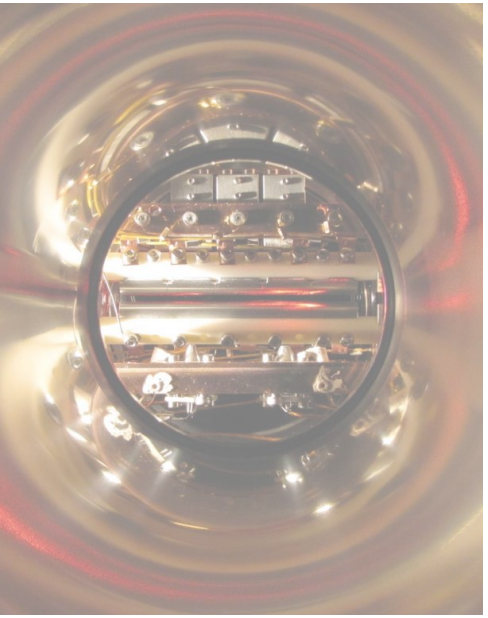


Long-haul White Rabbit for fundamental physics research, radio astronomy, and navigation

Jeroen Koelemeij, Vrije Universiteit Amsterdam

6th GA REFIMEVE+

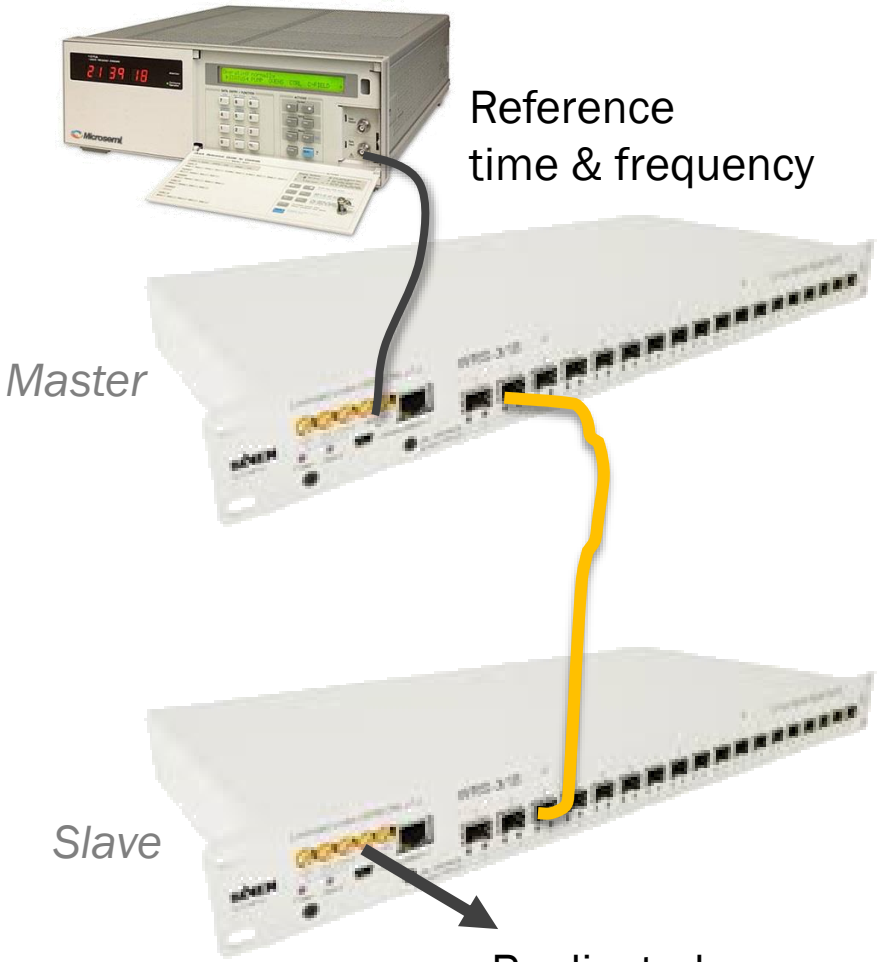
November 30, 2020

VU VRIJE UNIVERSITEIT AMSTERDAM

LASERLAB Amsterdam

White Rabbit

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



- Data, time & frequency distribution system originally developed for (and by) high-energy-physics research facilities (notably CERN/LHC)
- Open-source, open-hardware network equipment for optical **Gigabit Ethernet**

  +

- Optical **time distribution**: measurement and correction for round-trip delay

  +

- **Frequency distribution**: phase-coherent distribution of RF frequency

- NOT: ultrastable optical frequency transfer

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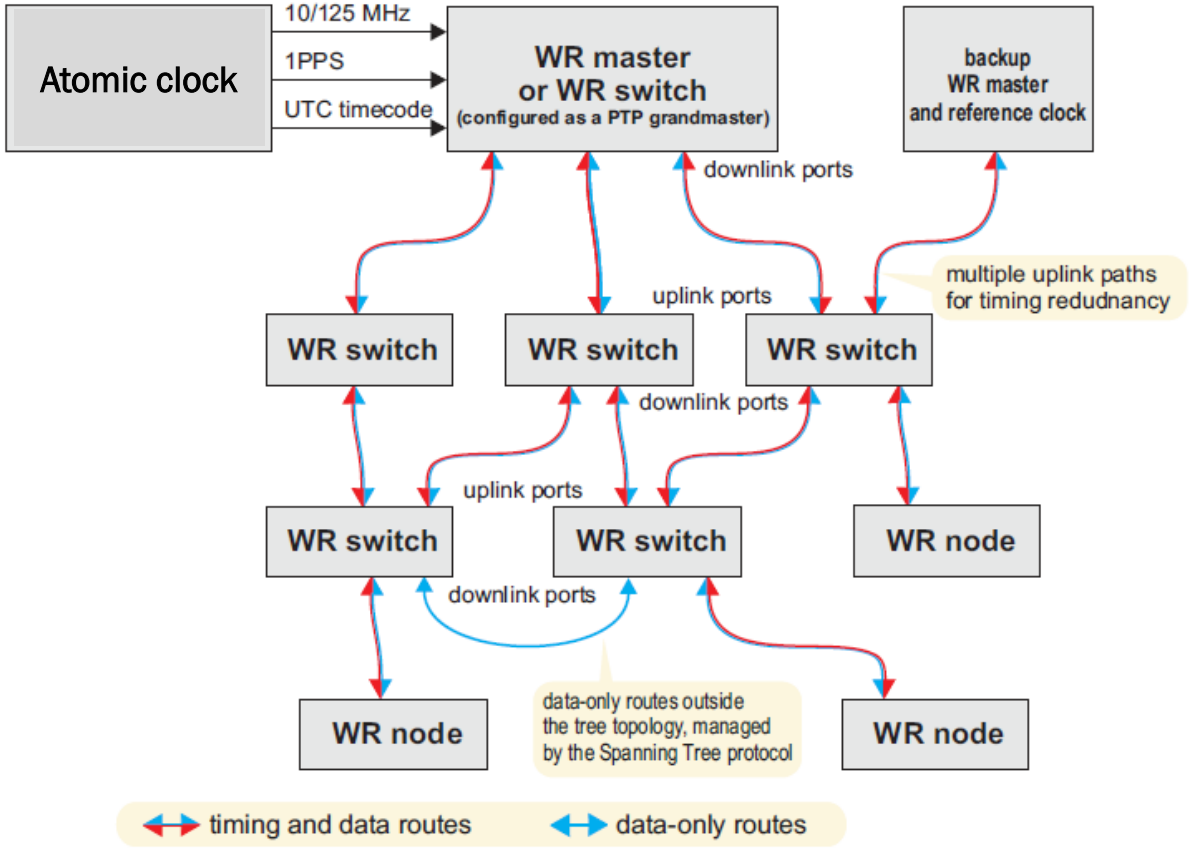
White Rabbit

