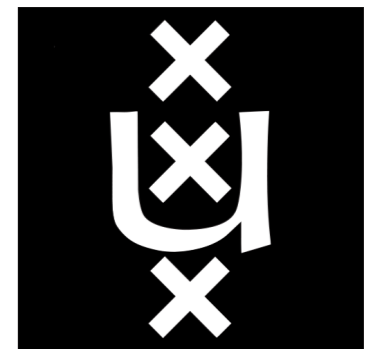


# High-precision fiber-optical timing distribution systems over large distances and their application to astroparticle physics facilities

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A. Balzer, D. Berge, P. Jansweijer, M. De Jong, J. Koelemeij, R. Kluit,  
TIPP 2014 - Emerging Technologies - Photonics  
04.06.2014, Amsterdam



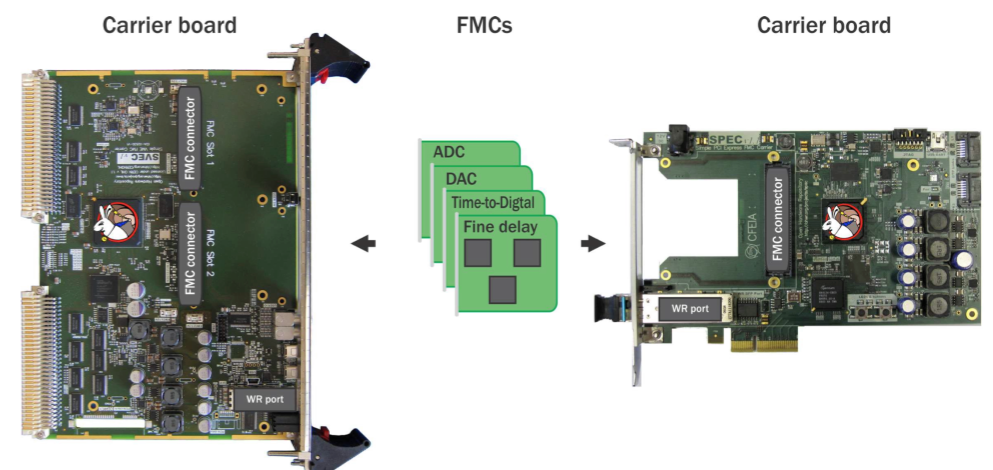
# White Rabbit



- Open hardware & open software project
- Based on proven technologies (synchronous Ethernet)
  - extension to IEEE1588
  - thousands of nodes
  - distances over several tens of kilometres
- Performance
  - sub-ns accuracy
  - ten-ps precision
- Core ingredients
  - White Rabbit switch
  - White Rabbit nodes



Courtesy SevenSoI



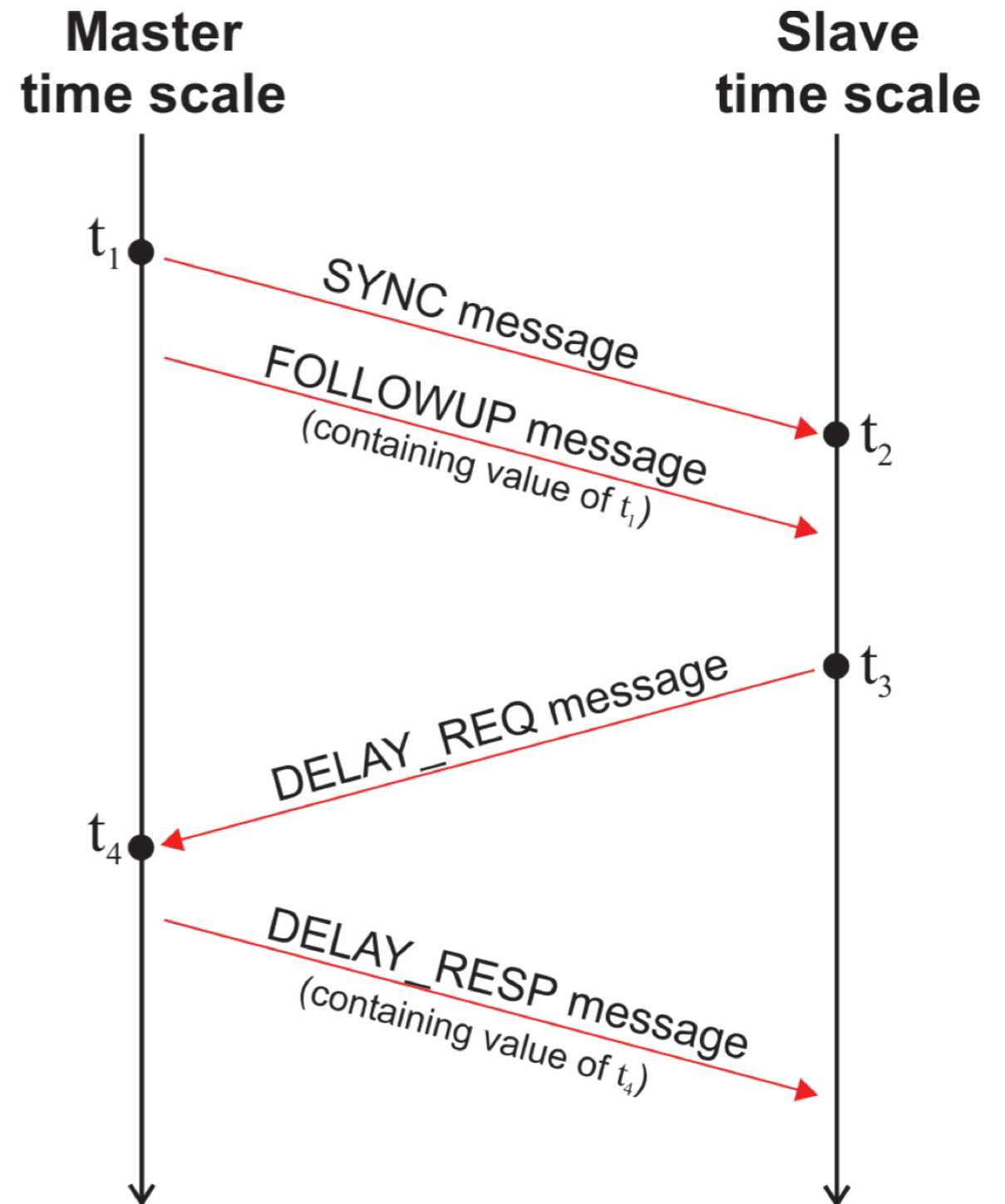
# Precision Time Protocol (IEEE1588)

