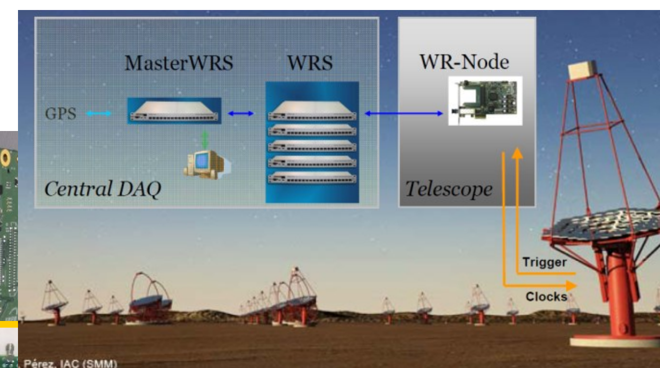
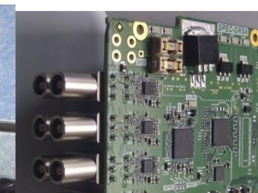
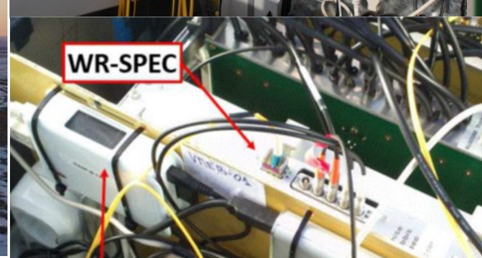
# Modern Timing Concepts for Astroparticle Physics

Ralf Wischnewski (DESY)

*Workshop on a Wide-FOV Southern hemisphere TeV gamma ray observatory, Puebla, 12.11.2016*






**Disclaimer:**

- This talk is not a general review on Timing

  Focus is on the "new fashionable system":

**WHITE RABBIT (WR)**

**Will answer this question:**

- ***"I bought a WR-Kit.***

  ***Nice - it works for synchronization !***

  ***Am I done ? "***

**Executive summary:**

- ***There is One and Only One Timing System for APP***
- **But: You bought a 'Mercedes' . It can play music, but it can also drive !**

DESY

# Outline

- **Precision timing in Astroparticle and Particle Physics Experiments**
  - **Requirements, design principles**
  - **Avoid custom systems by using a "standard technique"**
- **White Rabbit : an new technology for time-transfer**
  - **Basics**
  - **Pro's and Pro's ( no Con's )**
- **White Rabbit in operation: experience with Tunka-HiSCORE**
  - **Experience over 2012—2015**
- **Conclusion: make more of WR than only distributing PPS**

**Thanks to my collaborators**

**M. Brueckner (PSI), A.Porelli (DESY)**

**For more details see:**

**WR-HiSCORE: ICRC2013 (RW #1146, #1158, #1164)**

**ICRC2015 (RW PoS (1041) )**

**$9^{th}$ WR Workshop, Amsterdam, March 2016,**

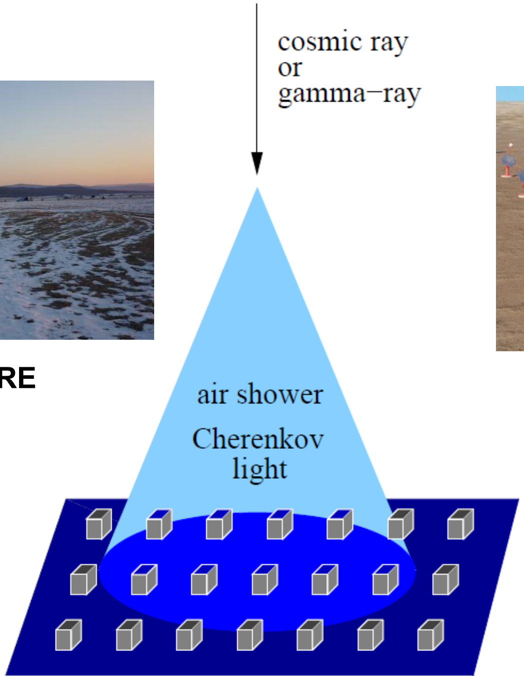
**CERN-WR: [http://www.ohwr.org/projects/white-rabbit](http://www.ohwr.org/projects/white-rabbit)**

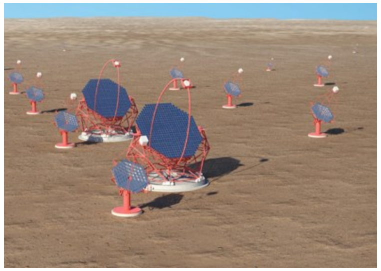
# Large-scale Astroparticle Experiments …

- Detectors are distributed over large areas
  e.g. Sensor stations, Cerenkov Telescopes, Water-Tanks, Ice Tanks, DOMSs/PMTs
- Measure:   temporal arrival pattern  of light-/radio-flashes/particles…
  - Examples: IceCube, Km3Net, CTA, HAWC, HiSCORE, LHAASO
- Area:   km$^2$ … 100km$^2$….
- Timing precision:   governs physics performance

  (sub-) nanosecond precision  (sensor, media)

**HiSCORE**



**CTA**

**LHAAO**

# … and Timing (Trigger) concepts

### *Centralized Arrays*

Some large-scale AP experiments still  do (like in compact accelerator experiments) :

(1) measure times against a central reference signal   (‘*common stop’)*

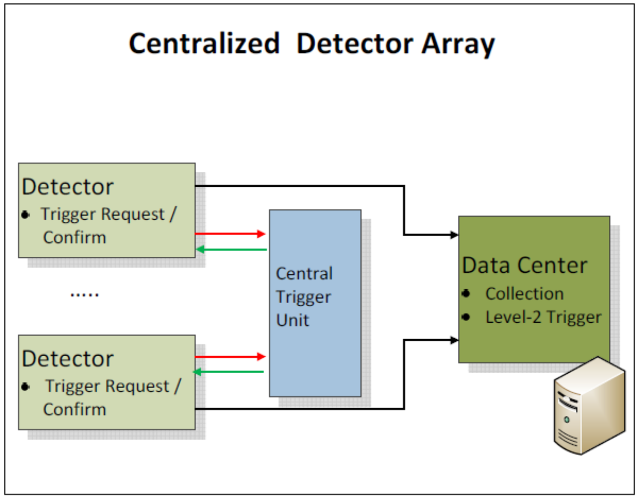
(2) trigger at a central place (confirming  the detector trigger-request signals).

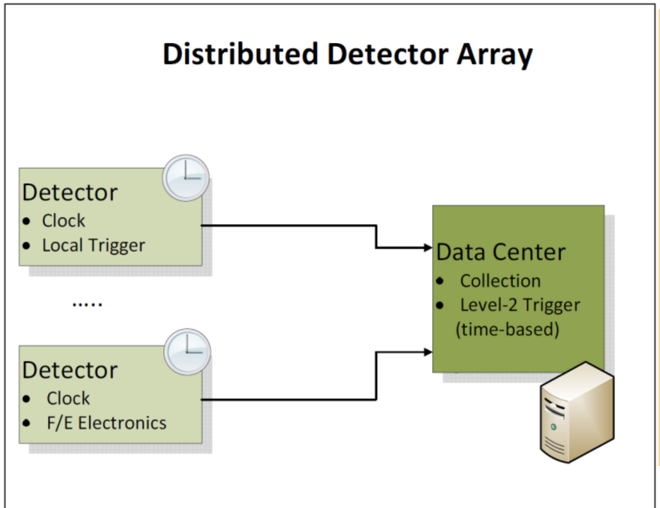
This “central triggering” can contribute to large dead-times, and analog-buffer depths.

### *Distributed Arrays*

Instead - with a precision clock in each detector,  locally triggered sub-events can be send  to a digital central processing unit (bandwidth and trigger-selectivity permitting).
This allows for complex array-triggering procedures, and low dead-times.

→ Clock reliability and precision is a system-critical parameter.

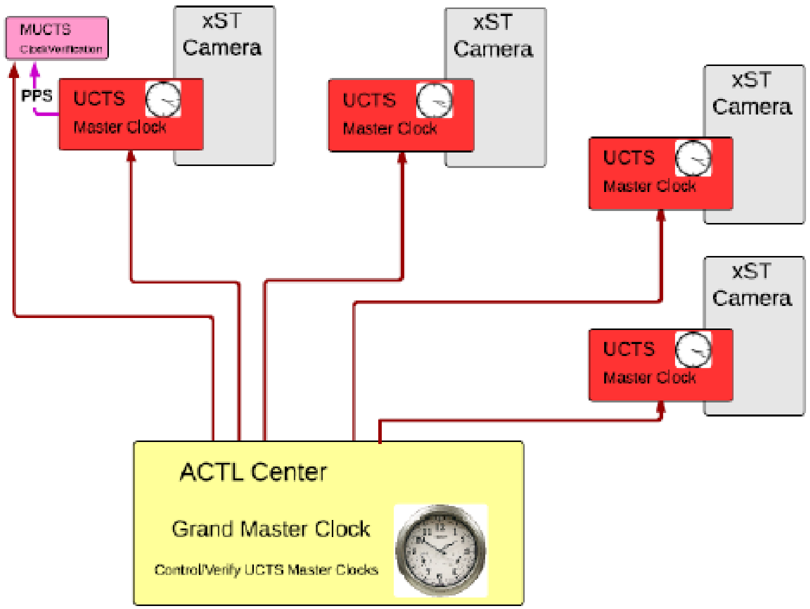



Each detector has a precision clock.

# Timing : Distributed Clocks

- Generic example: the array of CTA-cameras (or any other detectors)
- Each Camera has a precision clock, located on a Timing Card (UCTS).
- All clocks are autonomously synchronizing with the GrandMasterClock.
- Inter-Clock deviations are of o(200ps) rms




→ The array acts like a time machine, ie. must be able at each camera to either

(A) measure (timestamp) an “event occuring”, or to

(B) generate an “calibration event”, ie. issue a clock-driven timesignal to camera.

# Technical Realization: White Rabbit

WR is a fully deterministic Ethernet based network for data transfer and synchronization.

