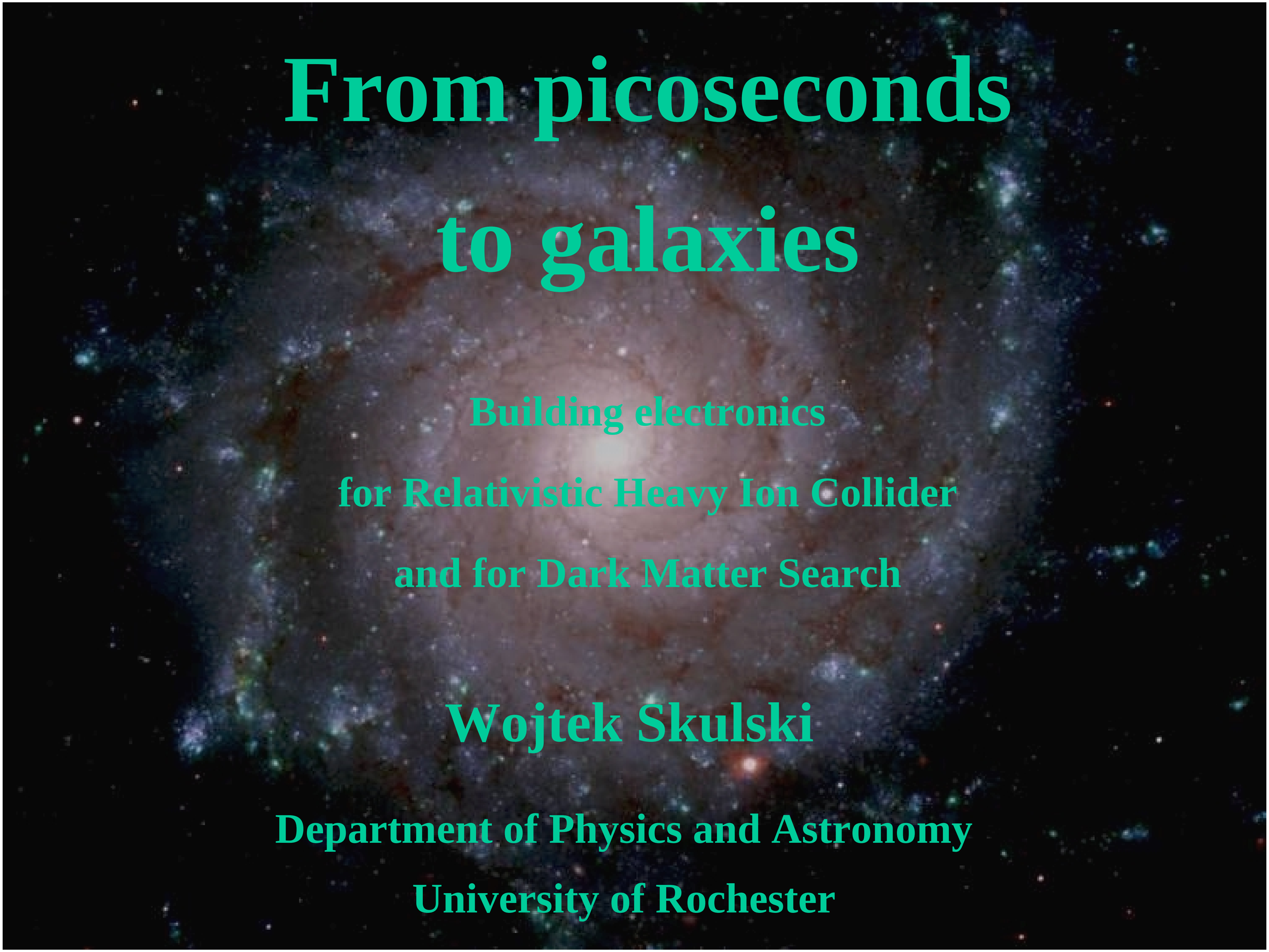

From picoseconds
to galaxies
Building electronics
for Relativistic Heavy Ion Collider
and for Dark Matter Search
Wojtek Skulski
Department of Physics and Astronomy
University of Rochester

# Outline

- Introduction.
- Electronics for PHOBOS at RHIC.
  - Time Equalizer electronics.
  - Universal Trigger Module for on-line trigger.
- Research and student projects at UofR.
- Electronics for Dark Matter Search.
- Tiled Diffraction Gratings at LLE.
- Summary and acknowledgements.

# Electronics and software help achieve scientific goals

- My electronics and software developments are driven by science.

  Tools to help achieve scientific goals rather than goals in themselves.
- The tools are meant to be used in mission-critical applications.
- Therefore, no compromises are allowed concerning their quality.
- Electronics development required all of the following:
  - Schematic design, board layout and board assembly.
  - Hardware testing and debugging.
  - Software for embedded microcontroller.
  - Firmware for on-board FPGA.
  - GUI design and programming.
- The “one-man show” brings coherence to my designs.

# Electronics for PHOBOS

# PHOBOS experiment at RHIC

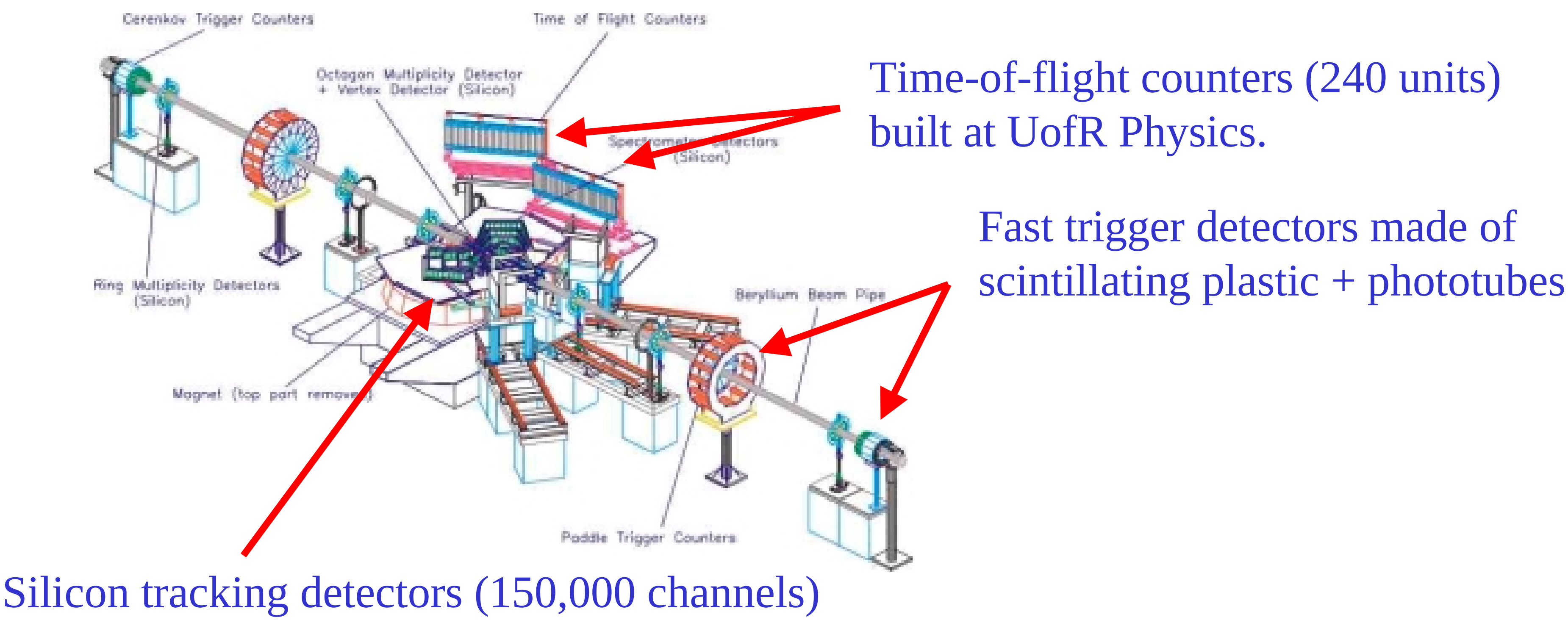
Relativistic Heavy Ion Collider, Brookhaven National Laboratory

Scientific goals:

Investigate hot, dense nuclear matter, that could have existed about 1μsec after the Big Bang .

Discover and characterize quark-gluon plasma.