- sub-microsecond precision
- simple calculation:

$$\text{link delay}_{ms}: \delta_{ms} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2}$$

$$\text{clock offset}_{ms} = t_2 - t_1 + \delta_{ms}$$

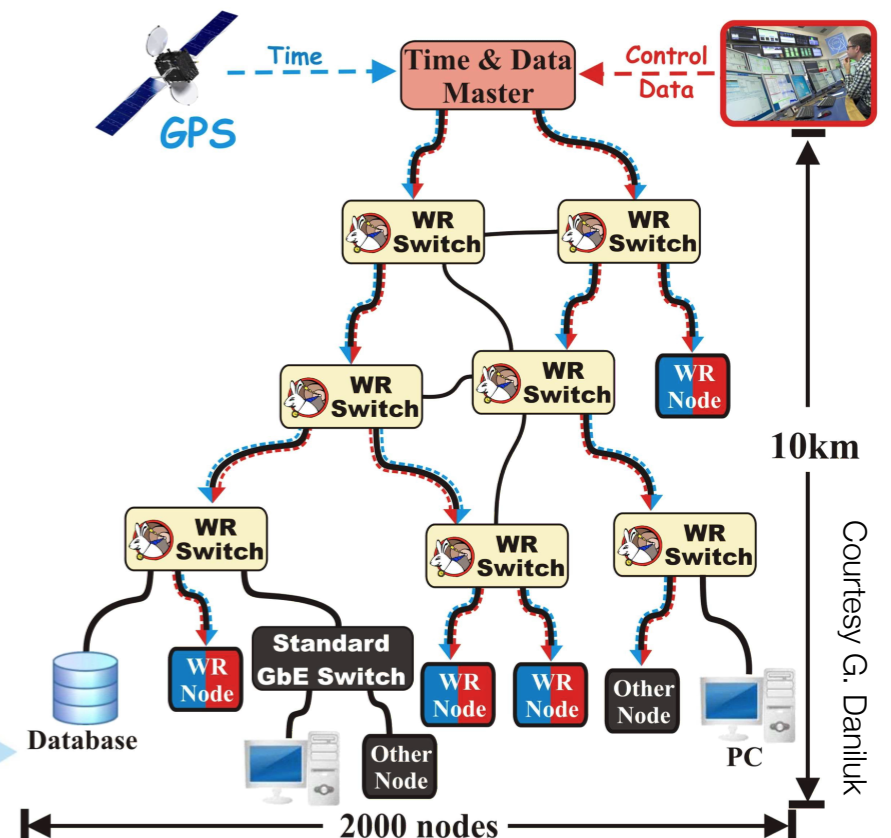
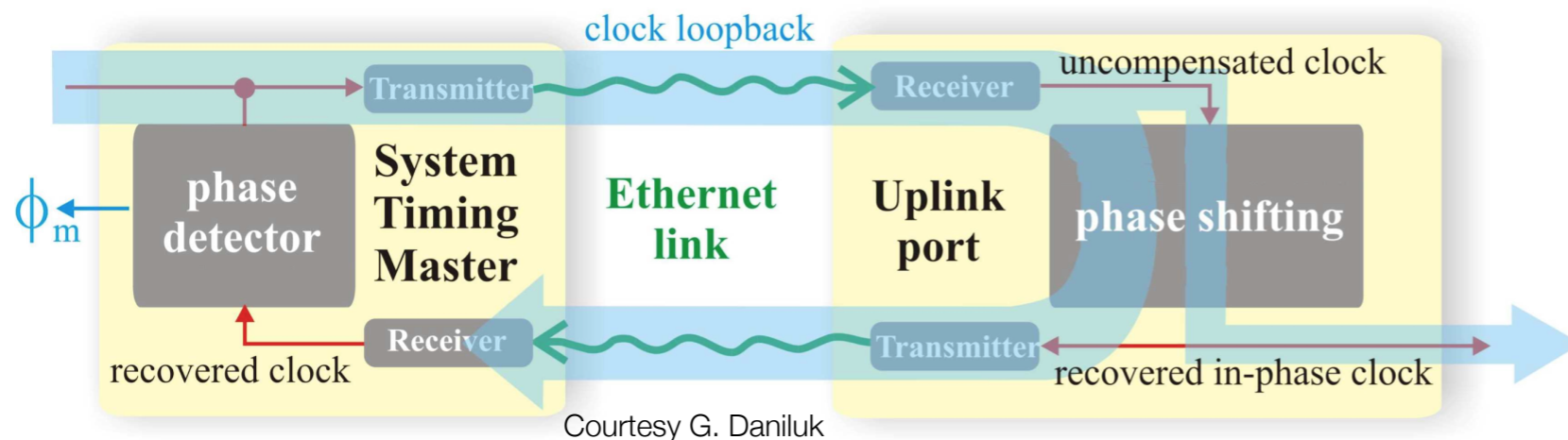
- assumes no link asymmetry
- free running oscillators



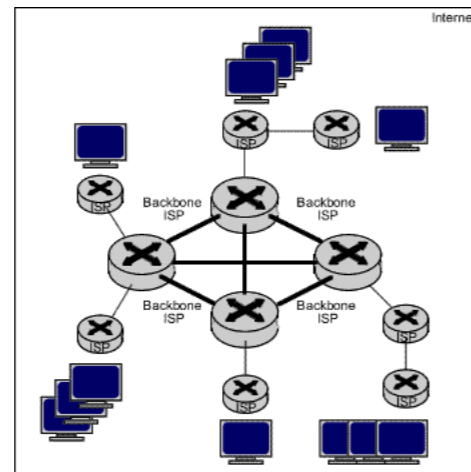
Courtesy G. Daniluk

# White Rabbit Synchronisation

- See White Rabbit for Time Transfer presentation by E. van der Bij tomorrow
- Transport synchronous clock via Ethernet
- Monitor phase of bounced back clock
- Extend PTP timestamp with phase measurement
- Most accurate PTP implementation