CERN requires Ethernet and timing @ LHC with uncertainty ≤1 ns

Upgrade of IEEE 1588 : **White Rabbit (WR)** http://www.ohwr.org/projects/white-rabbit



Essential for best performance: bi-directional communication over a single optical fiber

Graph: WR project website

White Rabbit research in the Netherlands

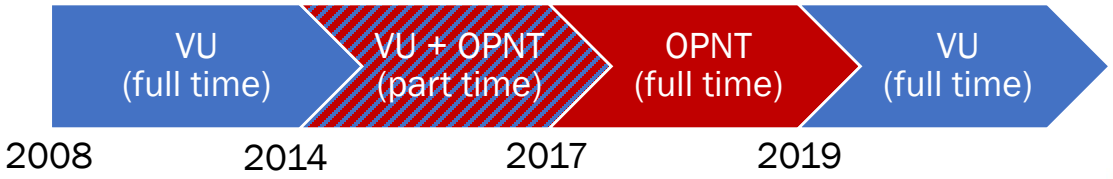
Many groups active in WR worldwide (*e.g.* Paris region: P.-E. Pottie *et al.*)

WR research in the Netherlands:

- Nikhef Amsterdam (WR hardware, KM3NeT neutrino telescope)
- VSL Delft [UTC(VSL)]
- SURF (NREN)
- JIVE Dwingeloo (VLBI radio astronomy)
- ASTRON (LOFAR radio telescope)
- **VU Amsterdam**

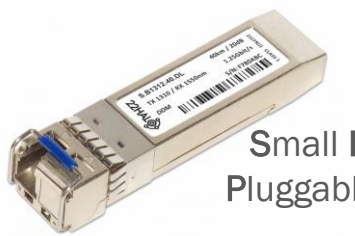
  ⇒ OPNT bv (spin-off company, founded 2014)

Recent employment history JK:

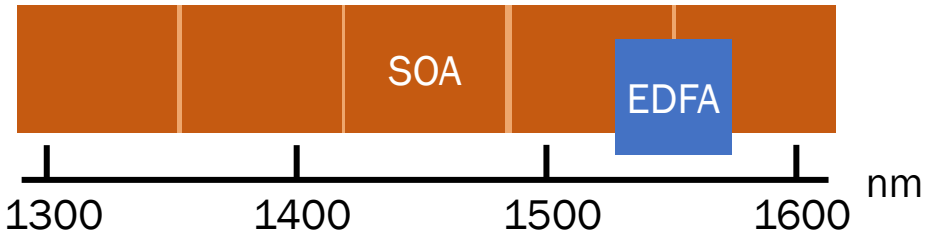


Implementing WR in long-haul links

- WR conforms to Gigabit Ethernet 1000BASE-BX1 standard
  - SFPs transceivers at 1310 nm and 1490 nm, **range limited to 25 km**
- But it is possible to use non-standard wavelengths and long-range SFPs
  - Rx sensitivity up to 40 dB ⇒ **160 km range**
  - Cascade WR devices to cover long distances
  - BUT cascading increases timing jitter (10 ps → 1 ns)
- True long-haul (>>100 km) requires bidirectional optical amplifiers
  - Need to stay out of DWDM/C-band? Use SOAs for out-of-band timing transport



Small Form factor
Pluggable transceiver

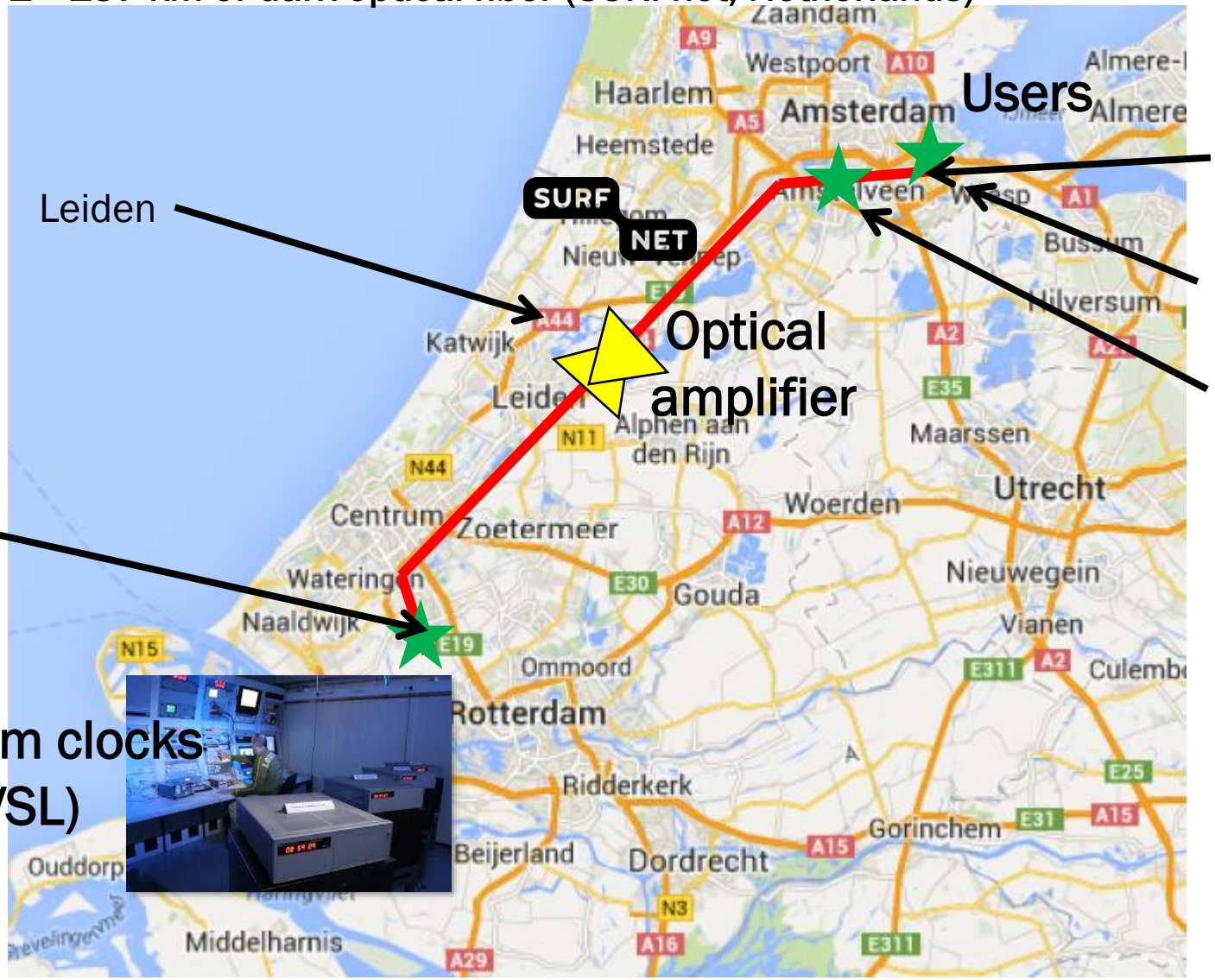


- 950 km demonstrated with EDFAs (MIKES Finland)*
- > 800 km range with SOAs seems feasible (simulations)**

* E. Dierikx *et al., IEEE Trans. Ultrason., Ferroelect. Freq. Control,* **63**(7), 945-952 (2016).
** Engineering Rules for Bi-Directional Photonic Transport White-Rabbit Time and Frequency Transfer Service on Existing In-Service Infrastructure, R. Smets, ASTERICS-H2020-653477 – Report D5.1 (2016) https://www.asterics2020.eu/documents#WP5