**PHOBOS @ RHIC**



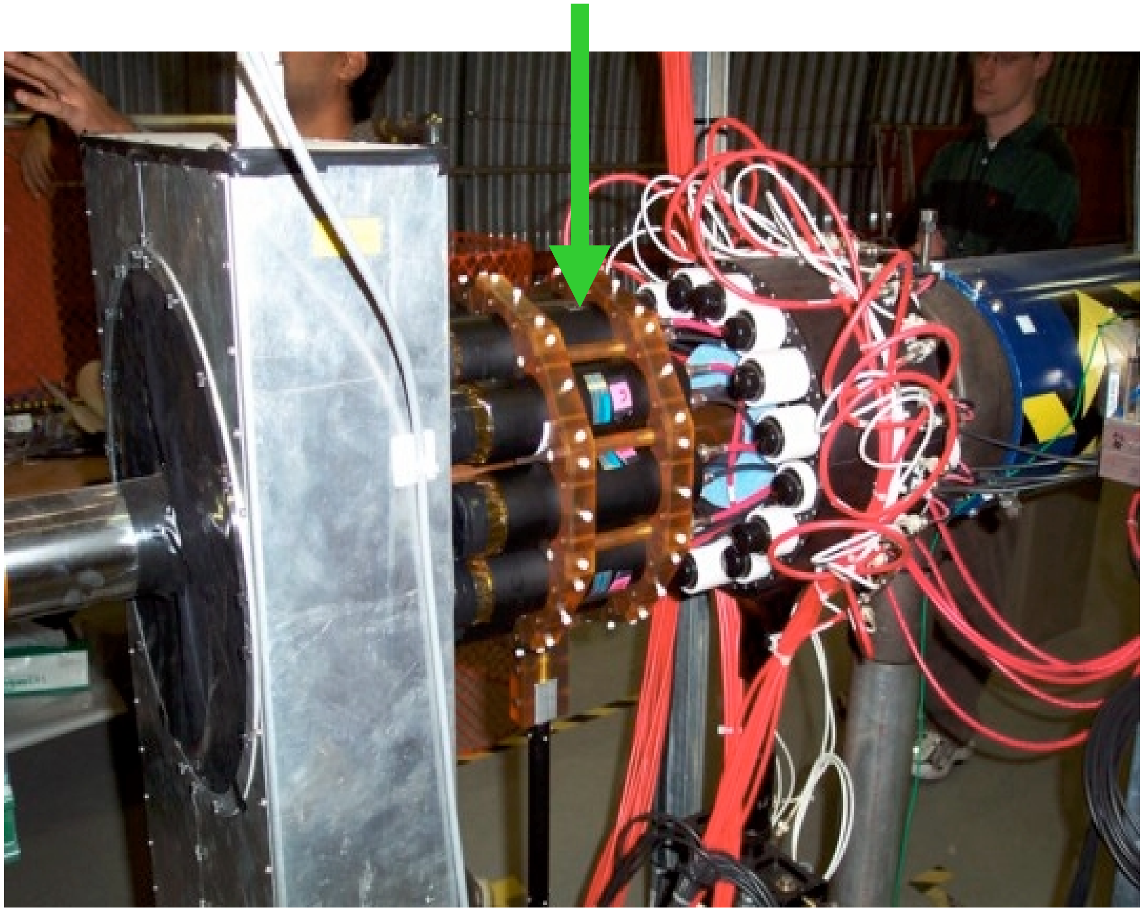
# Time Equalizer

# for PHOBOS

W.Skulski Laboratory for Laser Energetics, Rochester, 22 September 2004

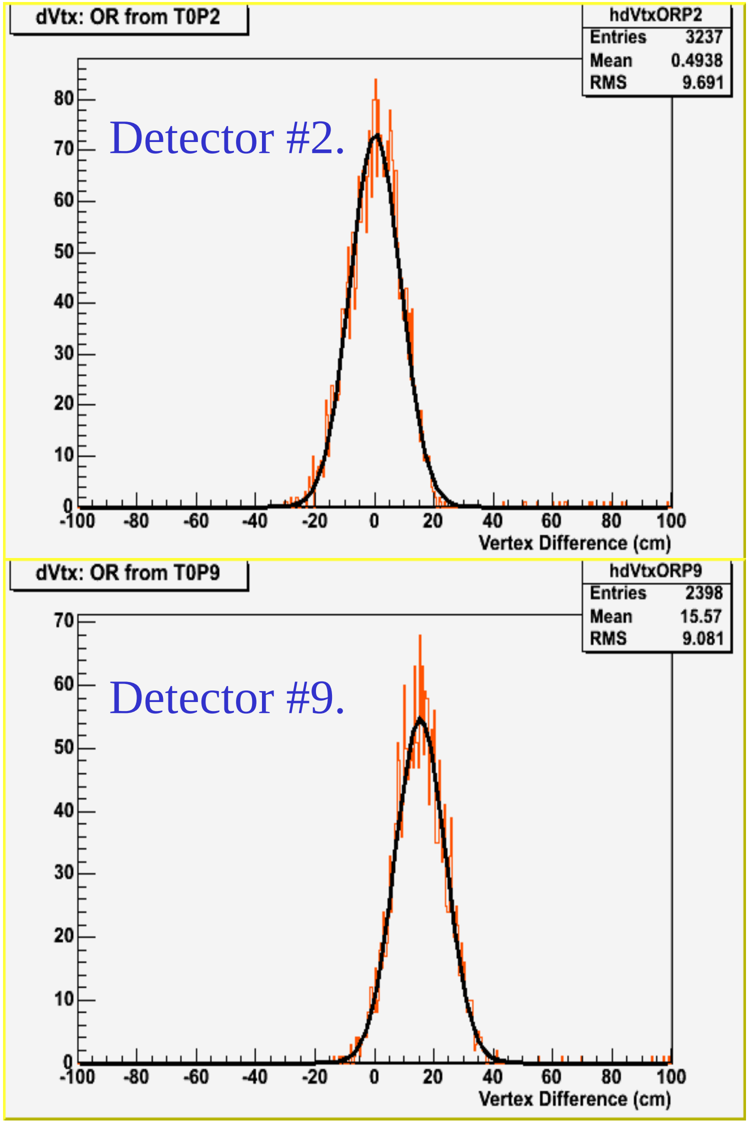
# Cerenkov T-zero detector arrays

- Developed by the UofR Time-of-Flight group: Frank Wolfs (PI), Wojtek Skulski, Erik Johnson, Nazim Khan, Ray Teng.
- Two circular arrays of 16 Cerenkov counters, ~60ps resolution each counter.



# Situation before Time Equalizer

- Individual Cerenkov T-zero detectors have a very good resolution of ~60ps.
- However, the time-of-arrival of signals from individual detectors was not aligned in the Counting House after propagation over long cables.
- The attainable spatial resolution would be adversely affected.
- What is plotted: time-of-arrival of a signal, translated to spatial domain (after taking the detector geometry into account).




Interaction vertex definition (cm)

# The purpose of the Time Equalizer

- I proposed, designed, and built the Time Equalizer in order to:
- Align timing signals from individual T-zero detectors.
- Preserve good timing resolution of individual detectors.
- Enable remote operation without entering the experimental area.
- Details:
  - **Number of channels** **16**
  - **Signal in and out** **ECL**
  - **Delay step** **10 ps**
  - **Number of steps** **256**
  - **Shortest delay range** **2.5 ns (in 256 steps)**
  - **Delay range can be adjusted by swapping resistors**
  - **Formfactor** **CAMAC**

