

STEP'UP Interview  
Investigating interferometry in  
GRAND<sup>1</sup>

E.T. de Boone

June, 2023

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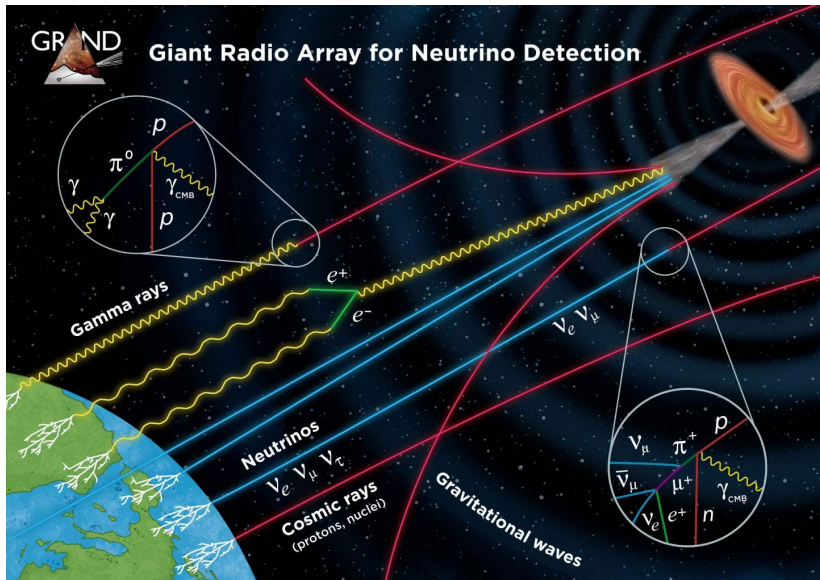
<sup>1</sup>Giant Radio Array for Neutrino Detection

# My Background

## Studies @Radboud University, Nijmegen

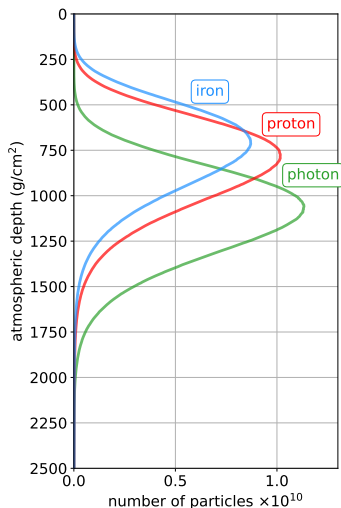
- ▶ Master's Physics and Astronomy (*1yr courses + 1yr internship*)  
Specialisation: Particle and Astrophysics  
Minor: Computational Data Science
- ▶ Master's Internship:  
Supervisor: Harm Schoorlemmer, IMAPP, Radboud University  
"Enhancing Timing Accuracy in Air Shower Radio Detectors"

# Ultra High Energy particles



1. arXiv: 1810.09994 [astro-ph.HE]

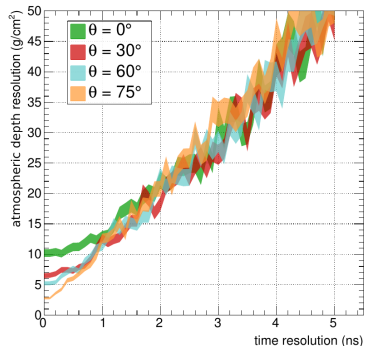
# Air Showers: Atmospheric Depth & Composition