WR link between VSL Delft and Amsterdam

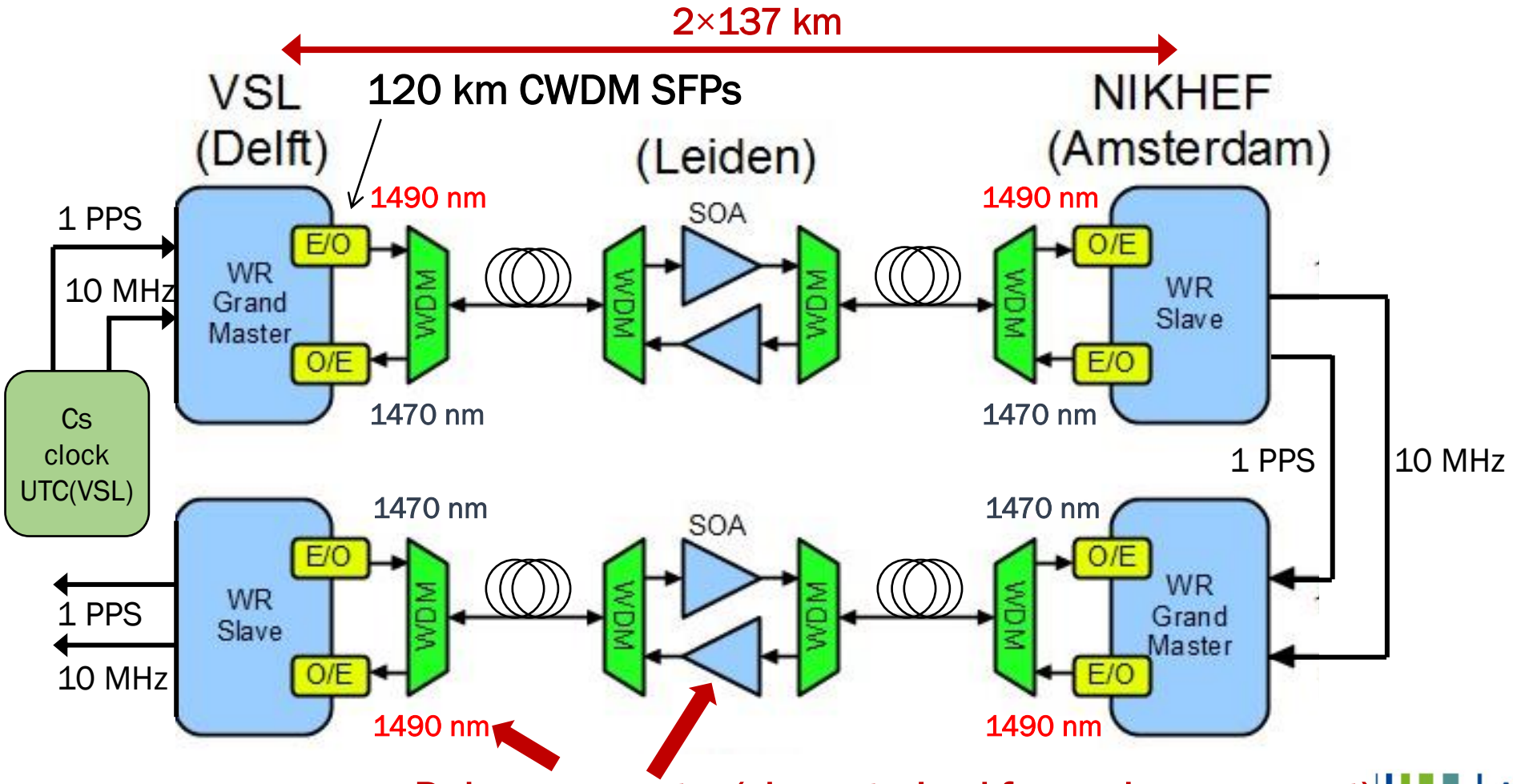
2× 137 km of dark optical fiber (SURFnet, Netherlands)



Cesium clocks
UTC(VSL)

Link Delft - Amsterdam

Amplifier concept: M. Amemiya *et al.* Proc. IEEE IFCS (2005), pp. 914–918.
E. Dierikx *et al.* , *IEEE Trans. Ultrason., Ferroelect. Freq. Control,* **63**(7), 945-952 (2016).



Delay asymmetry due to dispersion

- (Chromatic) dispersion is main source of delays asymmetry (and timing errors) on long fiber spans $\Rightarrow$ time error = $(\delta_{MS} - \delta_{SM})/2$
  - If left uncompensated: many nanoseconds error
- WR takes this into account through the fiber delay asymmetry parameter α:

$$\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}}$$

- Various methods* exist to determine α, and reduce error to sub-ns level

  *e.g. https://white-rabbit.web.cern.ch/documents/WR_Calibration-v1.1-20151109.pdf
  https://www.vsl.nl/sites/default/files/rtf/WR_Good_Practice_Guide.pdf

Three applications of long-haul WR

Radio astronomy/VLBI

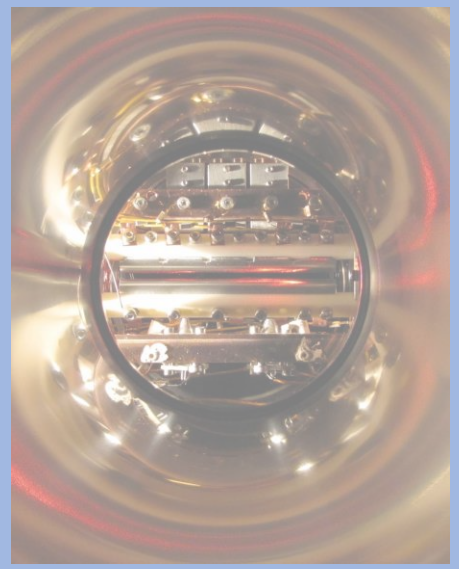
Precision measurements of atoms and molecules

Enhanced terrestrial positioning systems

Three applications of long-haul WR

Radio astronomy/VLBI

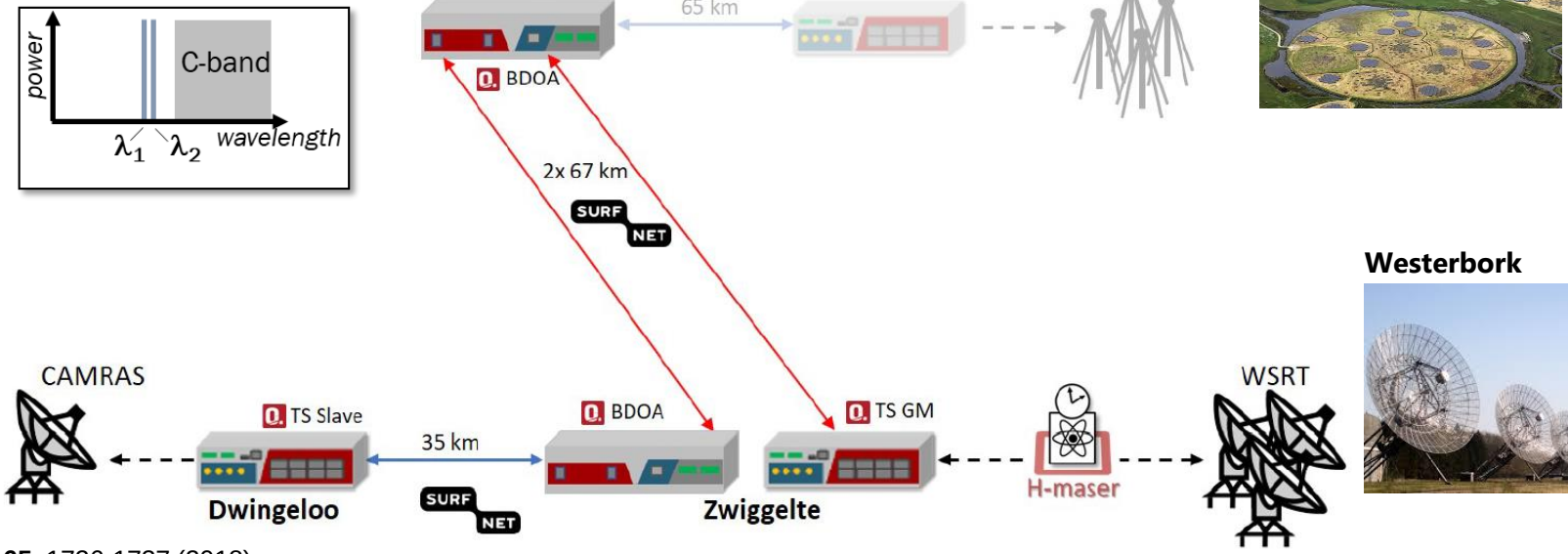
Precision measurements of atoms and molecules