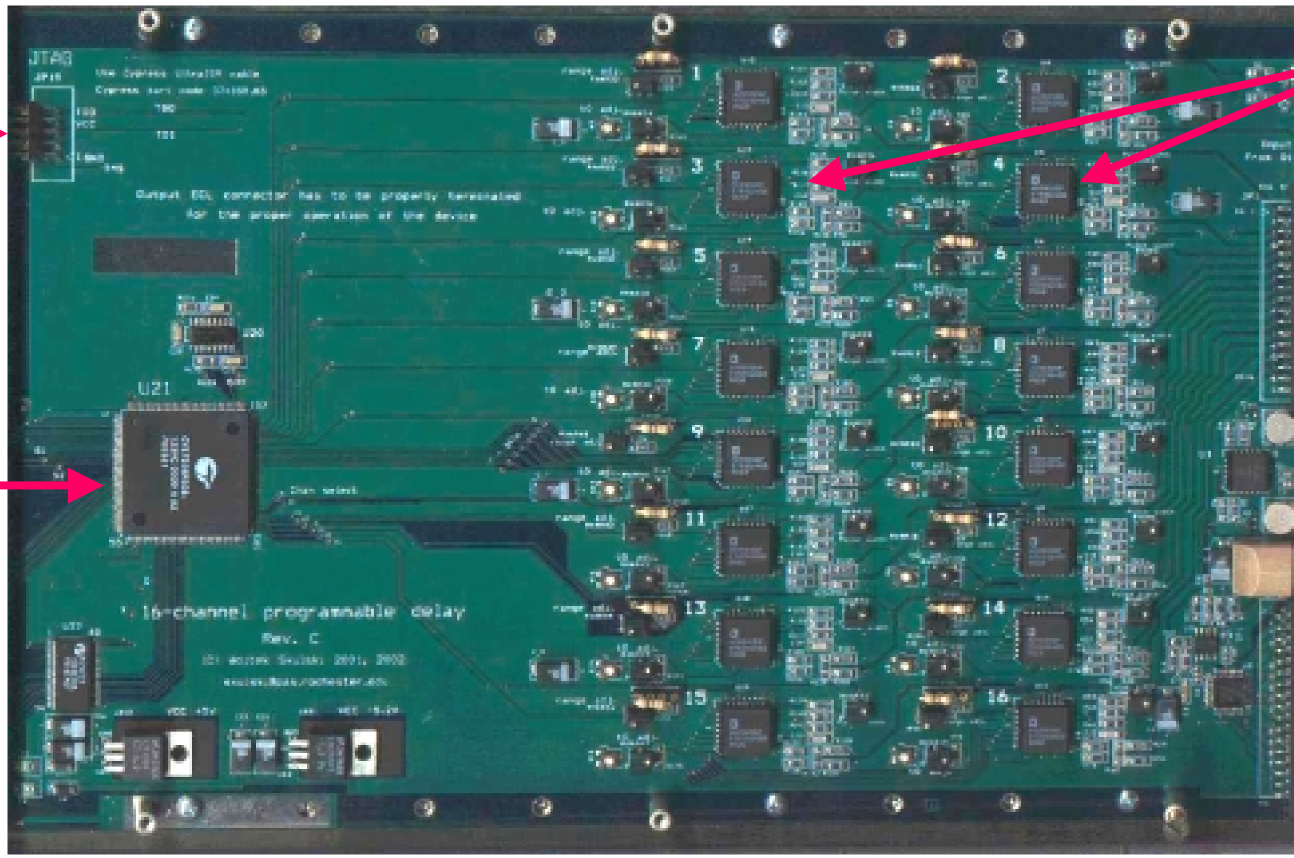
# Final version of the Time Equalizer

## Four such boards are installed at PHOBOS

JTAG

CAMAC interface chip

CAMAC connector



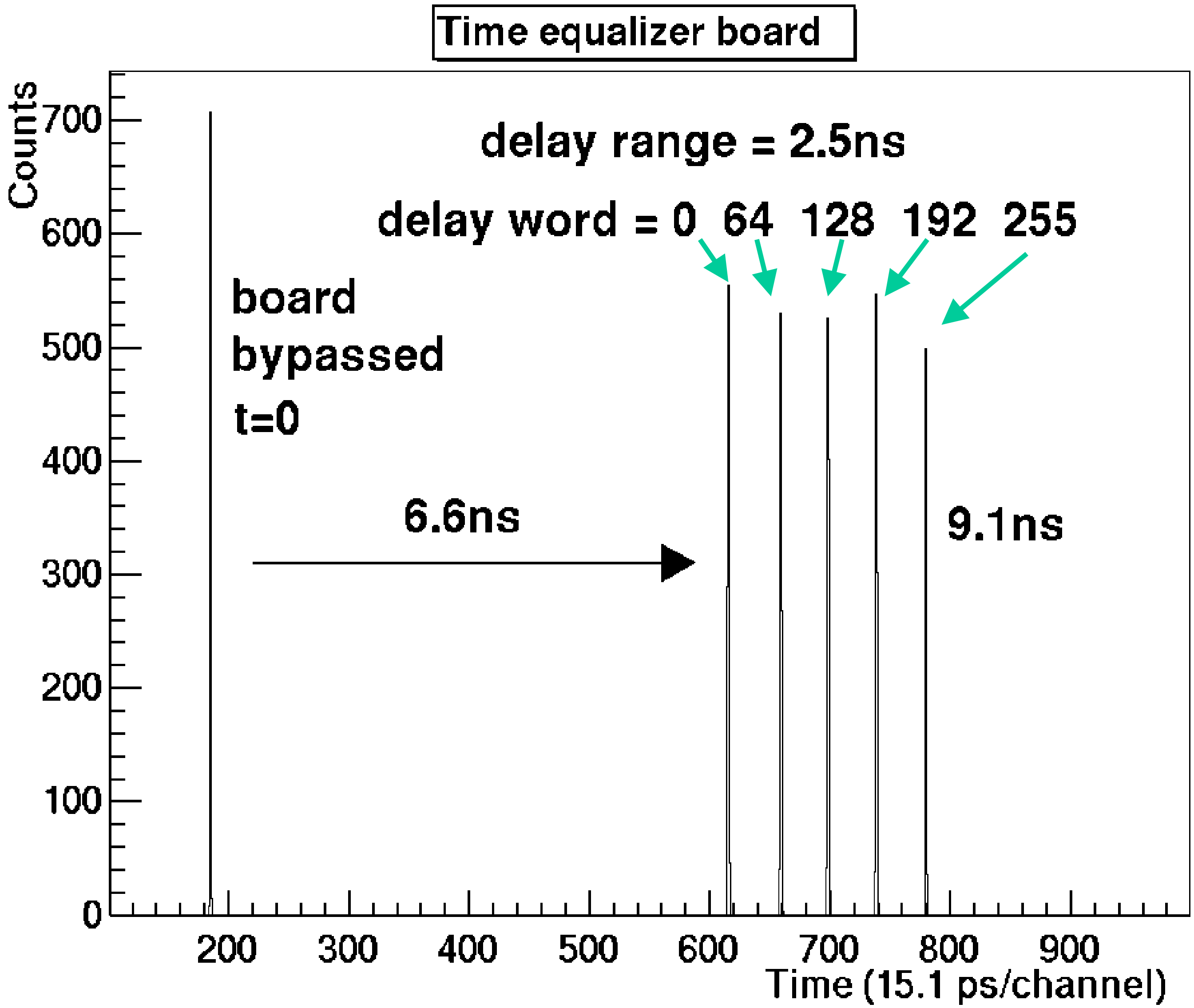

Delay chips

ECL IN

NIM OUT

ECL OUT

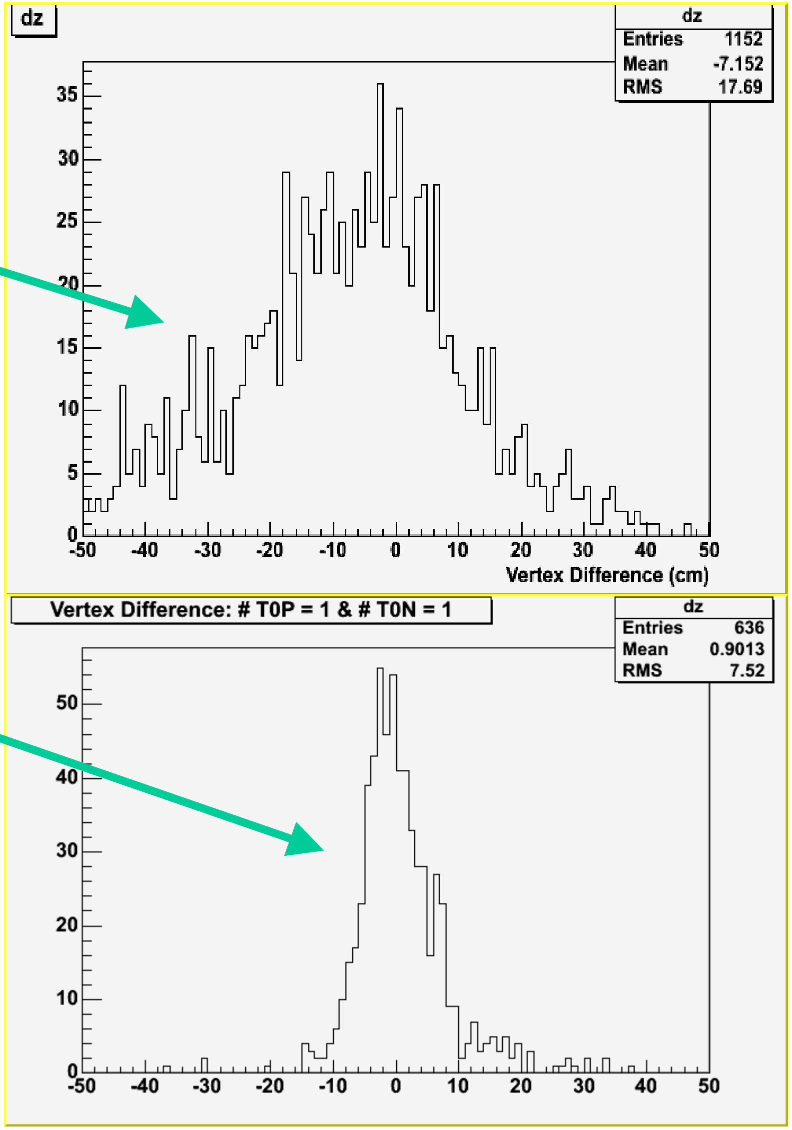
# Response of an individual channel to a pulser



# Result: improvement of vertex definition

- Detector delay not adjusted.

- Detector delay individually adjusted using Time Equalizer.




Interaction vertex definition (cm)

# Universal Trigger Module

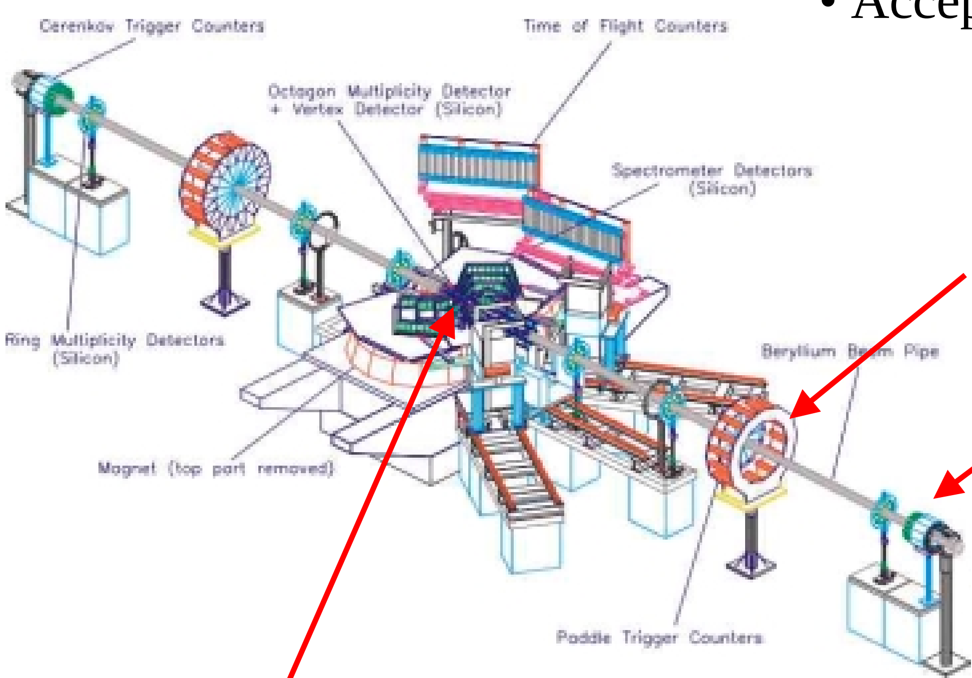
# for PHOBOS

# Universal Trigger Module for PHOBOS

## Goal: vertex and centrality definition in real time

- Analog signals: Paddles, T0, ZDC.
- Logic signals from conventional NIM.
- Signal processing: on-board FPGA.
- Accept/reject event within about 1 μsec.

**PHOBOS @ RHIC**



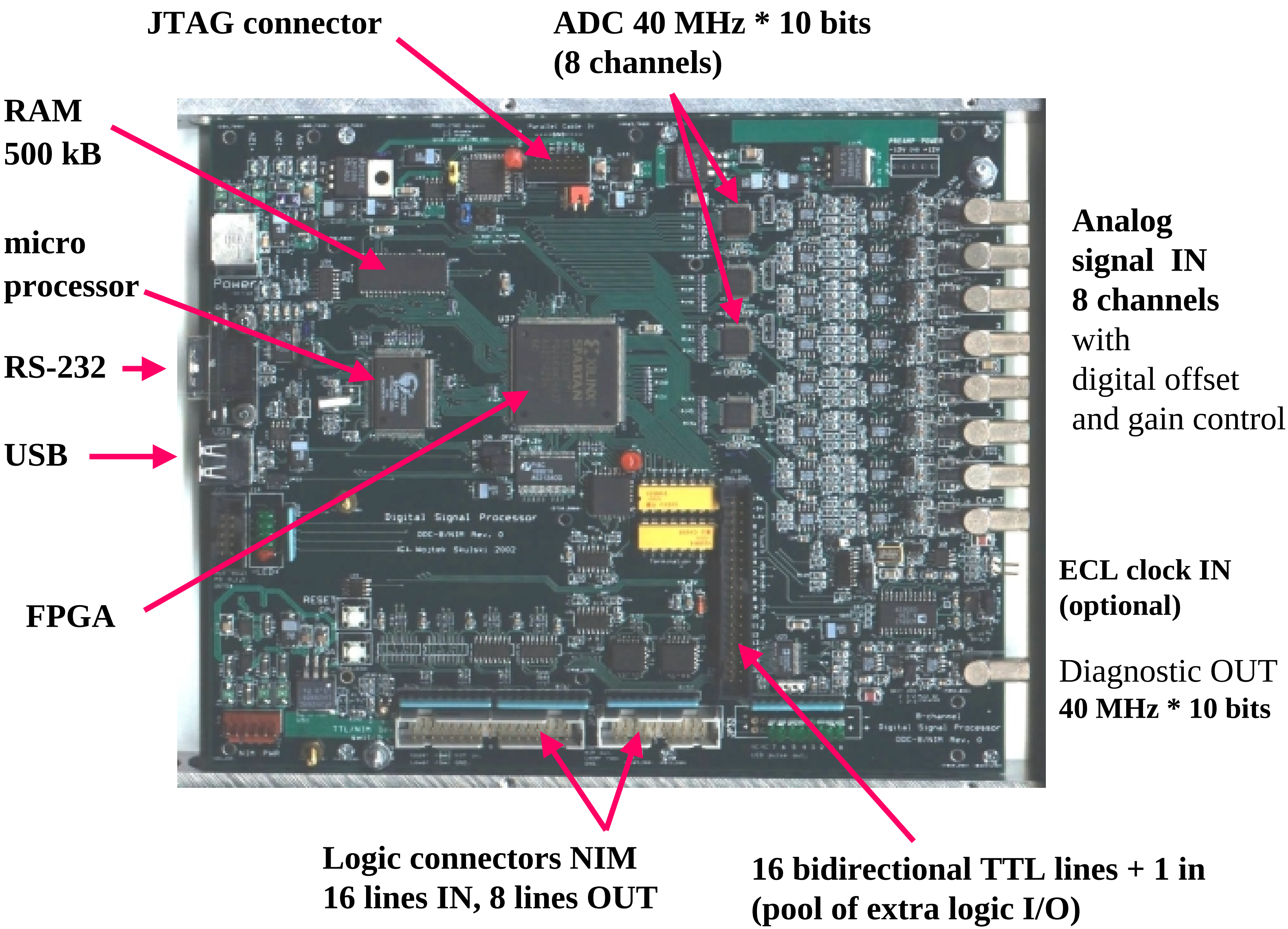

Centrality from paddle and ZDC.

Vertex definition from TACs.
T0 OR Δt,
Paddle Δt,
ZDC Δt.

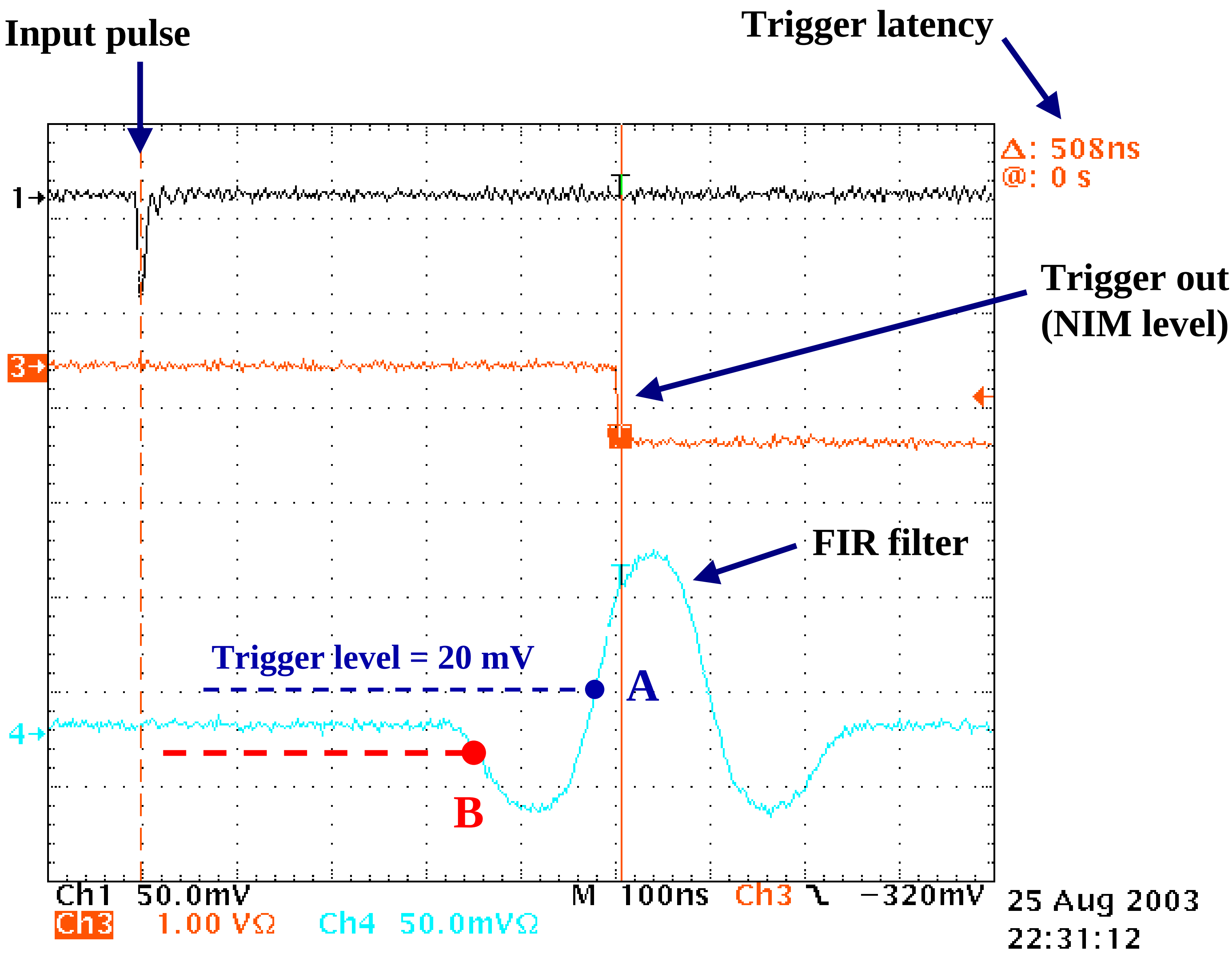
Interaction vertex is located inside silicon detector