# Long-haul fibre-optic White Rabbit links



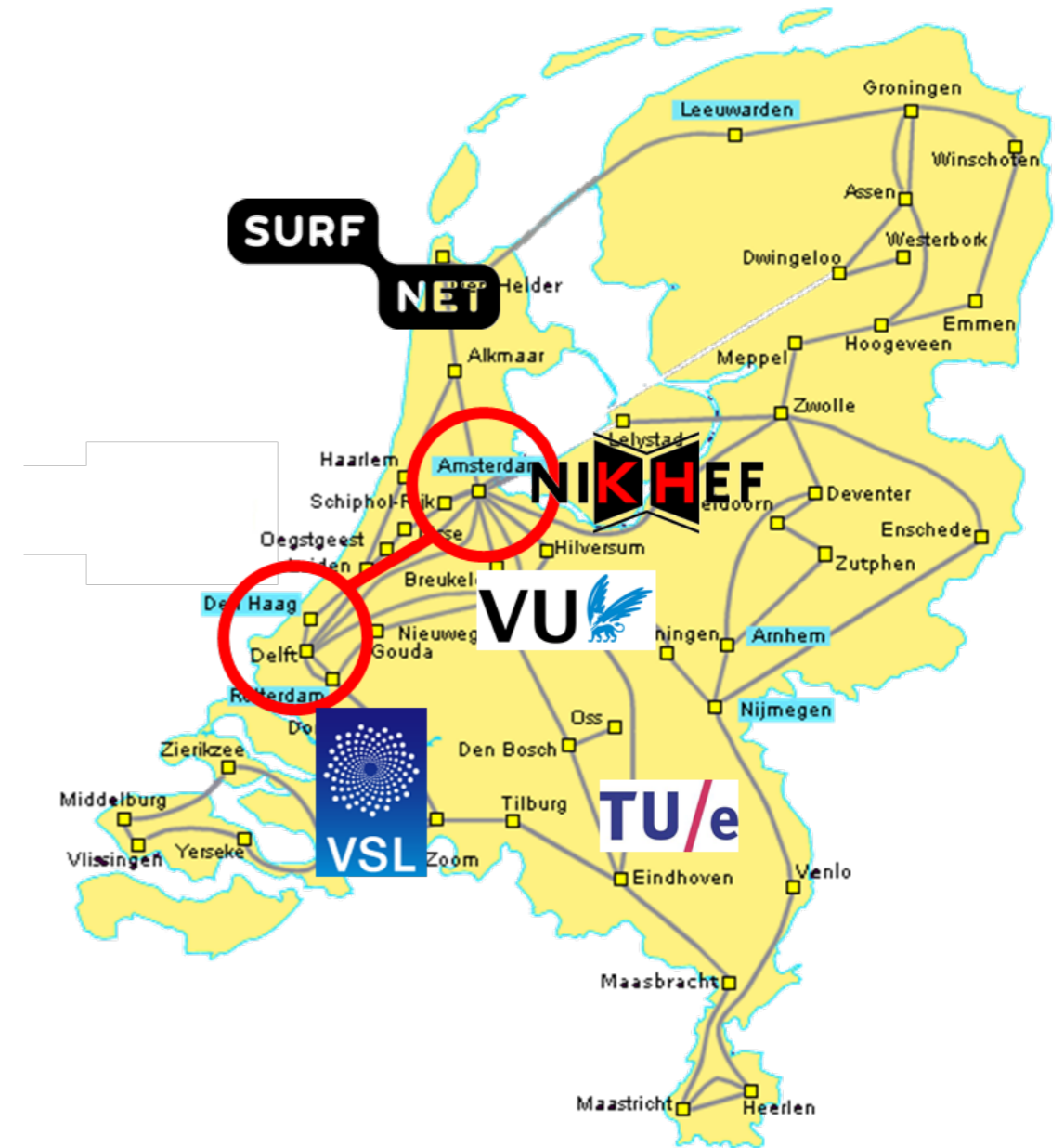
- Accurate time transfer via long-haul fibre is needed by many:
  - Metrology/time-keeping institutes, science & astronomy, vital infrastructure (GPS backup for telecom and electrical power grids), terrestrial positioning ('SuperGPS'), ...
- What timing performance can be expected for long-haul links (100+km, optical amplifiers, ...)?
- 2013: Laboratory, proof-of-principle demonstration (VU + SURFnet+ TU Eindhoven)\*
  - Calibrate propagation delays by exchange of 10 Gb/s data
  - 4 ps uncertainty achieved over 2x75 km of spooled fibre
  - Calibration of instruments possible at the ps level

\* N. Sotiropoulos, C.M. Okonkwo, R. Nuijts, H. de Waardt, J.C.J. Koelemeij, *Opt. Express* **21**, 32643 (2013).

