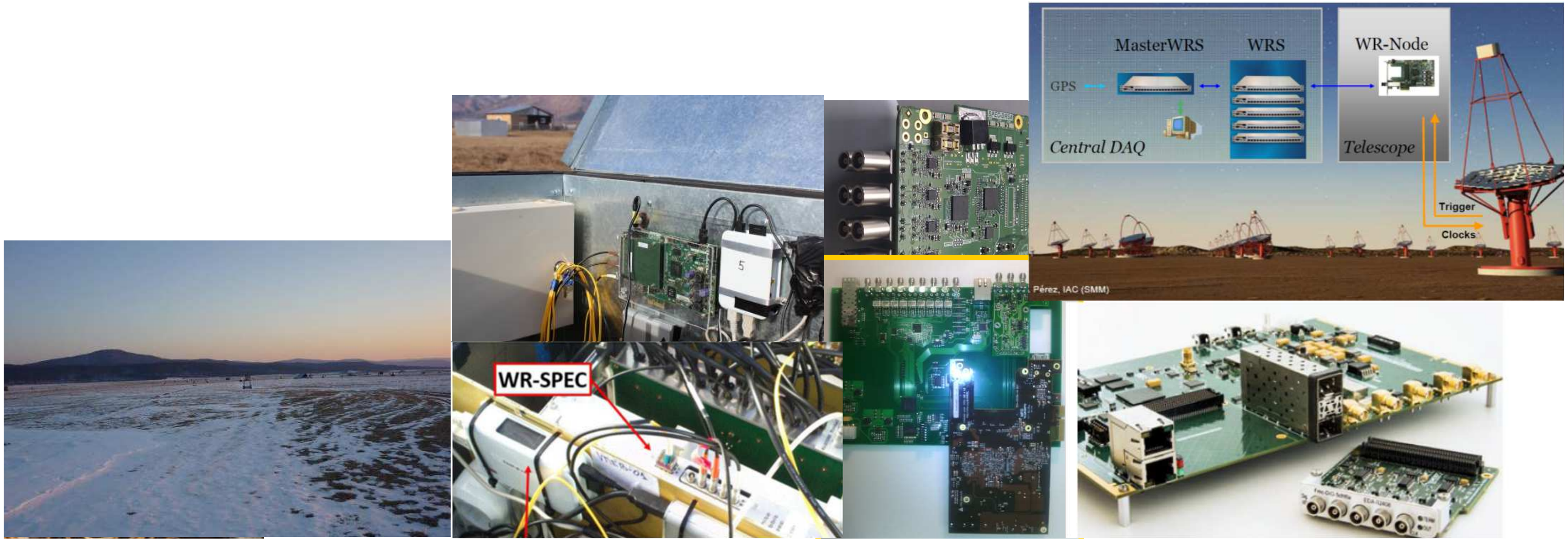
Timing Systems for Particle and Astroparticle Physics

Ralf Wischnewski (DESY)

TorVergata/Rome, 21.3.2016



“ … Timing Systems for Particle and Astroparticle Physics … “

Disclaimer

- **This talk is strongly biased by my recent experience**

  (after working with other “custom” timing systems in the past)

- **Executive summary:**

  “There is One and only One Timing System for APP “.

- **Focus is on Astroparticle. Particle physics may survive the old way.**
- **Accelerator applications will be briefly mentioned.**

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 (and no Con's)**
- **White Rabbit in operation: experience with Tunka-HiSCORE**
  - **Experience over 2012—2015**
  - **(some) conclusions for upcoming projects**
  - **Recent WR developments**
- **Conclusions**

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))

9th WR Workshop, Amsterdam, March 2016, RW

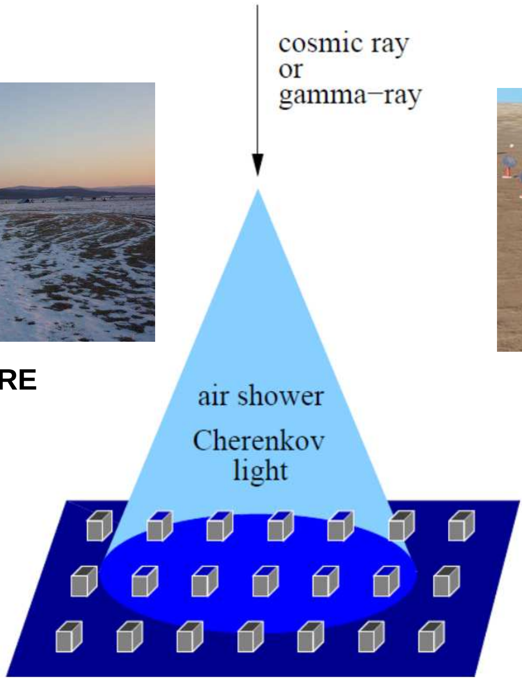
CERN-WR: http://www.ohwr.org/projects/white-rabbit

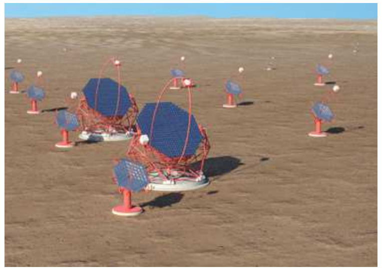
Large-scale Astroparticle Experiments …

- Are made of detector elements, distributed over large areas - like Sensor stations, Cerenkov Telescopes, Water-Tanks, Ice Tanks, PMTs in pressure housings
- Need to measure spatial / temporal arrival pattern of light-/radio-flashes/particles…
  - Examples: Km3Net, Ice3, CTA, HiSCORE, IceCube, HAWC, LHAASO
- Area: km^2 … 100km^2….
- Timing precision: governs data quality !

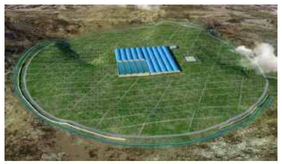
  (sub-) nanosecond precision (sensor, media)

HiSCORE

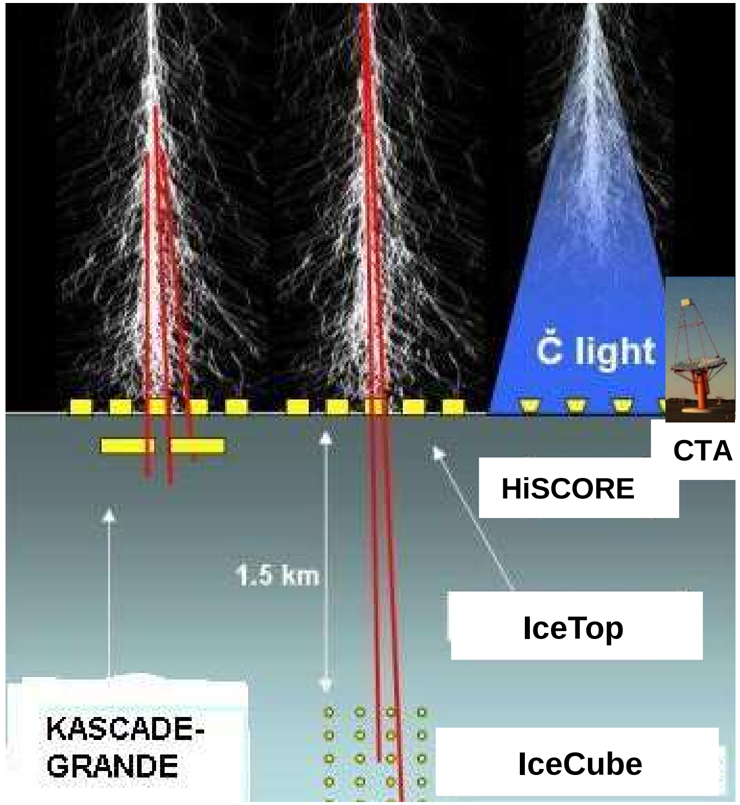




CTA



LHAAO



... and Timing (Trigger) concepts

Centralized Arrays

In large-scale AP experiments it is still common to (like in compact accelerator experiments) to

(1) measure times against a central reference signal (eg. *common stop)*

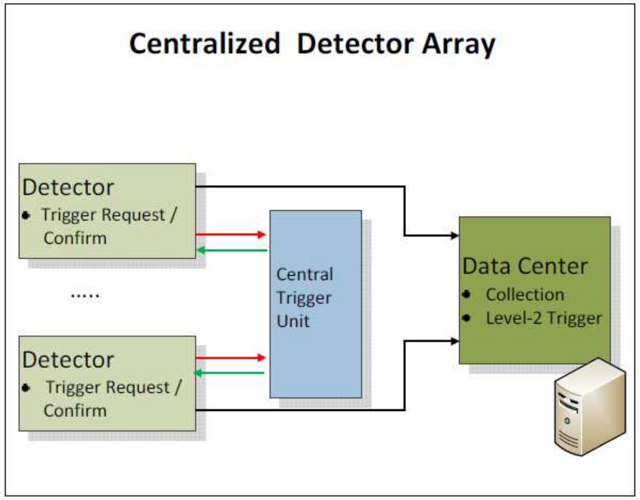
(2) trigger at a central place (confirming the detector trigger-request signals).

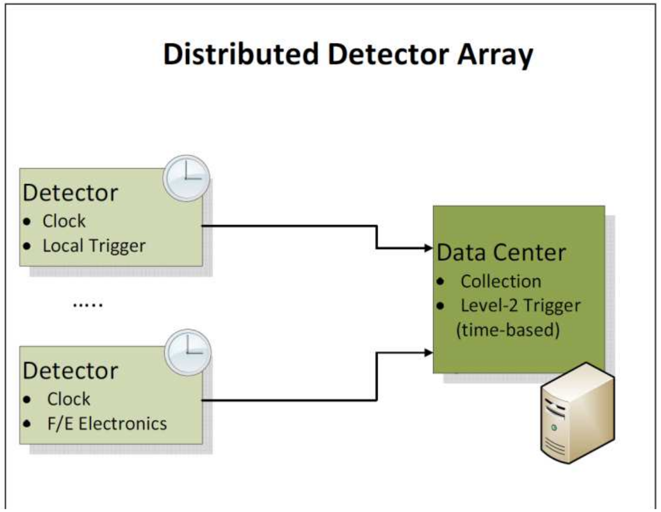
This "central triggering" can contribute to large dead-times, and analog-buffer depths.

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.

... and Timing (Trigger) concepts

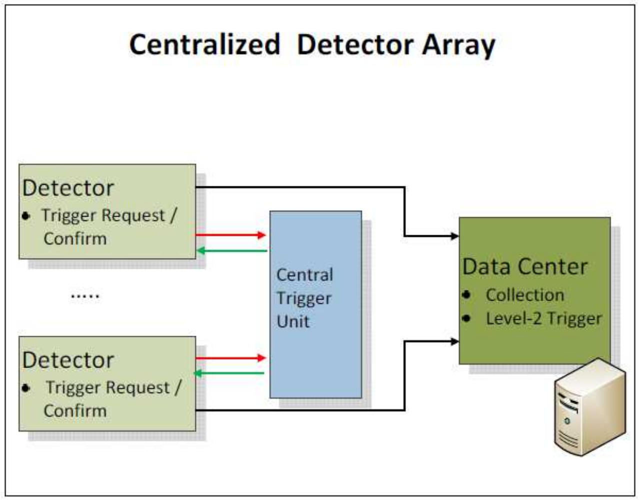
Examples:

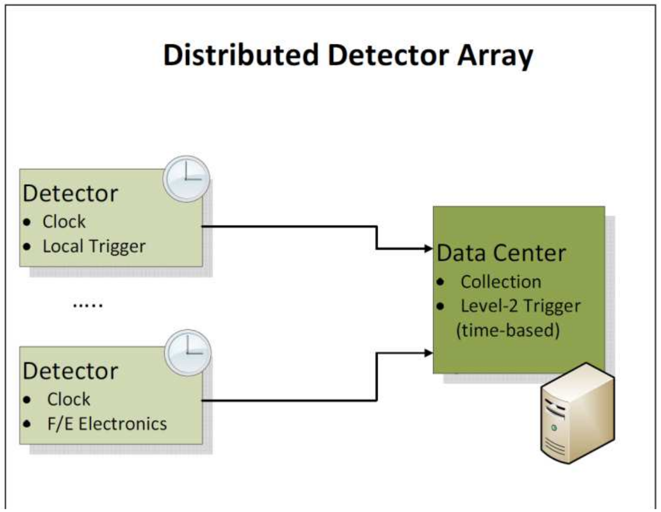
Centralized Arrays

- Amanda, Baikal Neutrino telescopes (1990-2005)
- Fixed target detectors

Distributed Arrays

- IceCube (5000 clocks under-ice; over copper wires)
- Antares, NEMO (clock on fiber)
- AUGER (GPS)





Each detector has a precision clock.

... and Timing : Using Distributed Clocks

Which Technologies to distribute nsec-precision clocks to each detector exist?

> **Custom made systems build over 20++ years for nsec-precision ☹**

For next generation projects: is there a "standard nsec-timing technique" ?

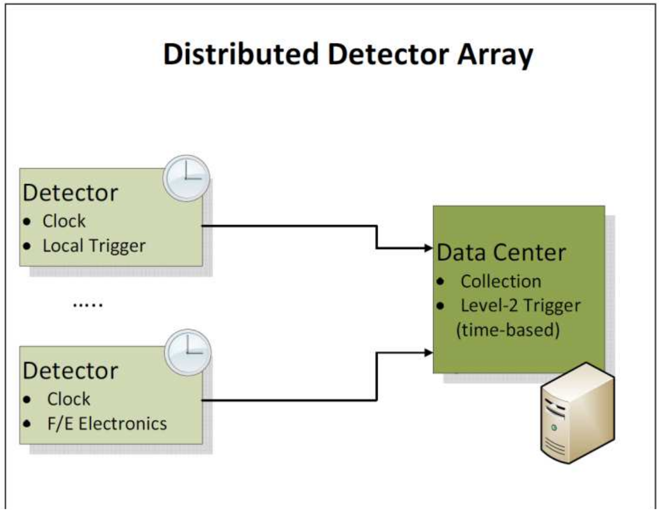
> **A new technique developed: " White Rabbit " → worth investigating ☺**

Note: Existing timing tools are not a generic solution

> GPS: precision (o(20-50ns)), reliability, price, availability

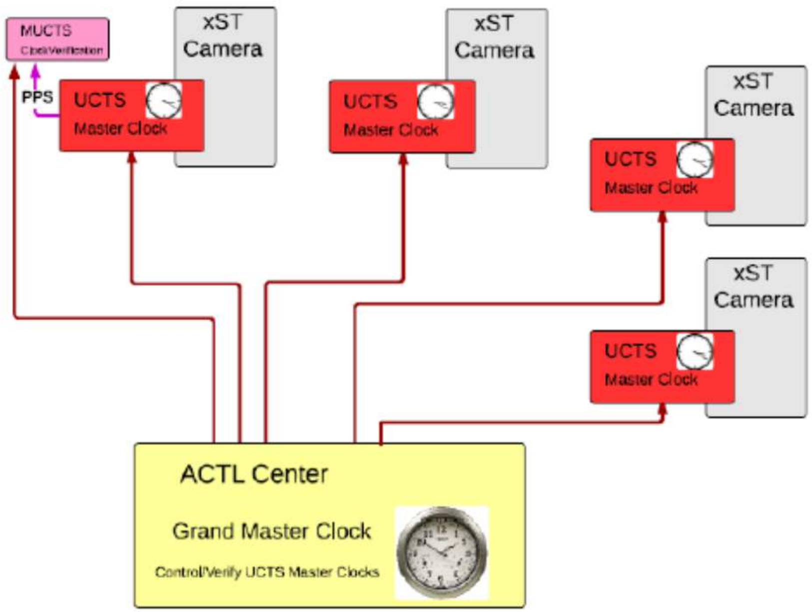
> NTP (network time protocol): ms-scale over LAN/WLAN network

> PTP "precision time protocol": ~usec-scale



Timing : Distributed Clocks

- Generic example: 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 → perfect for CTA-purposes



→ 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.

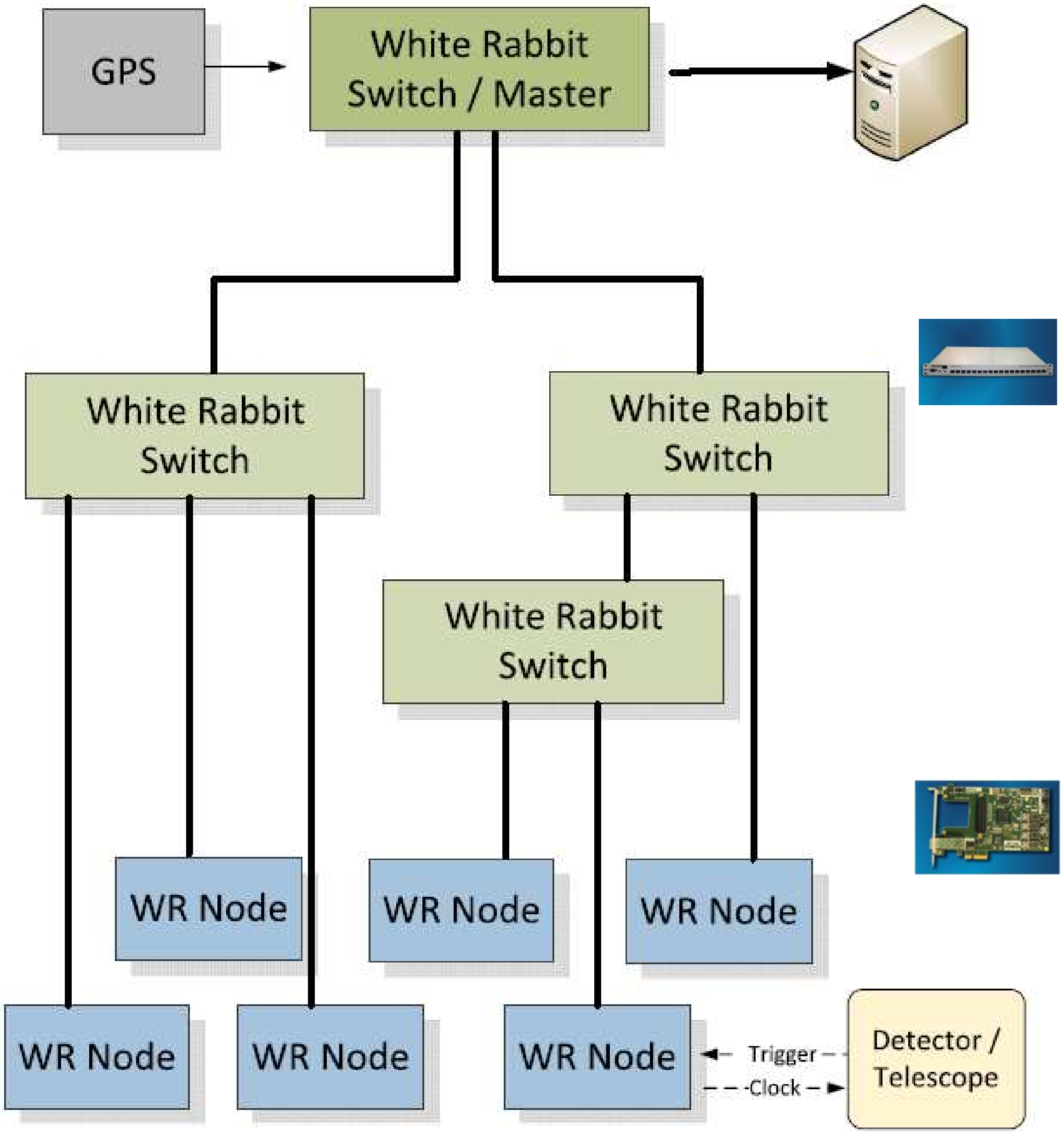
Extension of PTP. Uses proven 1GbE fiber technology.