# The purpose of the Universal Trigger Module

- I proposed, designed, and built the UTM in order to:
- Provide PHOBOS with a programmable trigger logic module.
- Base the level-1 trigger decision on both analog and logic signals.
- Meet stringent timing constraints for level-1 trigger.
- Reduce the complexity of present "random trigger logic".
- Details:
  - **Number of analog inputs** **8**
  - **Number of logic I/O** **41**
  - **Architecture** **continuous waveform digitizing**
  - **Time step** **25 ns**
  - **Digitizer precision** **1024 ADC counts (i.e., 10 bits)**
  - **Digital "processing power"** **300,000 logic gates**




W.Skulski Laboratory for Laser Energetics, Rochester, 22 September 2004


Input pulse
Trigger latency
Δ: 508ns
@: 0 s
Trigger out
(NIM level)
FIR filter
Trigger level = 20 mV
A
B
Ch1 50.0mV
M 100ns Ch3 ↘ −320mV
Ch3 1.00 VΩ Ch4 50.0mVΩ
25 Aug 2003
22:31:12

# Status of the Universal Trigger Module for PHOBOS

- Technical requirements were met.
- Hardware, firmware, and software working and tested.
- One board loaned to University of Illinois at Chicago (UIC).
- Firmware will be customized at UIC for PHOBOS trigger.
- Master Thesis for Ian Harnarine, UIC.

# R&D and student projects at Physics and Astronomy

# Single-channel, 12-bit DDC-1

Designed and built by WS.

Used in several student projects during last 2 years.

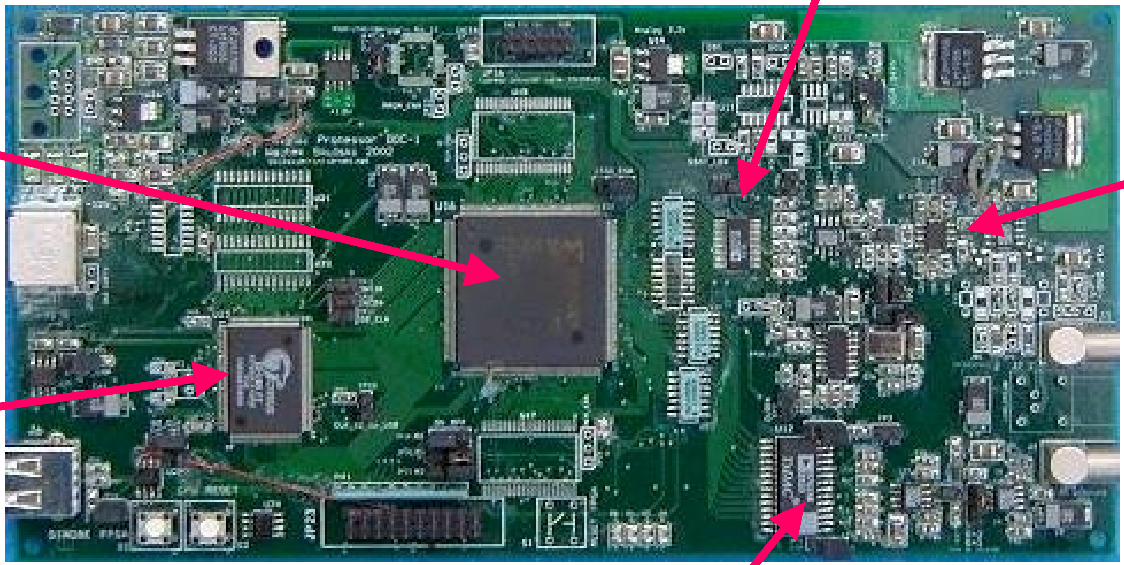
A predecessor of the Universal Trigger Module.

JTAG connector

ADC 65 MHz * 12 bits

FPGA

Variable gain amp



USB processor

connector

Signal IN

Signal OUT

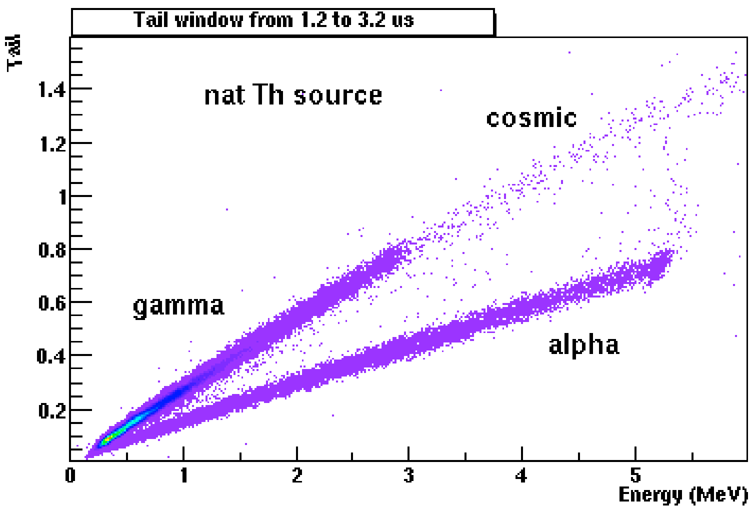
Fast reconstruction DAC 65 MHz * 12 bits

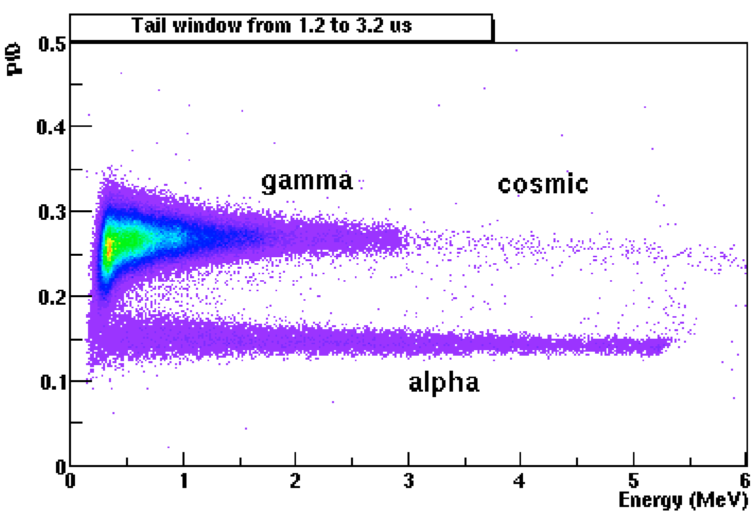
# Education and R&D projects at Physics and Astronomy

- S.Zuberi, *Digital Signal Processing of Scintillator Pulses in Nuclear Physics Techniques*, Senior Thesis, Department of Physics and Astronomy, University of Rochester. Presented at Spring APS meeting, April 2003, Philadelphia, PA.
  - Awarded the Stoddard prize for the best Senior Thesis in the Department.
- D.Miner, W.Skulski, F.Wolfs, *Detection and Analysis of Stopping Muons Using a Compact Digital Pulse Processor*, Summer Research Experience for Undergraduates, Department of Physics and Astronomy, University of Rochester 2003 (unpublished).
- P.Bharadwaj, *Digital and analog signal processing techniques for low-background measurements*, summer project 2004.
- F.Wolfs, W.Skulski, (UofR), Ian Harnarine, E.Garcia, D.Hofman (UIC), *Developing an efficient triggering system for PHOBOS at RHIC*, ongoing.

# Particle ID from CsI(Tl)

Senior Thesis by Saba Zuberi




Best Senior Thesis 2003

Dept. of Physics and Astronomy

University of Rochester

← Traditional slow-tail representation

1 $cm^3$ CsI(Tl) + phototube

Single-channel digitizer DDC-1

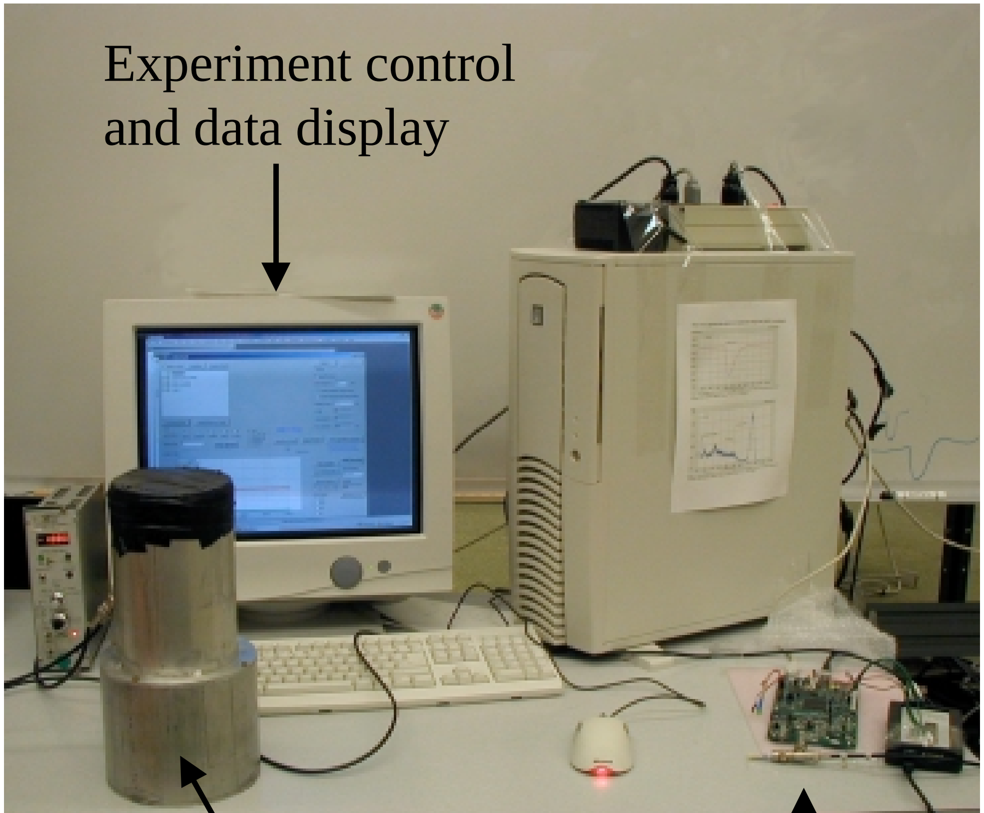
at 48 Msamples/s * 12 bits

${}^{nat}$Th radioactive source

← PID = TAIL / TOTAL

Note energy-independent PID

# Detection and analysis of stopping μ-mesons#




#Daniel Miner
University of Rochester
Summer 2003 REU

- Example of pulse processing & analysis
- Table-top experiment
- Several observables from one signal