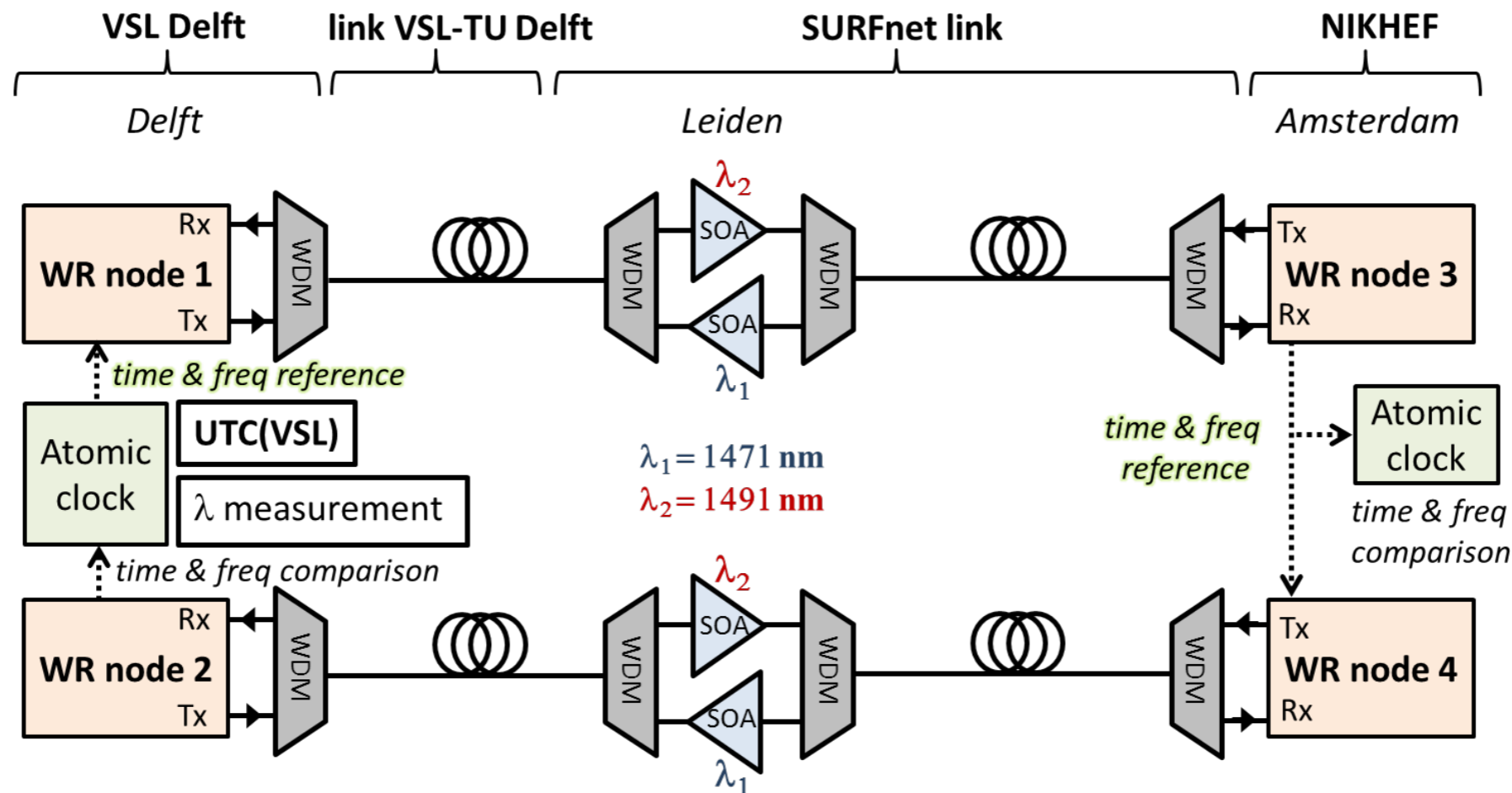
# White Rabbit link: VSL Delft - Nikhef Amsterdam



- Field trial in SURFnet 'dark' telecom fiber (2×80 km)
- Collaboration VU-SURFnet-VSL-NIKHEF
- Aim: sub-ns time transfer of UTC(VSL): Cs clocks + satellite link to TAI
- Equipment calibrated by VU-TU/e-NIKHEF
- Needed for optical frequency measurements at VU!
- Future: useful for VLBI, LOFAR?



# White Rabbit link: VSL Delft - Nikhef Amsterdam

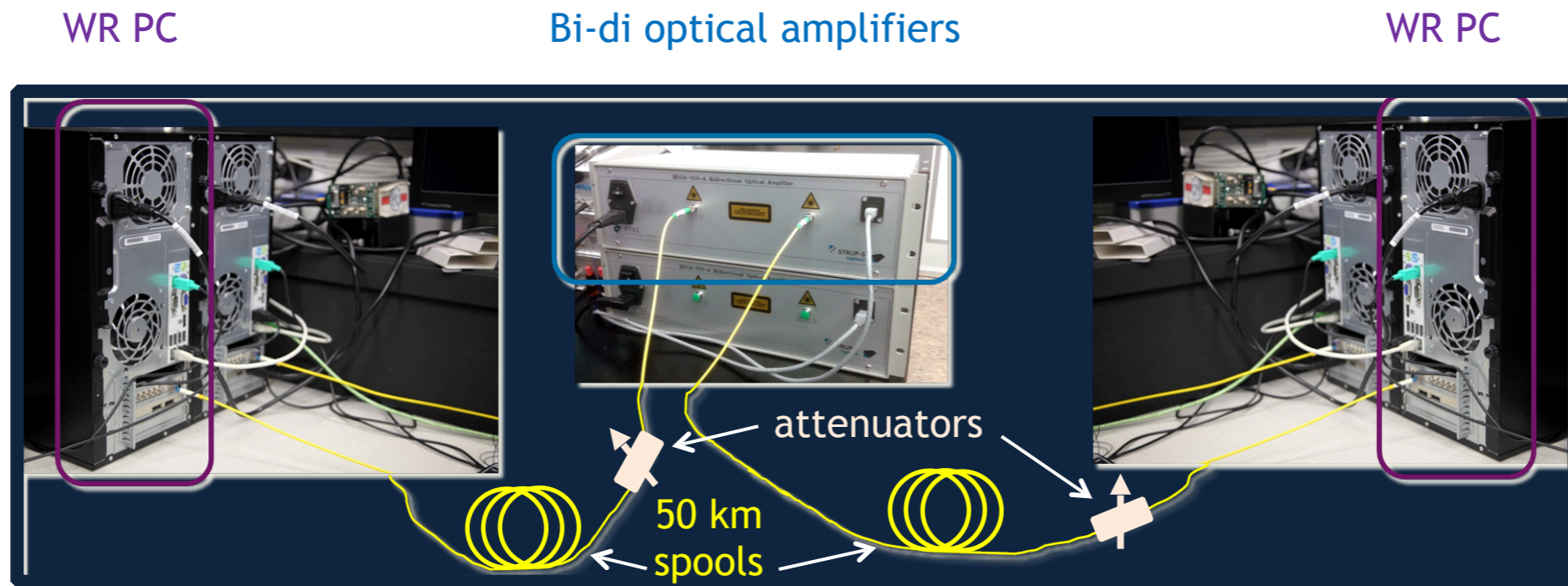


WDM: wavelength-division multiplexer; SOA: semiconductor optical amplifier

- Bidirectional optical amplifiers\* based on SOAs (wide choice of wavelengths)
- All fibres patched, amplifiers currently being installed, optical link up June 2014 (planned)