A WR network is made of

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

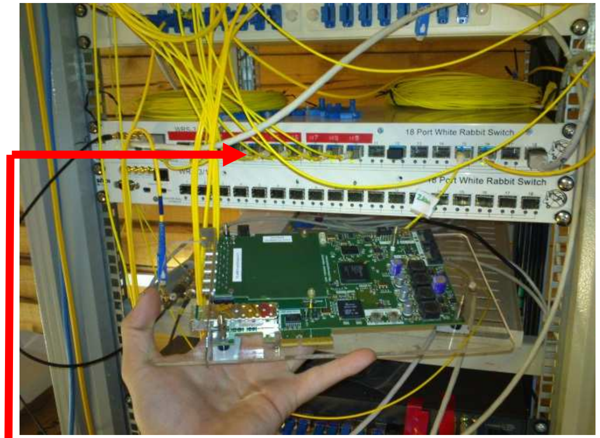
Parameter:

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



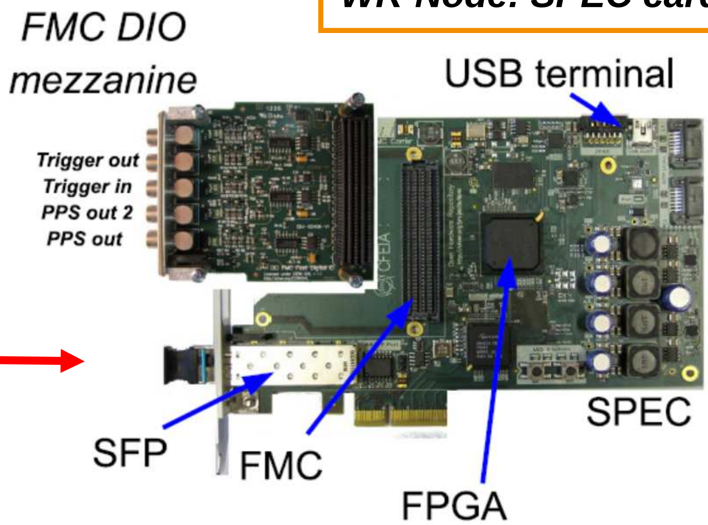
White Rabbit: The Hardware Components

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”)

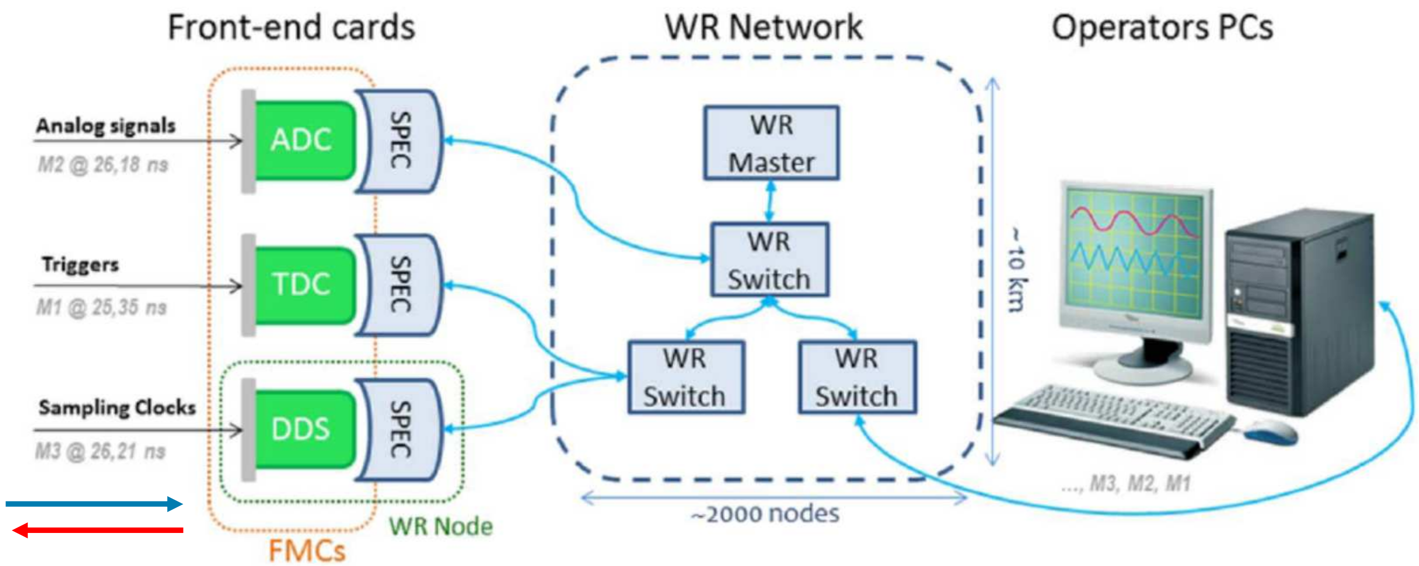
Spartan-6 based PCI-size card
1x FMC (Mezzanine)
1x SFP (WR fiber)

(the WR-Node workshorse since 2011)

White Rabbit - Application

Example - a distributed DAQ system.

Sensors located over a wide area, eg. accelerator.



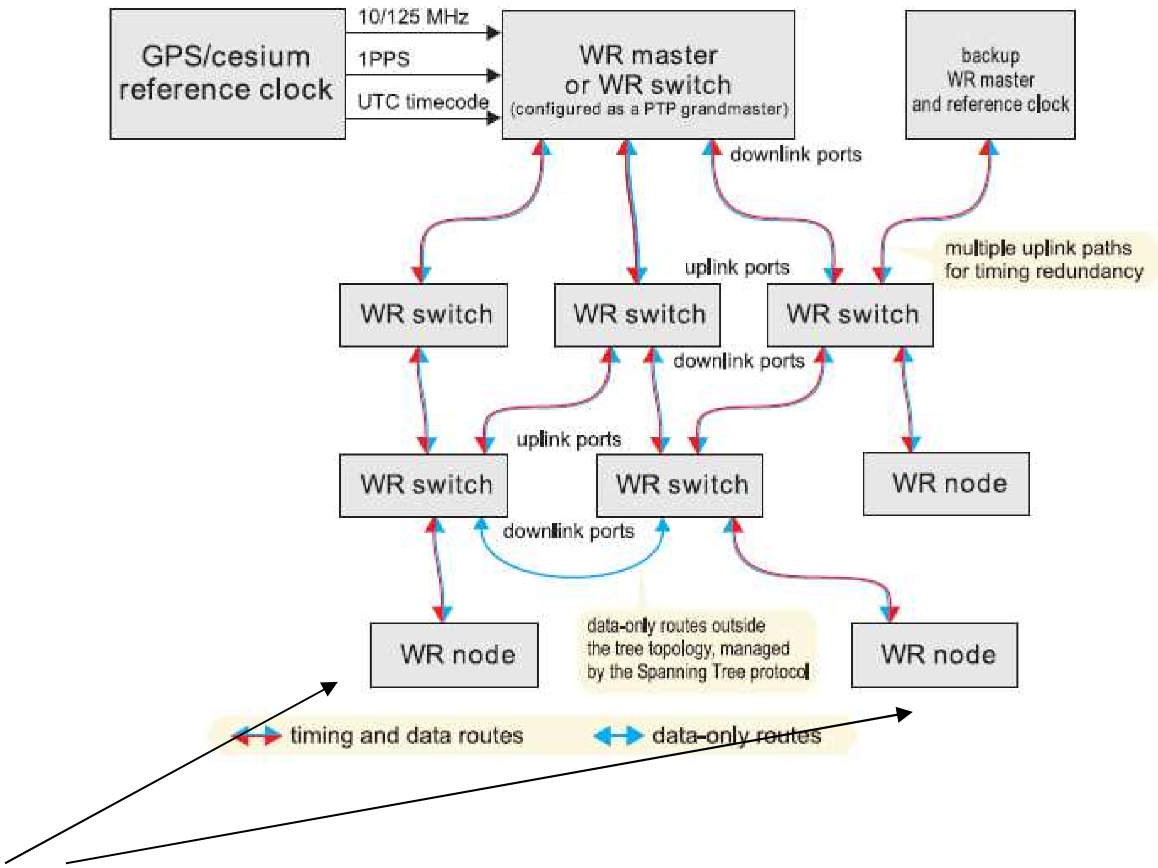
Functionality:

<u>Measure **AND** Control (In / Out)</u>,

by the same node with the clock-driven precision.

(see also pg.19)

White Rabbit - Network topology

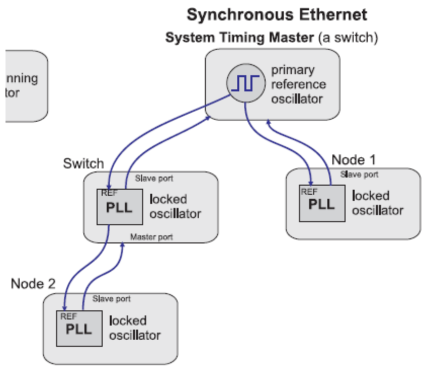


- **WR-Node = User modules with local clocks**
- **WR-Nodes are synchronized over the WR-network to the Master-switch (WRS).**
- **Master-WRS is connected to a reference clock (GPS/Caesium).**

White Rabbit - How does it work ?

> Sub-nsec synchronization reached by 3 ingredients

1. Clock is distributed from master via fiber cable to all nodes (Synchronous Ethernet), including switches



2. Slave bounces back the clock
   Master monitors phase of bounced-back clocks (DDMTD)

3. Master transmits absolute time and phase difference to Slave (Precision Time Protocol, IEEE1588)
   → Slave compensates link delay

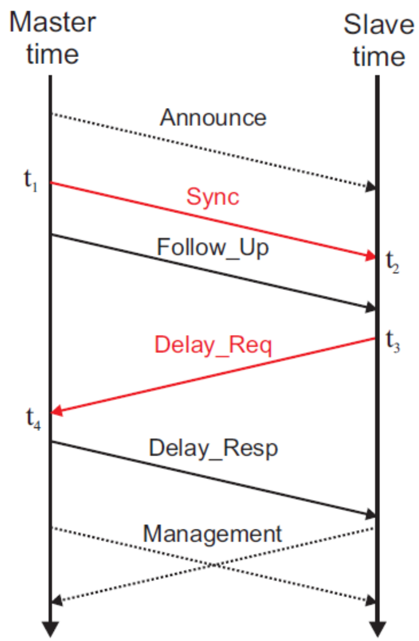
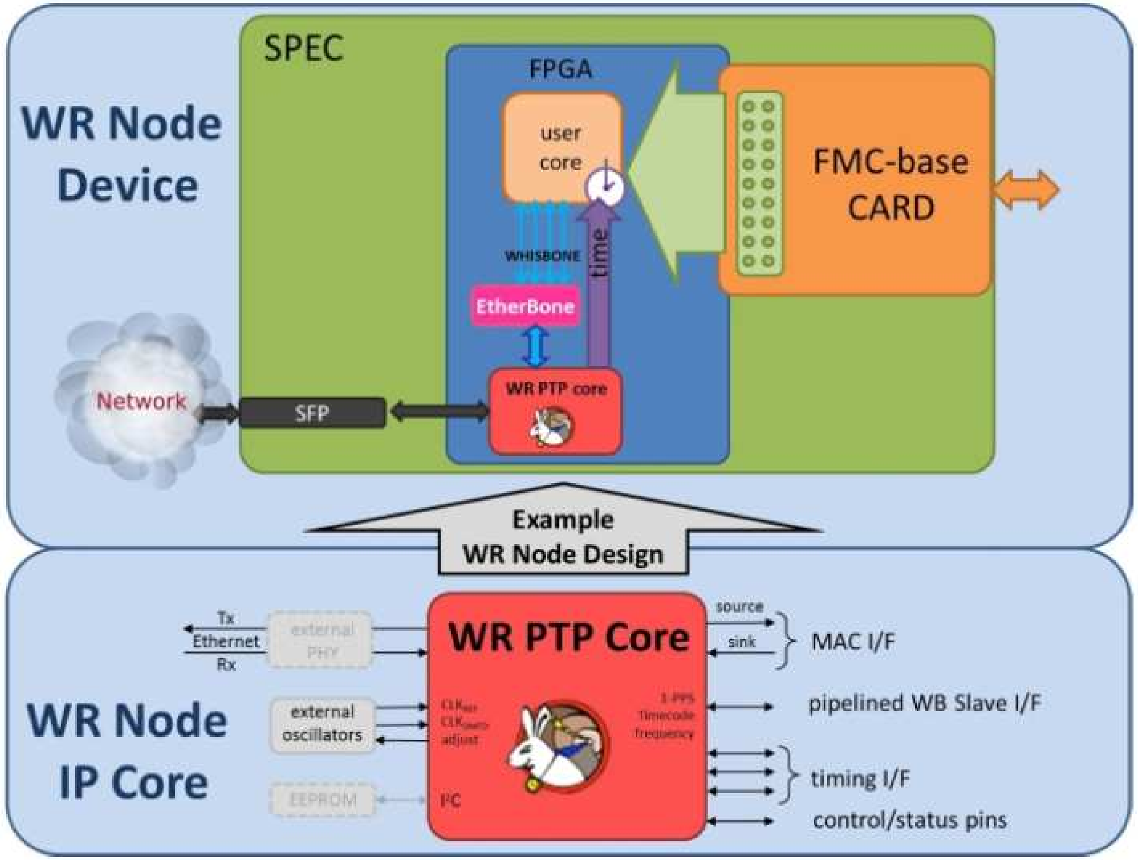
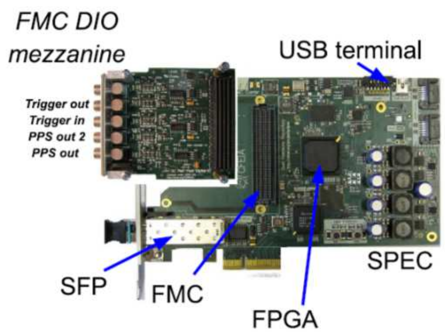


Figure 2: Simplified PTP message exchange di

An example WR-Node





(SPEC Board)

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.

Advantages :

> 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),

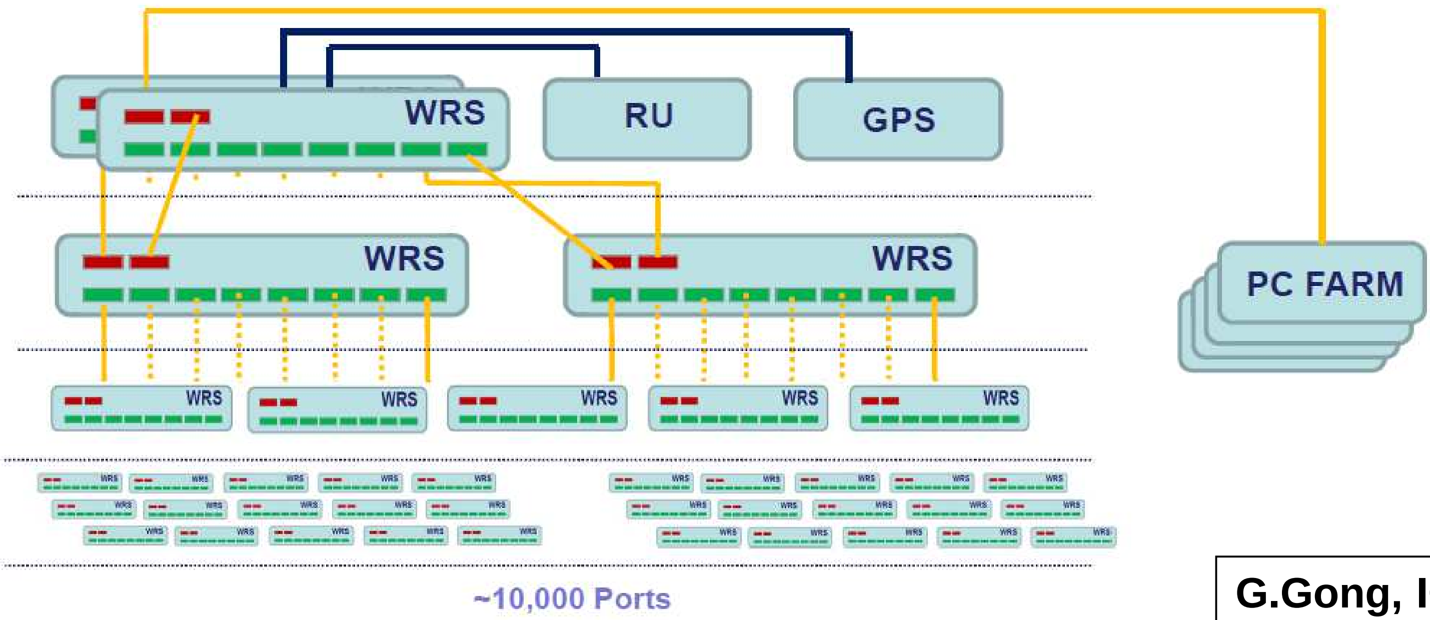
> WR Standardization is planned for Eth-PTP (IEEE1588…) in 2018

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

WR - Application :   LHAASO

LHAASO : ~10000 nodes to be synchronized.