Credit: H. Schorlemmer

Enhanced Xmax measurement  
with Interferometry

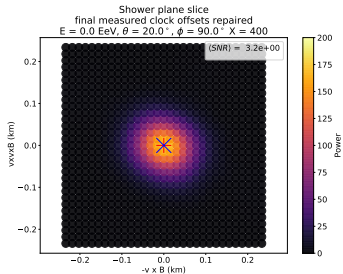
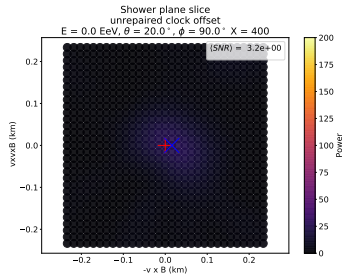
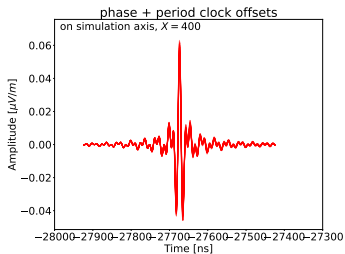
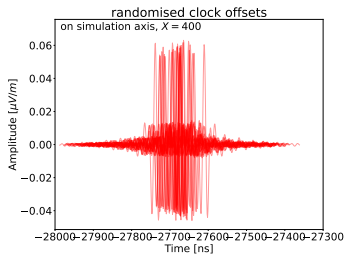
→ particle identification



4. arXiv: 2006.10348 [astro-ph.HE]

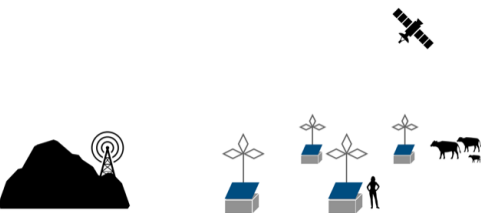
# Effect of Timing Synchronisation

Interferometry: Amplitude + Timing information of the  $\vec{E}$ -field



# Timing Synchronisation: Beacon

Required time accuracy  $\sim 1\text{ns}$



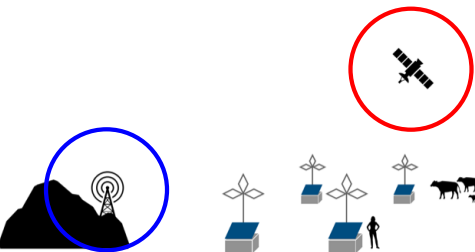
Credit: H. Schoorlemmer

# Timing Synchronisation: Beacon

Required time accuracy  $\sim 1\text{ns}$

GNSS, in Auger  $\gtrsim 5\text{ns}$

Beacon: Pulse or Sine



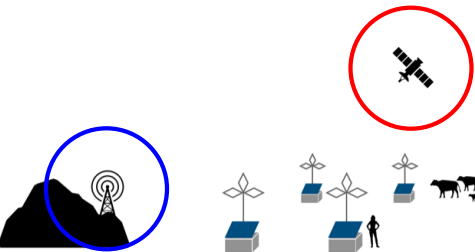
Credit: H. Schoorlemmer

# Timing Synchronisation: Beacon

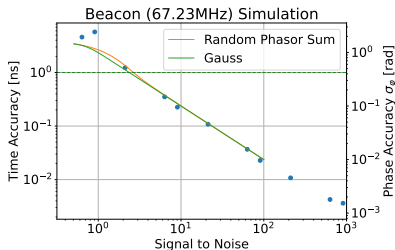
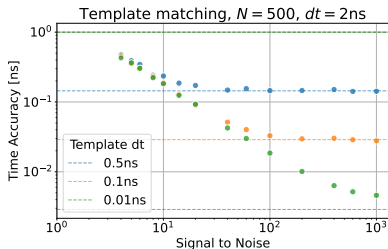
Required time accuracy  $\sim 1\text{ns}$