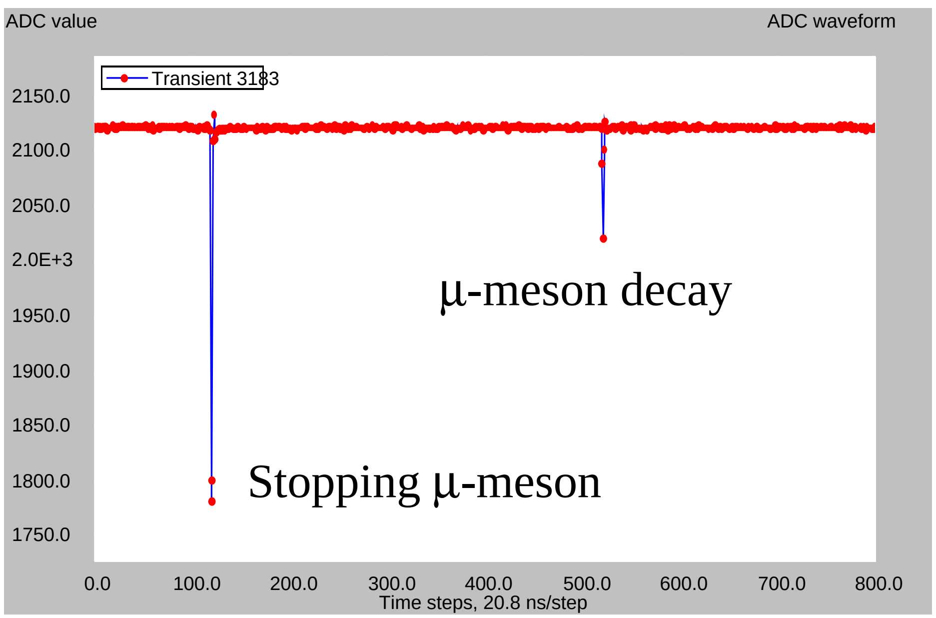
# Detection and analysis of stopping μ-mesons

## Daniel Miner, 2003 Summer Research Experience for Undergraduates

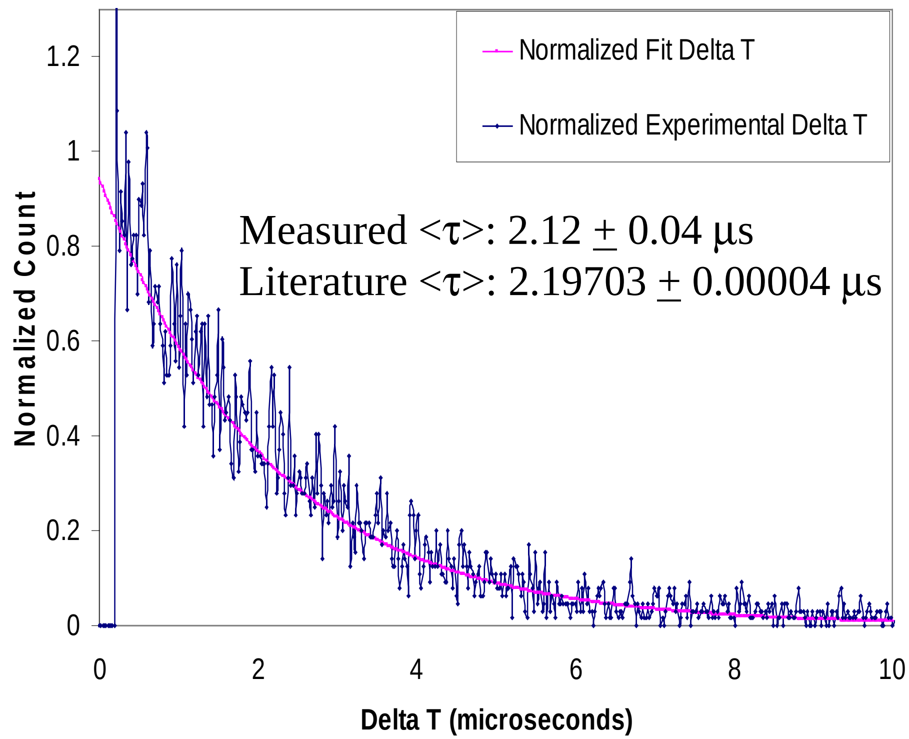
Waveform from a BC-400 5”x6” scintillator shows m-meson capture and subsequent decay.

After 4% capture correction the measured and accepted lifetimes agree to within 0.35%.

### Waveform from plastic scintillator




### Time between leading and trailing pulses

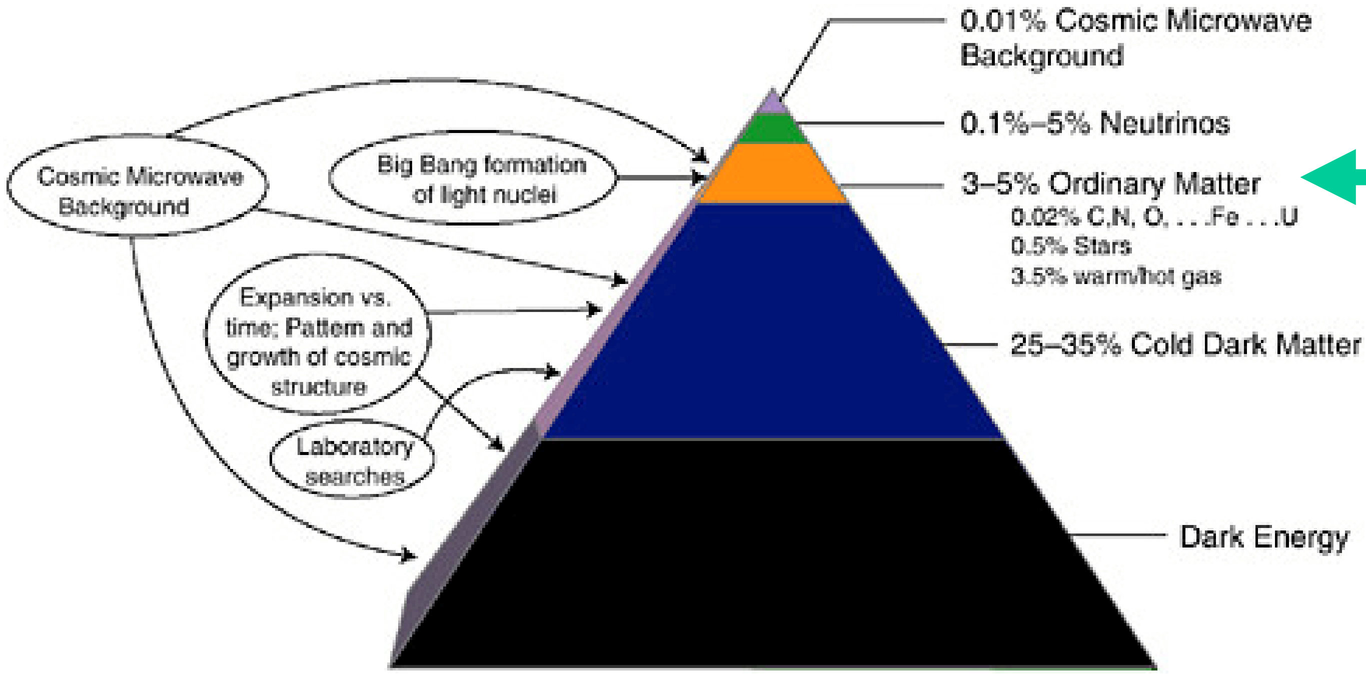


# Electronics for

# Dark Matter Search

# The biggest mystery: where is almost Everything?

- Most of the Universe is missing from the books…
- … should we blame Enron?



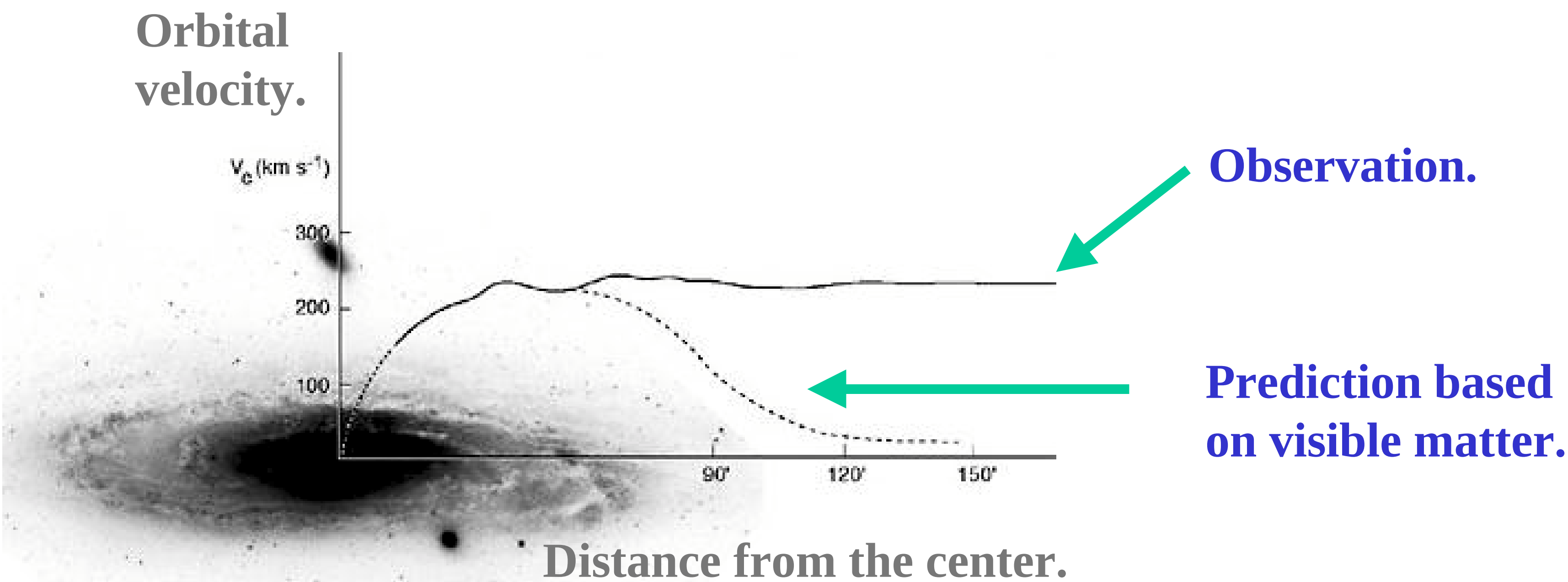

**We are here**

Source: *Connecting Quarks with the Cosmos*, The National Academies Press, p.86.

# The 1st smoking gun: galactic rotation is too fast.

- Gravitational pull reveals more matter than we can see.

Rotation curve of the Andromeda galaxy.




Source: *Connecting Quarks with the Cosmos*, The National Academies Press, p.87.

# The 2nd smoking gun: large-scale gravitational lensing.

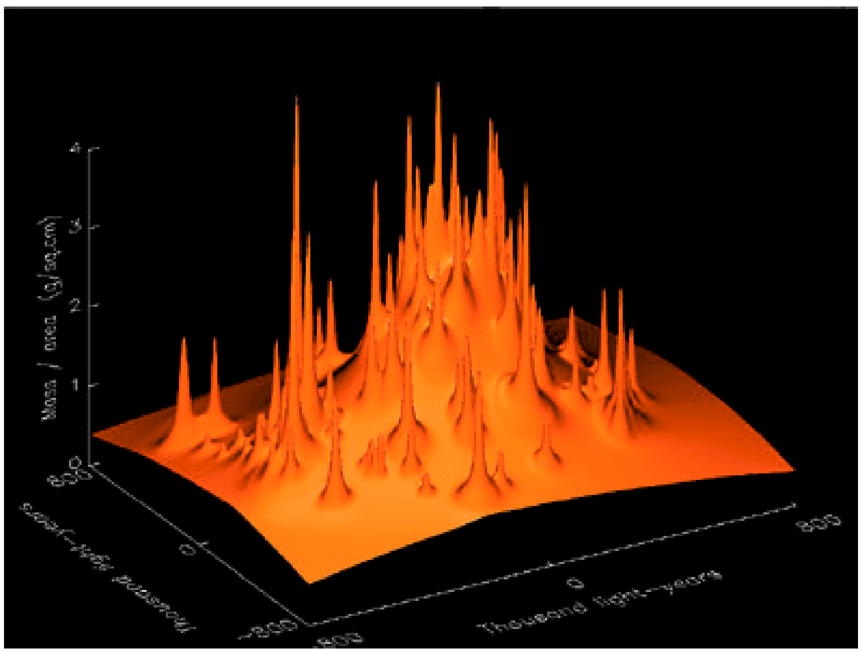
- Light from distant sources is deflected by clusters of galaxies.
- Visible mass cannot account for the observed lensing pattern.
- Reconstructed mass distribution shows mass <u>between</u> galaxies.