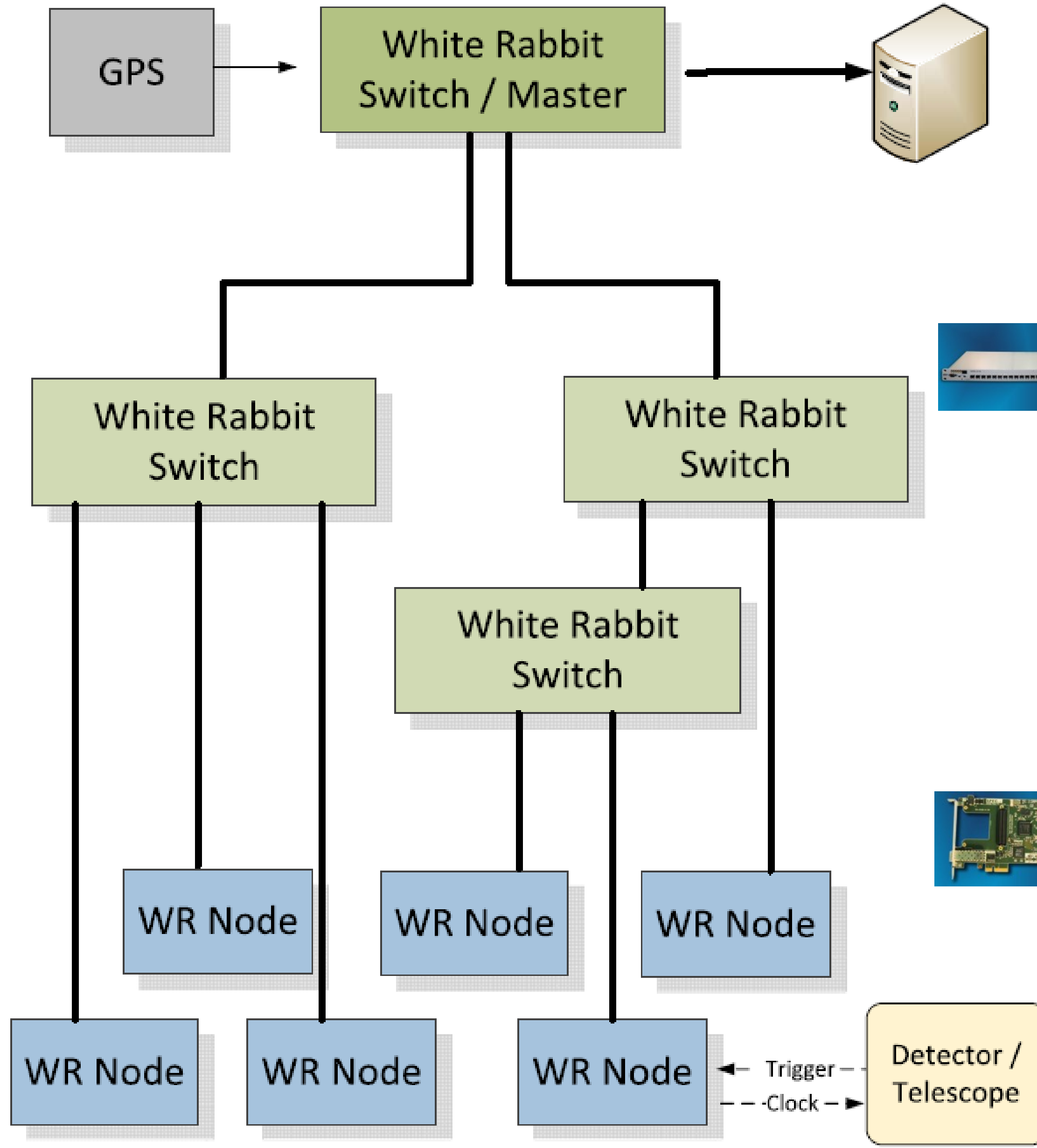
Extension of PTP. Uses proven 1GbE fiber technology.

A WR network is made of

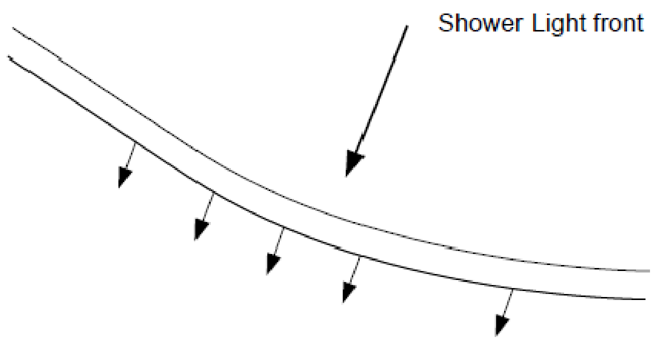
- ClockMaster (MasterSwitch+GPS)
- WR-Switch network
- WR-nodes with synchronized clock
- Standard GbE fiber connections.

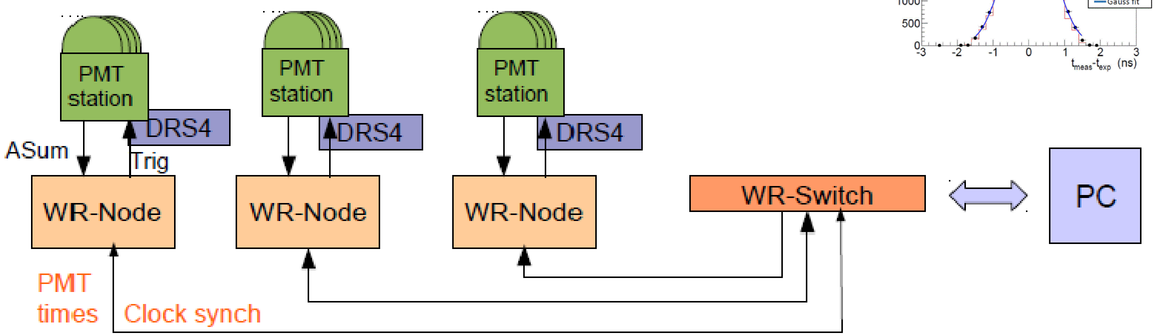
Parameter:

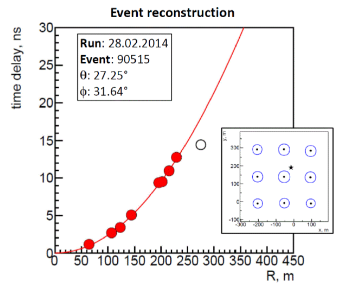
- Accuracy <1ns, Precision ~20ps
- Fiber links of 10km ..... 60-80km.
- >1000 nodes.

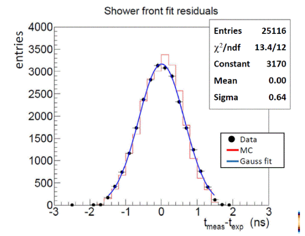


# BonusSlide.  Build your own nsec-DAQ




**Note:**

**This is an array- trigger free setup ! All detectors run standalone.**
**Out-of-the-box !**

**Allows for true-online data treatment at array-level (Trig/Filter/…)**

**Ingredients:**

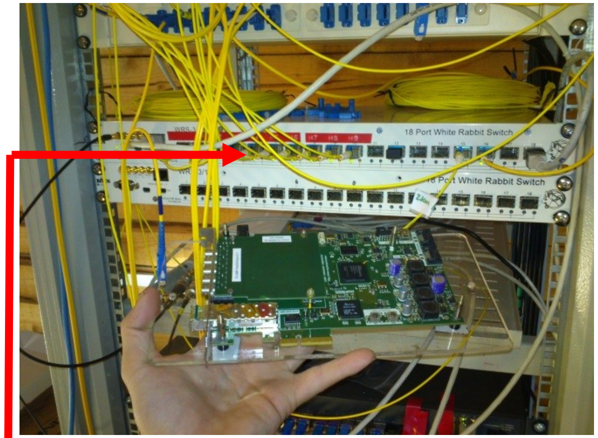
- **Detector stations (PMTs…)**
- **1x WR-SPEC per station**
  **(& your firmaware)**
- **Fiber cable to WRSwitch**

- **Collect  nsec-timestamps on your Laptop/PC**
- **Reconstruct EAS  wavefront  …**

**(Optional:  use  DRS4/EB boards for pulse-sampling )**

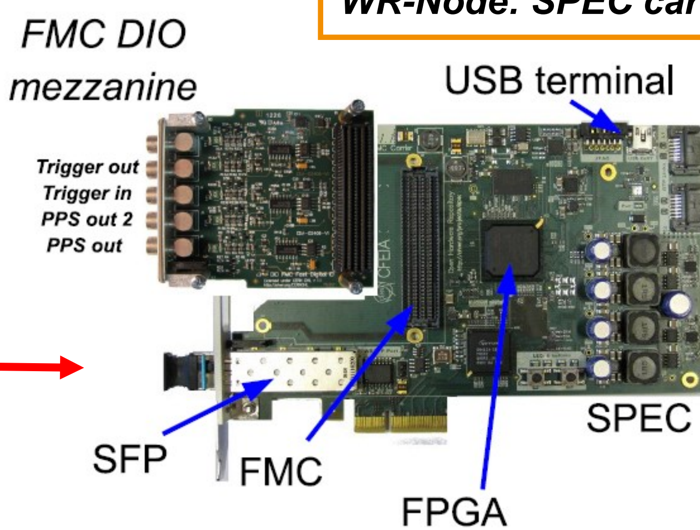
# White Rabbit: The Hardware Components

***WR Master: WR Switch***




***1Gbit fiber***

***WR-Node: SPEC card***




<u>The WR Switch:</u>

The synchronization master,
connects to up to 17 WR-Nodes.

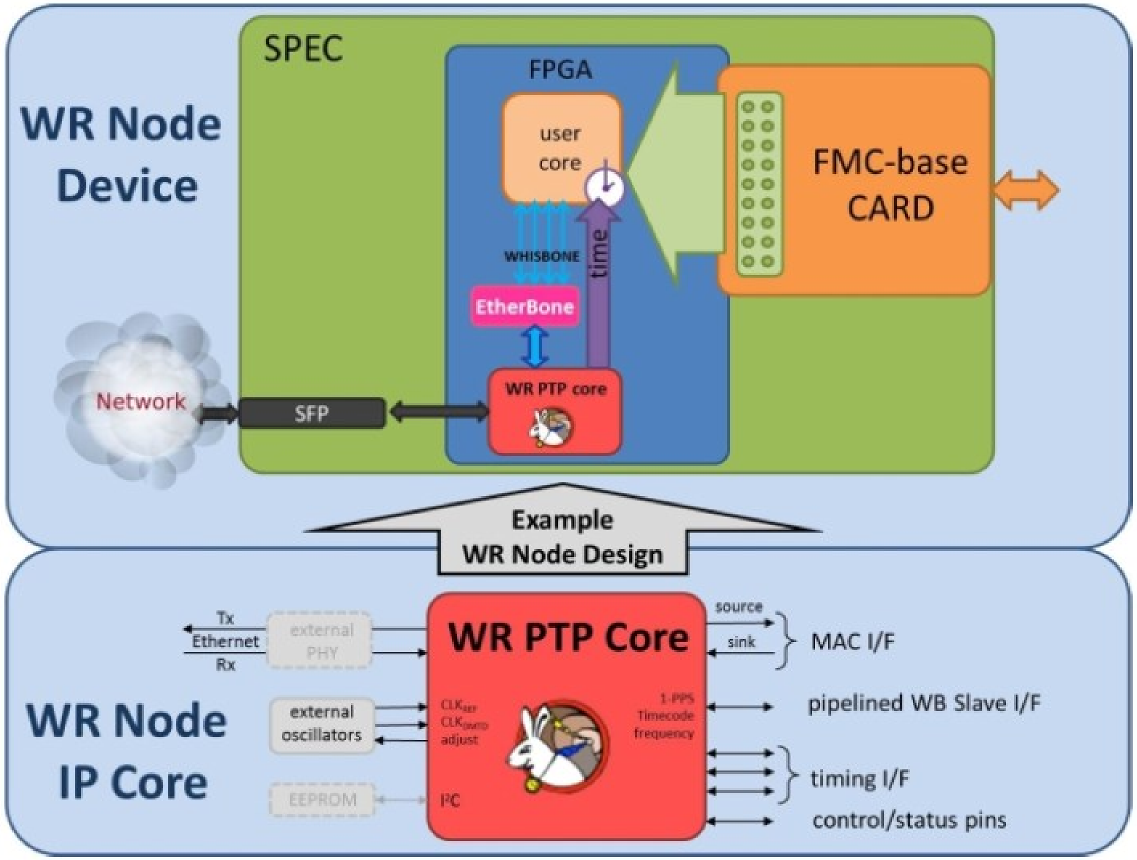
<u>A WR-Node: SPEC</u>
( “Simple PCI FMC Carrier” )

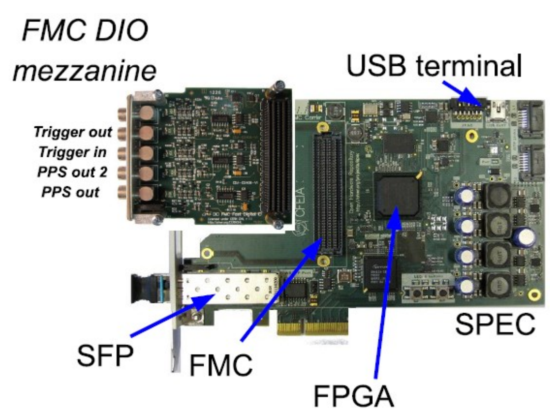
Spartan-6 based PCI-size card
1x FMC (Mezzanine)
1x SFP (WR fiber)

(the WR-Node workshorse since 2011)

(It’s the WR-Node that needs experiment
specific implementation)

# An example WR-Node




( example: WR SPEC )

# White Rabbit - Why is it attractive ?

WR is

- Supported by an active core-team @CERN,
- Planned for the LHC accelerator upgrade
- Growing participation from industry.