Enhanced terrestrial positioning systems

WR through live SURFnet and VLBI

- Part of H2020 ASTERICS project
- Goals:
  - High-stability White Rabbit*,** link to synchronize VLBI stations (and save €€€ on H-masers)
  - Proof-of-principle synchronization for multi-messenger astronomy (combine radio + optical + astroparticle + GW + …)
- Implementation: 169 km fiber link Westerbork-Groningen-Dwingeloo (multiplexed in live SURFnet8 network)
  - SFPs 100 GHz DWDM grid around 1511 nm
  - Two bi-di amplifiers (SOAs)



Westerbork

Paul Boven (JIVE)

Chantal van Tour (VU/OPNT)

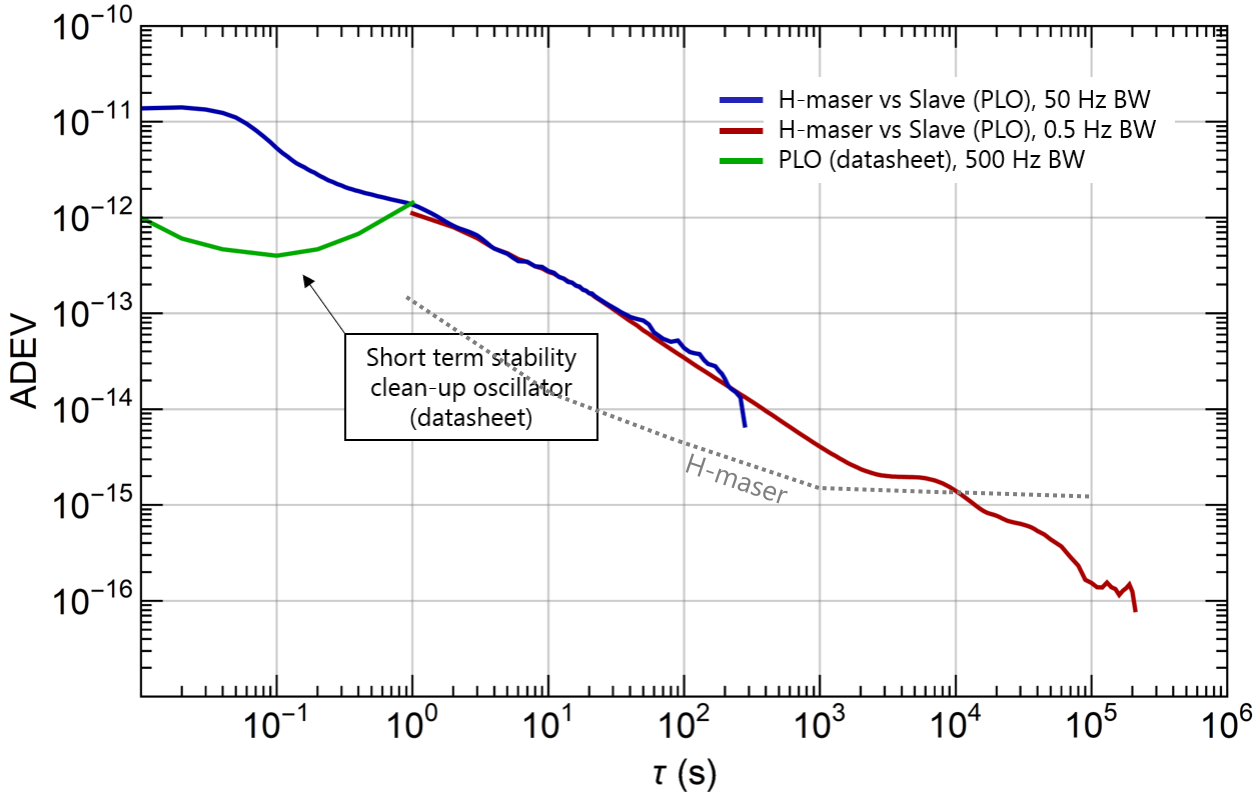
*M. Rizzi,*et al*. IEEE TUFFC **65,** 1726-1737 (2018)
**C. van Tour, J.C.J. Koelemeij, NRAO Memo Series for the Next-Generation Very Large Array, Memo #22 (2017).

WR link results

Setup before installation in SURFnet8

Results
Time offset 169 km link:
(–0.37±0.13) ns

ADEV (0.5 Hz BW):
10^{-12} @ 1 s
10^{-16} @ 2×10^{5} s



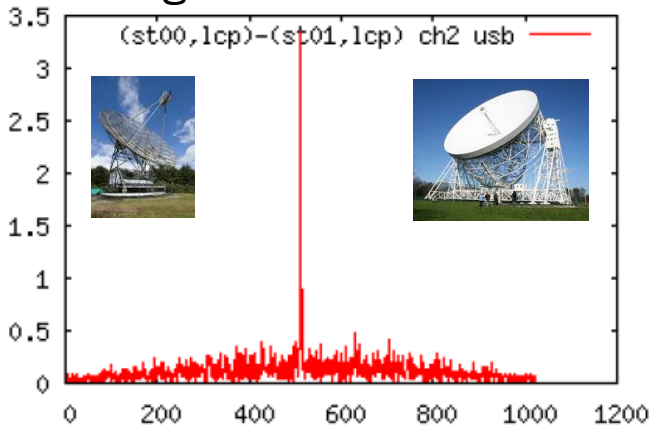
P. Boven, C. van Tour, J.C.J. Koelemeij et al. (in preparation);
https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.14.pdf

VLBI with White Rabbit synchronization

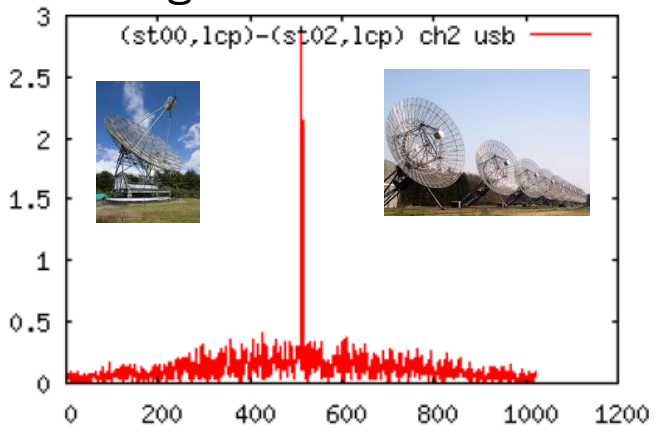
- Three telescopes: Westerbork, Dwingeloo, Jodrell Bank (UK)
  - Jodrell Bank, Westerbork: traditional synchronization (H-maser atomic clock)
  - Dwingeloo: synchronized to H-maser Westerbork via 169 km WR link (SURFnet)
- VLBI fringes (signal underlying radio astronomical images such as: ) observed at both telescopes with good SNR*!