**Observed lensing.**

(a)

**Reconstructed mass distribution.**

(b)

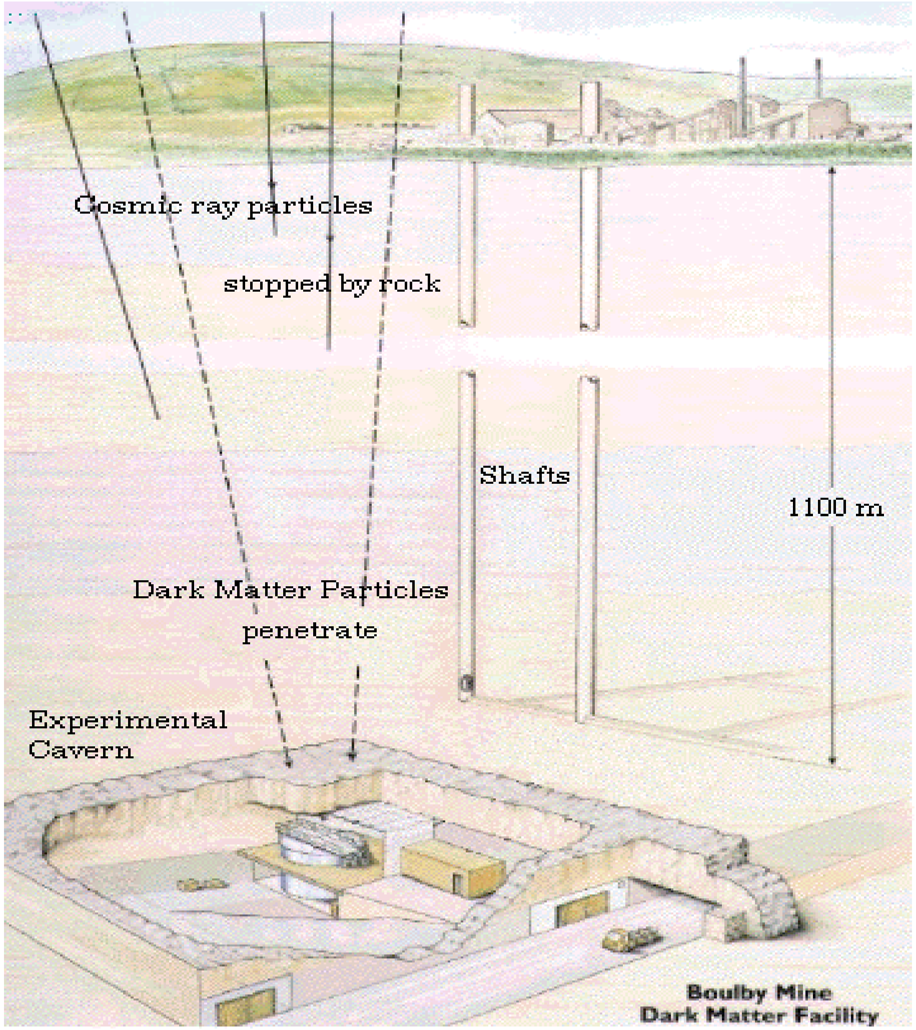



Source: *Connecting Quarks with the Cosmos*, The National Academies Press, p.89.

# Who are the suspects? How to find them?

- Nobody knows, but there are candidates predicted by the theory …
- Axions: light particles that may explain CP violation.
- Neutralinos: heavy particles predicted by SUSY.
- We focus on the latter.
- The neutralino is neutral, weakly interacting, and as massive as an atom of gold.
- Occasionally it will bounce off an ordinary nucleus and produce some ionization.
- We will wait for the occasion at Boulby mine in the UK.
- We will use a two-phase liquid xenon detector named Zeplin.

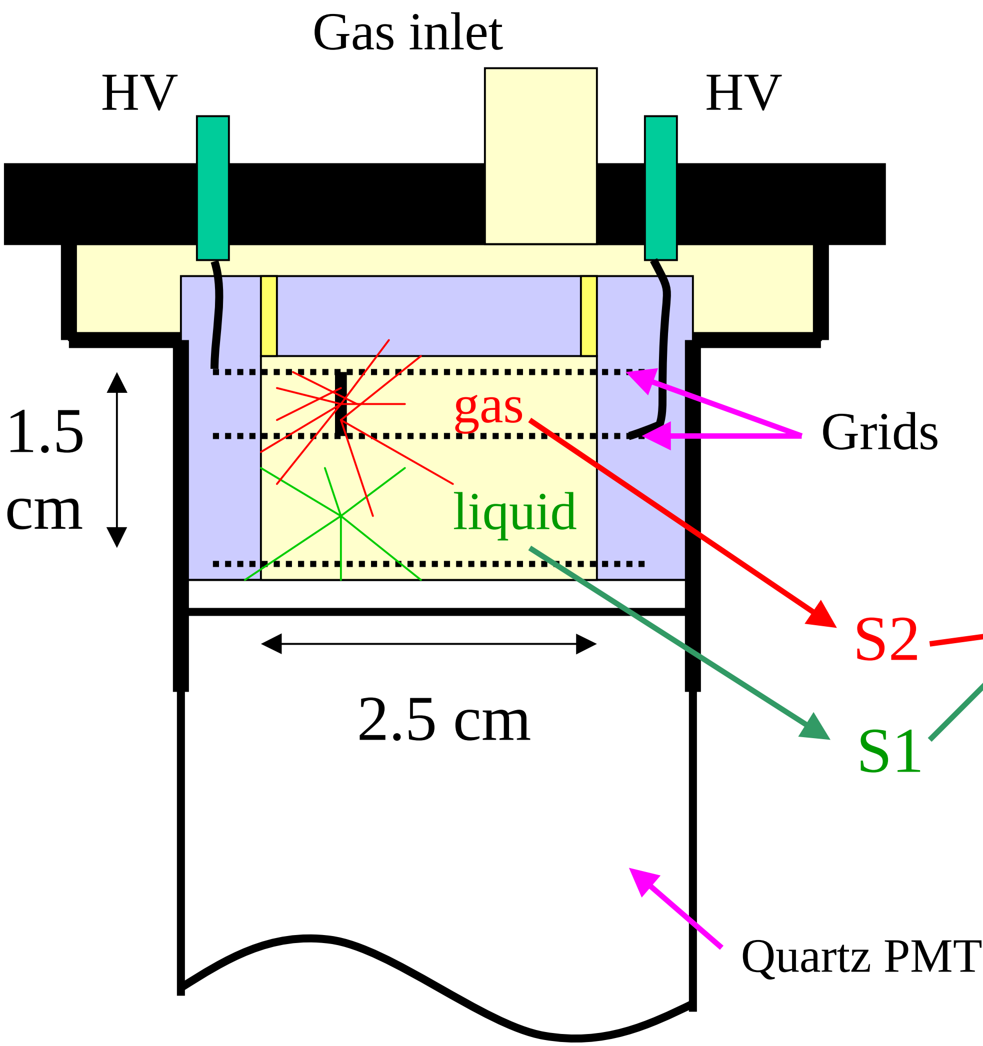
# Underground low-background laboratory

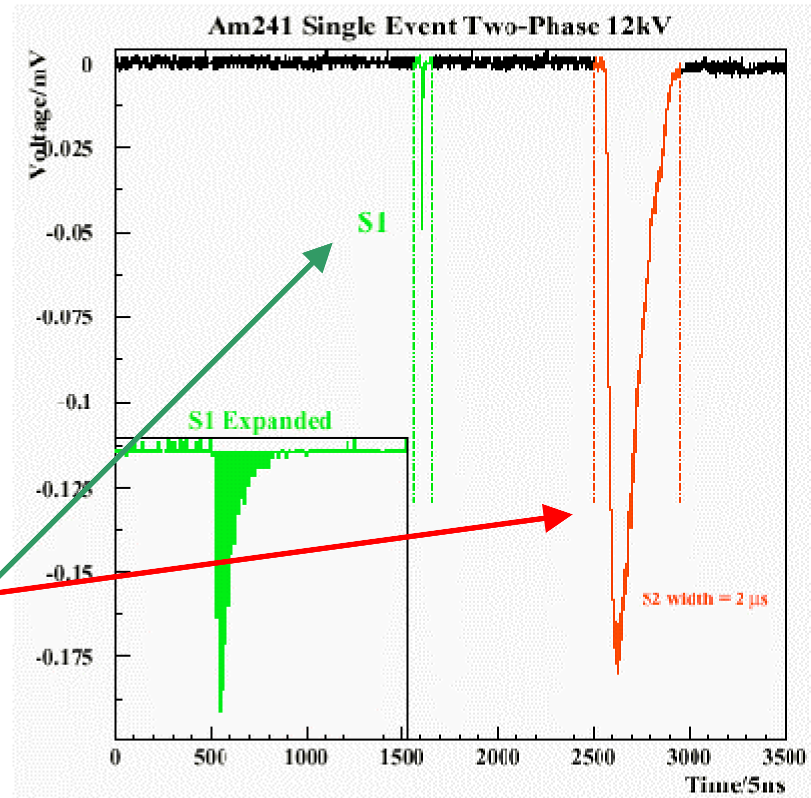



**Cosmic particles stopped by 1 km of rock.**

**Dark Matter particles penetrate freely.**

# The principle of 2-phase xenon detector




S1: scintillation in liquid Xe.

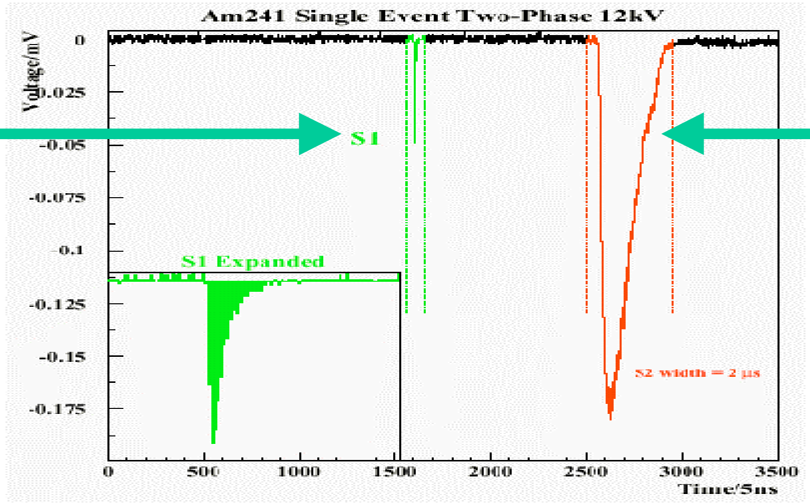
S2: electroluminescence in gas Xe.

Figure from: J.T.White, Dark Matter 2002.
http://www.physics.ucla.edu/hep/DarkMatter/dmtalks.htm

Figure from: T.J.Sumner *et. al.*,
http://astro.ic.ac.uk/Research/
Gal_DM_Search/report.html

# Recorded signal from a 2-phase xenon detector

Primary scintillation in liquid phase.




Secondary scintillation in gas phase (electroluminescence).