First astroparticle applications ("reference") are underway now (e.g. LHAASO, HiSCORE). Results are very encouraging.

<u>Advantages :</u>

> Development for CERN & GSI accelerator complex; much external interest

> Open Hardware & SW Project; peer reviewed; fully transparent to the user. Adapting to a use-case is easy and supported.

> Hardware is commercially available (growing #companies),

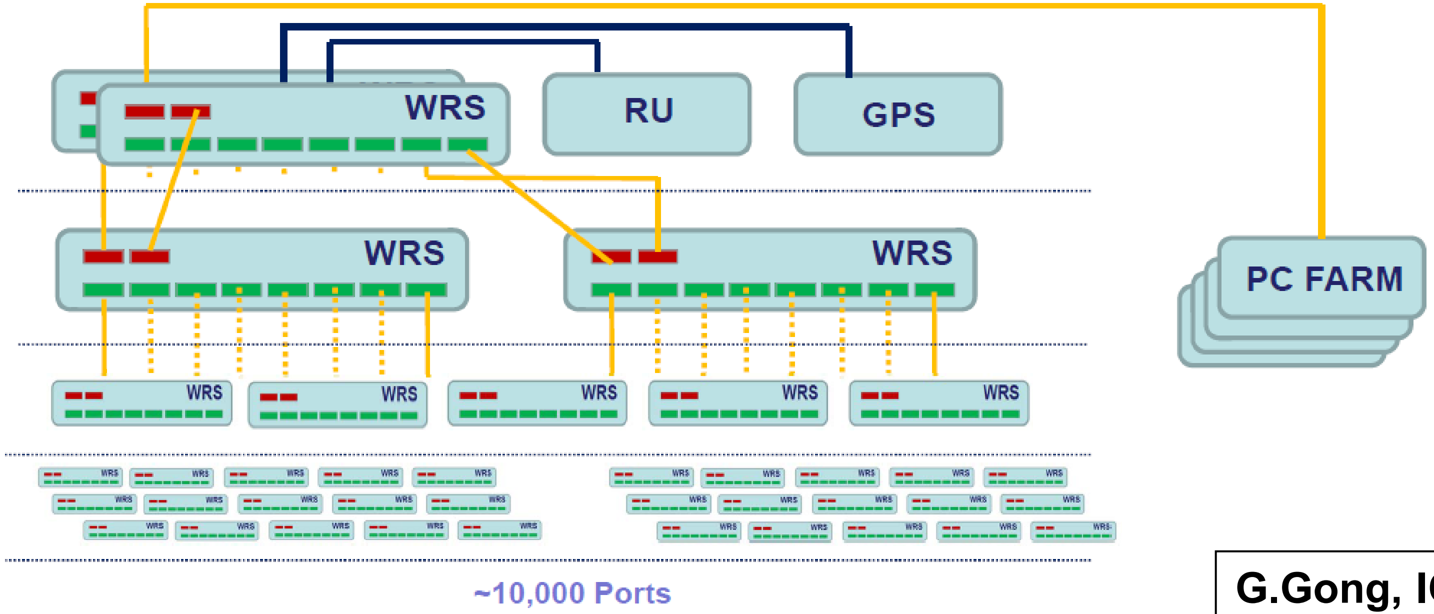
> WR Standardization is planned for Eth-PTP (IEEE1588…) in 2018

> A guaranteed large user community: it will be a well debugged system … !

# WR - Applications :   LHAASO

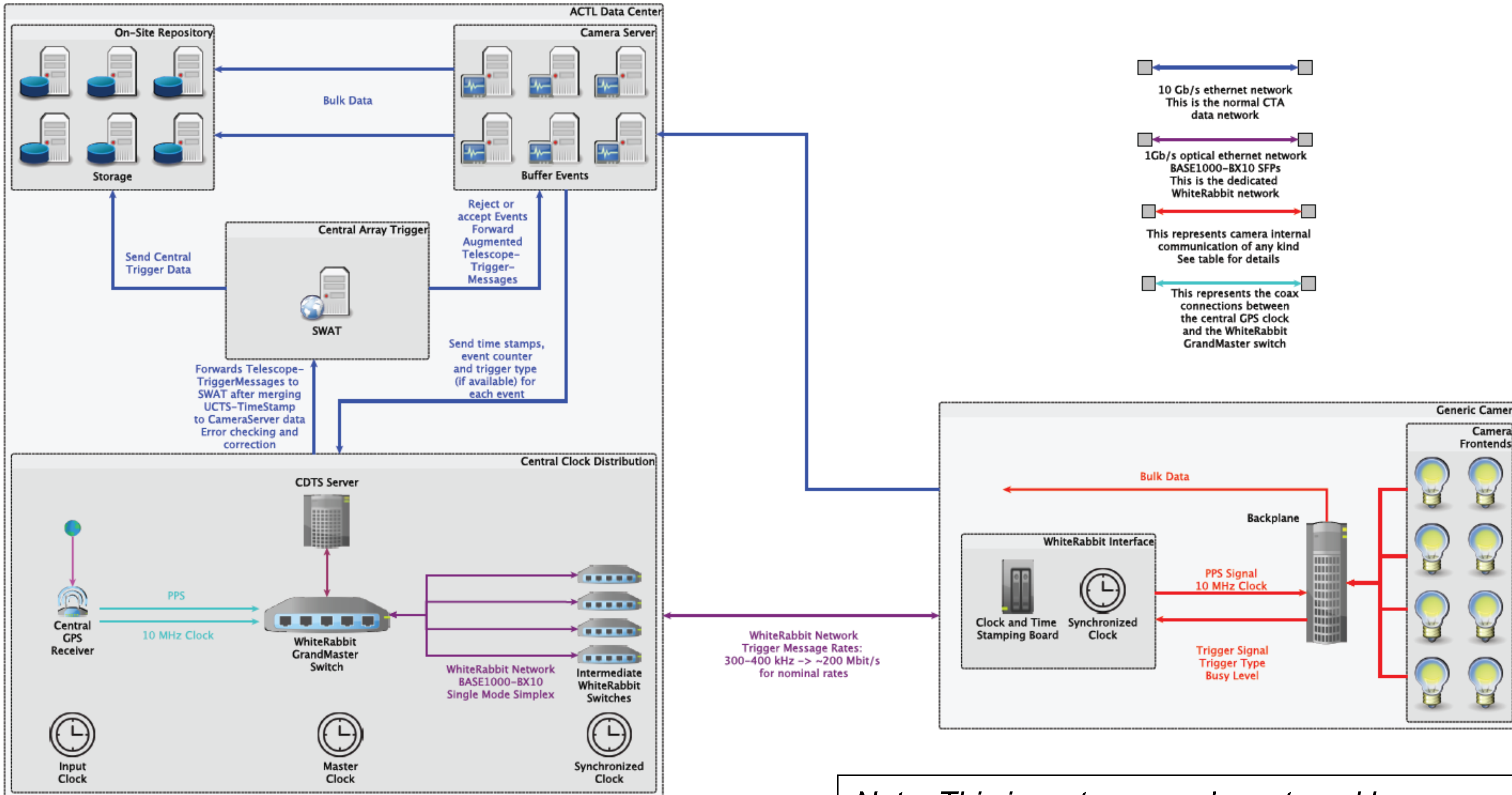
**LHAASO : ~10000 nodes to be synchronized.**

**Test setups running.**




**G.Gong, ICALEPCS, 2011, ICRC2015, ….**

# WR – Applications: CTA Telescope Timing & ArrayTrigger




*Note: This is a strawman-layout, and by no means final.*

*CTA is discussing the data-flow concept and network architectures; since 2013.*

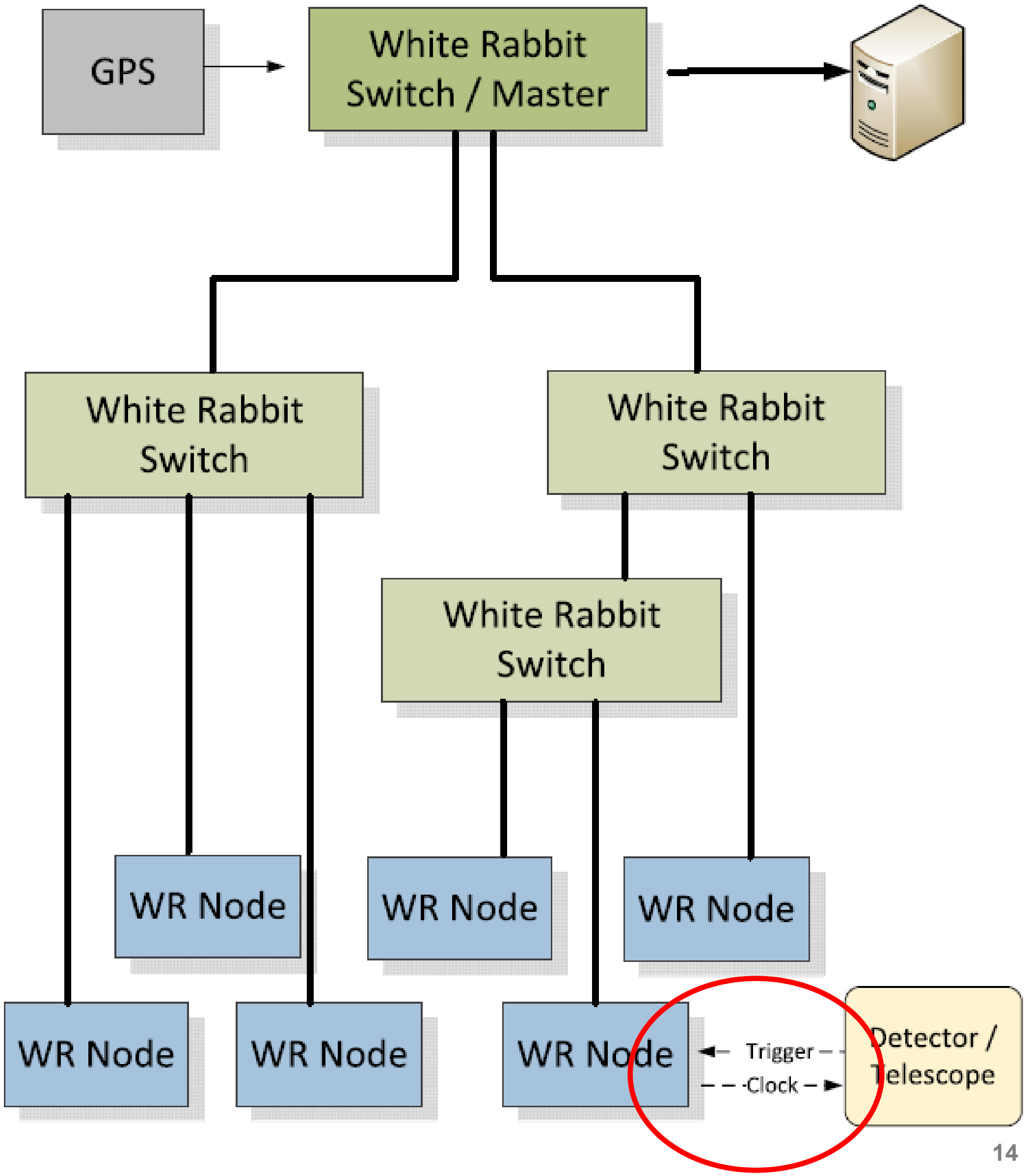
# ... and Timing : Using Distributed Clocks

AP experiments must act like a time machine, ie. at each detector being able

(A) to measure (ie. timestamp) a "local event occuring", or

(B) to generate an event, by issuing a synchronous (to all detectors) signal.