Image: Event Horizon Telescope
(not related to this work!)

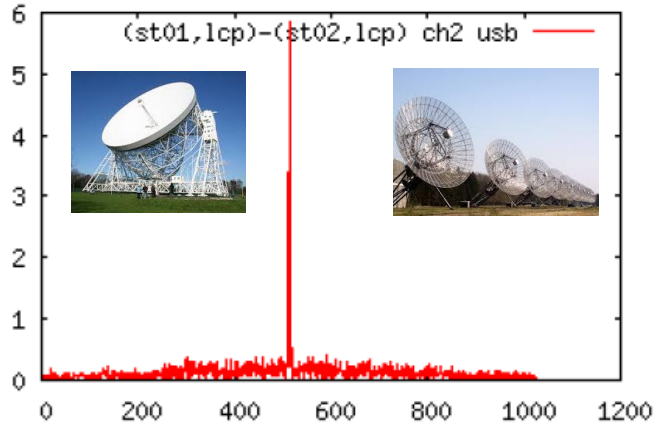
Dwingeloo vs Jodrell Bank



Dwingeloo vs Westerbork



Jodrell Bank vs Westerbork



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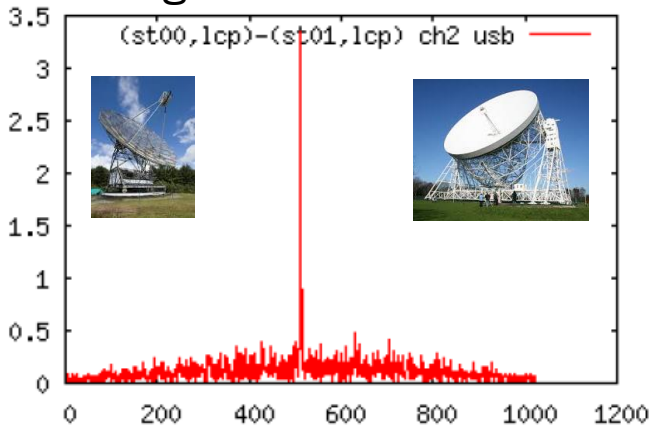
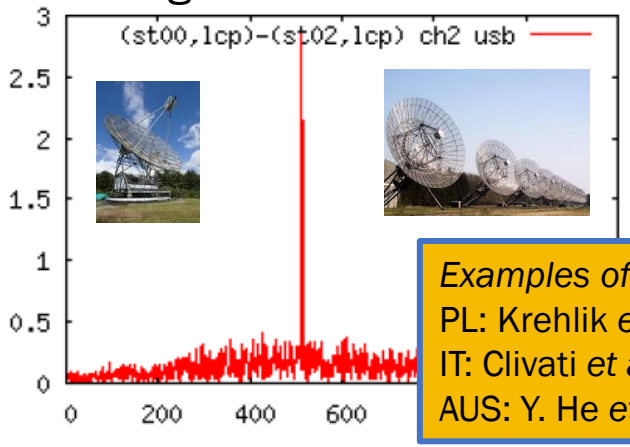
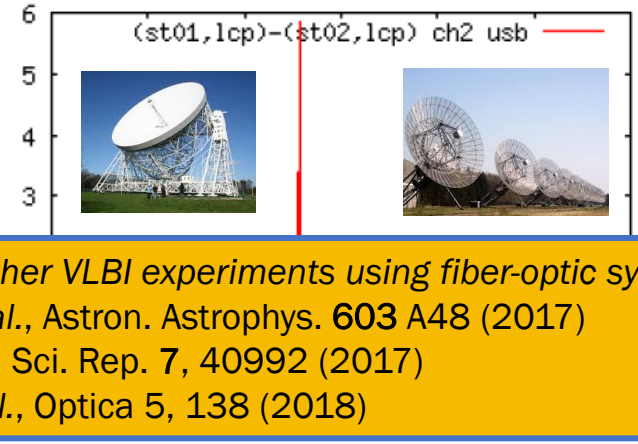


Dwingeloo vs Westerbork



Jodrell Bank vs Westerbork



Examples of other VLBI experiments using fiber-optic synchronization:
PL: Krehlik *et al.*, Astron. Astrophys. **603** A48 (2017)
IT: Clivati *et al.*, Sci. Rep. **7**, 40992 (2017)
AUS: Y. He *et al.*, Optica 5, 138 (2018)

P. Boven, C. van Tour, J.C.J. Koelemeij et al. (in preparation); https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.14.pdf

Three applications of long-haul WR

Radio astronomy/VLBI

Precision measurements of atoms and molecules

Enhanced terrestrial positioning systems

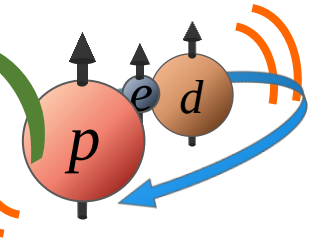
WR for precision measurements of HD^+

- H_2^+, HD^+ : simple three-body **molecules**

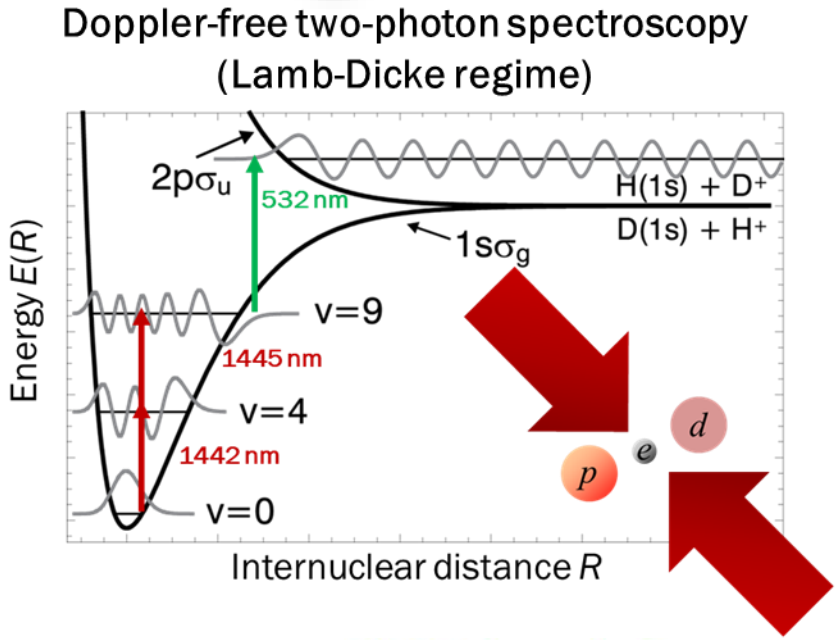
  Laser spectroscopy to study internal degrees of freedom:

  - Electronic
  - Vibrational
  - Rotational
  - Spin

  →
  - Dependence on m_p/m_e
  - Physics beyond Standard Model: fifth forces between nuclei?