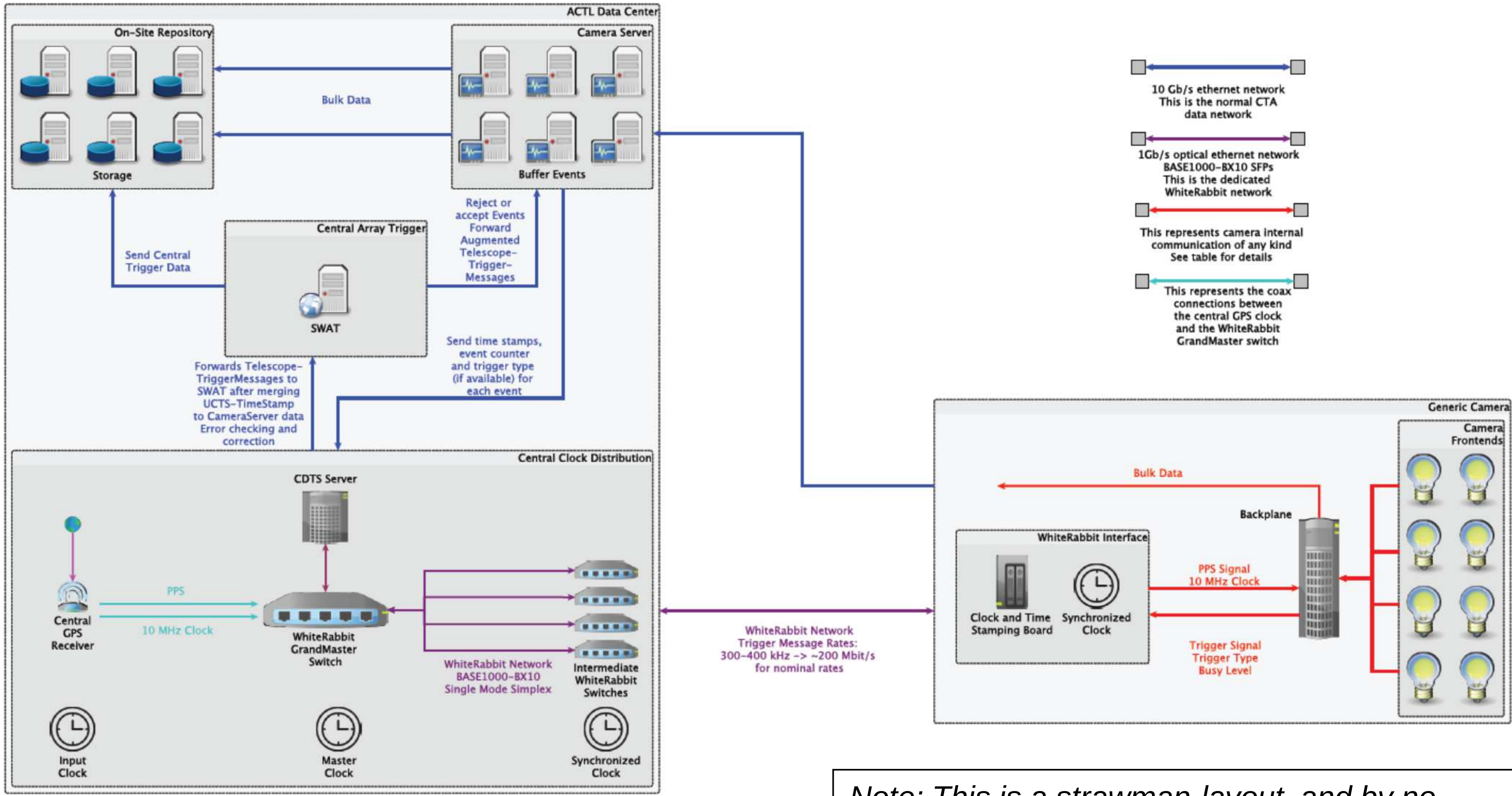
Test setups running.



G.Gong, ICALEPCS, 2011,

ICRC2015, ….

WR – Application / Plan : CTA Telescope Timing



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

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

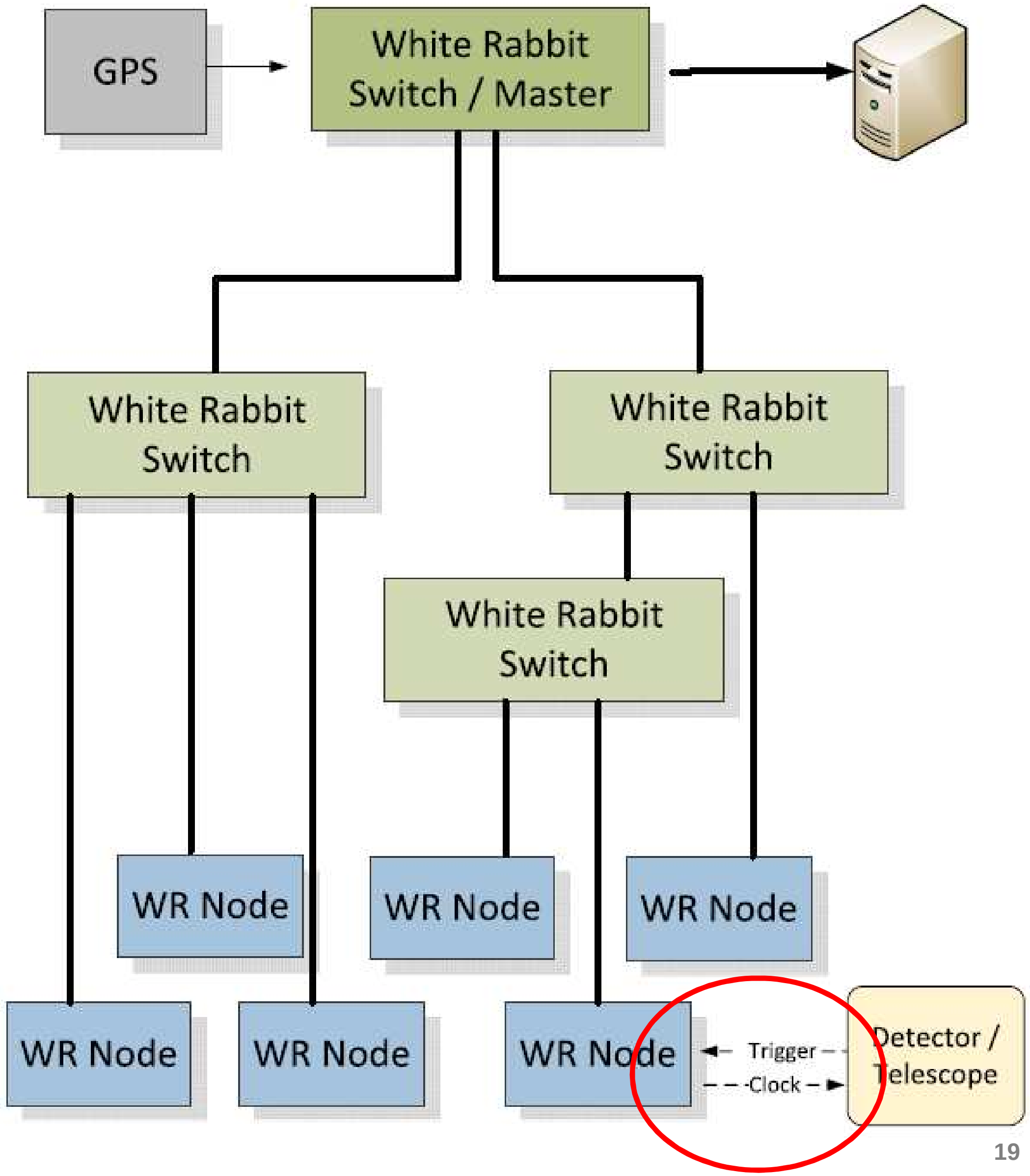
... and Timing : Using Distributed Clocks

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.

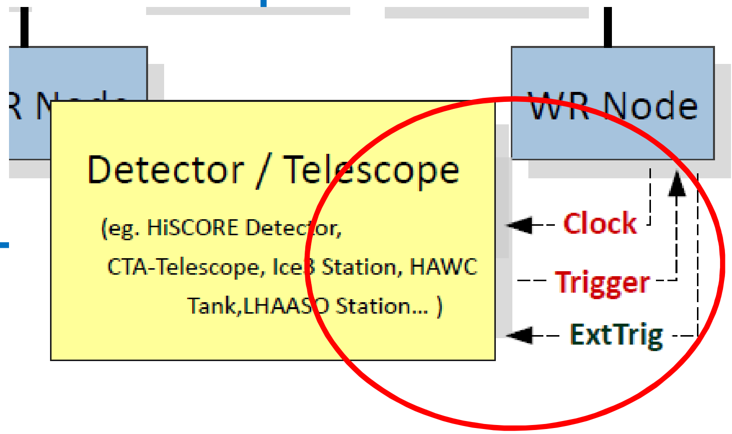
➔ WR is a natural technique to be used for this.



Detector and WR-Node : Baseline Interface

For each detector in the array it is required :

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



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-correctness 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 - Experience with White Rabbit

HiSCORE in Tunka, started 2012.

Since 2015 within the "TAIGA Collaboration"

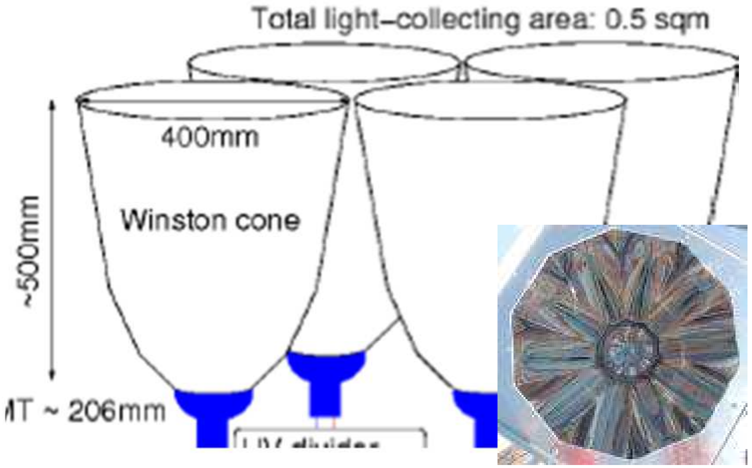
TAIGA =

Tunka Advanced Instrument for Gamma Astronomy and Cosmic Rays

TAIGA - HiSCORE : Concept

(Hundred*i Square-km Cosmic Origin Explorer)

Non-imaging Air Cherenkov Array
Angular resolution : ~ 0.1 deg
Large Field of view (FOV): ~ 0.6 sr
Area: 0.25 km² ⟹ 5 km²
Station spacing: 100-200m
~140 channels / km².

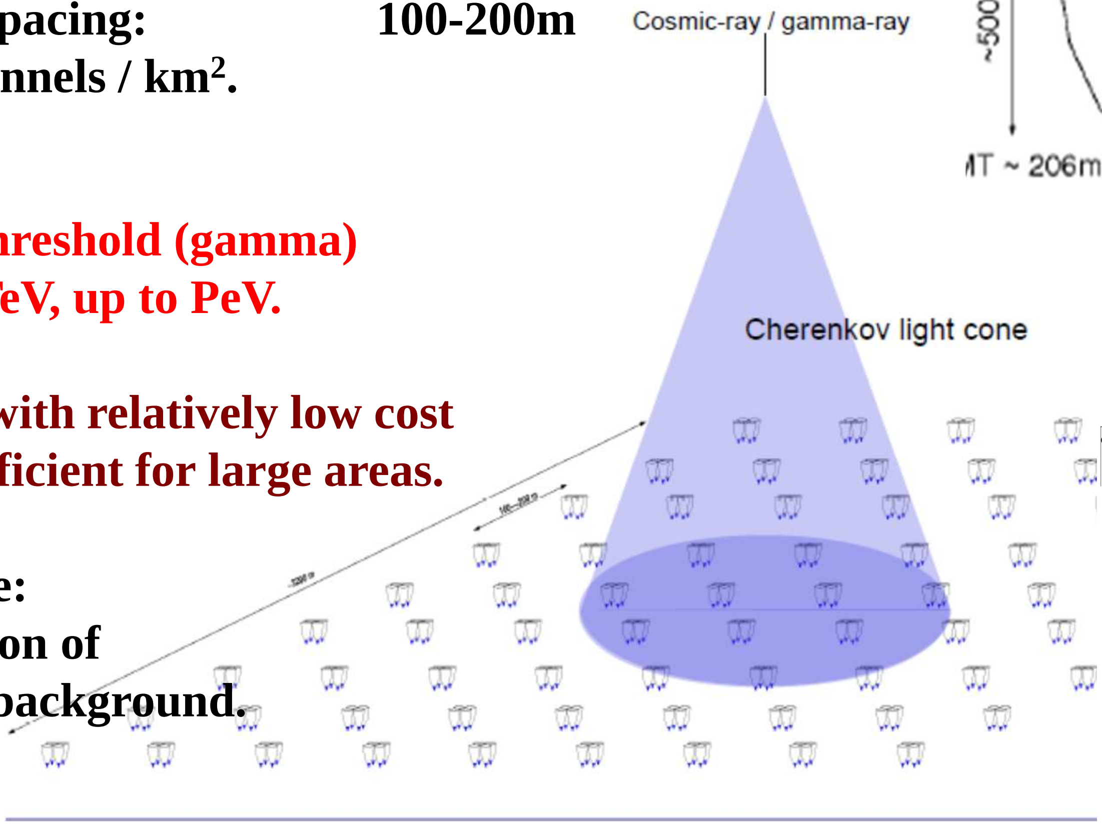


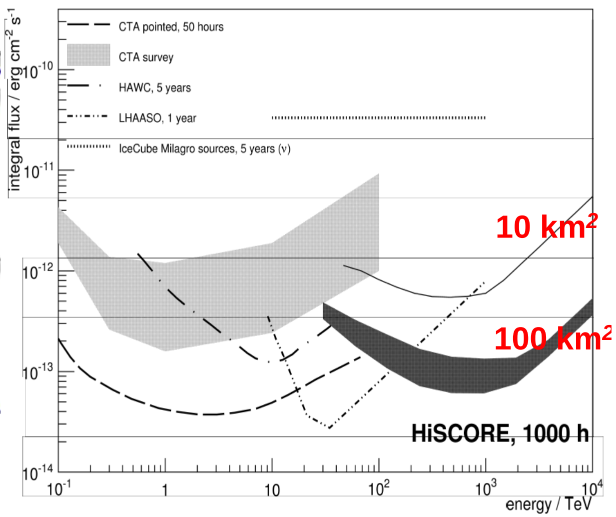
4 large PMTs per station.

Energy threshold (gamma)
Eγ > 30 TeV, up to PeV.

Stations with relatively low cost
→ cost efficient for large areas.

Challenge:
suppression of
of CRay background.





TAIGA: a Hybrid Gamma Observatory @ Tunka

+

+

TAIGA-HiSCORE

- 500 wide-angle Cerenkov stations on 5 km^2
- E_th = 30 TeV

Cost: ~ 8 M$

TAIGA-IACT

- 16 IACT Telescopes with mirror area 10 m^2
- E_th = few TeV

Cost: 0.3k$/Telescope; 5 M$

TAIGA-Muon

- Muon detectors A_total ~ 2.0 10^{3}m^2.

Cost: 3 M$

White Rabbit in HiSCORE - Brief History

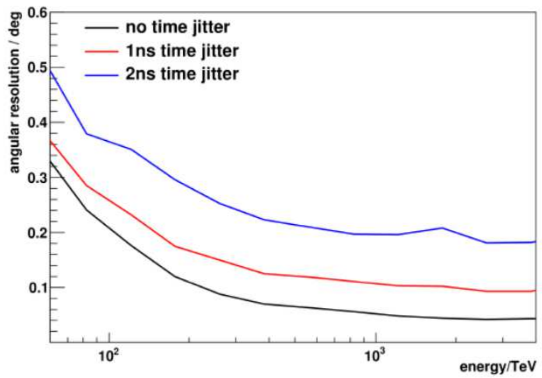
- Started in 2012 (HiSCORE)
- First WR field measurements : 04/2012
- Long duration tests : 10/2012-04/2013
- First reconstruction of cosmic ray showers (EAS) by WR-times: 04/2013

- HiSCORE -9 array: routine operation since 10/2013
- HiSCORE-28 array: commissioned 10/2015

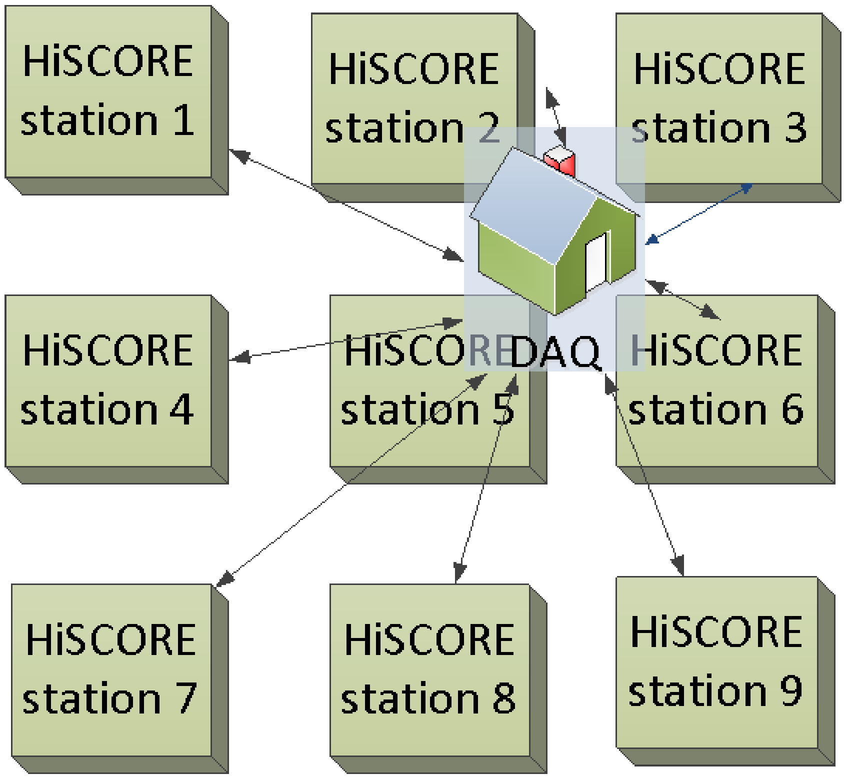
Timing in HiSCORE:

Crucial for pointing (MC):

Time Synchronization to <1ns



HiSCORE-9



First prototype array: since 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.