➔ WR is a natural technique to be used for this.

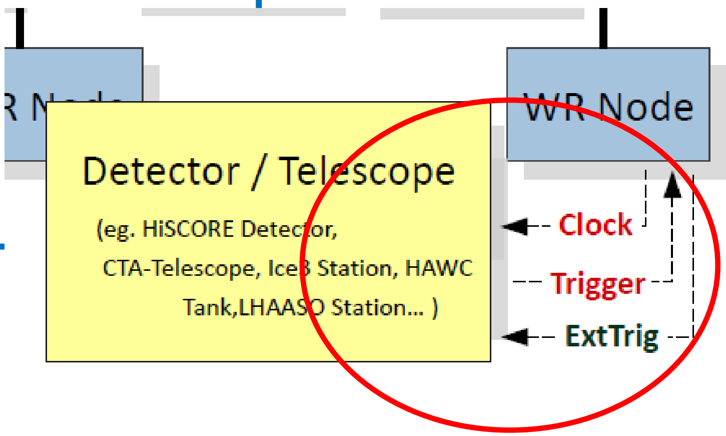


# Detector and WR-Node : Baseline Interface

Functionality:

- WR-Node → Detector : Clocks ( PPS / 10MHz )
- Detector → WR-Node : Trigger ( edge )
- WR-Node → Detector : External Trig Pulses

…




Comments.

(1) TriggerTimes are generated both on detector and WR-Node for each event.

This (time/counter) redundancy can be used to verify clock stabilities and data integrity: *"**DoubleClock/DoubleTimeStamping** architecture"*

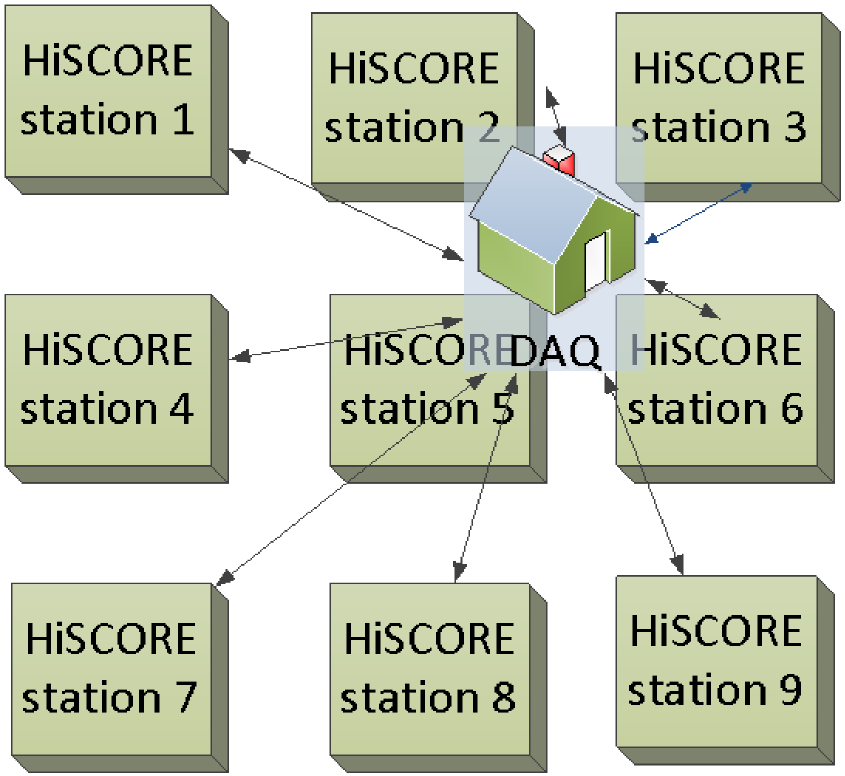
(2) Another request : Is in-situ verification of clock-performance possible ?

Allow for operation of a ***Monitoring-WR-Node*** at each detector, that cross-stamps the PPS. Cheap&sufficient; can be limited to verification and debugging phases.

# HiSCORE - Experience with White Rabbit

# HiSCORE-9






First prototype array: in 10/2013

A = 0.3 x 0.3 $km^2$

Each station detects Cherenkov light with 4 PMTs.

For precise shower direction reconstruction sub-nsec precision for arrival-timestamps at each station.

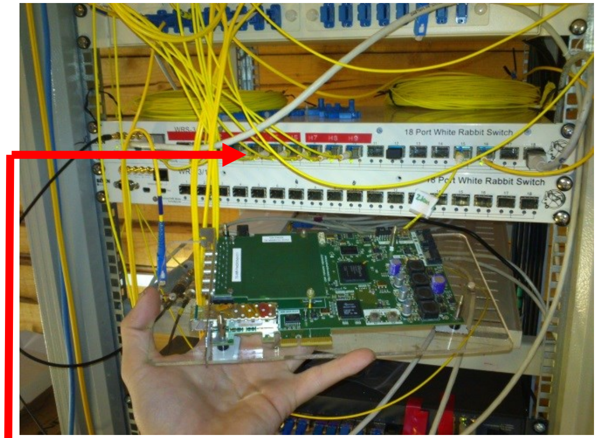
Prototyping with HiSCORE-9: Optical Stations / DAQ / Timing / …

Main Results:

- Air-Shower reconstruction
- Timing calibration by external LED

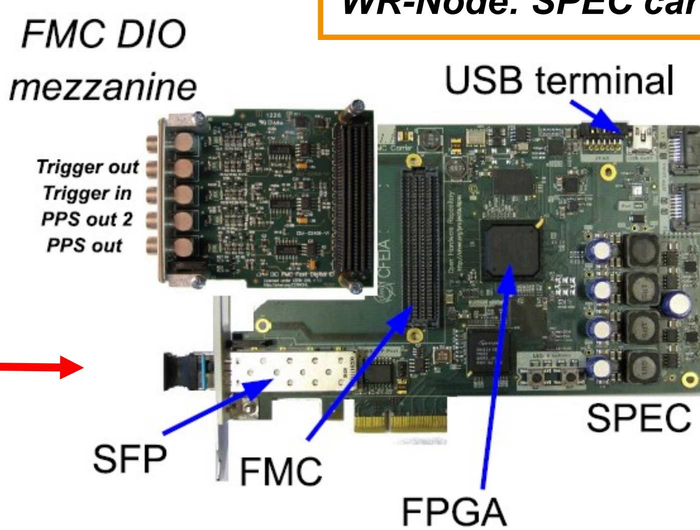
# HiS-9 Station: The SPEC as the WR-Node

**_WR Master: WR Switch_**




**_1Gbit fiber_**

**_WR-Node: SPEC card_**




<u>SPEC = "Simple PCI FMC carrier"</u>

Spartan-6 based PCI-size card
1x FMC (Mezzanine)
1x SFP (WR fiber)

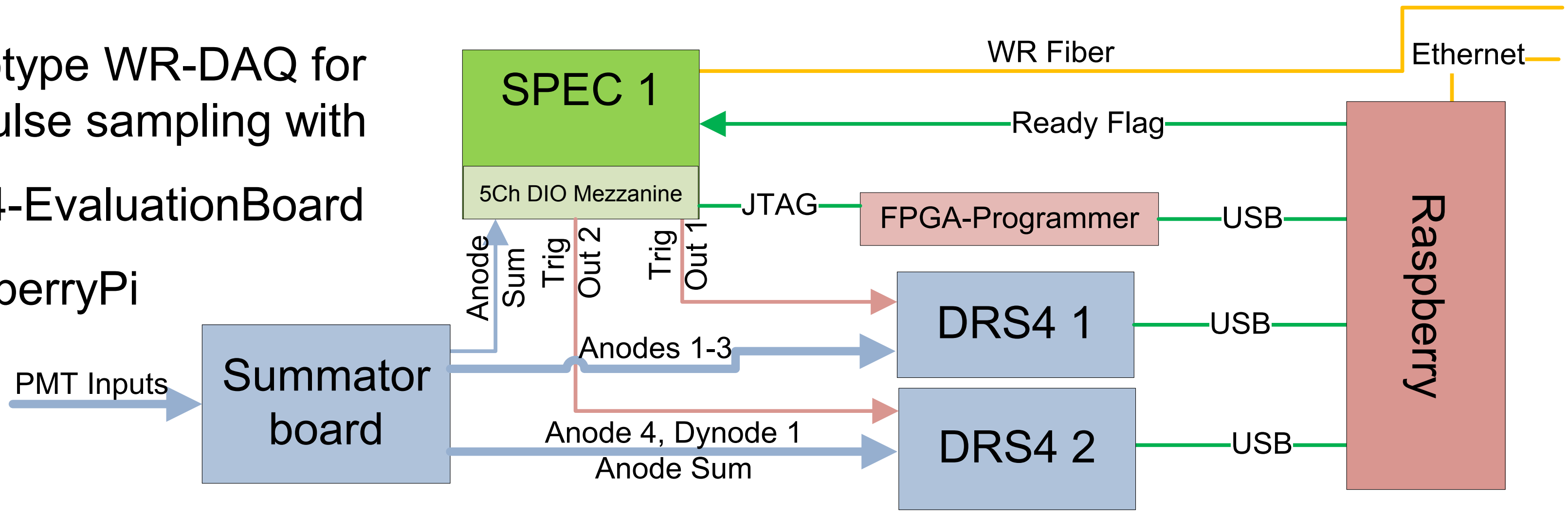
The workshorse for WR (2011-…)

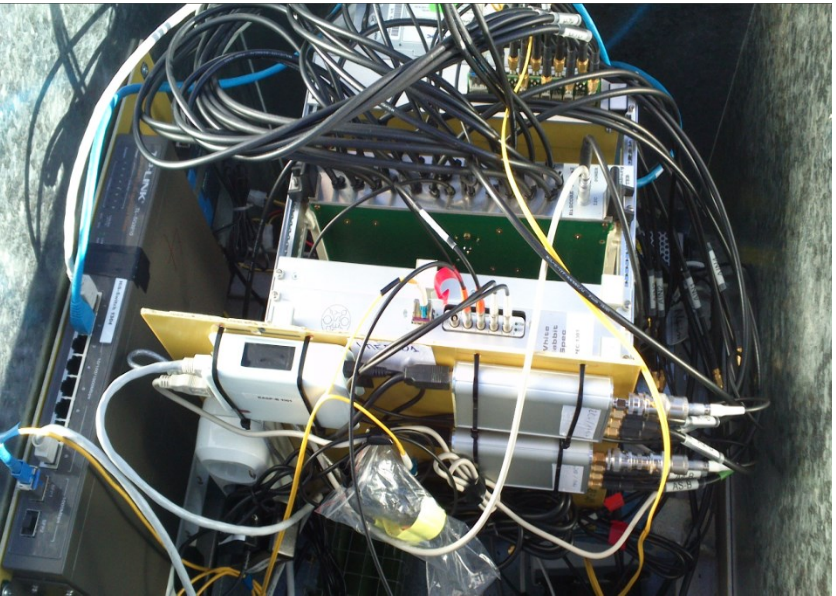
<u>DESY adapted to CTA/HiSCORE</u> (2012+)
-- nsec-timestamping
-- UDP timestamp transport
-- (PPSOut/) 10MHz out
-- DAQ/frontend triggering
-- status monitoring, …