- Very accessible to theory (relativistic QM and QED)
- Doppler-free laser spectroscopy of the v=0 – v=9 vibrational overtone*,**
  - Collaboration avec LKB (Karr, Hilico)
  - Similar experiment at HHU Düsseldorf (THz rotational spectroscopy of HD^+)



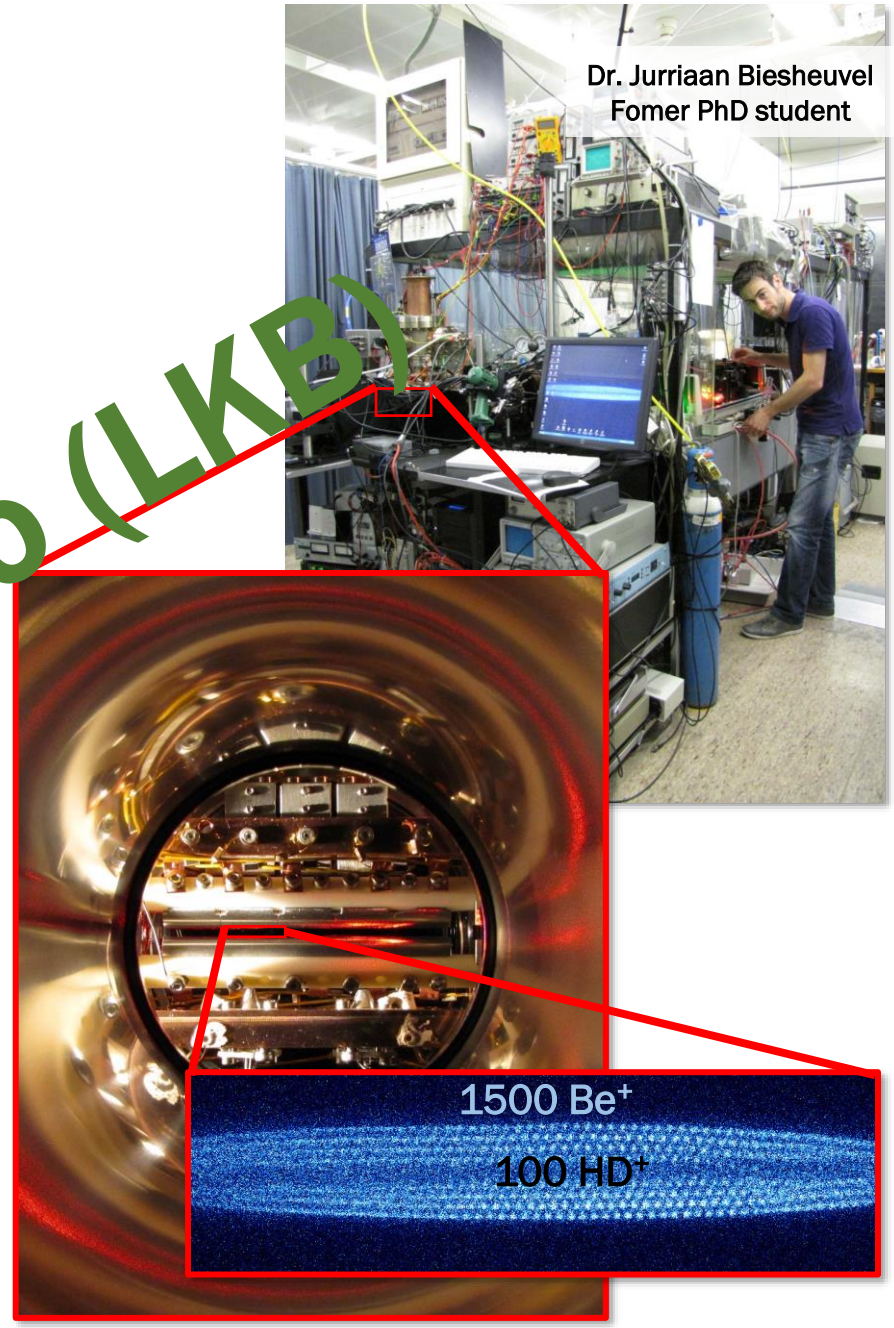
*V.Q. Tran, J.-Ph. Karr, A. Douillet, J.C.J. Koelemeij, L. Hilico, *Phys. Rev. A* **88,** 033421 (2013)

S. Patra, M. Germann, J.-Ph. Karr, M. Haidar, L. Hilico, V.I. Korobov, F.M.J. Cozijn, K.S.E. Eikema, W. Ubachs, J.C.J. Koelemeij, *Science* **369, 1238 (2020)

Laser spectroscopy of HD^+

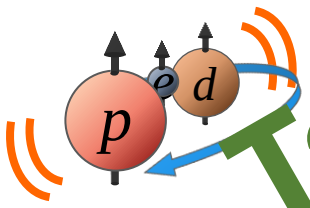
- Doppler-free laser spectroscopy of trapped HD^+ at 10 mK
  - Experimental uncertainty ~1 kHz (3 ppt)
- Theoretical predictions* (Karr, Hilico, Korobov)
  - Uncertainty 18 ppt
  - 8 ppt due to theory, 16 ppt due CODATA constants (m_p/m_e)
- Enables improved determination of m_p/m_e !

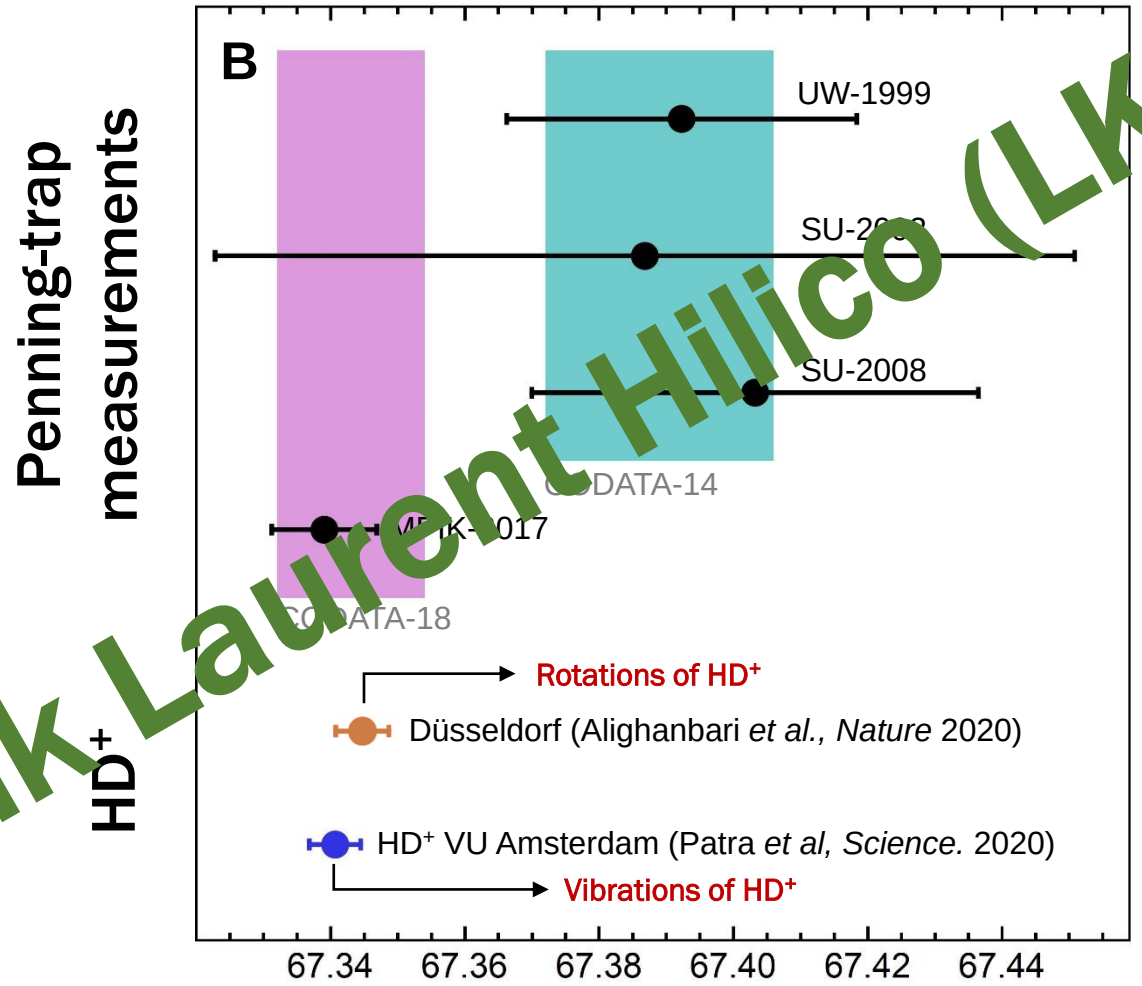
*Korobov, Hilico, Karr, *Phys. Rev. Lett.* **118,** 233001 (2017)