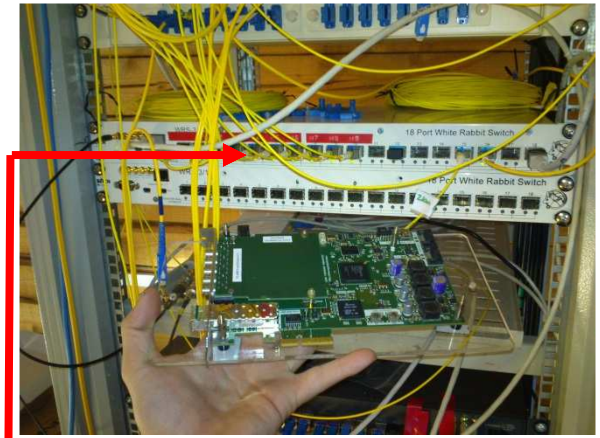
Prototyping with HiSCORE-9: Optical Stations / DAQ / Timing / …

Main Results:

- Air-Shower reconstruction
- Timing calibration by external LED

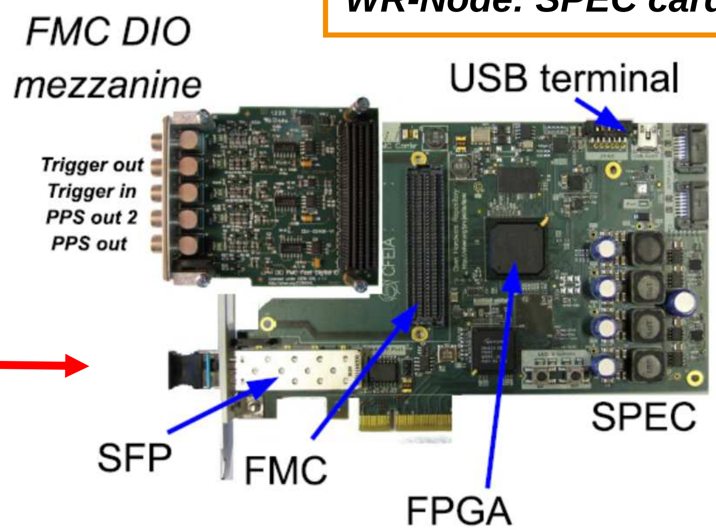
HiS-9 Station: The SPEC as the WR-Node

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, …

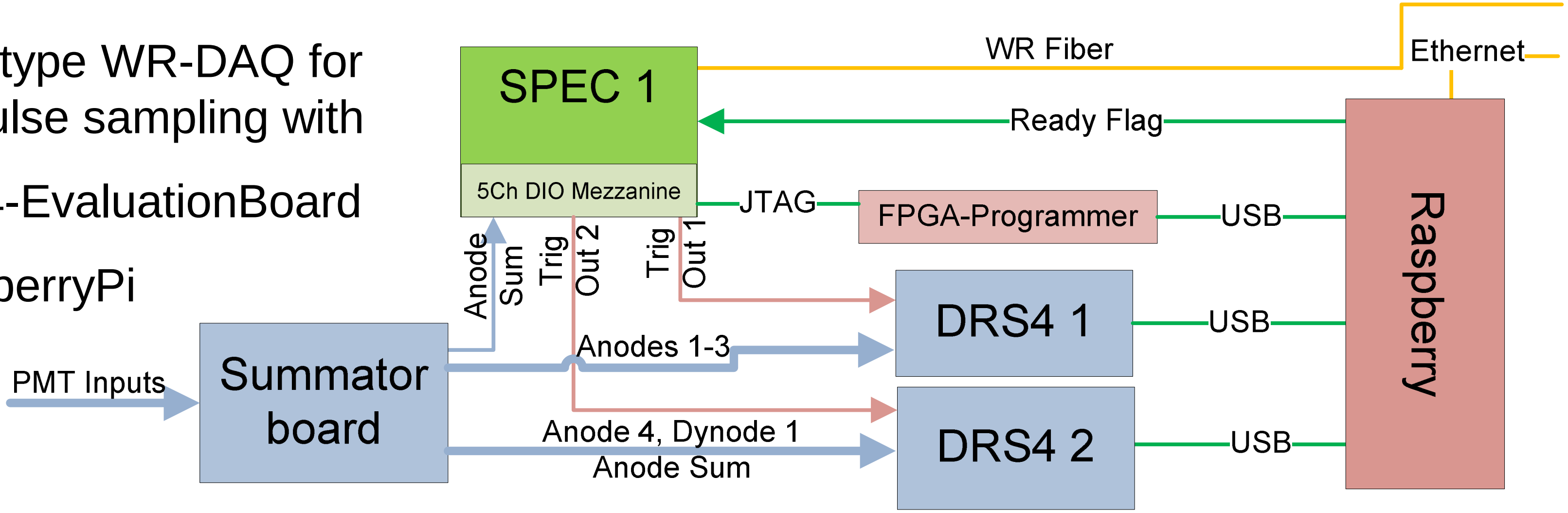
<u>APC adapted for CTA (2015)</u>
→ see Cedrick’s talk

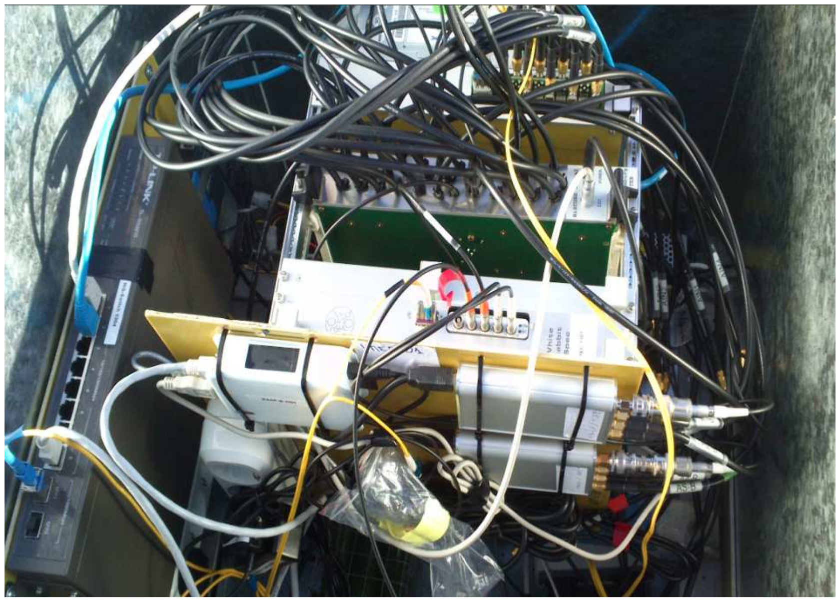
HiS-9 Station : a SPEC-based mini-DAQ

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

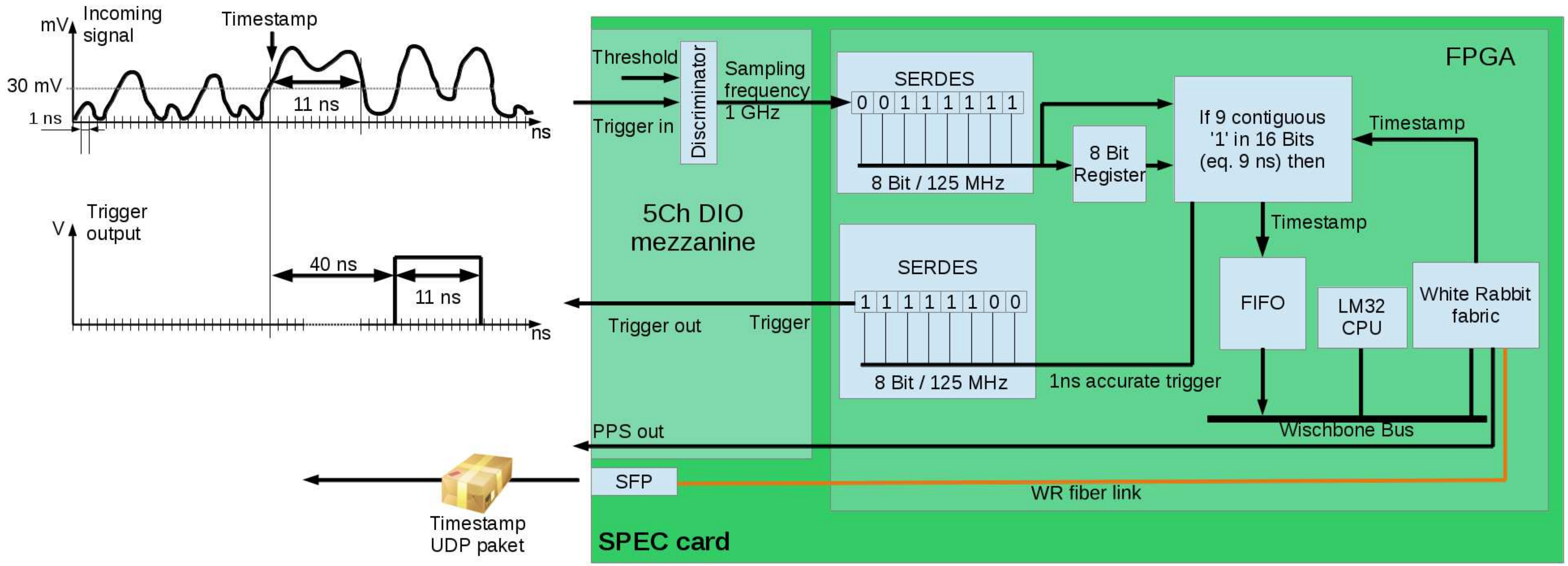
Raspberry

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

WR Node – the HiSCORE specific design

SPEC FPGA modifications

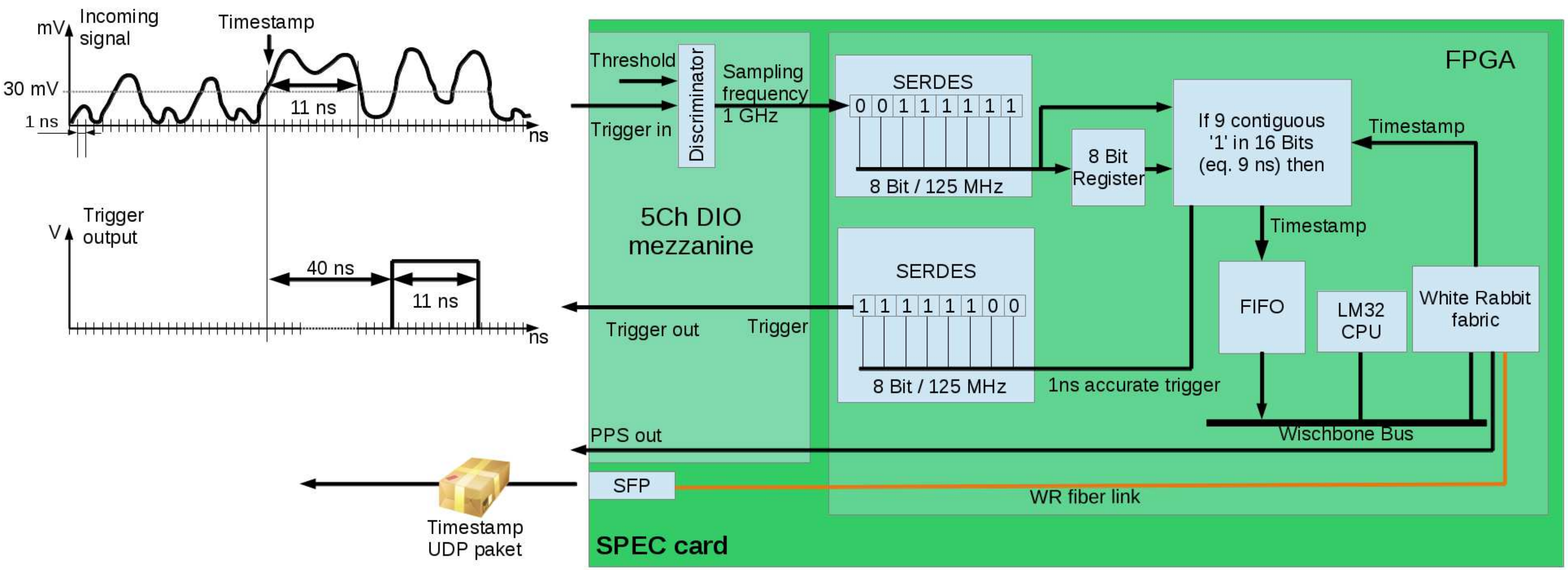
- Taking advantage of the features of the 5Ch DIO card
    - Configure some signals as input for the analog signal
    - Configure some signals as DRS4 trigger and handle Raspberry ready flag
    - Setting a threshold for incoming signals
- Using Spartan 6 SERDES blocks for deserialization



WR node – the HiSCORE specific design (2)

SPEC FPGA modifications

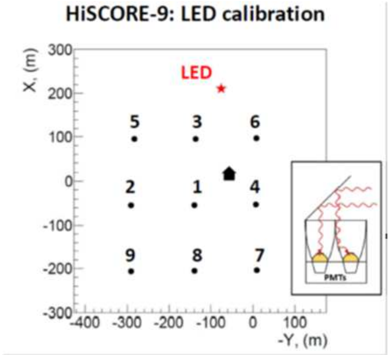
- Filter out signals shorter than 9 nsec (configurable)
- Timestamp the trigger arrival time
- Send timestamps over WR link to DAQ center (software)
- Introduce a command to adjust threshold over USB-UART

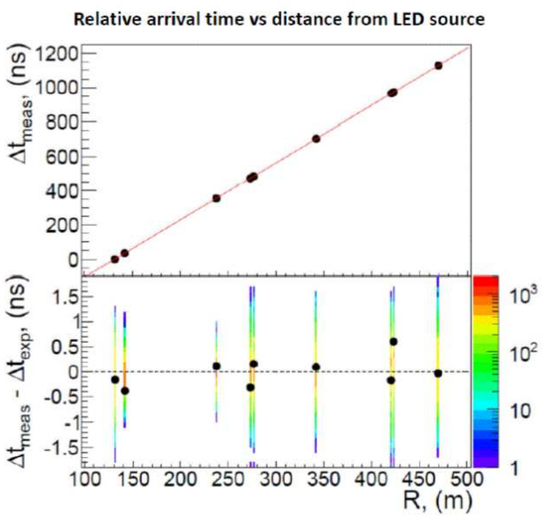


HiSCORE-9 WR Data: Timing with LED and Air Shower

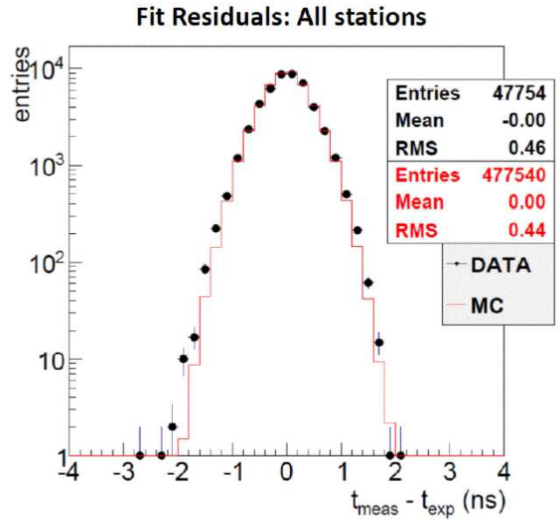
> **External LED-Calibration**

Fit-Resid ~0.44ns





(a)



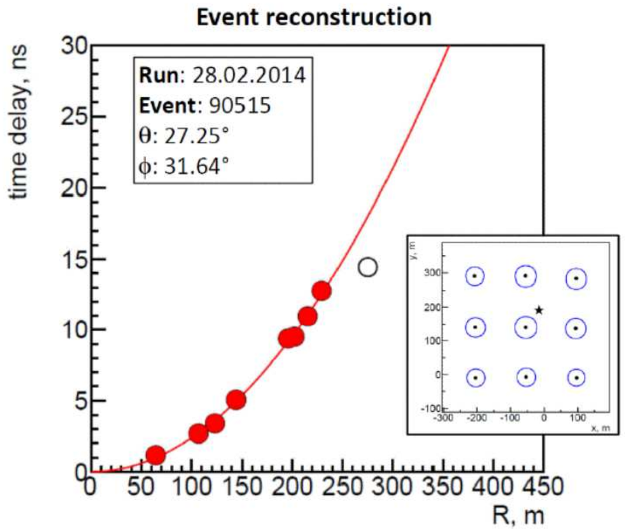
(b)

> **Cosmic Air Shower Reconstruction**

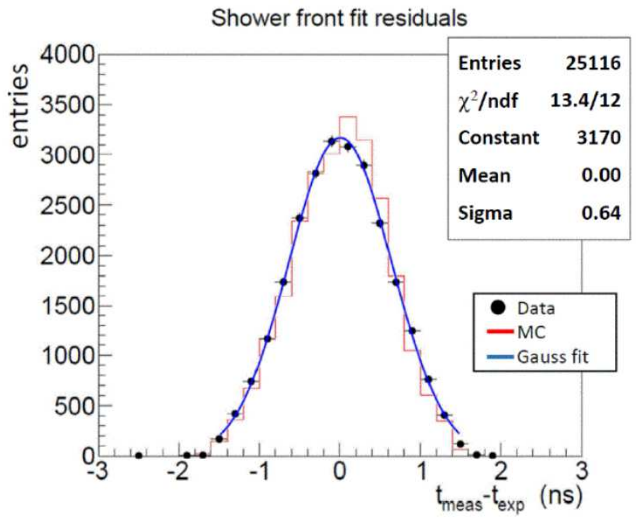
Fit-Resid ~0.6ns

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

(right) fit-residuals all stations



(a)



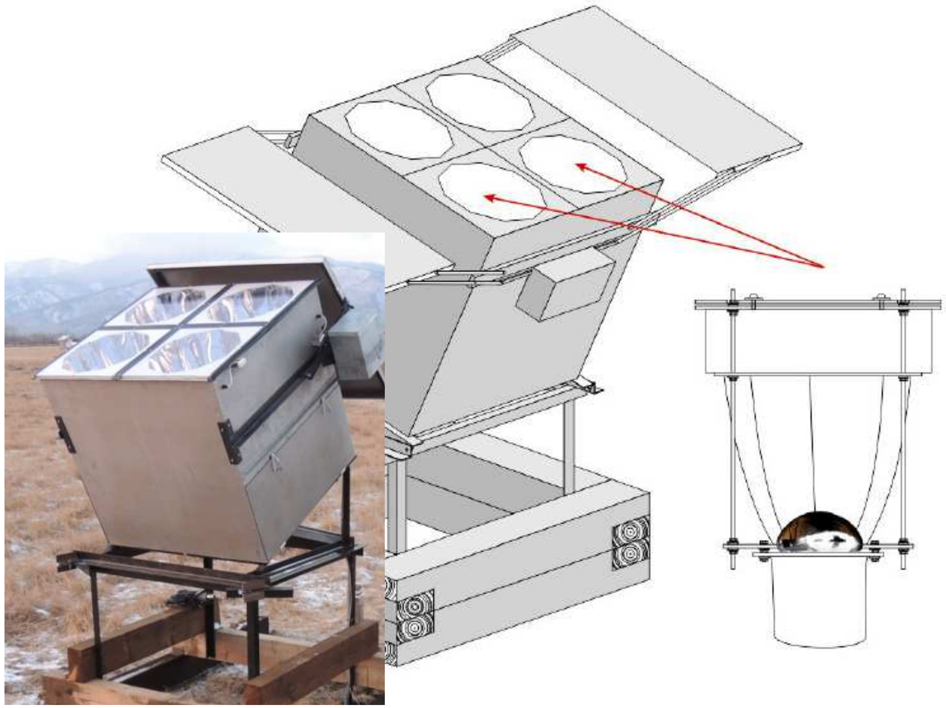
(b)