# HiS-9 Station :  a SPEC-based mini-DAQ

A prototype WR-DAQ for GHz pulse sampling with

- DRS4-EvaluationBoard
- RaspberryPi



SPEC card

- Runs WR  clock
- Stamps trigger-times + sends over WR fiber
- Transmits WR status over Etherbone

DRS4-EB (PSI)

- Capture analog PMT signals + WR triigger pulse

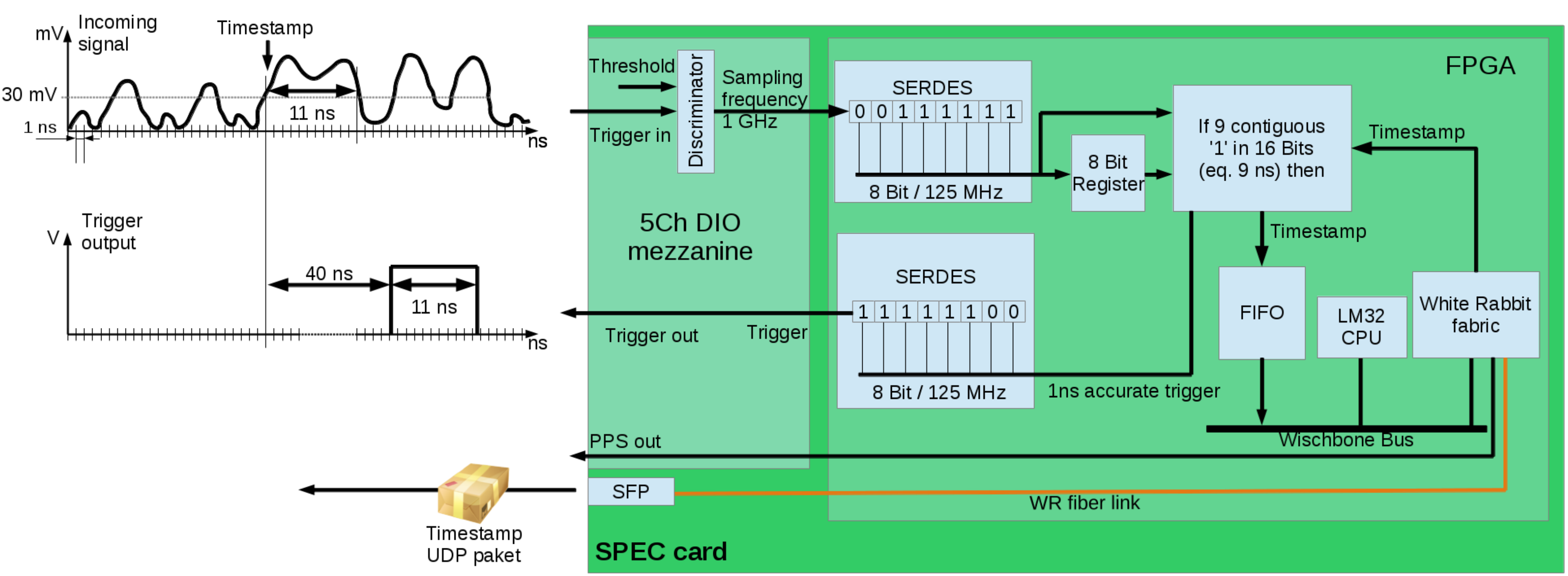
Raspberry

- Reads out DRS/EB board on trigger
- Uploads bulk data over a second fiber
- Programs FPGA / Backup SPEC-USB

# WR SPEC Node – the HiSCORE specific design

SPEC FPGA modifications

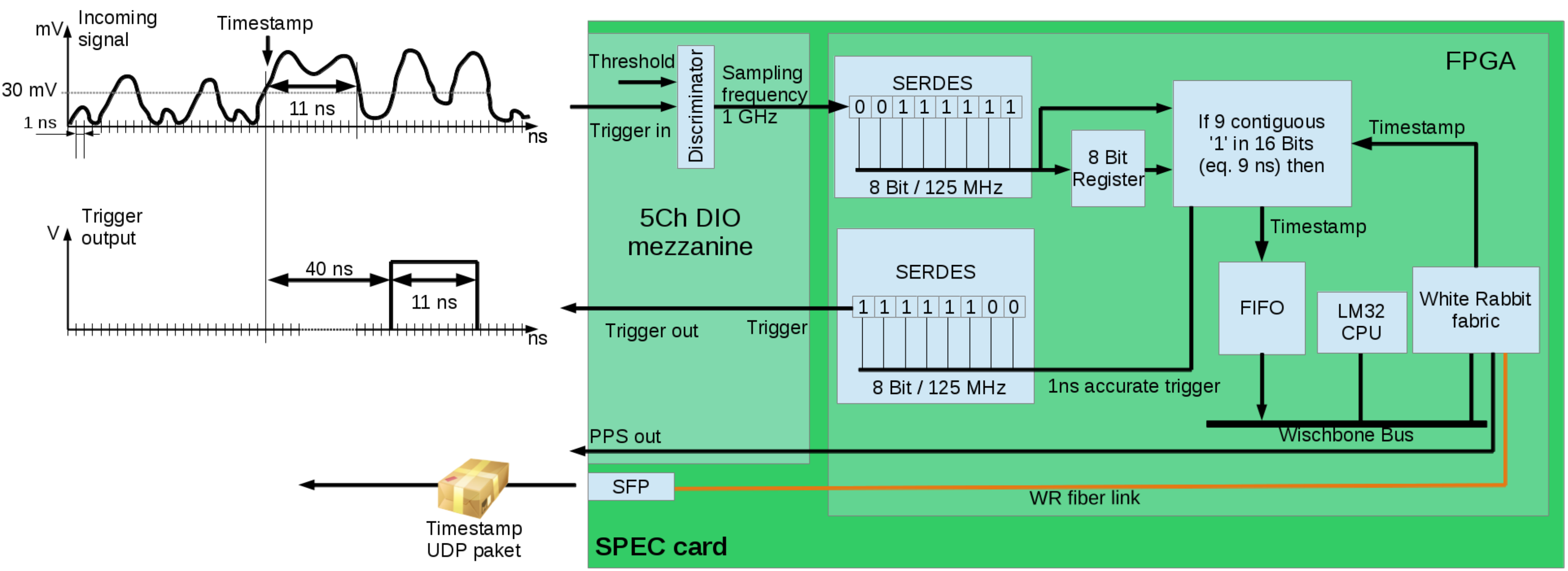
- Taking advantage of the features of the 5Ch DIO card
    - Configure some signals as input for the analog signal
    - Configure some signals as DRS4 trigger and handle Raspberry ready flag
    - Setting a threshold for incoming signals
- Using Spartan 6 SERDES blocks for deserialization



# WR SPEC node – the HiSCORE specific design (2)

SPEC FPGA modifications

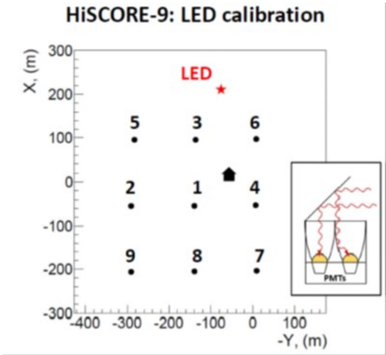
- Filter out signals shorter than 9 nsec (configurable)
- Timestamp the trigger arrival time
- Send timestamps over WR link to DAQ center (software)
- Introduce a command to adjust threshold over USB-UART

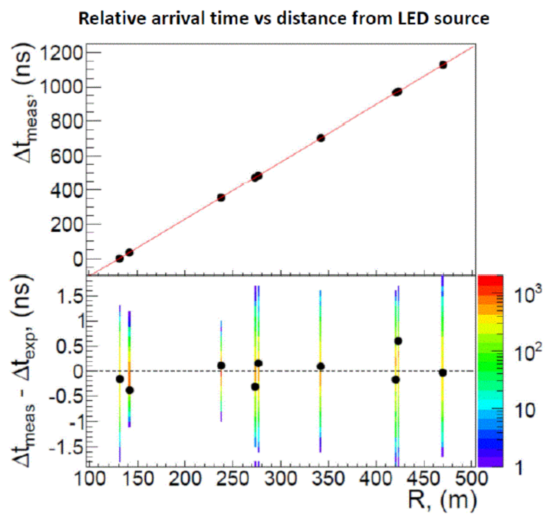


# HiSCORE-9 Results w/ WR Data only: LED and EAS

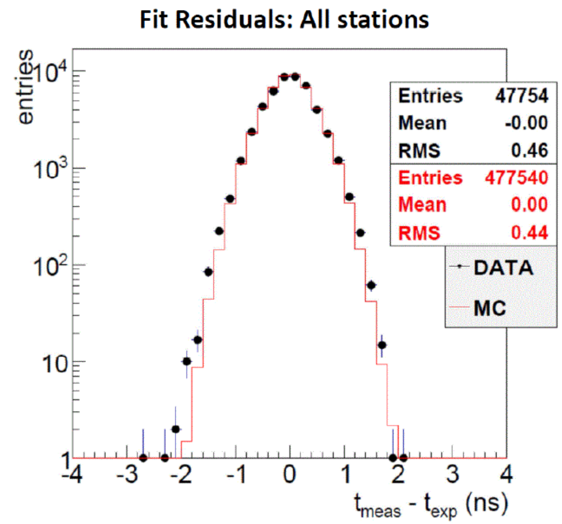
> **External LED-Calibration**

Fit-Resid ~0.44ns



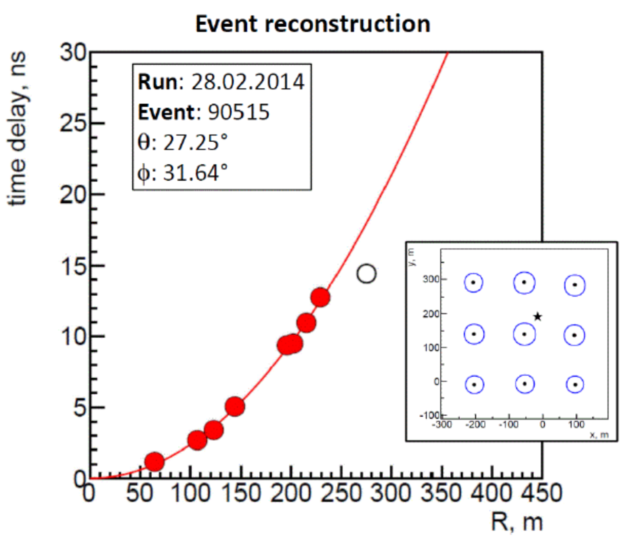

(a)