Talk Laurent Hilico (LKB)

Proton-electron mass ratio from HD^+





Talk Laurent Hilico (LKB)

$m_p/m_e = 1{,}836.152\ 673\ 406(38)$

Frequency references for HD^+ spectroscopy

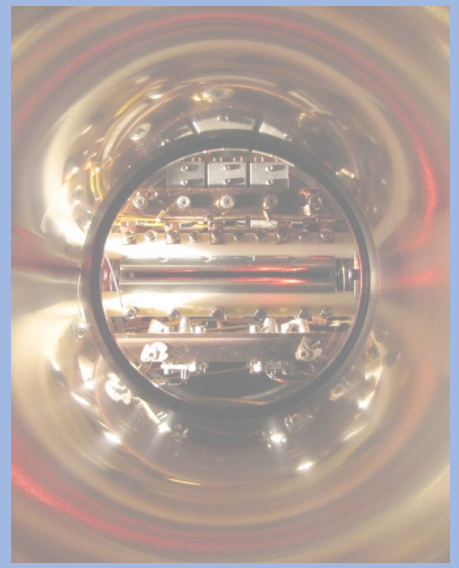
- Now: spectroscopy at 1 ppt resolution (0.4 kHz at 415 THz)
  - Frequency references in our lab: cesium atomic clock with 10^{-12} uncertainty + GPS-disciplined Rb clock
- Follow-up experiments: ~10^{-13} uncertainty (@ 10 s)
  - We need a better frequency reference (traceable to the SI second)!
- Plan: use WR link to VSL Delft for frequency uncertainty < 10^{-13}
  - WR offers sufficient frequency stability (~ 10^{-12} @ 1s, 10^{-16} long term)
  - REFIMEVE would also have been an good option!


UNIVERSITY OF AMSTERDAM
VU VRIJE UNIVERSITEIT AMSTERDAM
To ASTRON/ LOFAR, JIVE
To Germany
esa ESTEC
TU Delft
QuTech
VSL Dutch Metrology Institute
To Belgium, France
To north, east
Nikhef data center
Interxion (AMS9)
Strontium optical clock (F. Schreck)
UvA IoP
To VU
To south

Three applications of long-haul WR

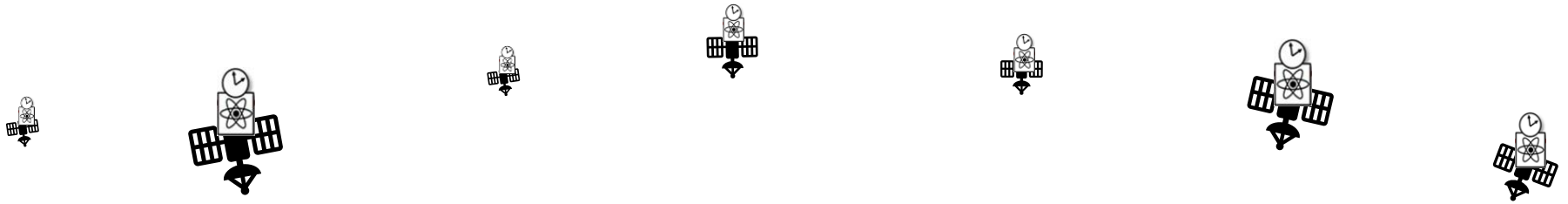
Radio astronomy/VLBI

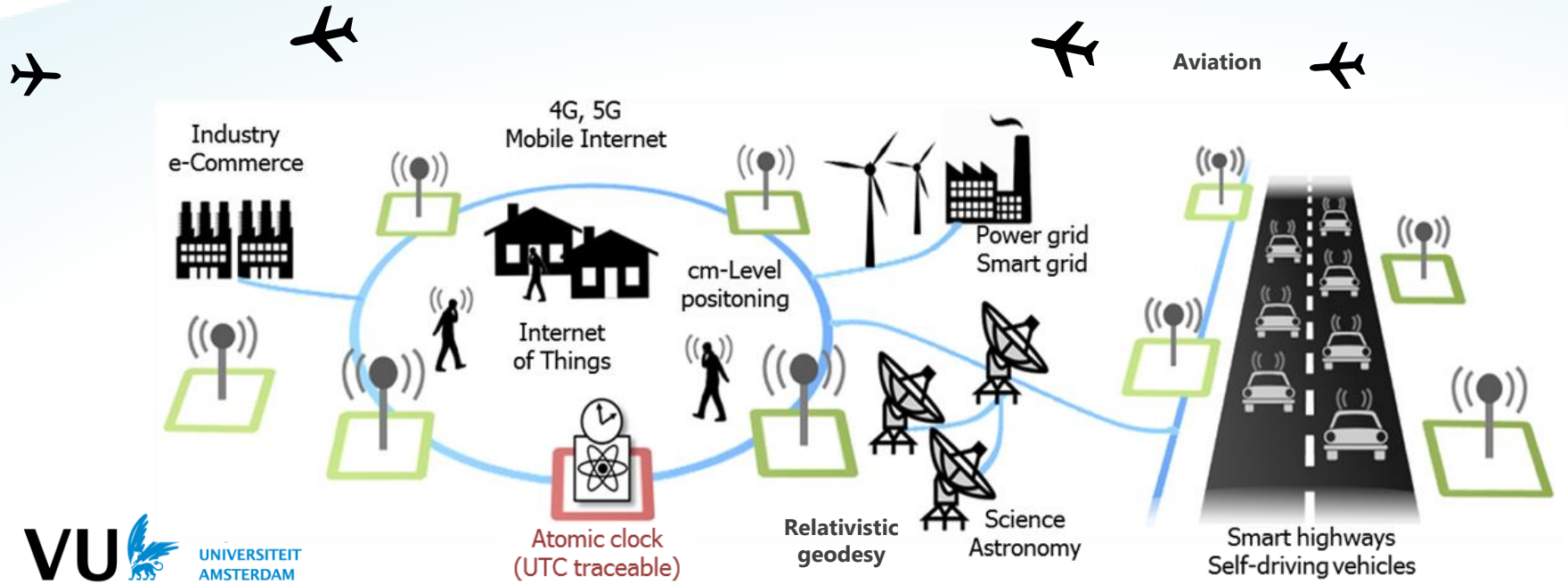
Precision measurements of atoms and molecules