\* Design similar to that of Amemiya *et al.*, Proc. 2005 IEEE IFCSE pp. 914 -918

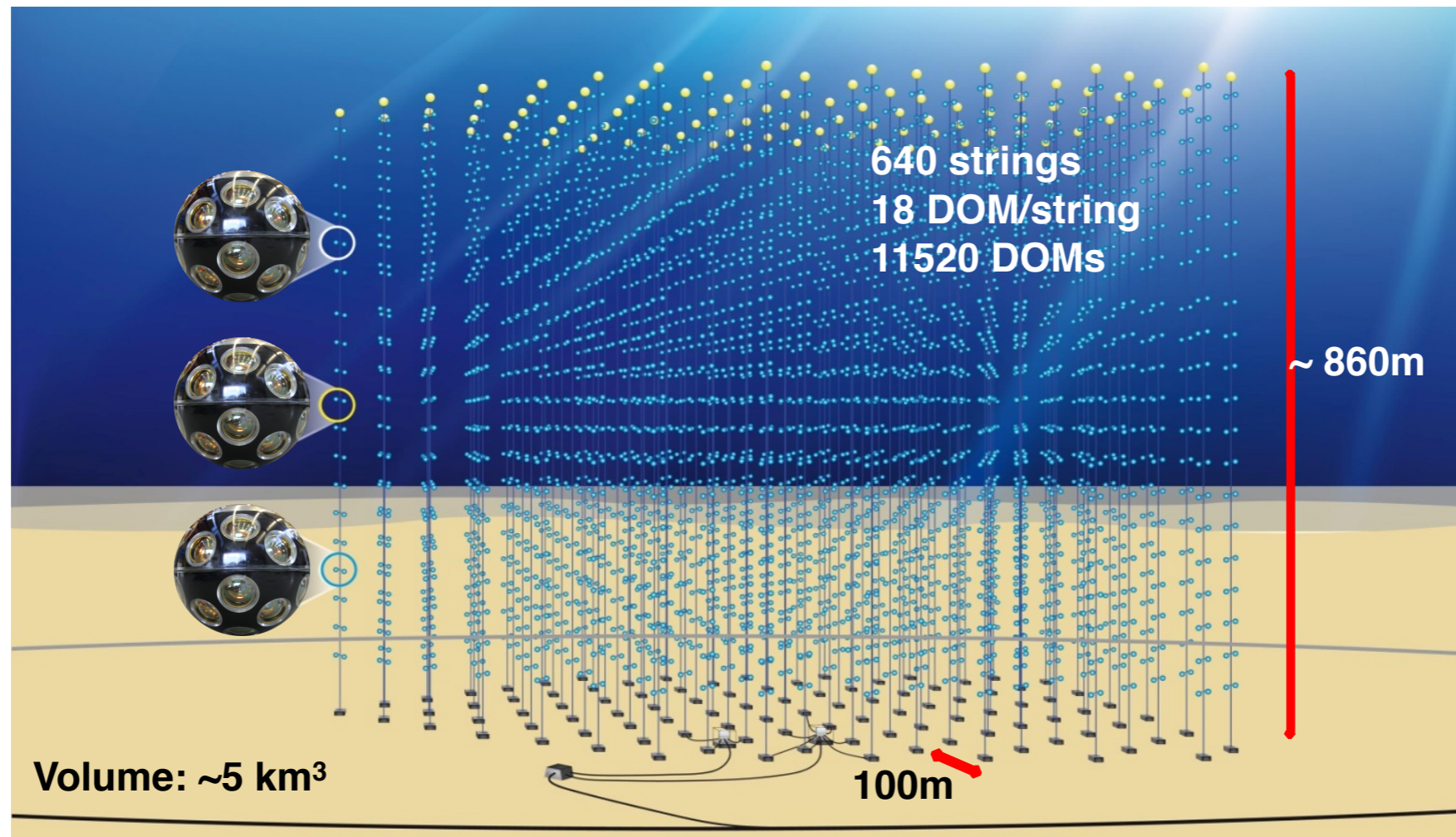
# Staging the White Rabbit link (Nikhef, VU)



- Successful test of White Rabbit + amplifiers with 2x 50 km fibre spools + attenuators (NIKHEF-VU)
- White Rabbit link stays in sync for ~hours
- Components commercially available ([www.sevensols.com](http://www.sevensols.com), [www.opnt.nl](http://www.opnt.nl))
- Underway: calibration of White Rabbit equipment