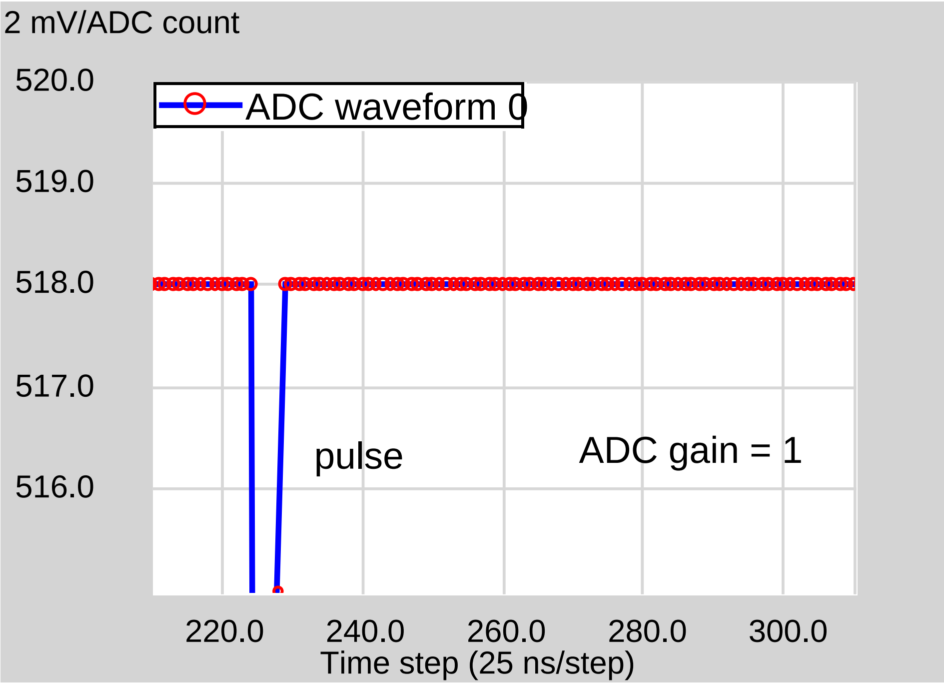
- Signal/background discrimination is derived from ratio S1/S2 and from S1 shape.
- Objectives: measure the areas of S1 and S2 pulses and analyze the shapes.
- The "intelligent waveform digitizer" is an ideal tool to meet the objectives.

- Low noise (see next slide).
- Large dynamic range.
- On-board user-defined data processing.

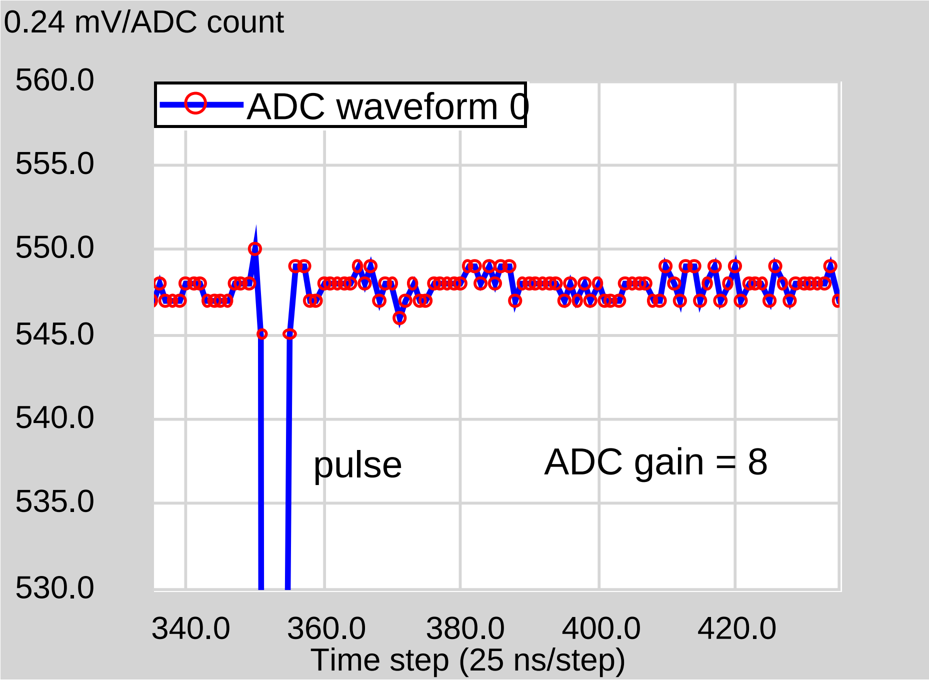
Figure from: T.J.Sumner *et. al.*, http://astro.ic.ac.uk/Research/Gal_DM_Search/report.html

# UTM has intrinsic noise below 1 mV

Gain=1, noise below 1 LSB

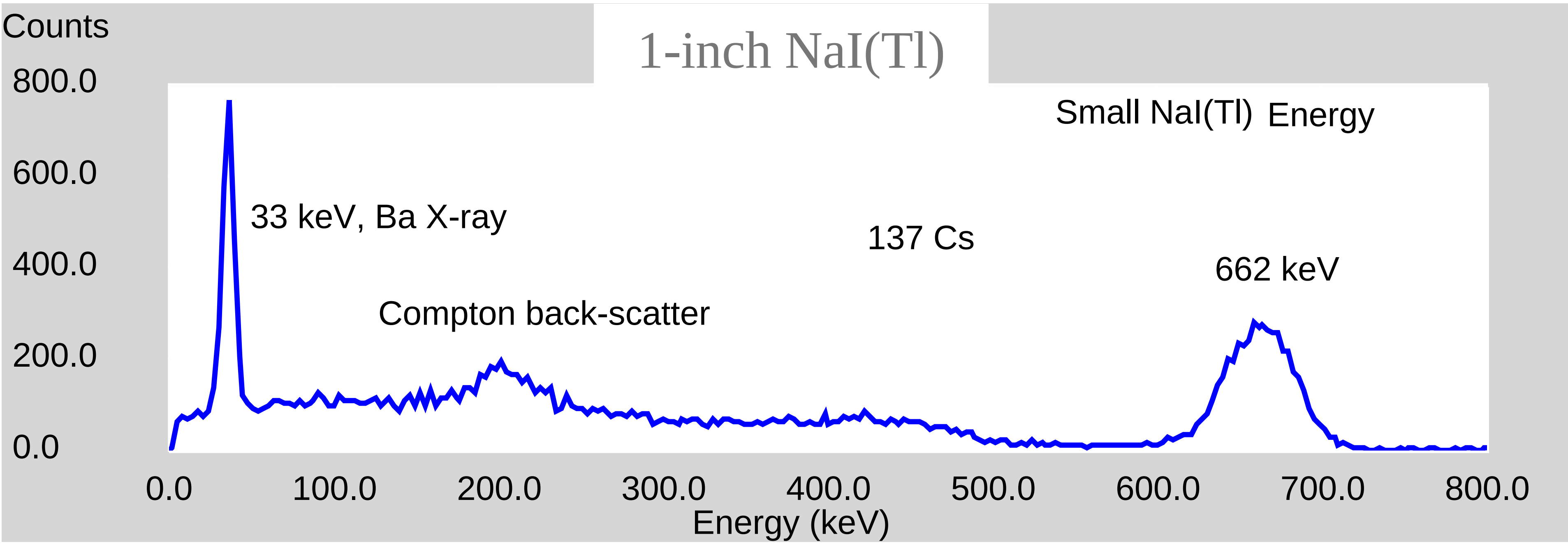



Gain=8, noise ~3 LSB (peak-peak)




Waveforms recorded with UTM

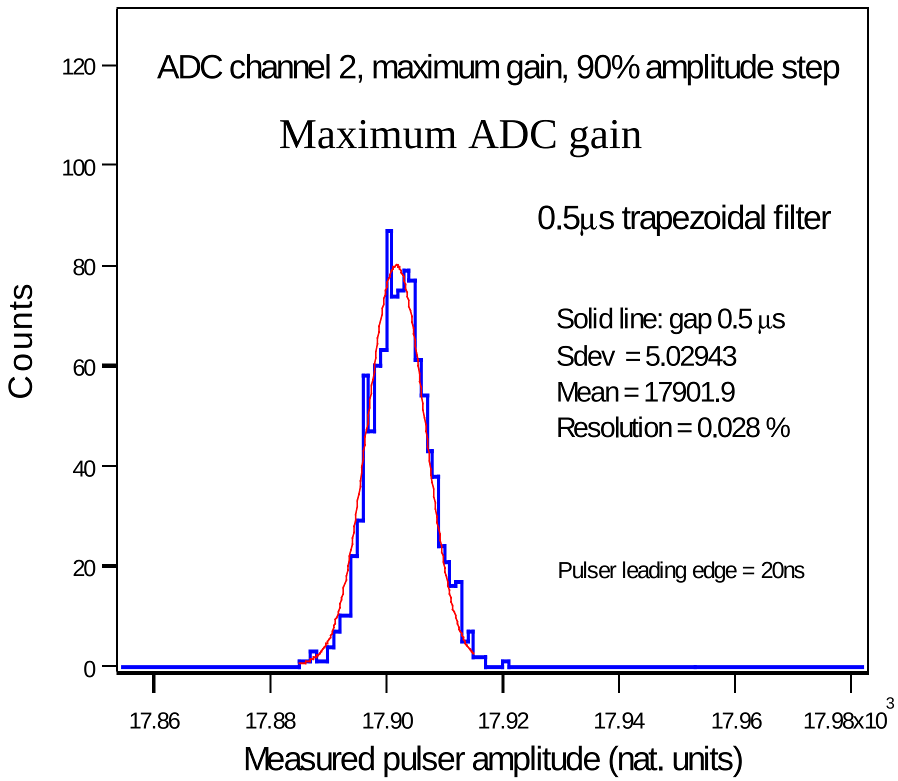
# Low noise translates to low threshold = 5keV



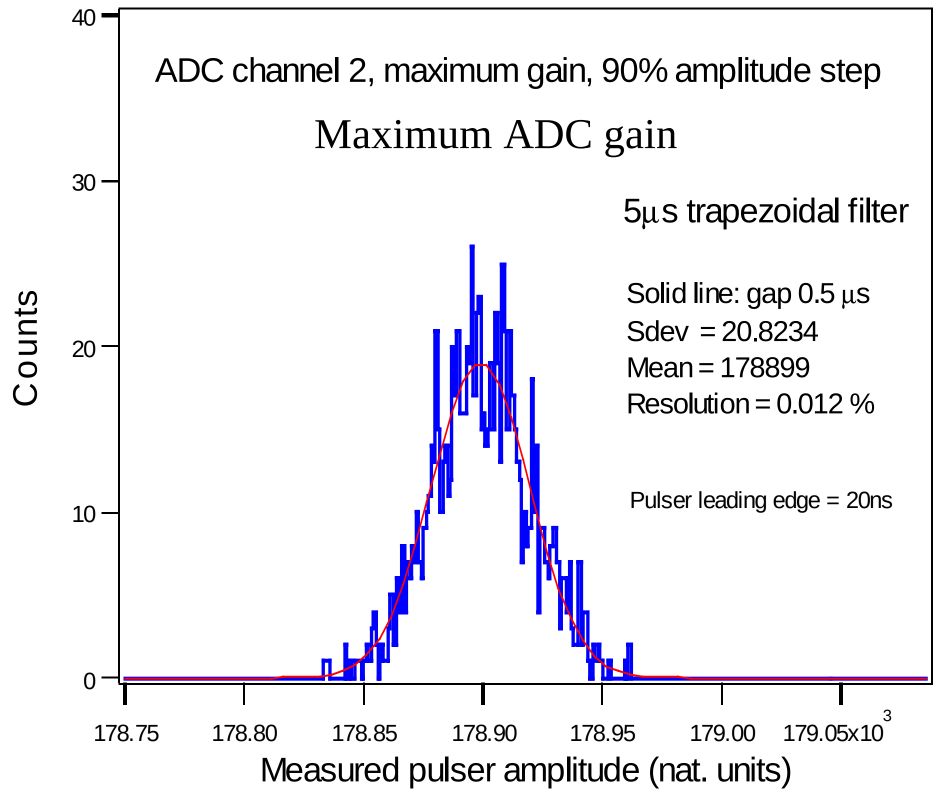

Pulse-height histogram measured with UTM

# Dynamic range = 18 bits, resolution < 0.2 keV

Short filter, pulser resolution 0.37 keV




Long filter, pulser resolution 0.16 keV




Pulser peak = 179,000 ==> 18 bits

# Plans for Dark Matter electronics

- Motivated by excellent performance of the UTM,

  I proposed to develop a digitizer board for Dark Matter Search.
  - 16 channels, 12/14 bits, 65 megasamples per second.
  - On-board Digital Signal Processor (800 mega-operations per second).
  - Remote control and diagnostics.
  - Low cost per channel.
  - Integration with existing infrastructure (VME).
- Status: schematic 75% finished.
  - Prototype can be ready this Winter.
- Applications other than Dark Matter.
  - Gamma-ray spectroscopy, neutron/gamma discrimination.
  - Arbitrary waveform processing.