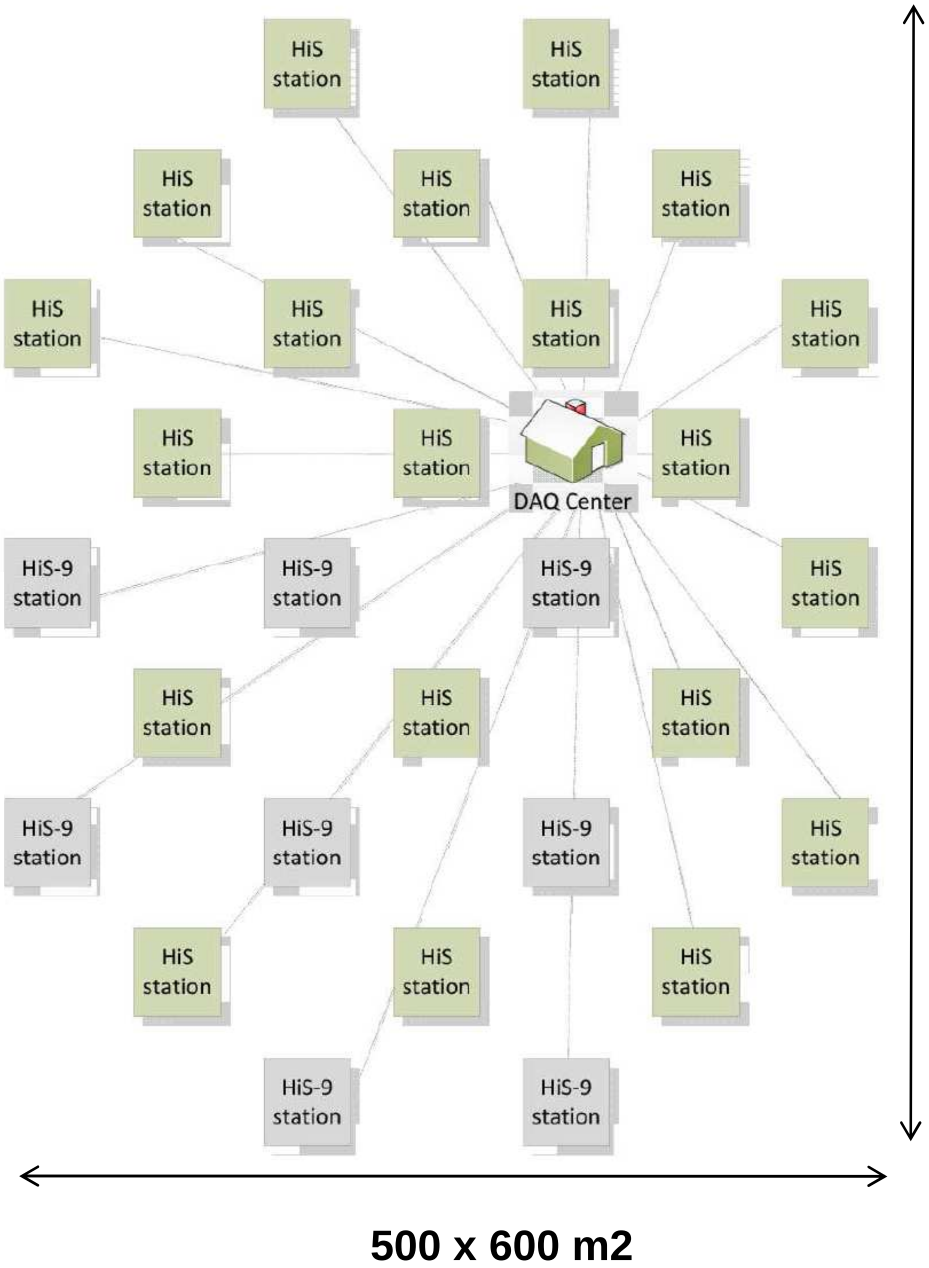
Figure 9: EAS shower reconstruction. (a) Arrival time delay vs dista

ICRC2015, 1041

HiSCORE
28 Station Array

- **0.3 km^2**
- **Installed: fall 2014; operation since 2015**
- **Hybrid nsec-Timing**
- **Modernized electronics + mechanics**
- **Threshold: few 10 TeV.**

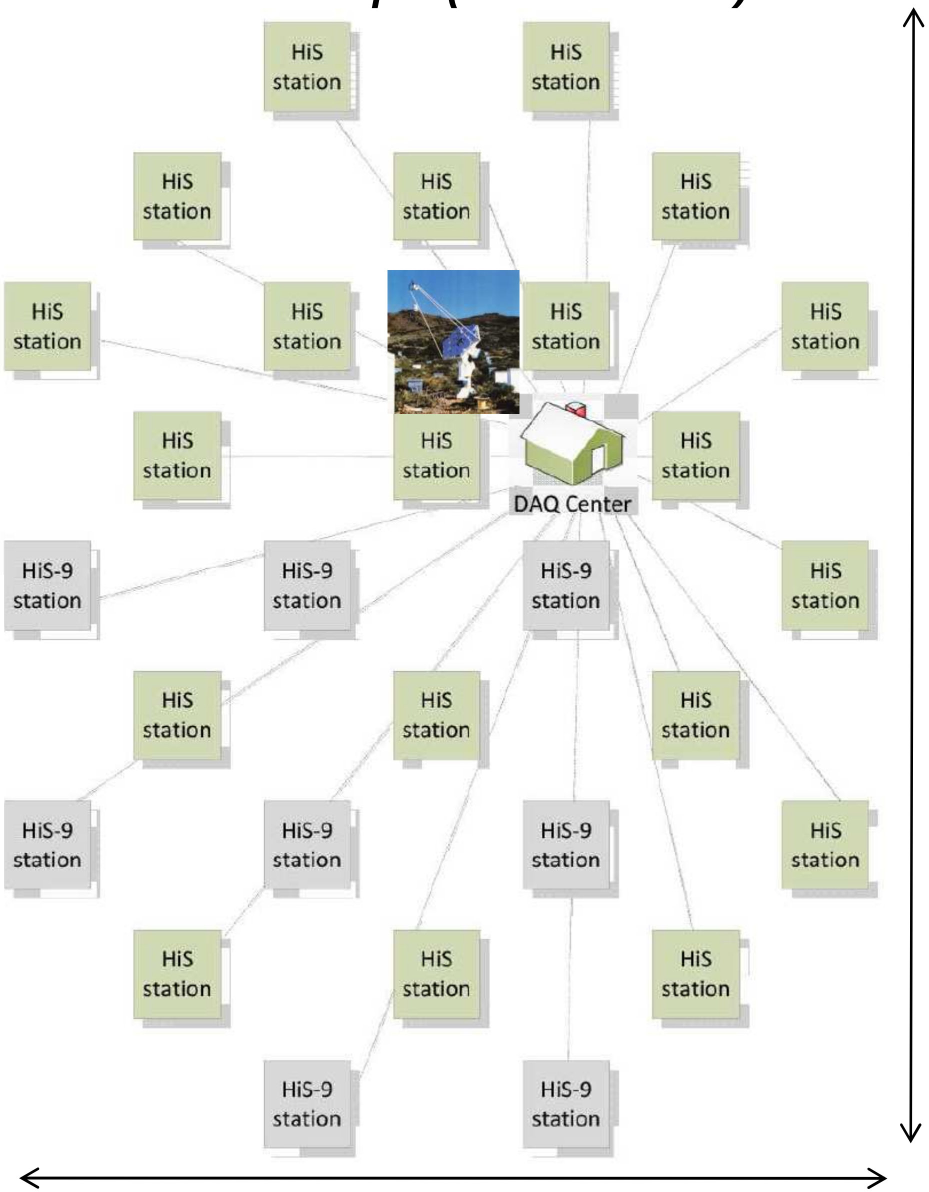




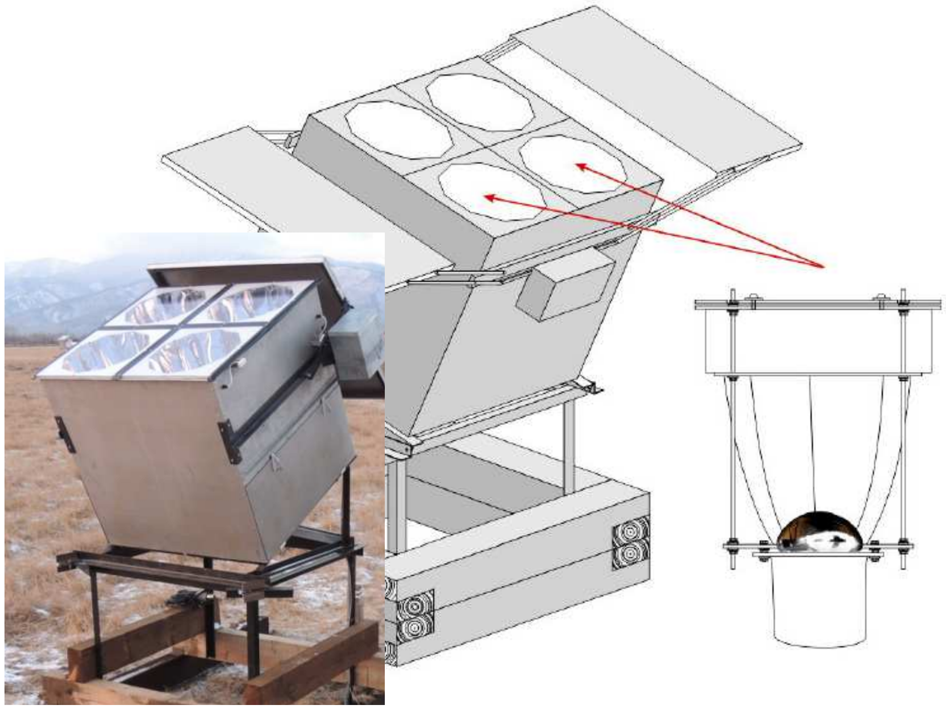
HiSCORE
28 Station Array

- **0.3 km^2**
- **Installed: fall 2014; operation since 2015**
- **Hybrid nsec-Timing**
- **Modernized electronics + mechanics**
- **Threshold: few 10 TeV.**

Fall 2016: 1[st] Imaging Cerenkov Telescope (HEGRA-class)

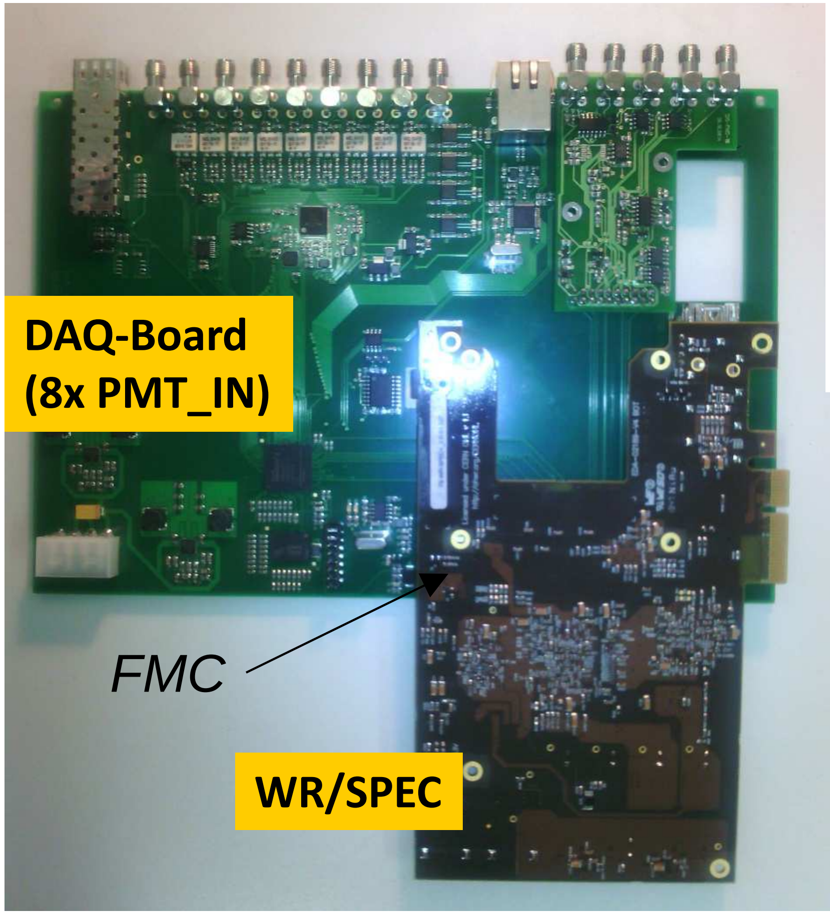


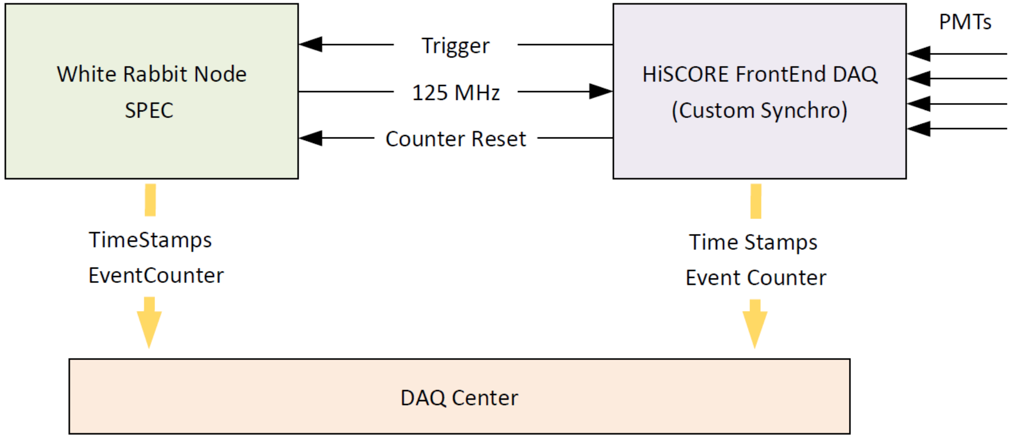
500 x 600 m2



HiS-28 : A Hybrid Timing DAQ

AddOn Board
(5 x I/O)





Parallel operation of two time-stamping:

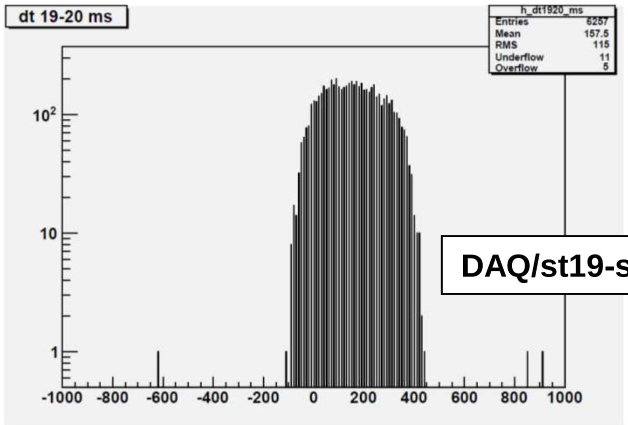
Custom timing and WR (SPEC).

→ Verification event by event.

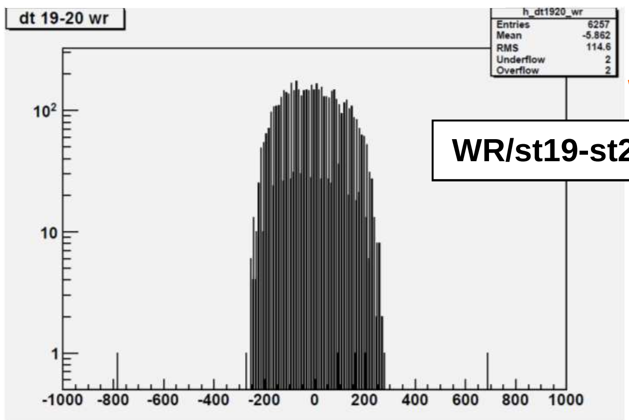
HiS-28: Compare DAQ + WR Times from Cosmic Showers

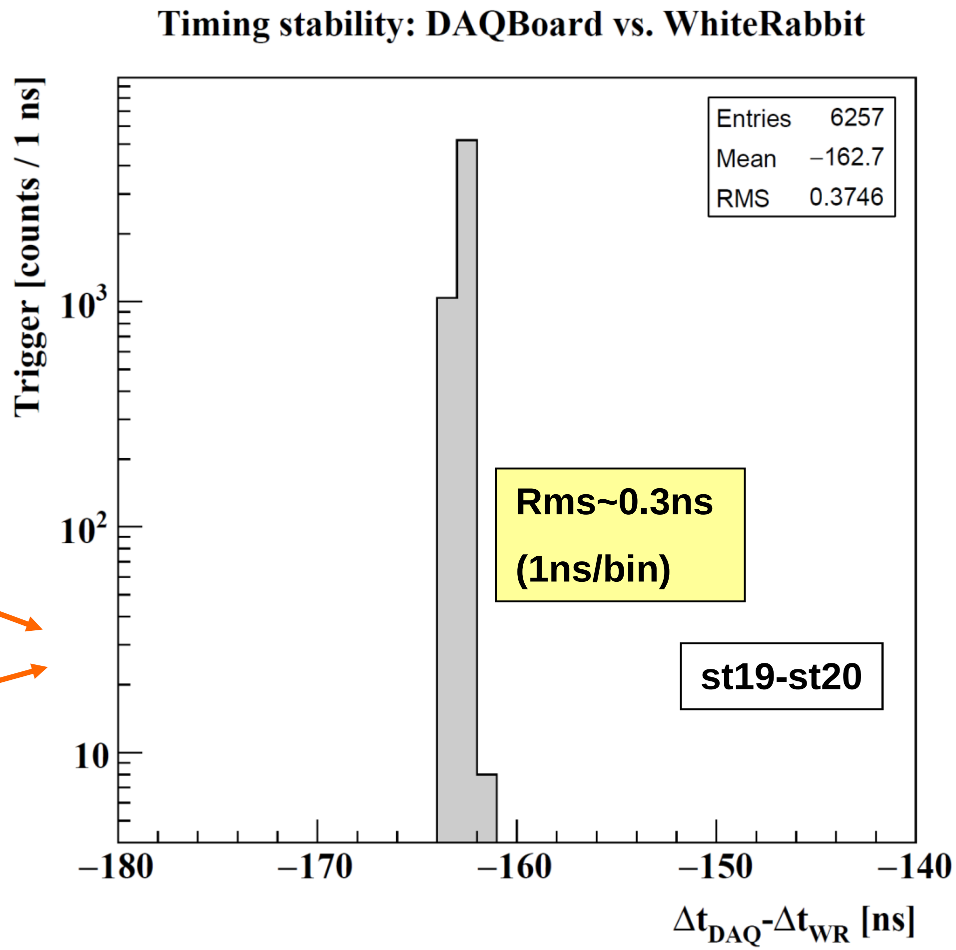
Trigger time differences from two independent clock systems (DAQ/ WR).
(eg. Stations 19 & 20)

dt_daq = t_daq_19 - t_daq_20



dt_wr = t_wr_19 - t_wr_20



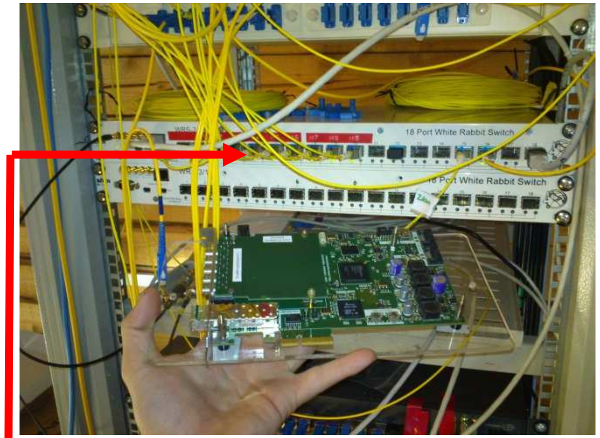


Very good long-term precision & stability. Accuracy: in progress.