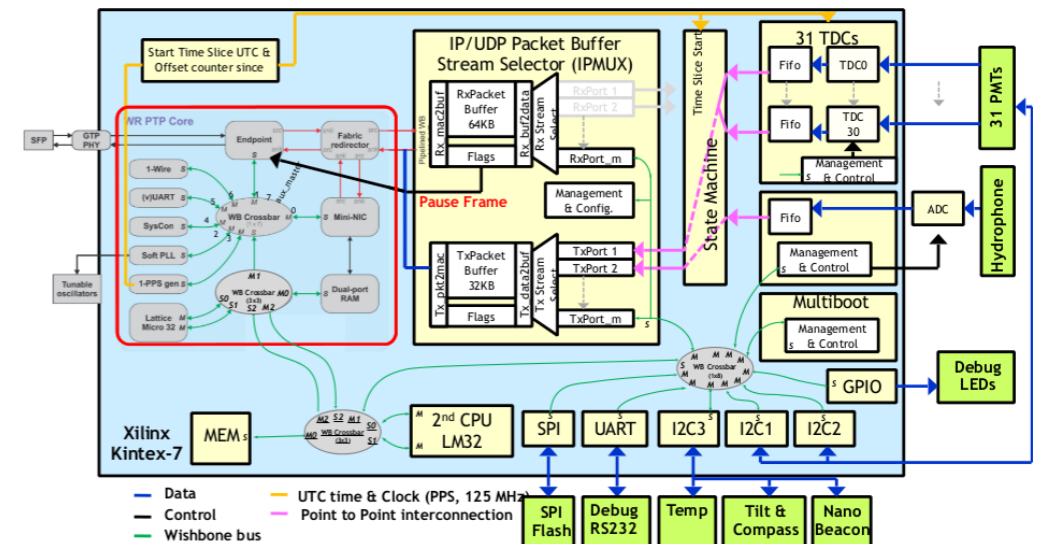
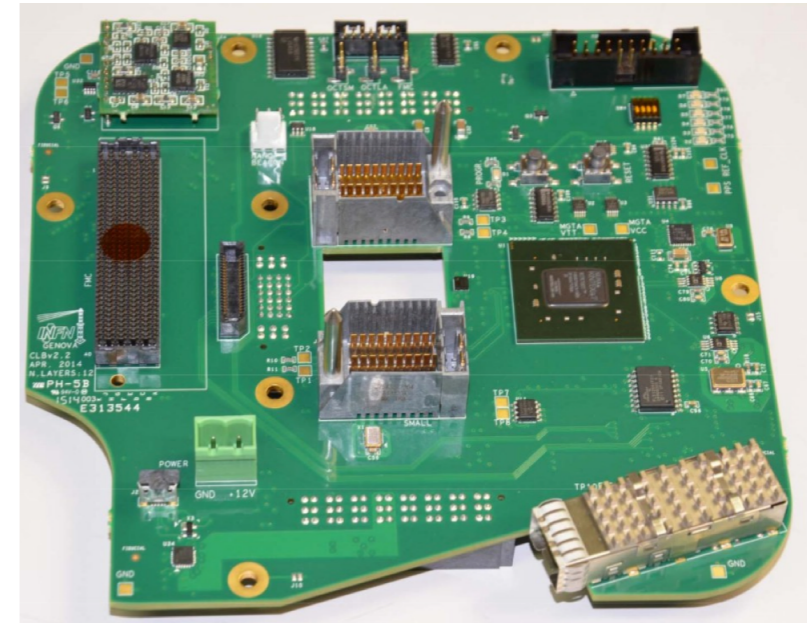
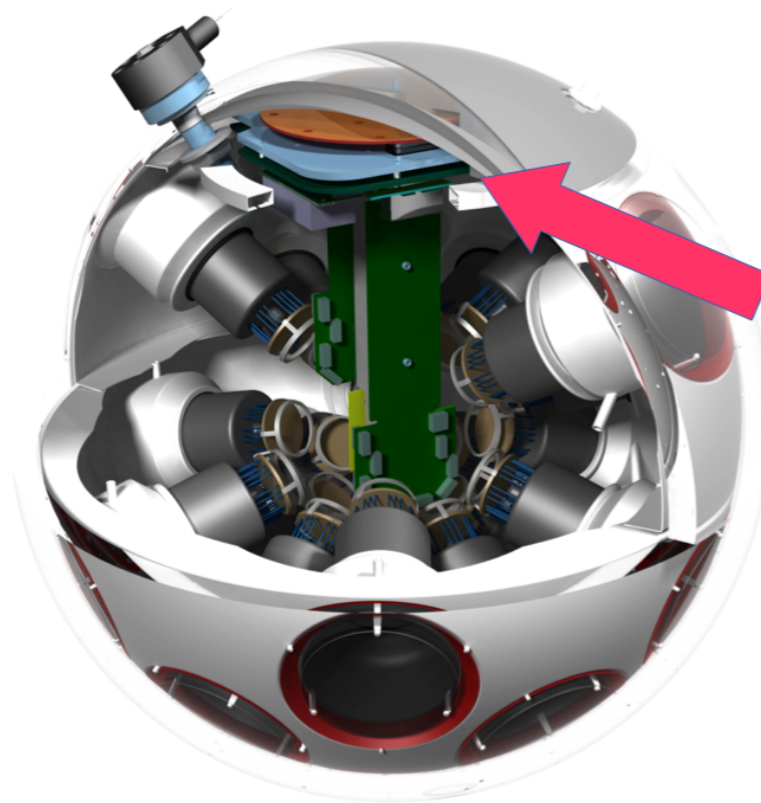


# KM3Net



- <http://www.km3net.org>
- The next generation multi-km<sup>3</sup> neutrino telescope located in the Mediterranean Sea
- 11,520 DOMs in the deep sea at 3-5 km depth with point-to-point connection to shore