**GNSS**, in Auger  $\gtrsim 5\text{ns}$

**Beacon**: Pulse or Sine



Credit: H. Schoorlemmer



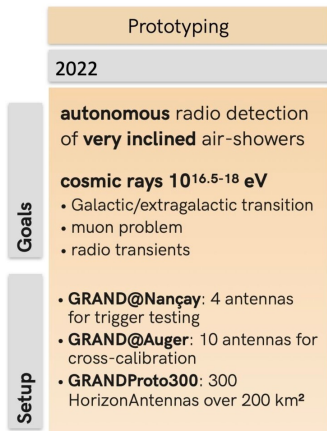


# Radio Interferometry in GRAND

	Prototyping	GRAND10k	GRAND200k
	2022	2025	203X
<b>Goals</b>	<p><b>autonomous</b> radio detection of <b>very inclined</b> air-showers</p> <p><b>cosmic rays <math>10^{16.5-18}</math> eV</b></p> <ul style="list-style-type: none"> <li>Galactic/extragalactic transition</li> <li>muon problem</li> <li>radio transients</li> </ul>	<p><b>1st GRAND sub-array</b></p> <ul style="list-style-type: none"> <li><b>discovery of EeV neutrinos</b> for optimistic fluxes</li> <li>radio transients (FRBs!)</li> </ul>	<p>sensitive <b>all-sky</b> detector</p> <p><b>1st EeV neutrino detection and/or neutrino astronomy!</b></p>
<b>Setup</b>	<ul style="list-style-type: none"> <li><b>GRAND@Nançay</b>: 4 antennas for trigger testing</li> <li><b>GRAND@Auger</b>: 10 antennas for cross-calibration</li> <li><b>GRANDProto300</b>: 300 HorizonAntennas over 200 km<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>10,000 radio antennas over 10,000 km<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>200,000 antennas over 200,000 km<sup>2</sup></li> <li>20 sub-arrays of 10k antennas</li> <li>on different continents</li> </ul>

Adapted from <https://grand.cnrs.fr/overview/roadmap/>

# Radio Interferometry in GRAND in Conclusion



Adapted from <https://grand.cnrs.fr/overview/roadmap/>

[//grand.cnrs.fr/overview/roadmap/](https://grand.cnrs.fr/overview/roadmap/)

1. Timing Requirement in Hardware test beacon at Auger/GP300
2. Setup Interferometric Analyses adapt to GRAND
3. Particle ID through Xmax and Shower Axis reconstruction