NewTechnology

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))

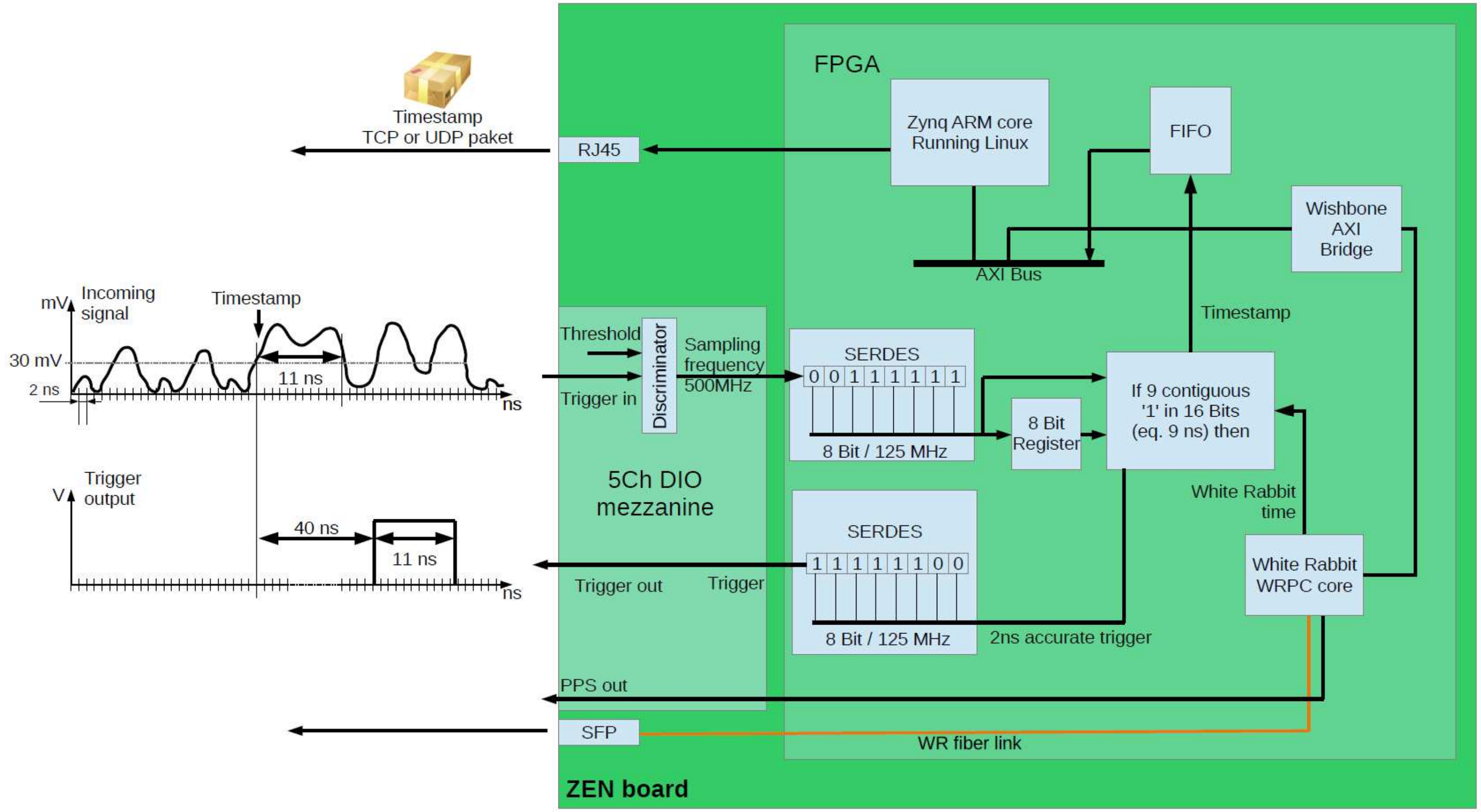
→ Performance, timing, stability, …:
… is excellent !

ZEN : Timestamp with Standard TDC

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

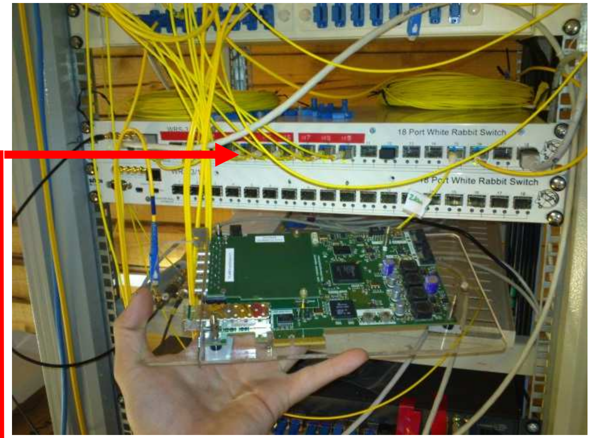
  Implementation similar to our TDC on the SPEC

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



ZEN : Timestamp Test

WR Master: WR Switch

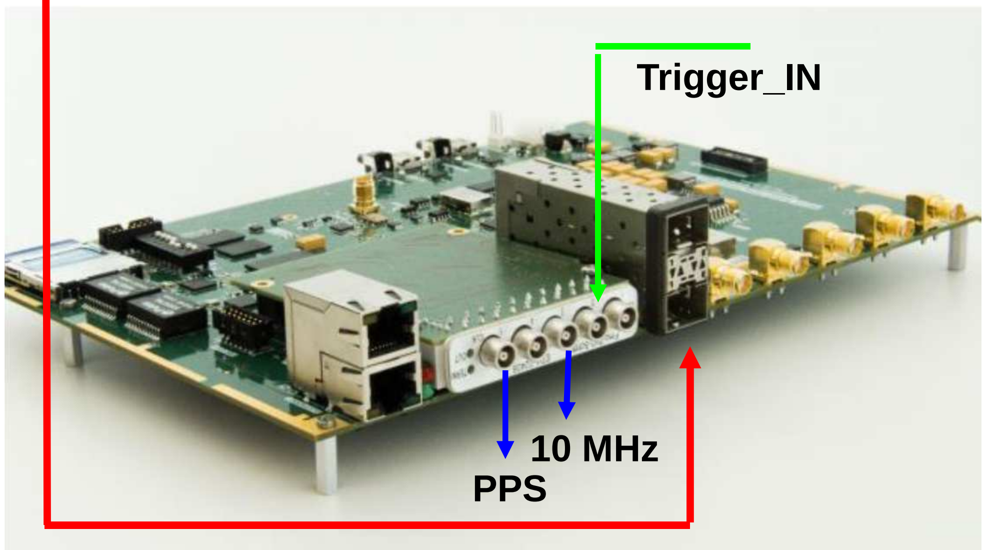


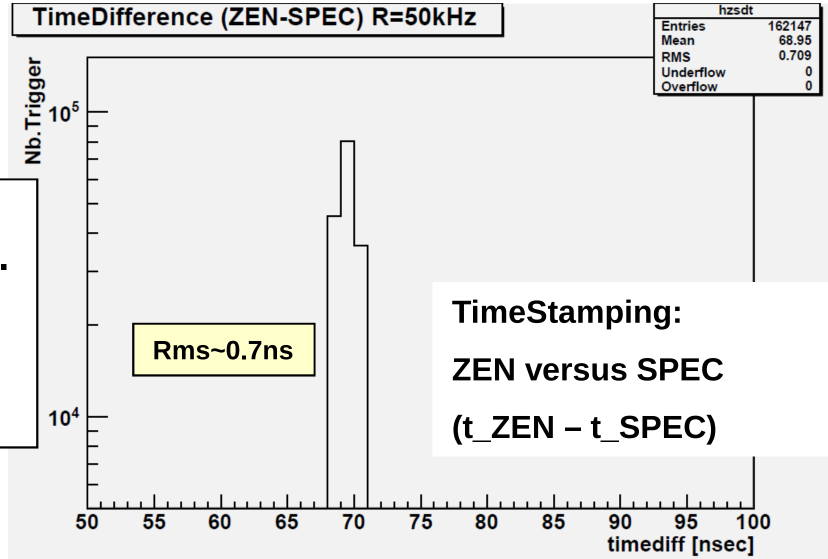
ZEN: verifying the time-stamping (2ns).

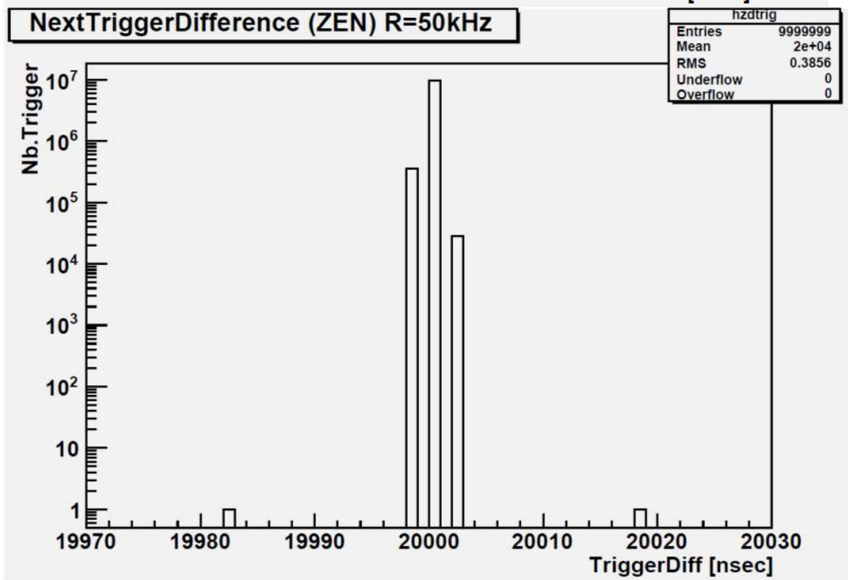
High trigger rate proven. ~500kHz is realistic.

1Gbit fiber

WR-Node: ZEN card





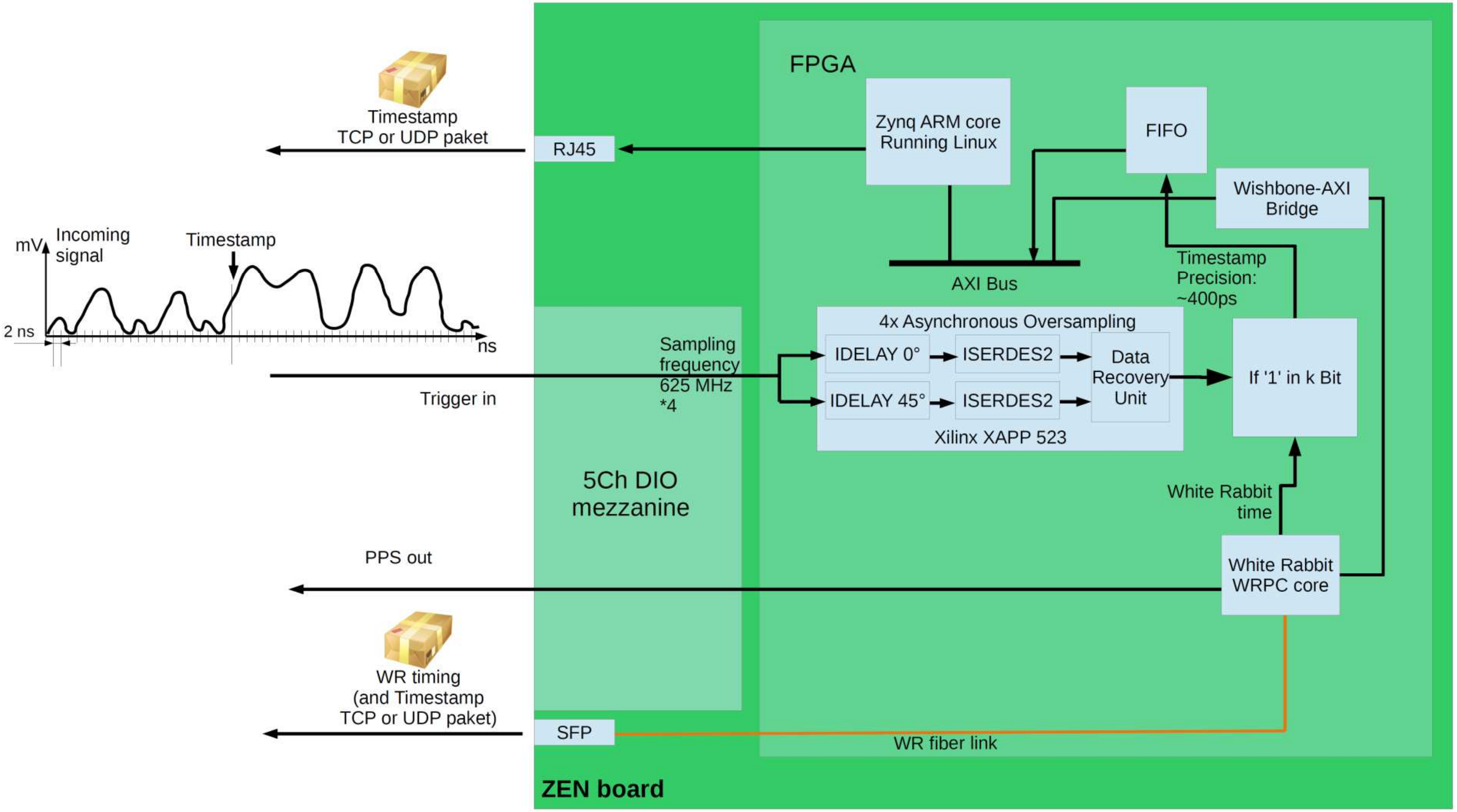


ZEN-only test: NextTrigger Time-difference with nsec (very stable pulser).

Next: ZEN Timestamping with <1ns resolution

Aim: Reach 0.5ns, 0.25ns TDC bins with asynchroneous oversampling

(see Xlinx XAPP-523). In collaboration with Yassir Moudden (Saclay).



Conclusions

Conclusions (1)

> **White Rabbit is a new standard for Clock and Frequency Transfer over Ethernet**

> **A number of large-scale AstroParticle experiments need sub-ns-timing …**

> **…. White Rabbit (WR) perfectly fits their requirements**

- **Clock distribution**
- **Trigger time stamping**
- **Active calibration (‘ext. trigger’)**
- **In-situ-verification (data or/and hardware redundancy)**
- **10-20 Picosecond-scale precision, still improving**

> **WR allows to <u>avoid custom solutions</u> per experiment , that are**

- **expensive, hard to maintain**
- **less reliable and precise**
- **hard to precisely calibrate , …..**

Conclusions (2)

> **WR**

- **based on standard GbE (Ethernet technology)**
- **as an open hardware / software project it offers good user-support**
- **commercial support (>3 companies), which are well debugged**
- **documented calibration / verification procedures**
- **works almost “out of the box”**

> **WR is considered for future projects: LHAASO, CTA, ICE3-Gen2, …**

> **WR was implemented, and is operating in the HiSCORE Prototype**

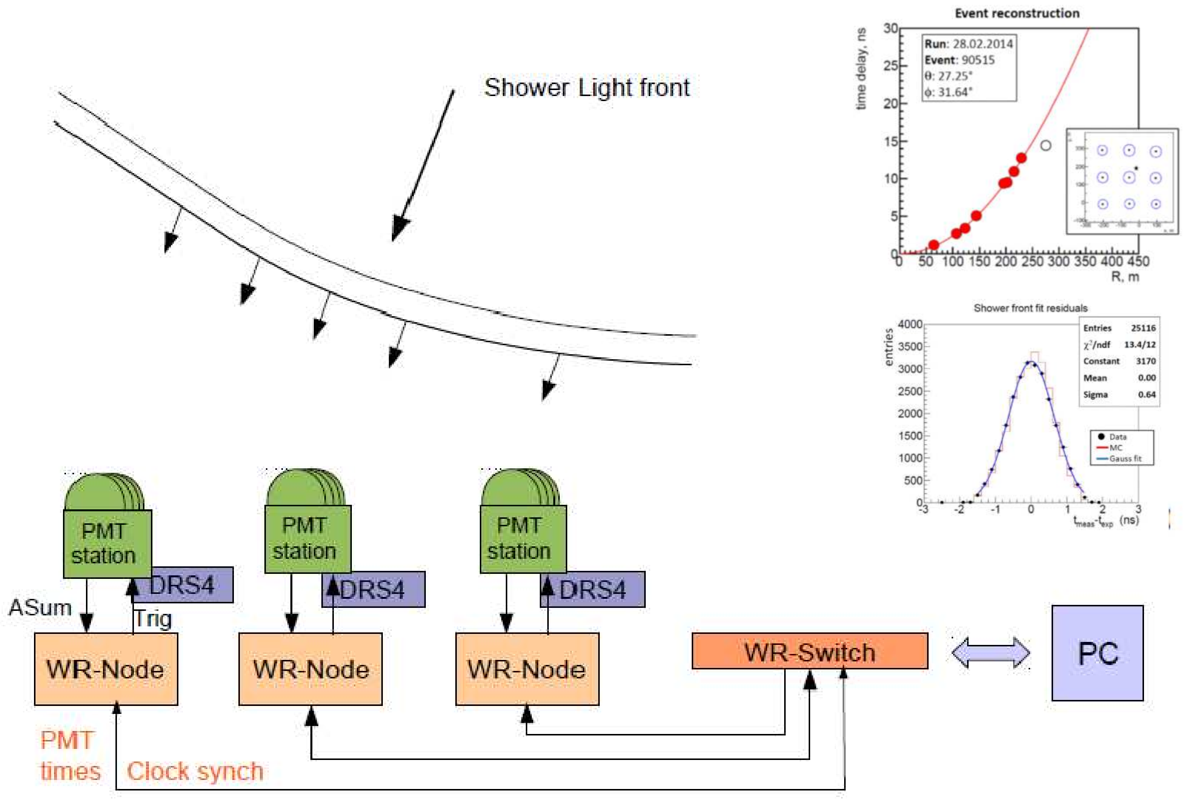
- **Time-stamping**
- **Operating as expected: precision, accuracy … first physics EAS results (‘end-to-end test by shower‘)**
- **Long-term cross-checks (since 2013…)**
- **Bonus: a fully WR-based GHz prototype DAQ, ready for >km2-scale**
- **Timing-solution is generic – and easily adapted to other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

Conclusions (3) - Technicalities

- **Time-stamping with o(1 nsec)**
  - SPEC : ‘1 nsec’ by now >2 implementations on SPEC (DESY, APC/Paris, …)
  - ZEN : 2 nsec ok → 1 nsec next week ☺ (DESY)
  - In preparation: resolution < 1 ns…..
- **Accumulated WR-experience shapes design of CTA + …**
  - **Basics methods**
  - **Intrinsic data-redundancy (!)**
  - **Optional self-verification (!)**
- Next: exploit the system-aspects, intrinsic to complex, WR-driven DAQ’s.
- Impressive progress over last few years
  - **new WR-devices, improved precision and services**
  - **new users / applications**
- Finally: Many thanks to the excellent work & support by the WR-team, and by the companies 7Sols, CreoTech.

Thank you.

BonusSlide. Build your own nsec-DAQ



Ingredients:

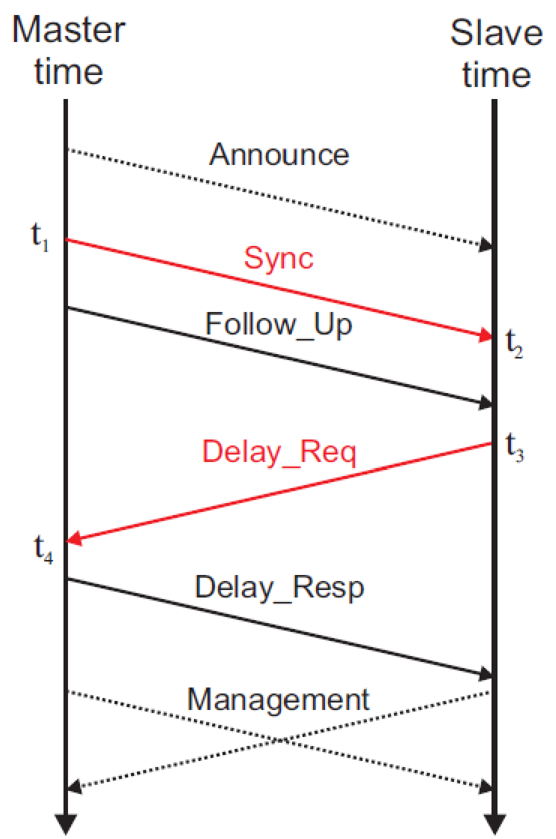
- **N stations (scintillator / PMT)**
- **1x SPEC per station**
- **Fiber cable to WRSwitch**

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

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

…. Backup slides ….