# KM3Net DOM Details



- 12+19 PMTs per DOM
- Requirement: 1 ns time resolution





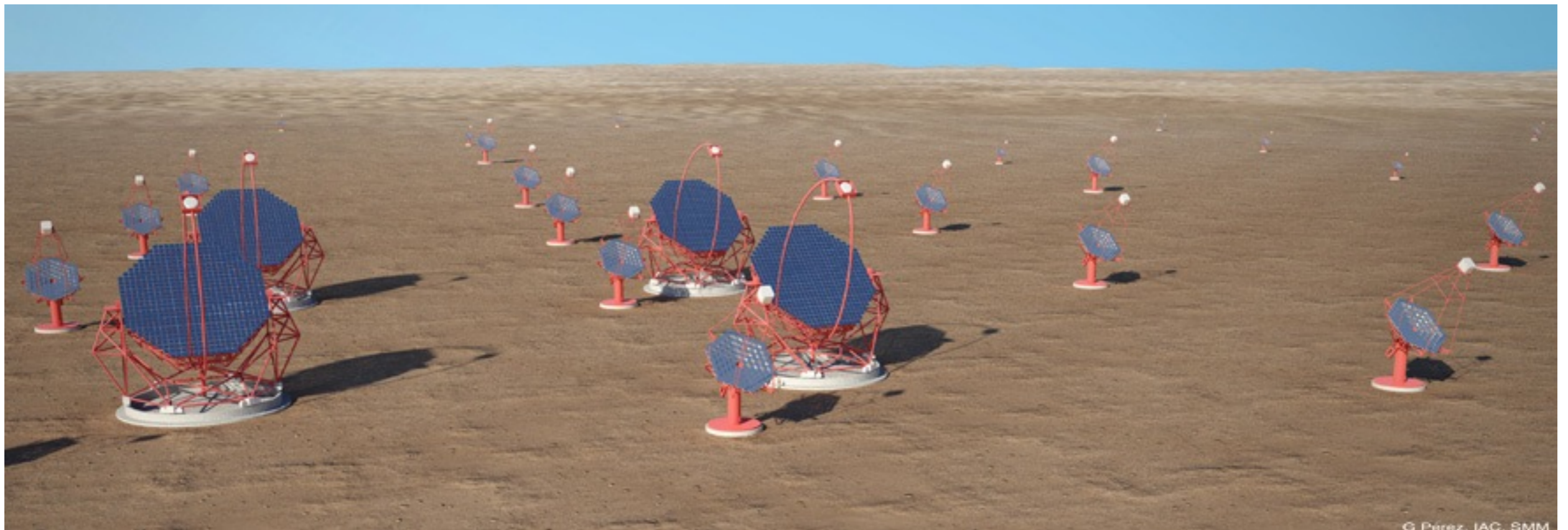
# KM3Net Results

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- Ported White Rabbit core to Kintex-7 FPGA
  - will look into Artix-7 as well
- Use White Rabbit with wavelength-division multiplexing (WDM)
- Deep sea deployment will render default maintenance methods useless
  - Developed new software & firmware deployment methods as well as debugging access
- Several enhancements to White Rabbit core code
- Close cooperation with CTA group in Amsterdam concerning bulk data transfer tests and clock stability tests (see slide 14)
- May cooperate with CTA to add a 10 Gb/s SFP up link for bulk data to the White Rabbit switch together with SevenSols

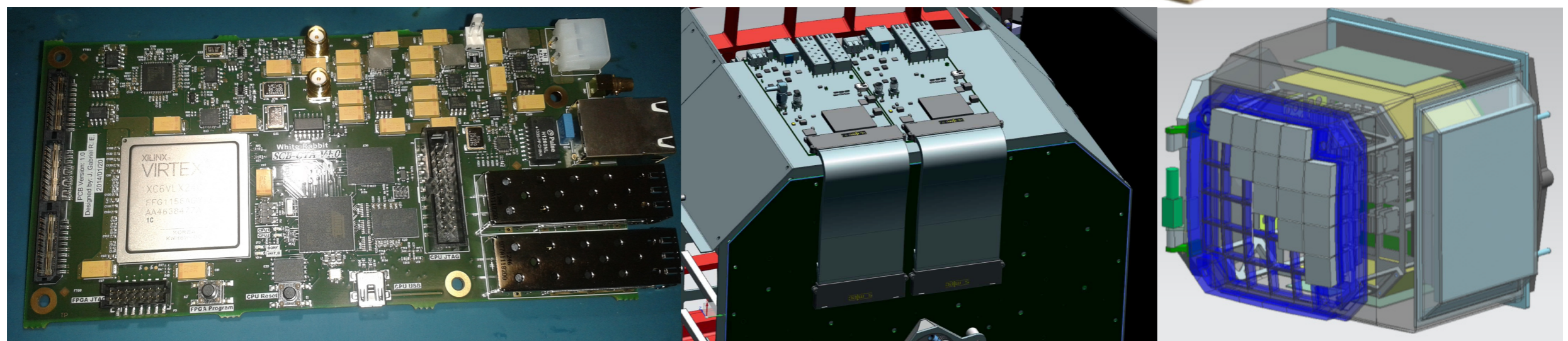
# The **C**herenkov **T**elescope **A**rray

- <http://www.cta-observatory.org>
- Next generation Imaging Atmospheric Cherenkov Telescope array currently in the preparatory phase
- ~100 M€ project as a world wide joint effort
- ~100 optical telescopes in three different sizes
- Requirement: sub-ns inter-telescope timing over ~5 km