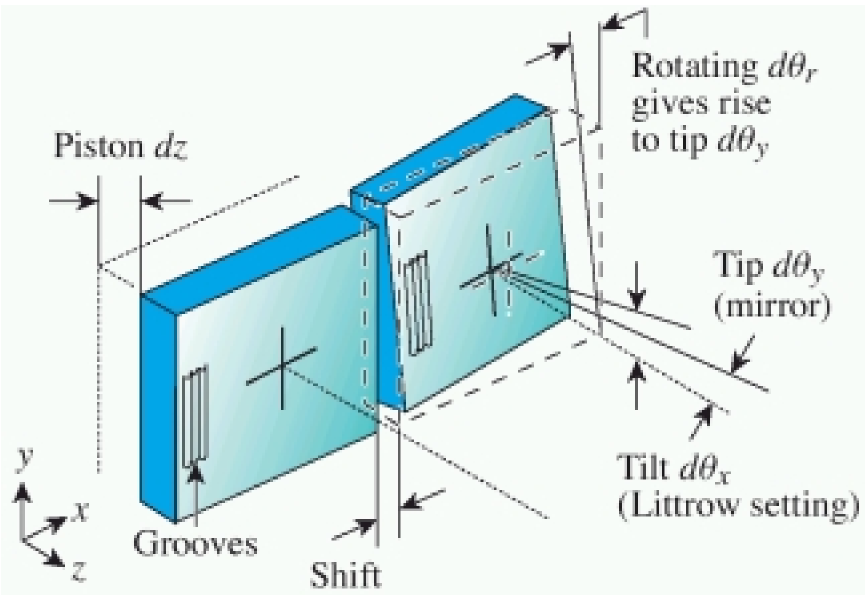
# Tiled Grating Assembly

# at LLE

# Adaptive Optics Control Software for Tiled Diffraction Gratings

Laboratory for Laser Energetics, University of Rochester

- Goal: align positions of tiled diffraction gratings in a closed loop.

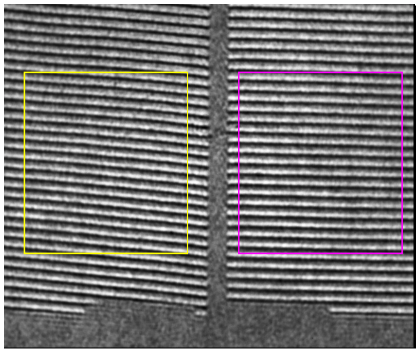


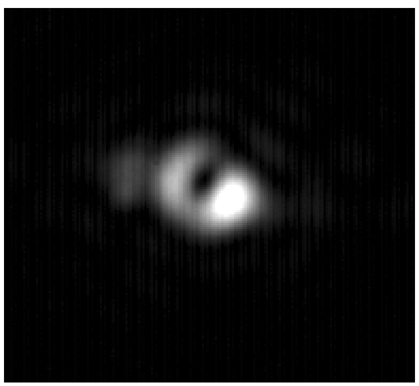

- Interferogram acquired from the CCD camera.
- Calculation of tip, tilt, and piston.
- Calculation of actuator steps.
- Recording of history of tip, tilt, and piston.
- Acquisition and recording of Far Field.
- Open-ended and modular design:
  New features added as needed.
- Internal variables and matrices available
  for inspection.
- Intuitive GUI and graphics.
- Robust: run-time crash does not happen.

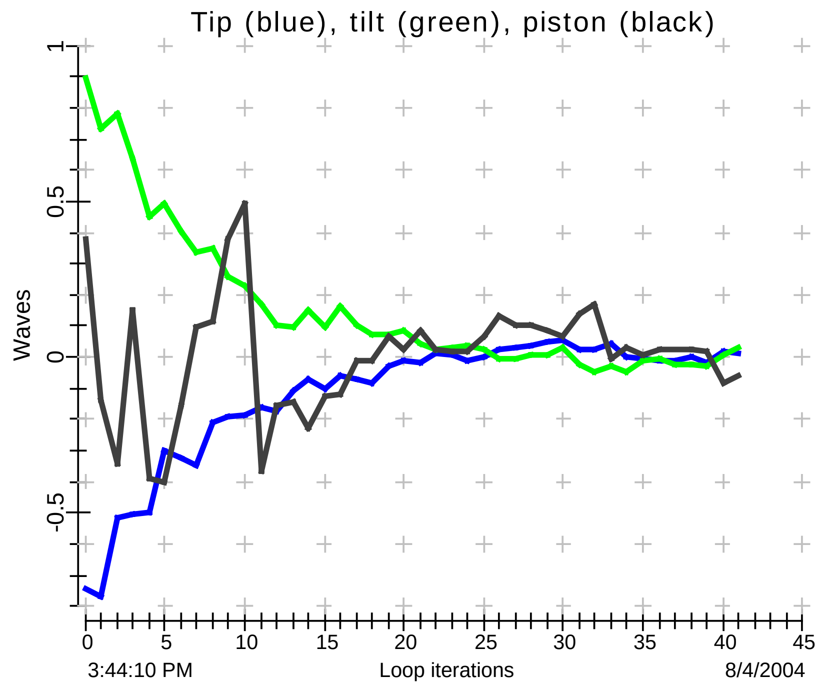
# Adaptive Optics Control System for Tiled Diffraction Gratings

Laboratory for Laser Energetics, University of Rochester

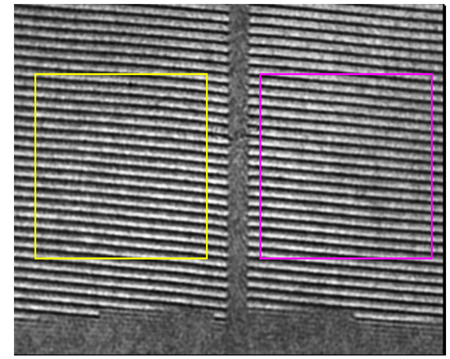
Before...

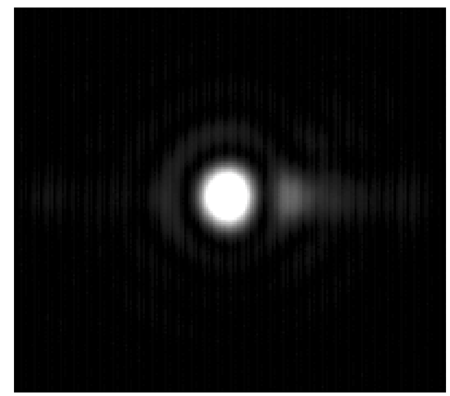







…after





Record of a control run with motors engaged.
Two out of three motors (motors A and B) were driven by (+50,-50) steps, then software was allowed to take control.

# Summary

- Development of TGA software at LLE has been a success. Software is intuitive, open-ended, and robust.
- Electronics development required all of the following:
  - Schematic design, board layout and board assembly.
  - Hardware testing and debugging.
  - Software for embedded microcontroller.
  - Firmware for on-board FPGA.
  - GUI design and programming.
- Time Equalizers are being used in a mission-critical application.
- Waveform digitizers are under development for PHOBOS, Dark Matter Search, in-beam spectroscopy, and other demanding applications.
- Several student projects and table-top experiments were completed.

# Possible applications at LLE

- Software: control and data processing systems that are robust, open-ended, and graphically rich.
- Time Equalizer: accurate alignment of fast timing pulses.
- Waveform digitizers and digital signal processors. Their function is defined by embedded firmware and software (FPGA and DSP).
    - Pulse-height spectroscopy.
    - Pulse shape analysis.
    - Particle discrimination (e.g., gamma/neutron).
    - Real-time processing of arbitrary waveforms.
    - User-defined data acquisition and processing.

# Acknowledgements


- **SkuTek Instrumentation.**
  - **Joanna Klima, WS (Principal Investigator for electronics).**
- **University of Rochester.**
  - **Frank Wolfs, Ray Teng, Tom Ferbel (Physics), Jan Toke (Chemistry).**
  - **Joachim Bunkenburg, Larry Iwan, Terry Kessler, Charles Kellogg, Conor Kelly, Matthew Swain (LLE).**
- **Robert Campbell (BAE Systems).**
- **Wolfgang Weck and Cuno Pfister (Oberon Microsystems).**
- **PHOBOS Collaboration.**
- **Students.**
  - **Erik Johnson, Nazim Khan, Suzanne Levine, Daniel Miner, Len Zheleznyak, Saba Zuberi, Palash Bharadwaj.**
- **My work was supported by grants from NSF and DOE.**

# Time Equalizer design specs

| | |
|---|---|
| • **Board form factor** | **CAMAC single width** |
| • **Number of channels** | **16** |
| • **Signal in and out** | **ECL** |
| • **Individual connectors** | **ribbon in and out** |
| • **OR connector** | **LEMO twinax** |
| • **Shortest possible delay tpd** | **6.5 ns** |
| • **Shortest possible delay step** | **10 ps** |
| • **Number of steps** | **256** |
| • **Shortest delay range** | **2.5 ns (in 256 steps)** |
| • **Delay tempco** | **7.5 ps/degree C** |
| • **Delay jitter** | **10 ps nominal** |
| • **Single step size** | **10 ps nominal** |
| • **Max trigger rate per channel** | **in the MHz range** |
| • **Output pulse width** | **3 ns minimum** |

**(to specs in September 2001)**

# Universal Trigger Module specs

| | |
|---|---|
| # of analog input channels | 8. |
| # of analog output channels | 1. |
| # of logic inputs NIM | 16. |
| # of logic outputs NIM | 8. |
| # of in/out lines TTL | 16+1. |

**Features**

| | |
|---|---|
| Fast interfaces | USB, parallel. |
| Slow interfaces | RS-232, SPI, $I^2C$. |
| Waveform memory | 12 μsec. |
| On-board microprocessor | 8 bits, 4 MIPS. |
| Microprocessor memory | 0.5 MB. |
| Packaging | NIM, single or double width. |

**Applications**

Real-time triggering (e.g., PHOBOS trigger), table-top acquisition systems, research projects, algorithm development.

# About myself

Education:

| | | |
|---|---|---|
| Warsaw University, Warsaw, Poland | M.Sc. 1980 | Physics |
| Warsaw University, Warsaw, Poland | Ph.D. 1990 | Physics |

Work experience:

University of Rochester
Oak Ridge Nat'l Laboratory
Lawrence Berkeley Nat'l Laboratory
Warsaw University (Poland)
Soltan Institute for Nuclear Studies (Poland)
X-Ray Instrumentation Associates (industry)
SkuTek Instrumentation (own company).

Specialties:

Nuclear Physics, programming, electronics, and tiling ;-)

Other specialties:

Downhill skiing, hiking, sailing.