WR basics….



Simplified PTP message exchange diagram.

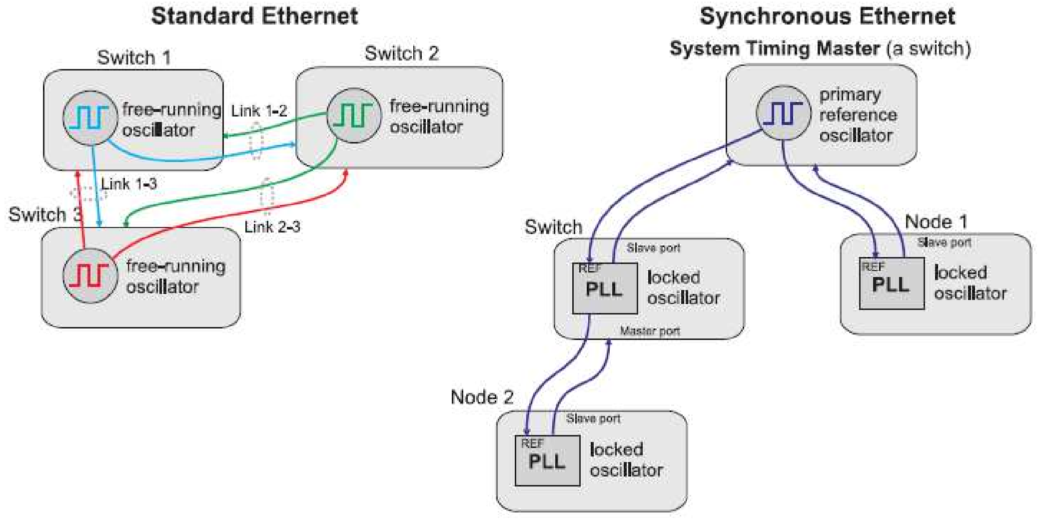


Figure 3: Simple illustration of layer-1 syntonization.

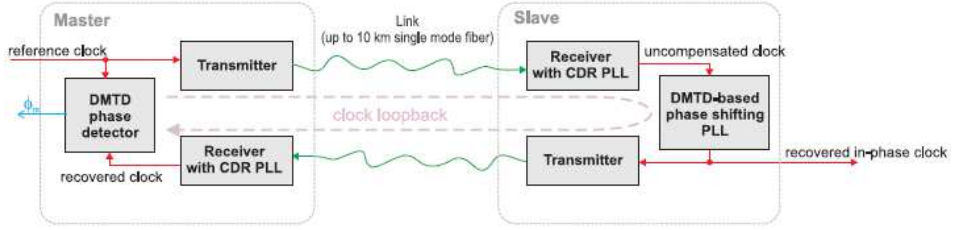
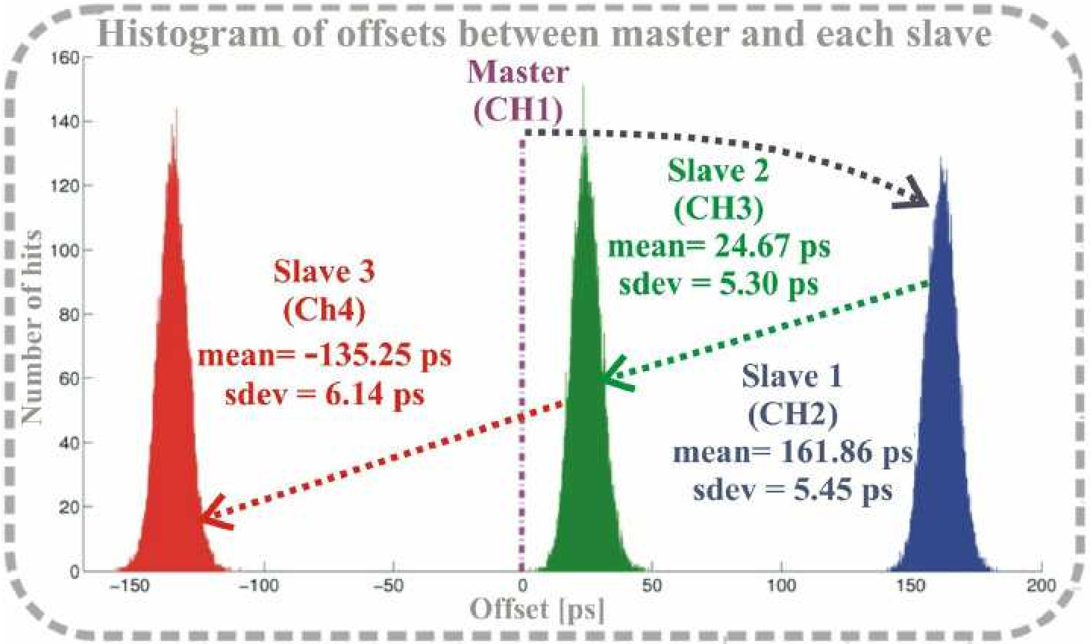


Figure 4: Phase tracking block diagram.



... Figure 8: Histograms of PPS output offsets of three cascaded WR switches with respect to the PPS pulse output in the master switch.

An example WR-Node

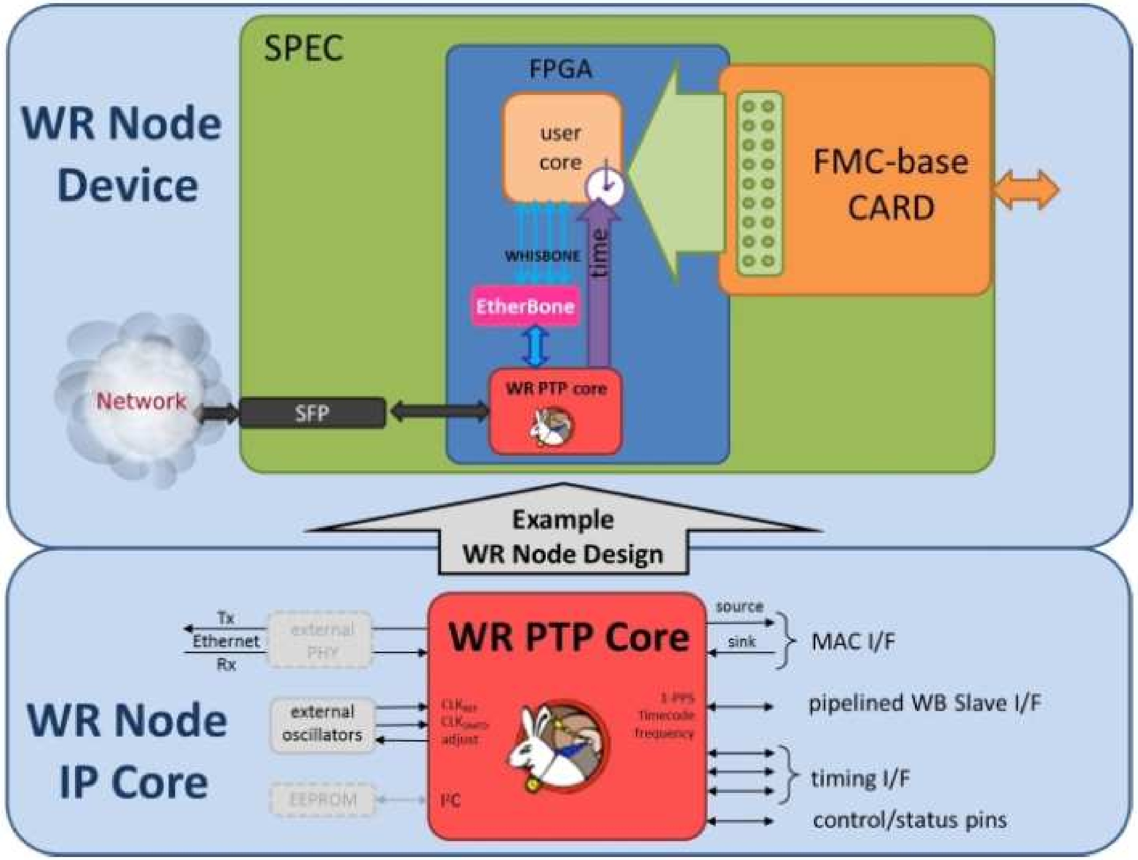
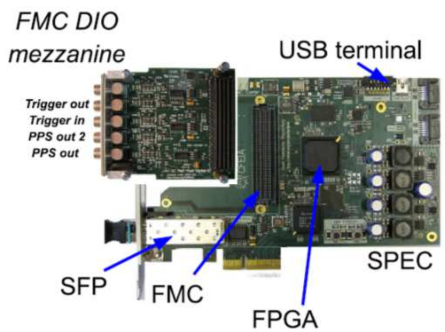
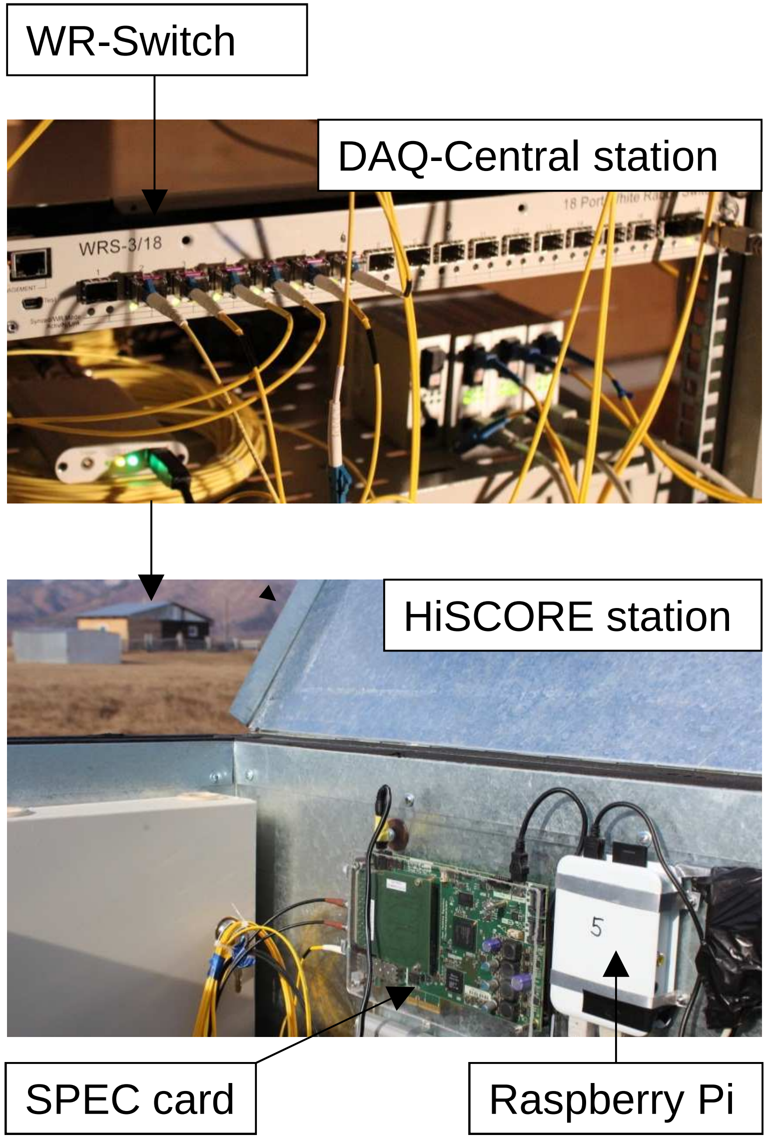
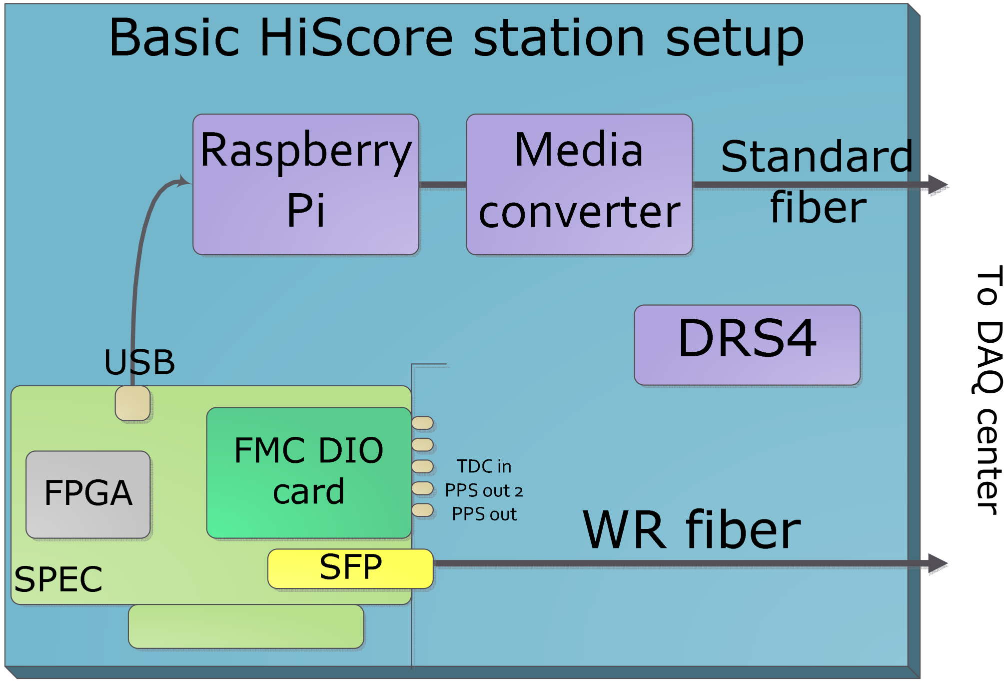


Figure 9: An example WR node.



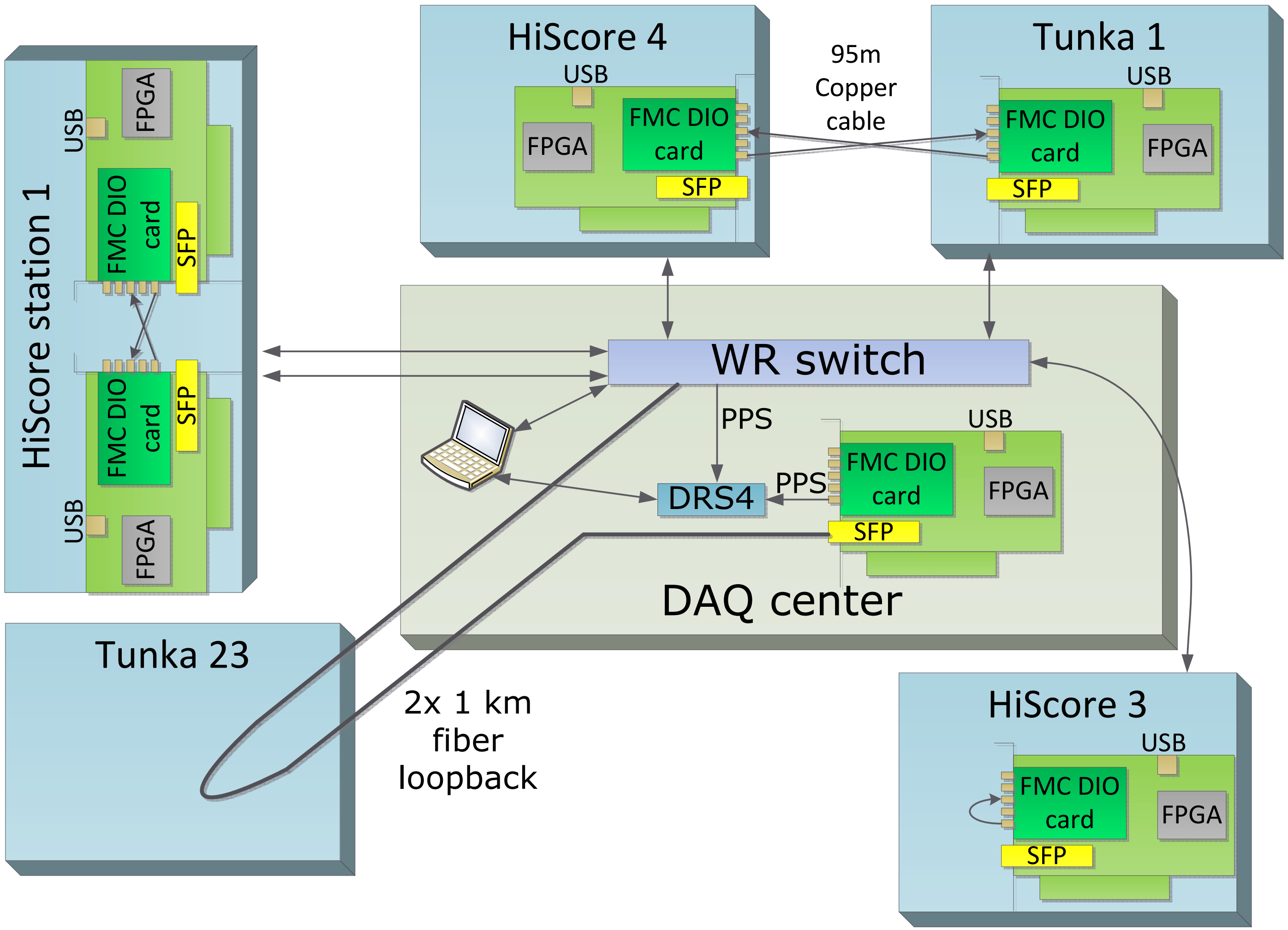
HiSCORE setup overview





- 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)