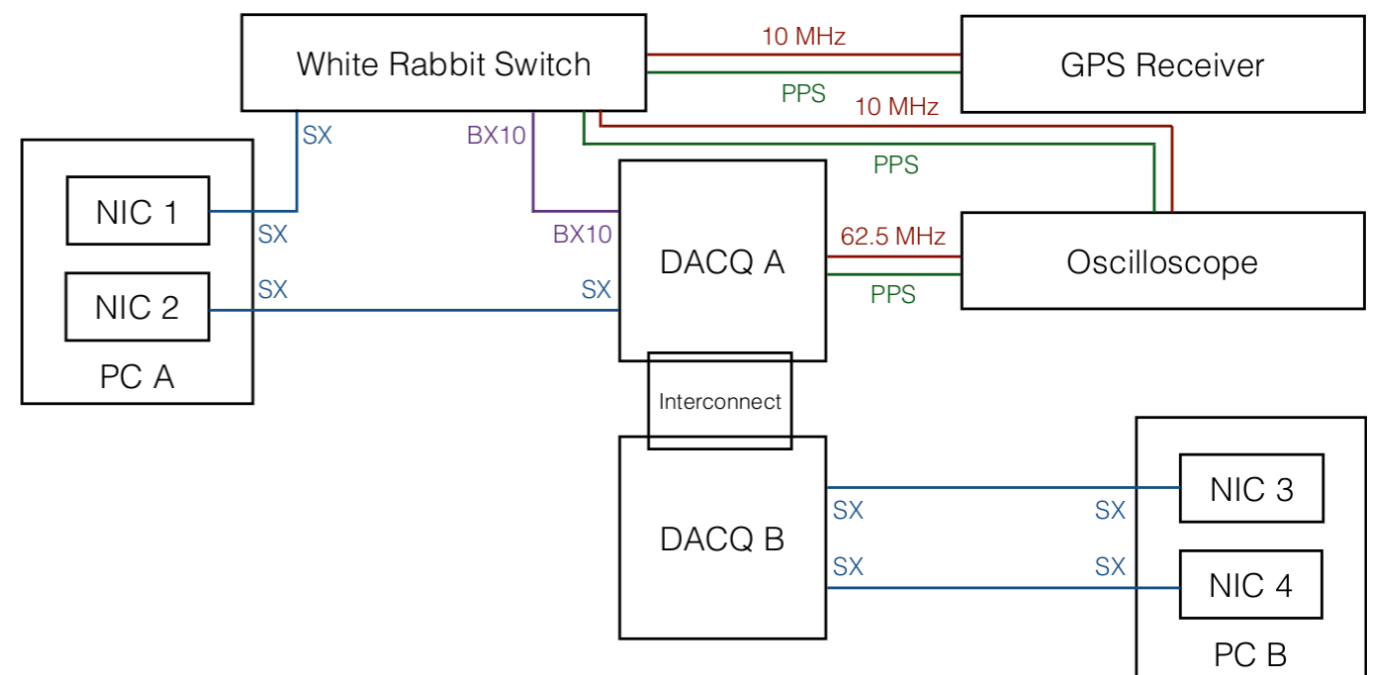
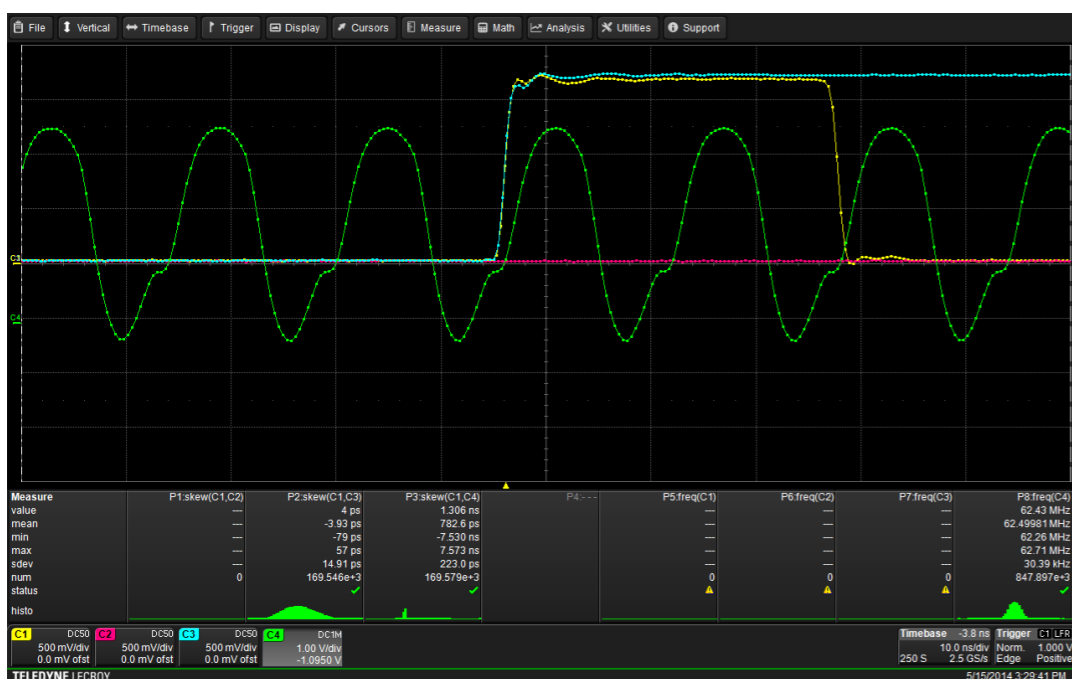
# Compact High Energy Camera

- <https://www.cta-observatory.ac.uk/>
- Build by a subset of the CTA Collaboration
  - UvA is i.a. responsible for the DACQ boards
- Two custom White Rabbit switch boards from SevenSolutions
  - 2 \* 1 Gb/s optical fibre up-links to outside world per board
  - ~3.6 Gb/s bulk data over White Rabbit network
  - 62.5 MHz camera clock via White Rabbit
  - Time stamping via White Rabbit
- Close cooperation with KM3Net@Nikhef



# CHEC DAC Boards Lab Results

- White Rabbit clock distribution stable during 4 Gb/s traffic using a 10 km fibre
  - achieved nominal White Rabbit performance
  - PPS-Signal: Offset: -3.93 ps Jitter: 14.91 ps
- Sometimes loss of sync (~ once every 72 hours)
- Still work to be done for jumbo frames
- Over-saturating a link will result in loss of sync



# Summary & Outlook

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- White Rabbit is a promising extension to the **P**recision **T**ime **P**rotocol achieving sub-ns accuracy and ten-ps precision
- Contributions to White Rabbit from the VU, UvA and Nikhef
- Wide range of application in astroparticle physics facilities (and others), especially KM3Net and CTA
- Future: a SuperGPS system for science and society
  - 4 ps  $\Leftrightarrow$  2.4 mm uncertainty (4D positioning)

# Contributions from

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- Tjeerd Pinkert, Jeroen Koelemeij (VU)
- Ruud Kluit, Maarten de Jong, Henk Peek, Peter Jansweijer (NIKHEF)
- David Berge, Taco Walstra, Arnim Balzer (UvA)
- Erik Dierikx, Martin Fransen (VSL)
- Rob Smets (SURFnet)
- Nikos Sotiropoulos, Chigo Okonkwo, Huug de Waardt (TU/e)
- White Rabbit community (CERN and many other places...)