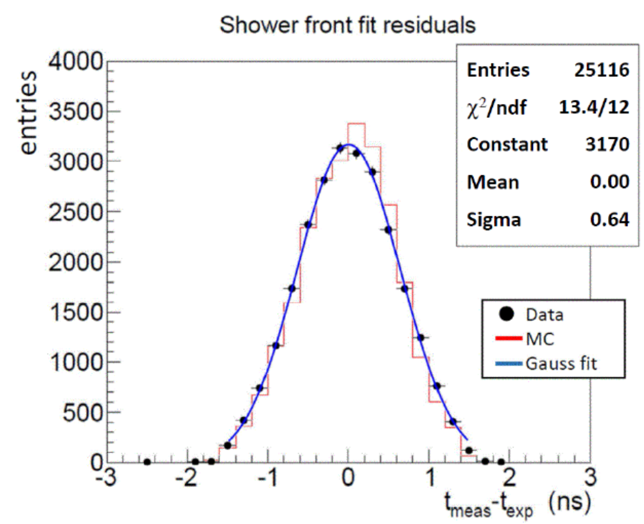

(b)

> **Cosmic Air Shower Reconstruction**

Fit-Resid ~0.6ns




(a)




(b)

(left) Shower front: time-delay vs. radius

(right) fit-residuals all stations

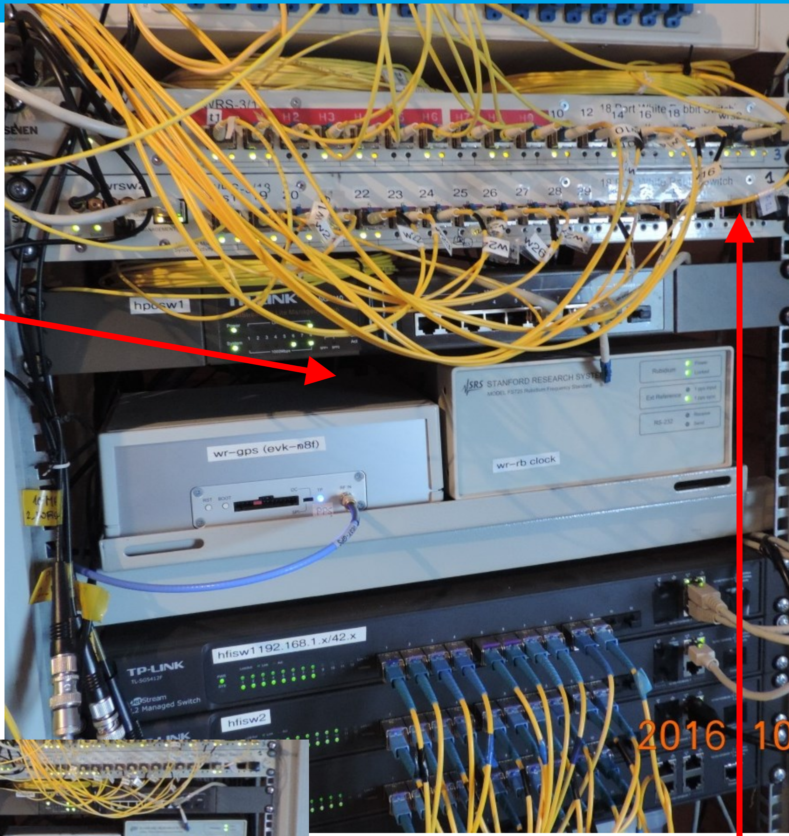
Figure 9: EAS shower reconstruction. (a) Arrival time delay vs dista

ICRC2015, 1041

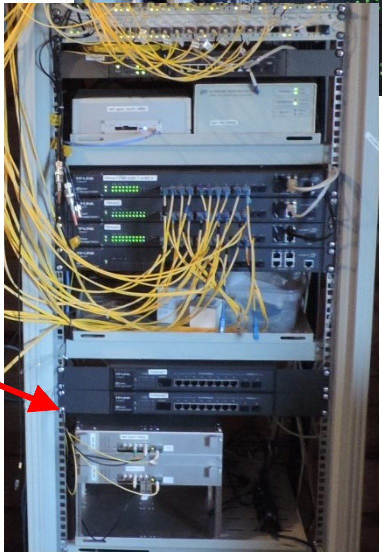
# WR ClockMaster – an end-to-end Timing Setup

- Completed the HiSCORE WR setup by a GPS-disciplined RbMaster Clock

  (Oct.2016)




- Central nsec-monitoring all other subsystem clocks running at the TAIGA-site by:
- WR-SPEC cards running in "nsec-TDC mode" (time-stamping)



WR-Switches: GrandMasterSW + BoundarySW

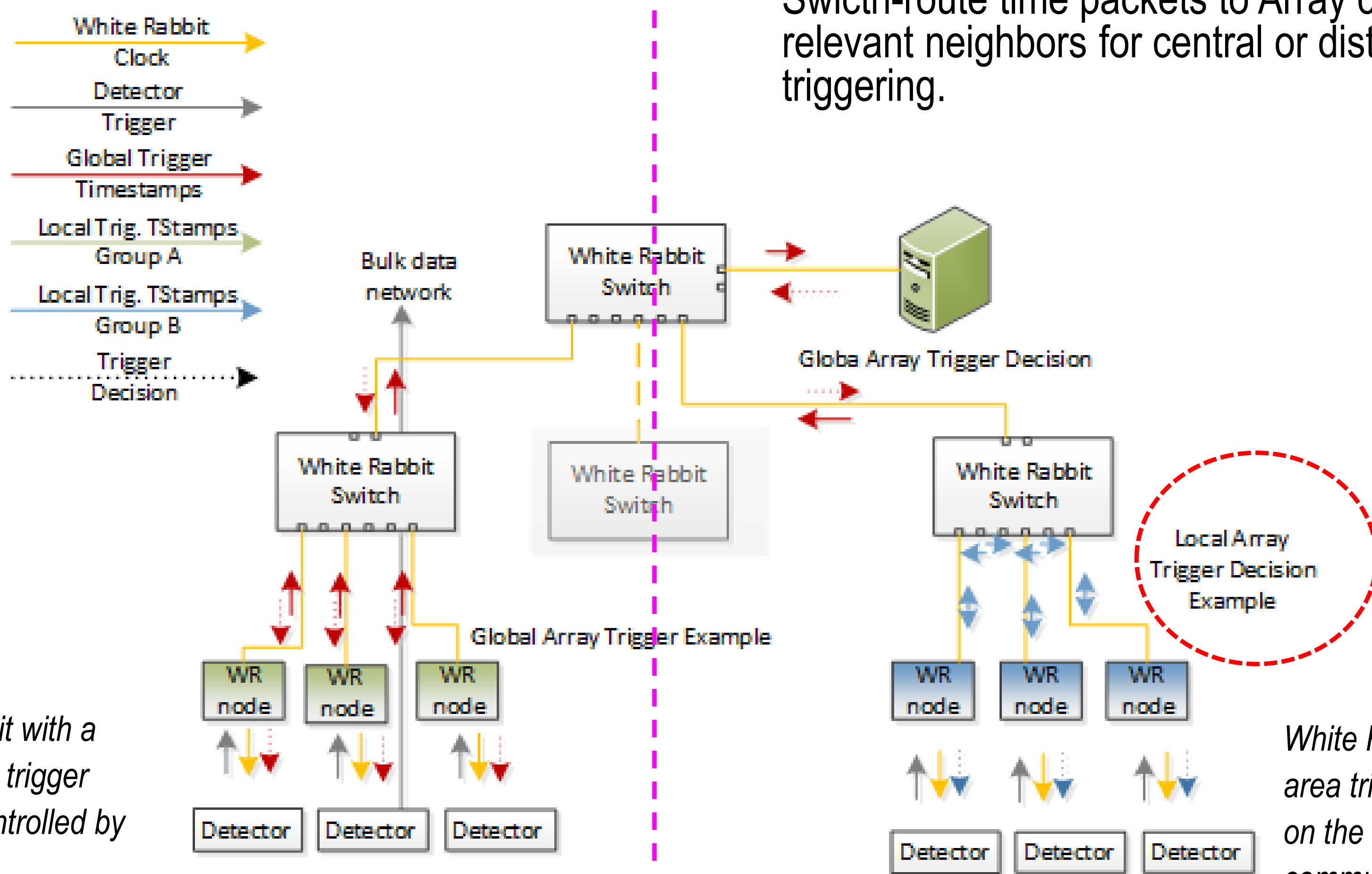
# A more complex WR-application (proposal) ….

# WR-driven Array Trigger Concepts

***(A) Standard application*: WR-timestamps are used to correlate the data offline**

***(B) Optional*: WR-timestamps are routed for fast online triggering and / or filtering locally. Flexible topologies.**

Swicth-route time packets to Array center or to relevant neighbors for central or distributed triggering.




*White Rabbit with a global array trigger decision controlled by the center.*

*White Rabbit with a local area trigger decision, based on the neighbor's directly communicated triggertimes.*

# Conclusions (1)

- Large-scale AP experiments need distributed ns-timing …

- …. WR perfectly fits requirements
  - Clock distribution
  - Trigger time stamping
  - Active calibration (‘ext. trigger’)
  - In-situ-verification ( data or/and hardware redundancy )
  - … more complex triggering

- WR has been implemented, and operating in HiSCORE
  - Time-stamping
  - Operating as expected: precision, accuracy … first physics EAS results
    ( ‘end-to-end test by shower‘ )
  - Long-term cross-checks (since 2013…)
  - Bonus: a fully WR-based GHz prototype DAQ, ready for >km2-scale
  - Timing-solution is generic – and easily adapted to other applications

# Conclusions (2)

- **Time-stamping with o(1 nsec )**
  - WR-SPEC or WR-ZEN (ZynqARM-based)
  - In preparation: resolution < 1 ns

- **WR-experience shapes the design of new projects: CTA + …**
  - **Basics methods**
  - **Intrinsic data-redundancy (!)**
  - **Optional self-verification (!)**

- Next: exploit the complex system-aspects, intrinsic to WR-driven DAQ's

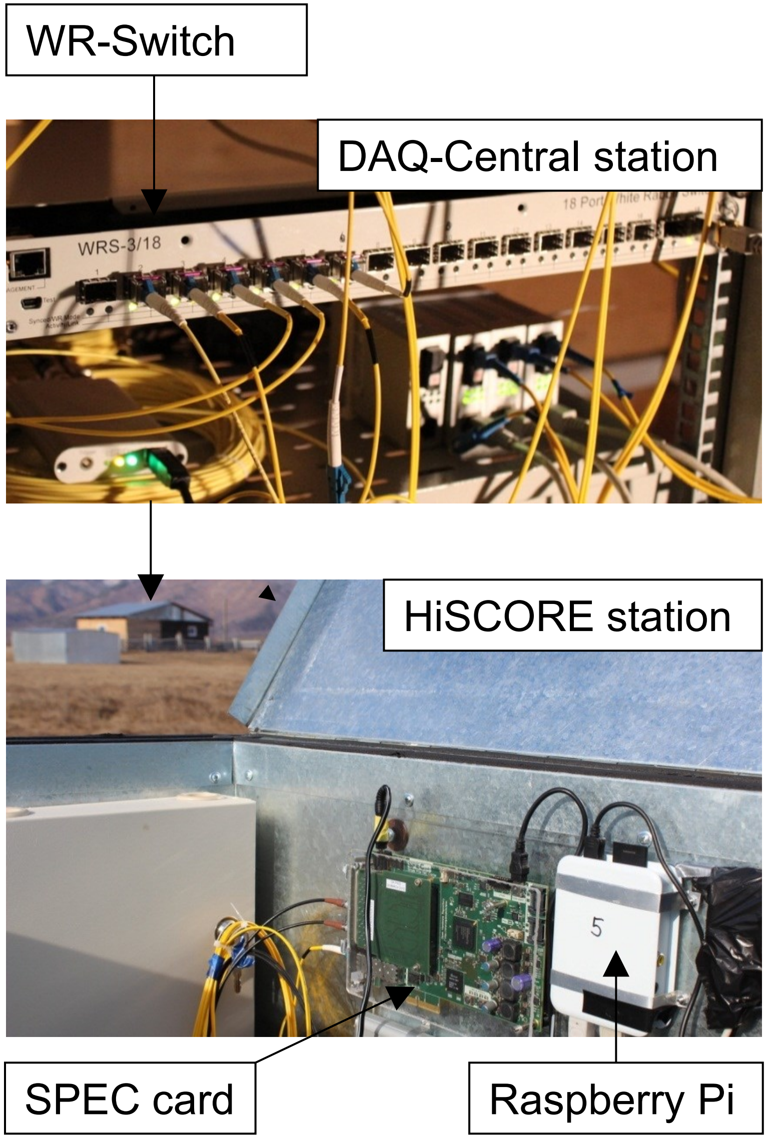
- ***Account for the unique WR-features from early stage design of new DAQ-architecture, e.g. of HAWC-South.***