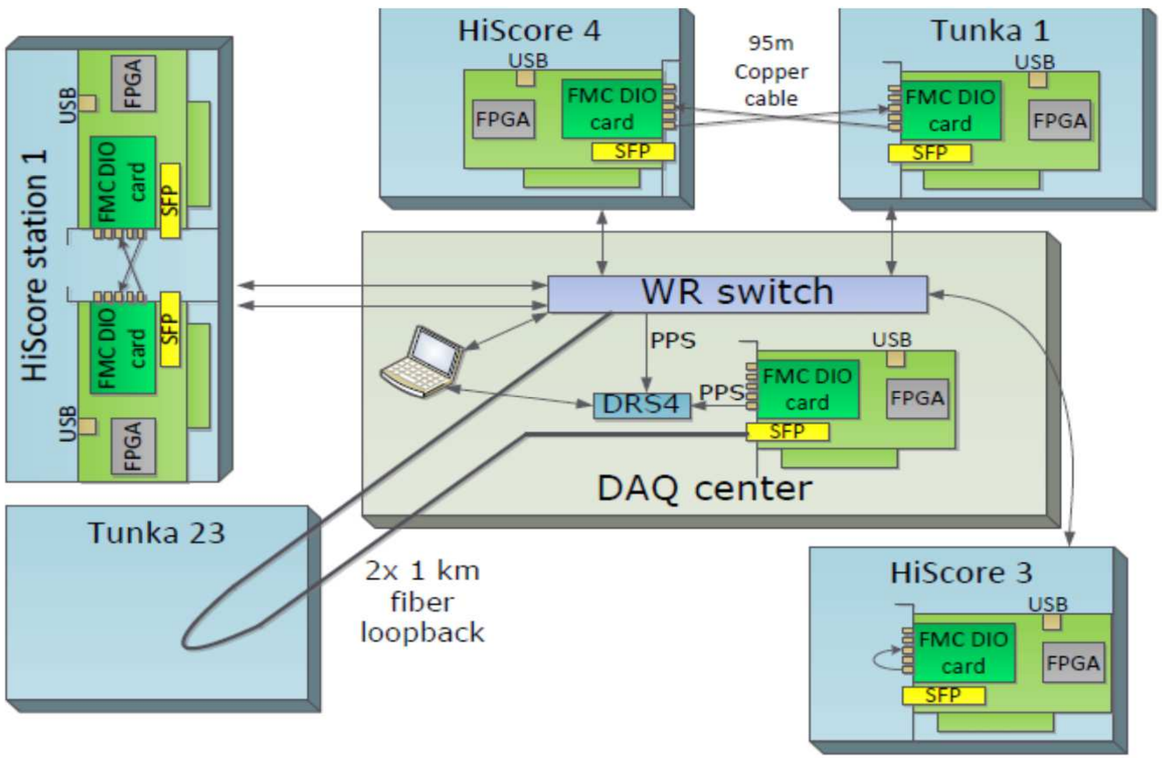
WR – setup in Tunka

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)**



CTA Timing (zoomed) : UCTS-Card and Cameras

- UCTS = "Unified ClockDistribution & TimeStamping Card" at each Camera

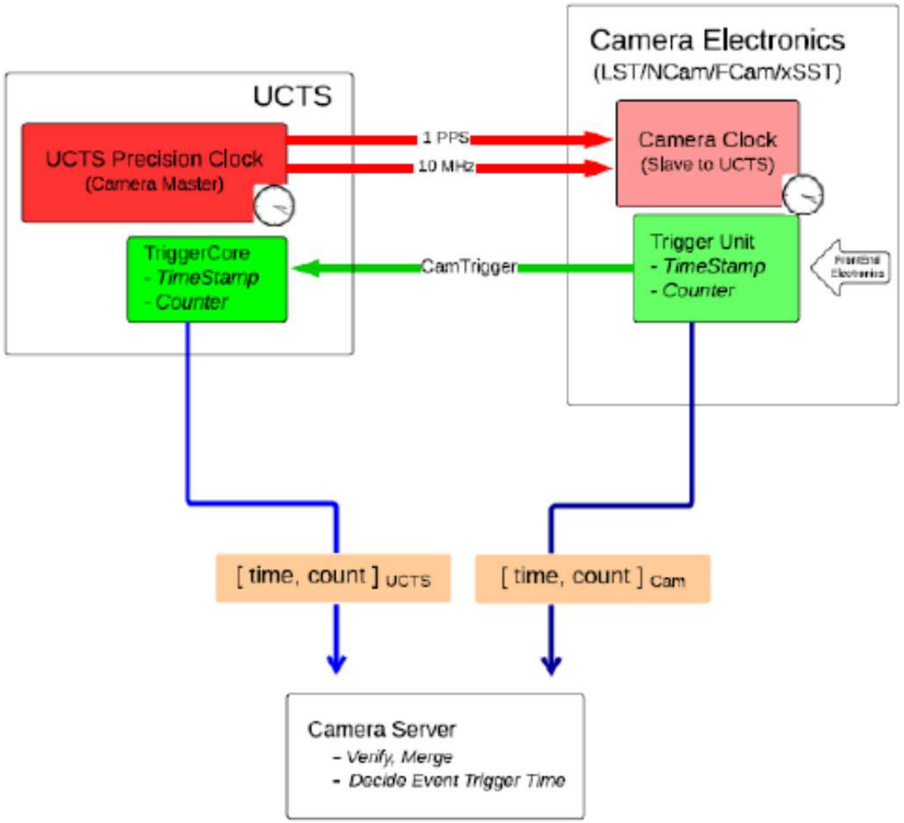


Figure 1: Layout of the Double-Clock/Double-Timestamping architecture using a generic camera and the UCTS-Board. Both UCTS-Board and camera electronics generate a trigger message [t, count] including a time stamp *t* and an event counter *count*. The camera server verifies the integrity of event counter and time stamp.

UCTS Interface w/ Camera:

1. **Receive CamTrigger**
2. **Send Clock (PPS/10MHz)**

Details of data flow still to be decided (CServ,…)

CTA Timing (zoomed) : UCTS-Card and Cameras

- UCTS = "Unified ClockDistribution & TimeStamping Card" at each Camera

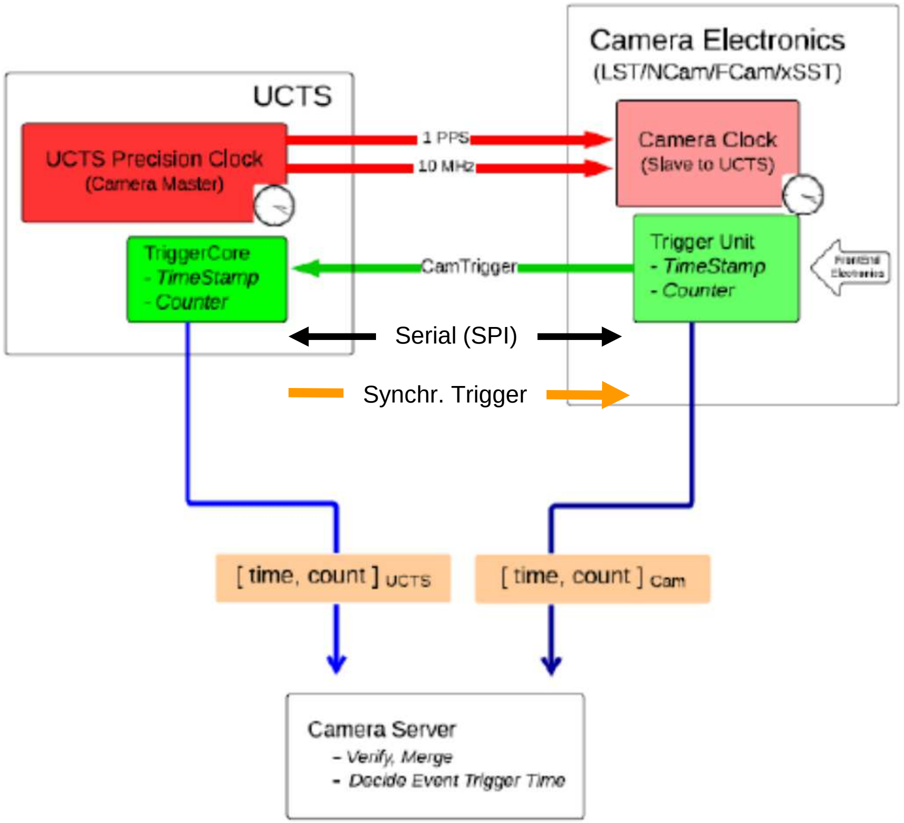


Figure 1: Layout of the Double-Clock/Double-Timestamping architecture using a generic camera and the UCTS-Board. Both UCTS-Board and camera electronics generate a trigger message [t, count] including a time stamp *t* and an event counter *count*. The camera server verifies the integrity of event counter and time stamp.

UCTS Interface w/ Camera:

1. **Receive CamTrigger**
2. **Send Clock (PPS/10MHz)**
3. **Serial line (aux.info // bidir.)**
4. **Send Synchron. Trigger**

Note: A <u>synchronous trigger</u> is pre-programmed, and issued with ns-resolution and 200ps jitter – with respect to all cameras/ devices.

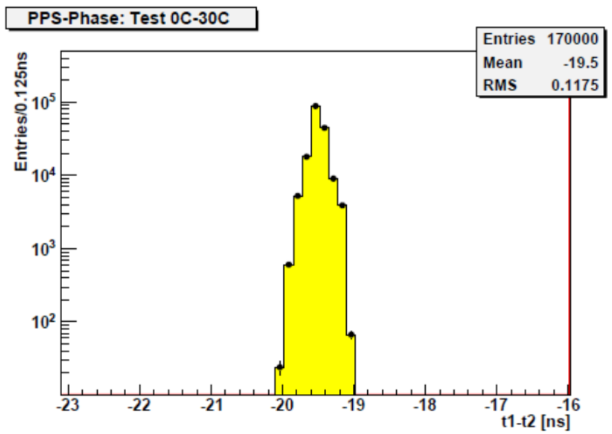
White Rabbit - Executive summary (3)

> Longterm-tests @ DESY-Environmental Chamber

- **DESY environmental-chamber (CTA-mirror tests); April/May, 2013: ~10 days of tests**
- **Temperature -20C … +40C 2-3 days cycles → FiberCable 500m**
- **0C … +30C 2-3 days cycles → WR-Node (the camera card)**
- **No measureable temperature effects observed**

→ Trigger-stamps : +-1ns → rms<0.5ns

→ Phase of 1 PPS-references : rms < 200ps



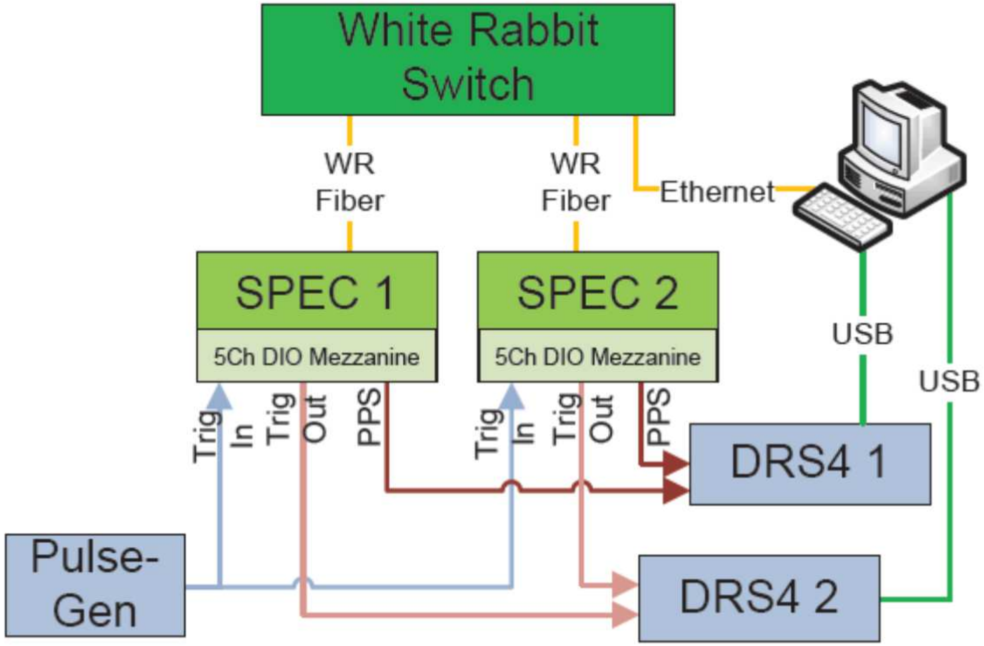
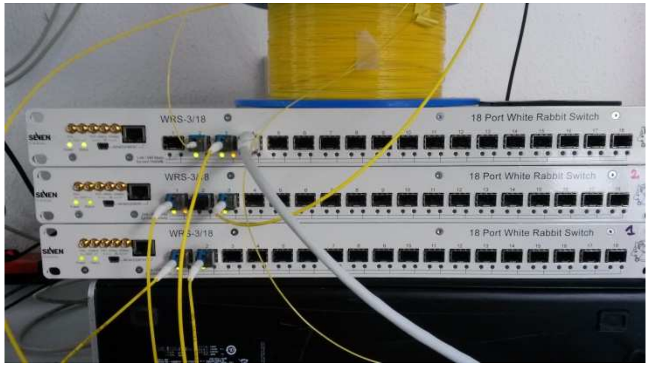


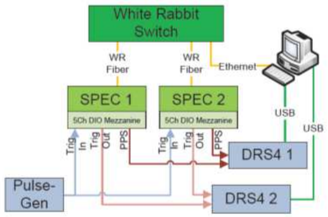
Figure 4: Experimental Setup (baseline configuration). WR fibers are 20 m long to SPEC1 and 520 m to SPEC2. For tests in the environmental chamber, the 500 m WR-fiber and/or the SPEC2 card are located in the DESY-climate chamber.

White Rabbit - Executive summary (4)

- Network structure
- Tests-A: single WR-Switch (max. 17 Telescopes) ➔ OK
- Tests-B: two-level WR's 17x17 = 289 Telescopes



3x WRSwitch + DRS setup adapted



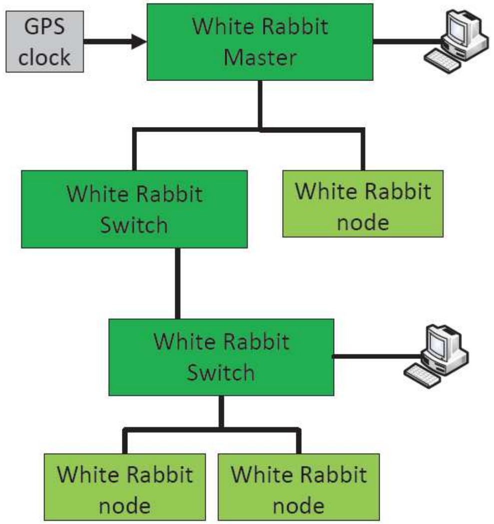
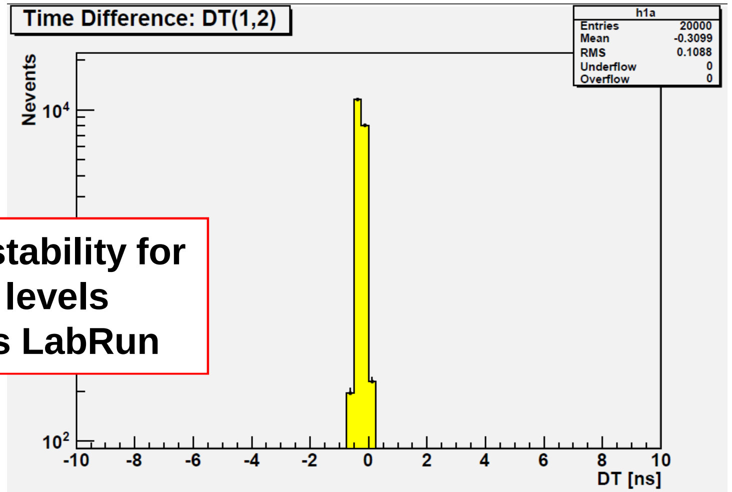


Figure 1: The White Rabbit network

- No measureable network effects observed ➔ ~300 Telescopes are safe
  - → Trigger-stamps : +-1ns → rms<0.5ns
  - → Phase of 1 PPS-references : rms < 200ps



Timing stability for
- 2 WRS levels
- 20000 s LabRun

- Do we want next step (3 levels) ?

17^3 = 4913 Telescopes

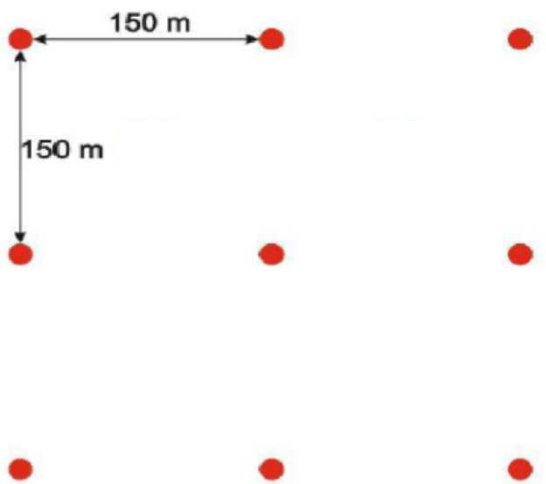
White Rabbit - Next HiSCORE setup

Plan for October 2013:

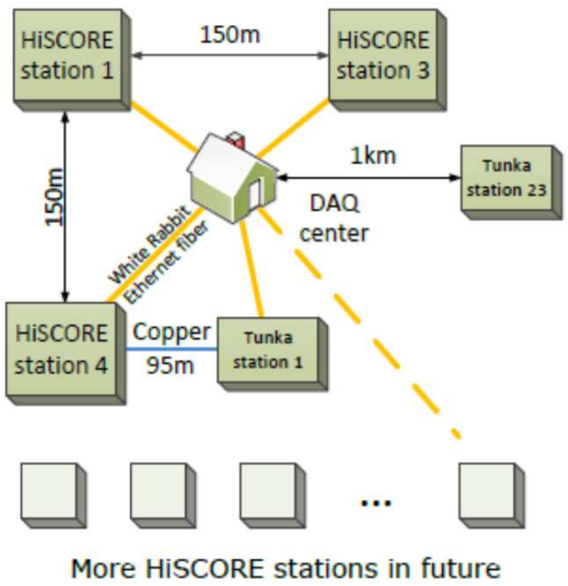
> HiSCORE array:

Install the 9 station array with WhiteRabbit (0.1 km2)

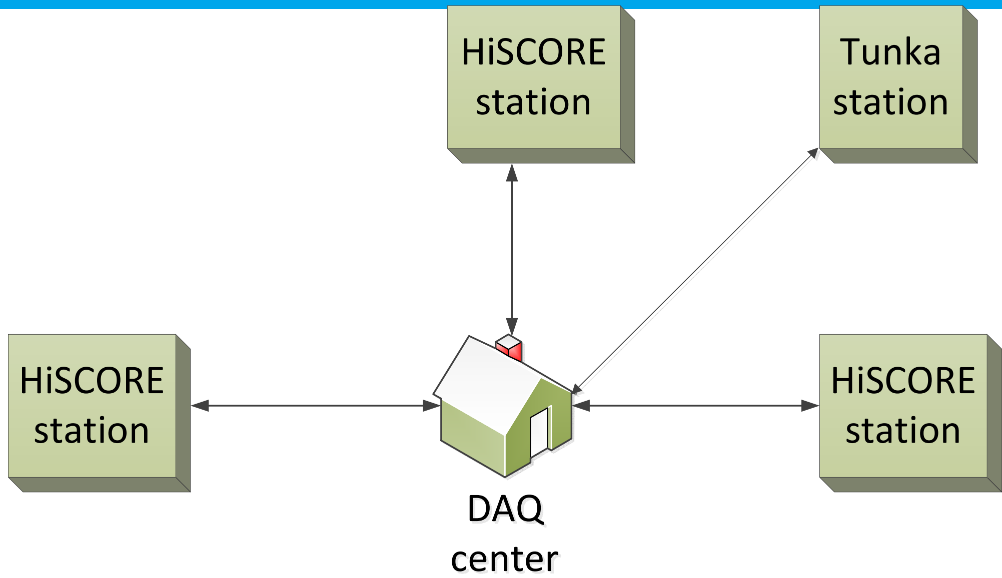
- **A full-scale test (aiming at 50TeV gamma's)**

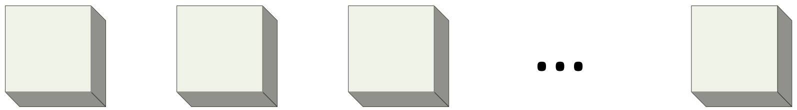


The HiSCORE-2013 array: 9 stations



HiSCORE setup overview (Oct.2012 comissioned)





More HiSCORE stations in future

- 1 km² in 2013/14 : 20-40 stations
- 100 km²: > 2000 stations