Enhanced terrestrial positioning systems

SuperGPS project



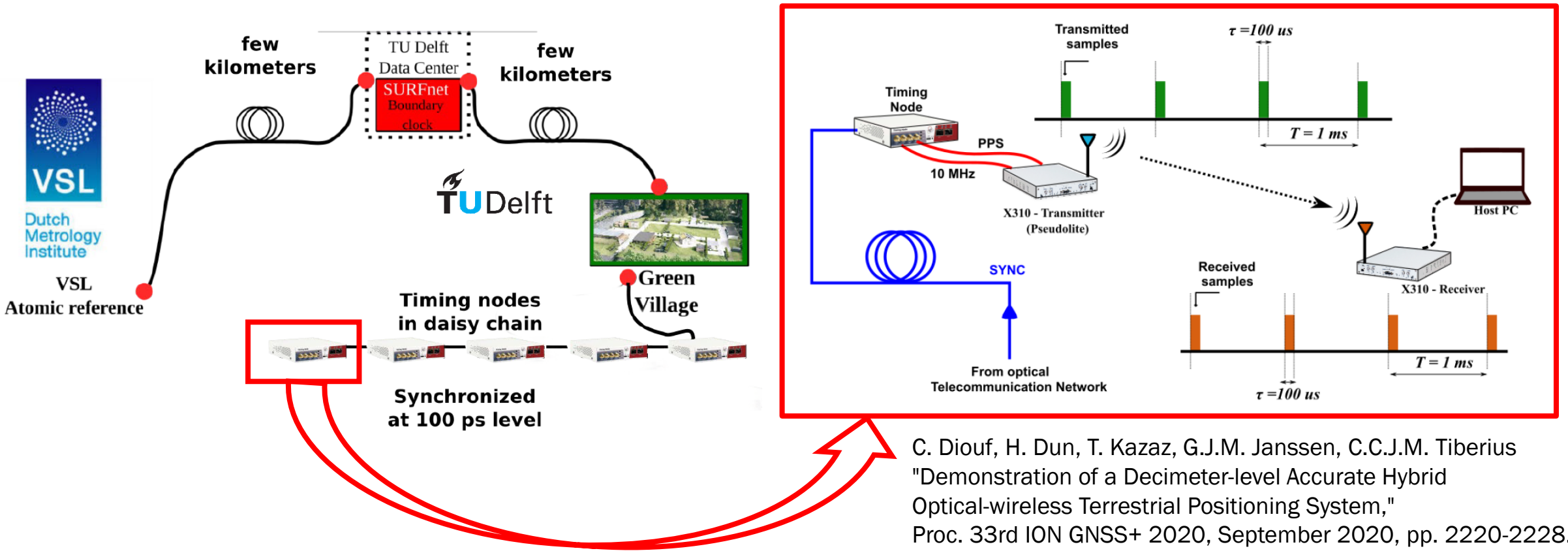


Network of the future:

+ Connectivity
+ Navigation
+ Time/frequency

First positioning trial at “The Green Village” (TU Delft, Sep 2020)

- WR fiber-optic time distribution with few-0.1 ns uncertainty (0.1 ns ⇔ 3 cm at speed of light)



C. Diouf, H. Dun, T. Kazaz, G.J.M. Janssen, C.C.J.M. Tiberius "Demonstration of a Decimeter-level Accurate Hybrid Optical-wireless Terrestrial Positioning System," Proc. 33rd ION GNSS+ 2020, September 2020, pp. 2220-2228.

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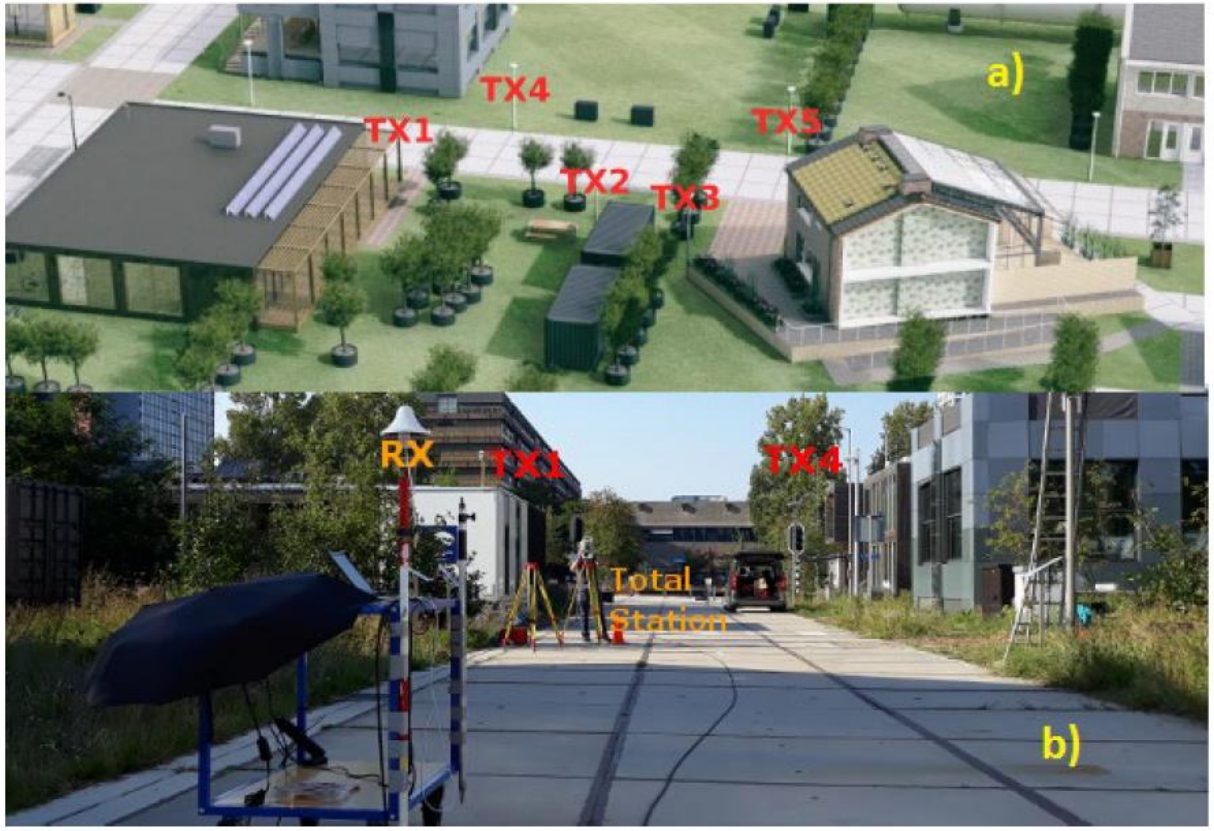

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"Demonstration of a Decimeter-level Accurate Hybrid Optical-wireless Terrestrial Positioning System,"
Proc. 33rd ION GNSS+ 2020, September 2020, pp. 2220-2228.

- Concept of hybrid optical/wireless system conceived by TU Delft and VU Amsterdam
- Time distribution based on WR technology developed at VU/OPNT
- Positioning by time difference of arrival (TDOA) estimation and trilateration
- Wideband radio signals: better suited to combat reflections (multipath)
- Initial test by TU Delft: **0.3 m uncertainty** in presence of multipath (compare GPS 5-10 m in open field, and worse than that in case of multipath)

Thank you!

Questions: j.c.j.koelemeij@vu.nl

VU

Sayan Patra

Matthias Germann

Tjeerd Pinkert

Chantal van Tour

Frank Cozijn

Kjeld Eikema

Wim Ubachs

TU Delft

Christian Tiberius

Gerard Janssen

VSL

Erik Dierikx

Yan Xie

Marc Pieksma

JIVE Dwingeloo

Paul Boven

Arpad Szomoru

Nikhef

Peter Jansweijer

Henk Peek

Guido Visser

SURF

Rob Smets

Roeland Nuijts

ASTRON

Peter Maat

LKB Paris

Jean-Philippe Karr

Laurent Hilico

JINR Dubna

Vladimir Korobov

OPNT

Marco Gorter

Adrian Savencu

Nico Coesel

Tjeerd Pinkert

Cedric Plantard

Aloys Erkelens

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Namneet Kaur

VU VRIJE UNIVERSITEIT AMSTERDAM

LASERLAB Amsterdam