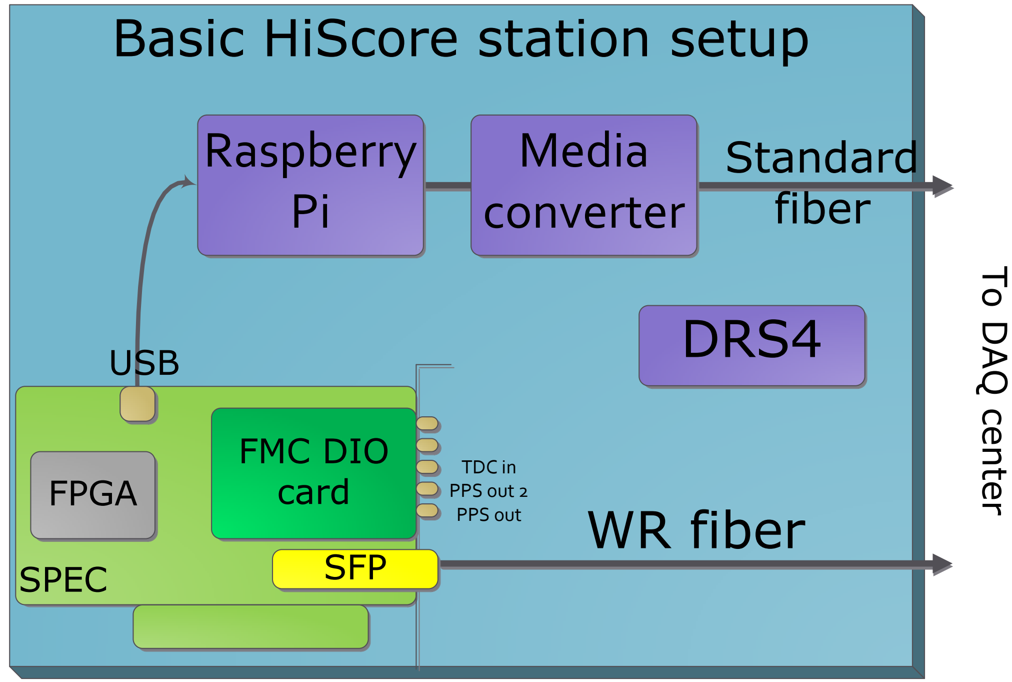
  ***Clock, trigger-timestamping, precision calibration pulses, …***

The DESY group is willing + interested to contribute.

... Backup slides .

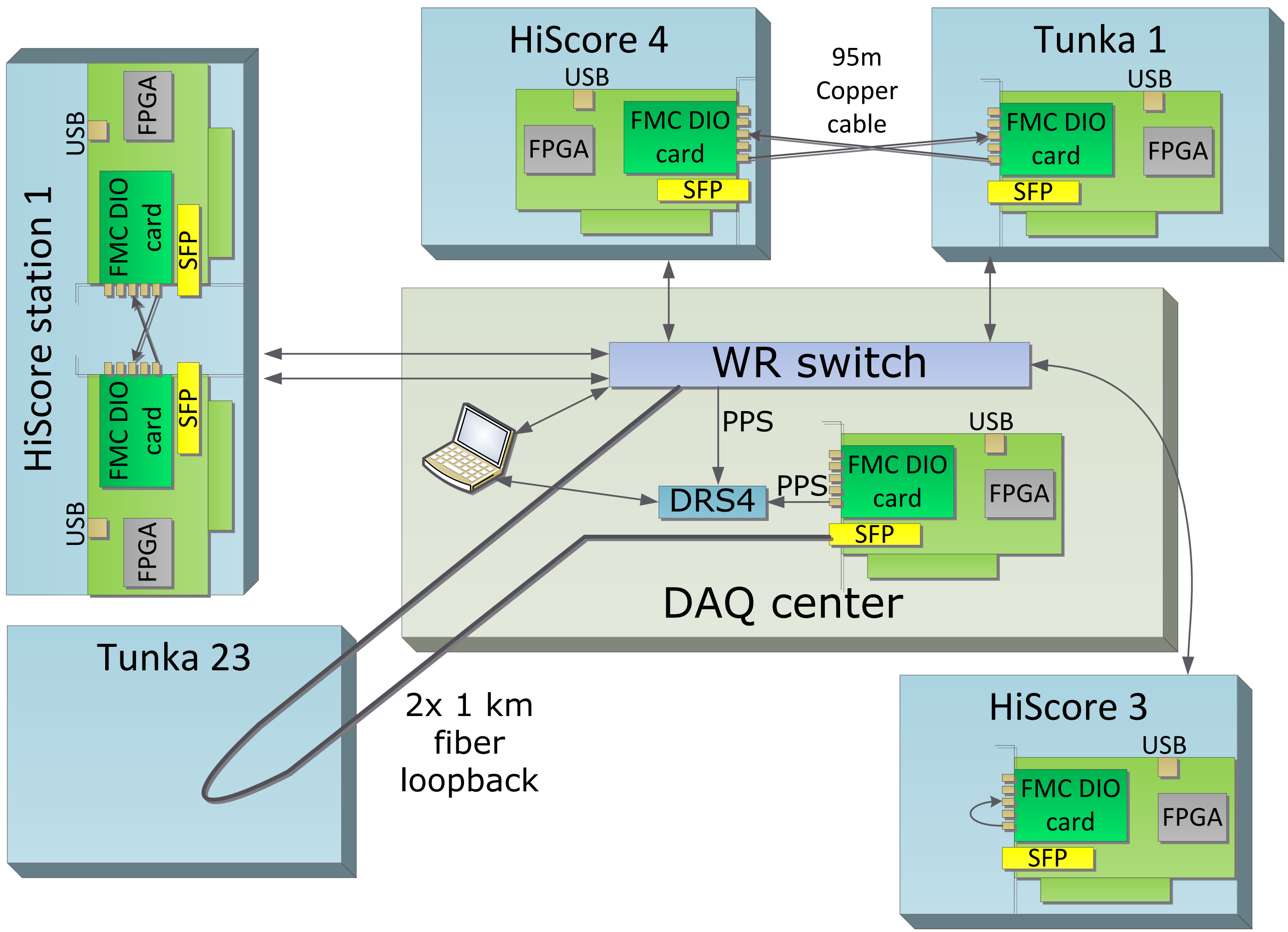
# HiSCORE setup overview




- DRS4 as 5 GHz “digital scope”
- Raspberry Pi transports
    - USB Terminal
    - DRS4 (Domino Ring Sampler)
    - Temperature sensor
    - …

# HiSCORE : WR Test-Setup 2012




PPS signals (DIO output 1) connected to TDC-inputs (DIO input 3)

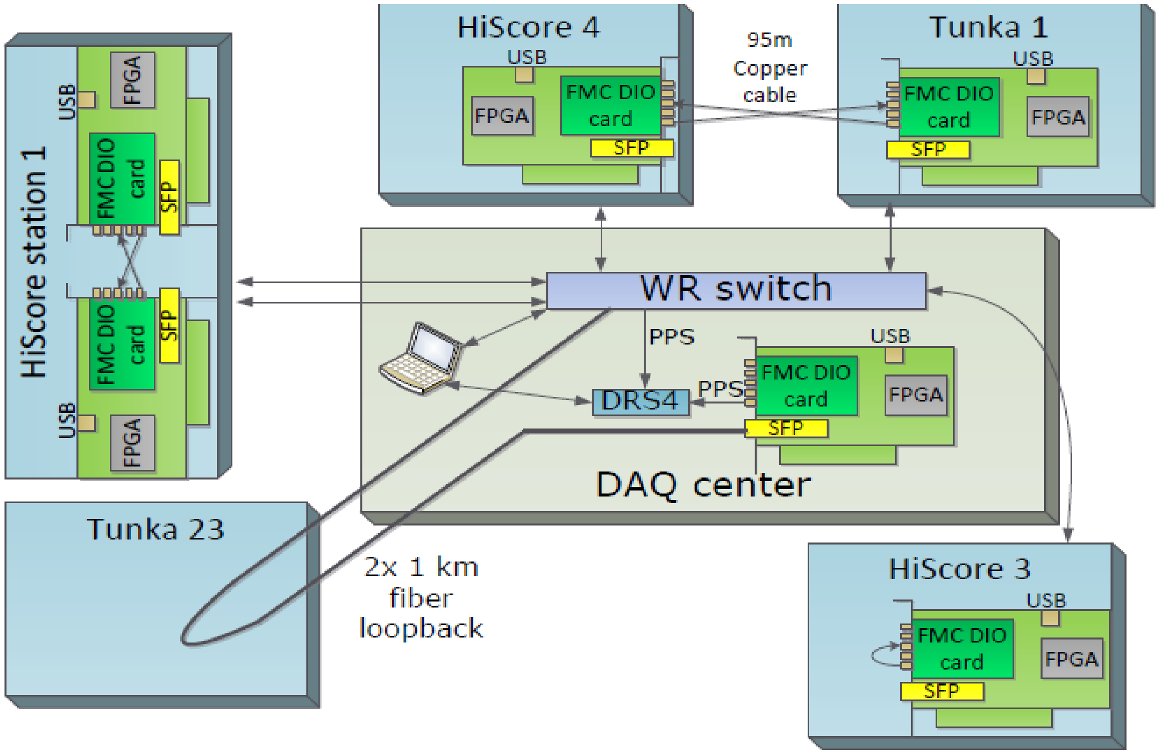
# WR – setup in Tunka

**White Rabbit Installation with a maximum of redundant cross-calibration options (October 2012 - today):**

> **2km loopback fiber cable connected to DRS4 to compare WRS and SPEC (2km) PPS clocks**

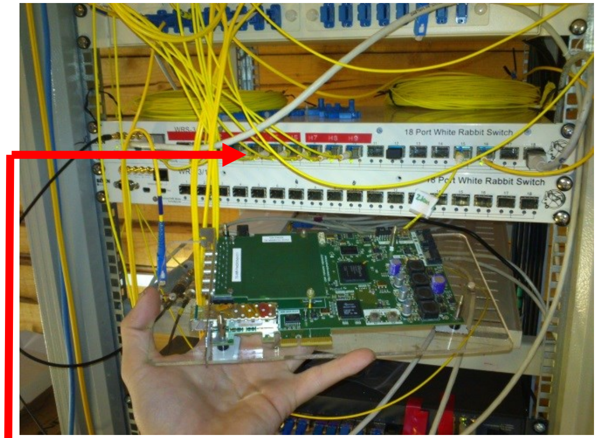
> **Crosswise PPS->TDC connection to test TDC and White Rabbit**
  - **2x SPEC within HiS1 station**
  - **2x SPEC in 2 stations (HiS4 + Tunka-1)**

> **Loopback PPS connection to test TDC performance (HiS 3)**



# NewTechnology: Timing with ZEN (Zynq Embedded Node)

**_WR Master: WR Switch_**




**_1Gbit fiber_**

**_WR-Node: ZEN card_**

ZEN board (by SevenSols)

Xilinx Zynq Z7015 based w/ 2x ARM9
- 1x FMC
- 2x SFP (DaisyChain, WR redundancy)
- 2x Gbit Ethernet
- Improved clock precision
- LinuxKernel

DESY adapted for HiSCORE/CTA (2015)

- FMC-based operation (DIO, …)
- "nsec-timestamping"
  - 2 ns now: Zynq Grade -1 (933 MHz)
  - 1 ns soon: faster Zynq by 7Sol
- TCP timestamp transport
- (( PPSOut /10MHz out ))

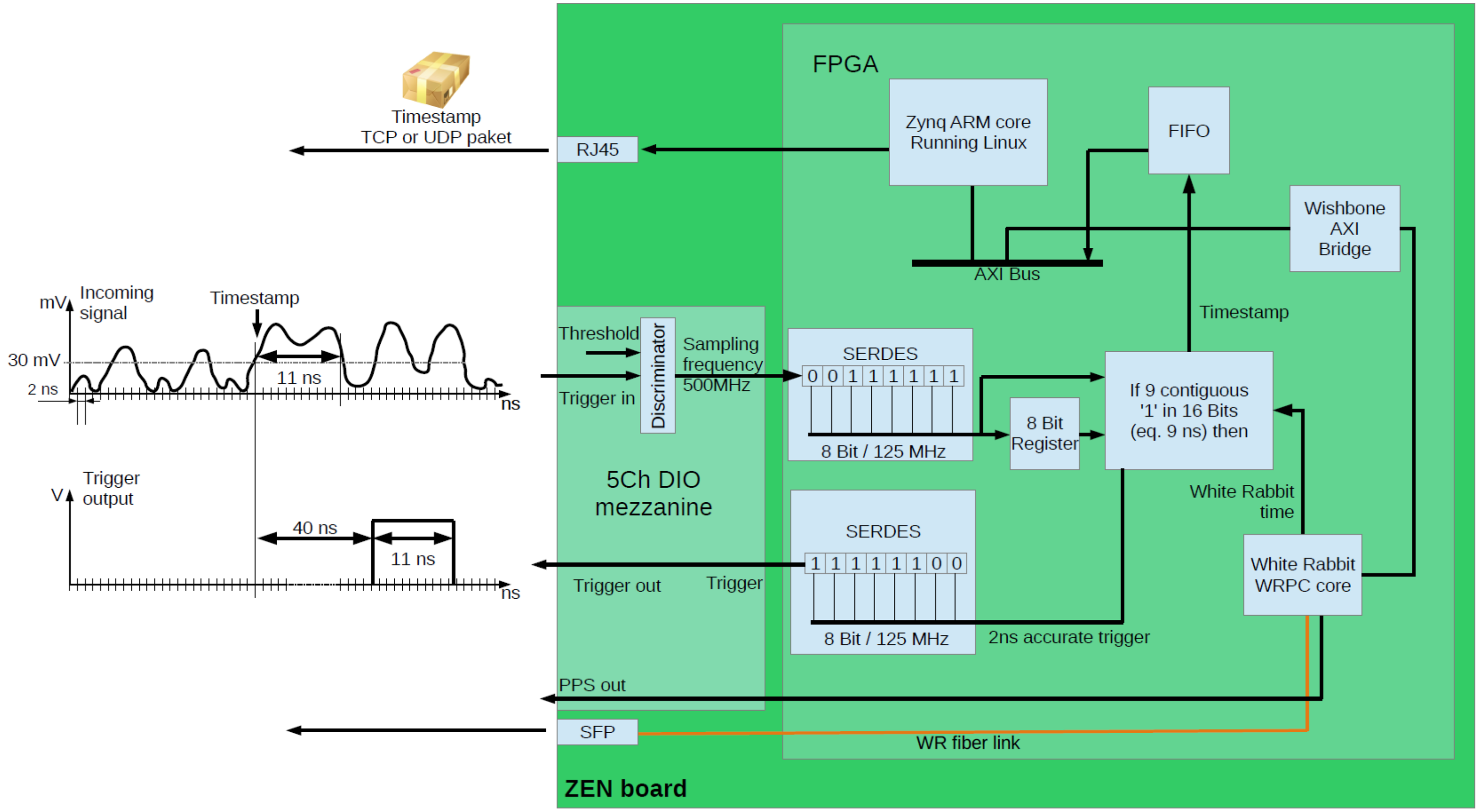
→ Performance, timing, stability, …:
… is excellent !

# ZEN : Timestamp with Standard TDC

- ZEN with time-stamping 2ns (→ 1ns with grade -3)

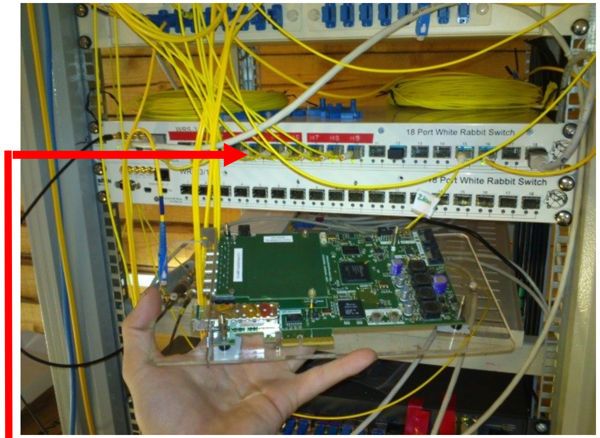
  Implementation similar to our TDC on the SPEC

  (w/ INPUT signal analysis, TRIGOut for local DAQ)



# ZEN : Timestamp Test

**_WR Master: WR Switch_**

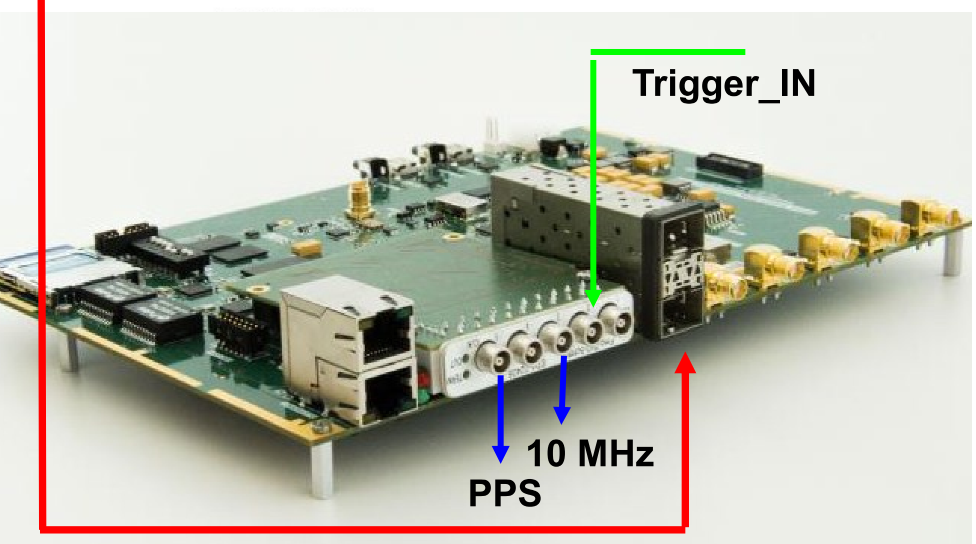


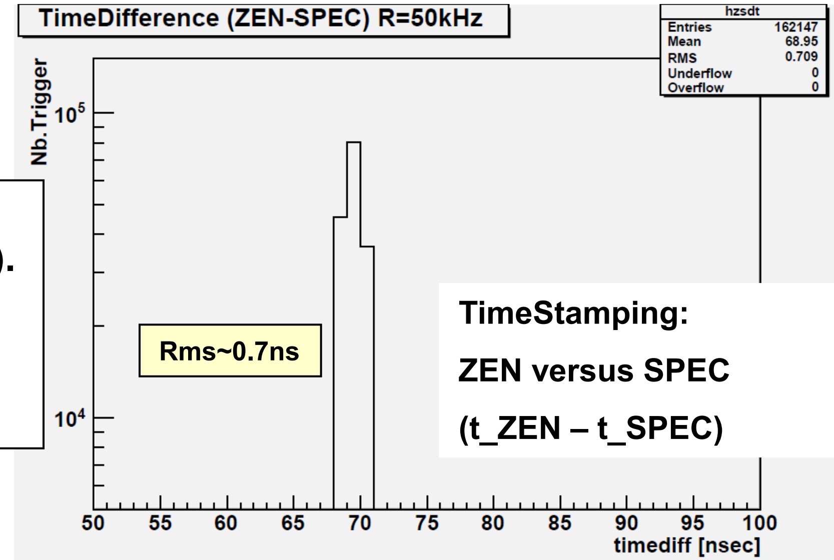
**ZEN: verifying the time-stamping (2ns).**

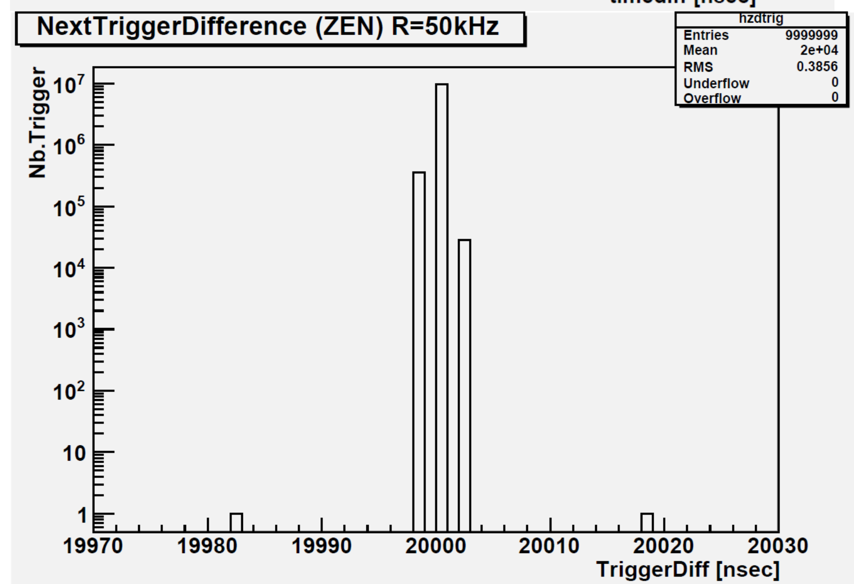
**High trigger rate proven. ~500kHz is realistic.**

**_1Gbit fiber_**

**_WR-Node: ZEN card_**




**ZEN-only test: NextTrigger Time-difference with nsec (very stable pulser).**