## Supplemental material

# Table of Contents

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Radio Interferometry

Time Synchronisation

Expected Time Accuracies vs SNR

Sine

Pulse

Single Frequency Beacon

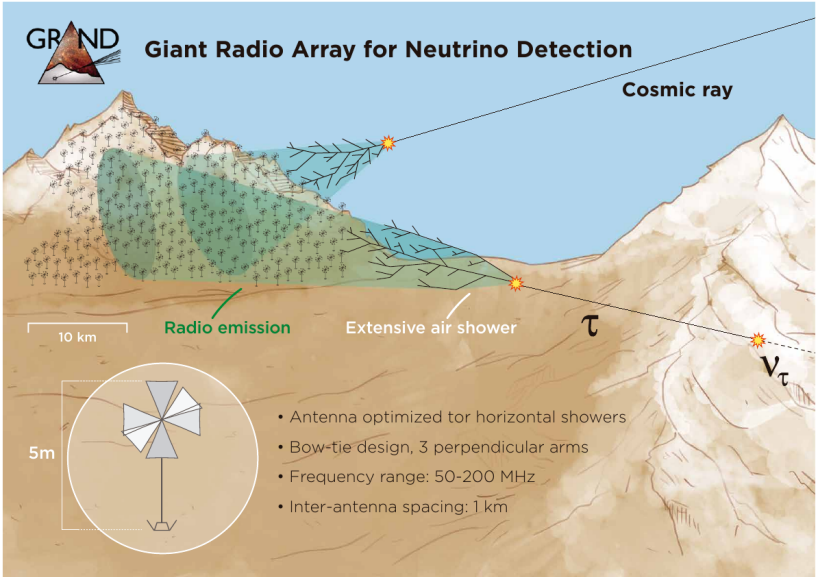
GNSS clock stability

In the field

White Rabbit

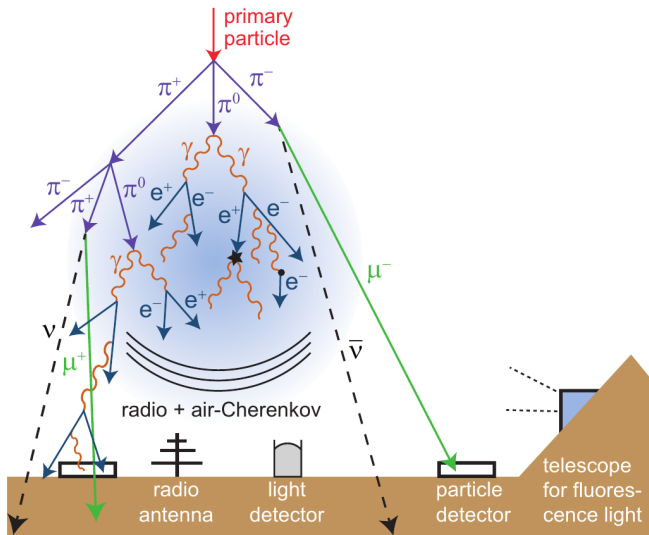


## Giant Radio Array for Neutrino Detection



1. arXiv: 1810.09994 [astro-ph.HE]

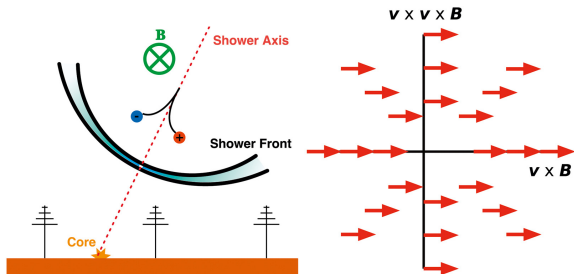
# Airshower development



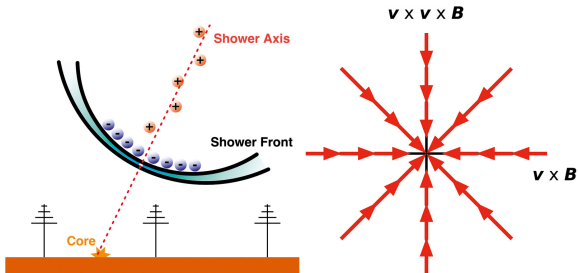
5. arXiv: 1607.08781 [astro-ph.IM]

# Polarised Radio Emission

Geosynchrotron



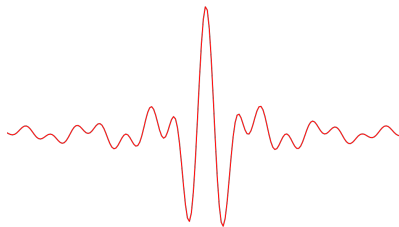
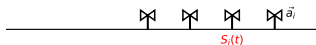
Askaryan



3. arXiv: 1701.02995 [astro-ph.IM]

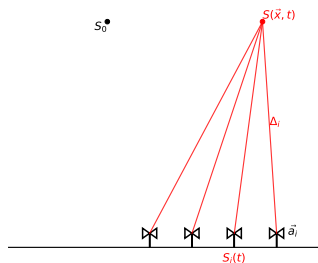
# Radio Interferometry: Concept

- ▶ Measure signal  $S_i(t)$  at antenna  $\vec{a}_i$





# Radio Interferometry: Concept



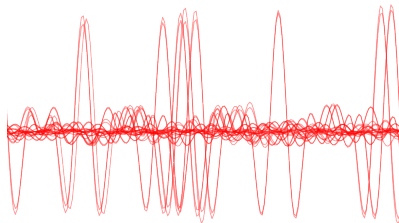
- ▶ Measure signal  $S_i(t)$  at antenna  $\vec{a}_i$

- ▶ Calculate light travel time

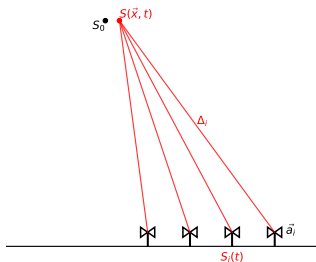
$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i|}{c} n_{eff}$$

- ▶ Sum waveforms accounting for time delay

$$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$



# Radio Interferometry: Concept



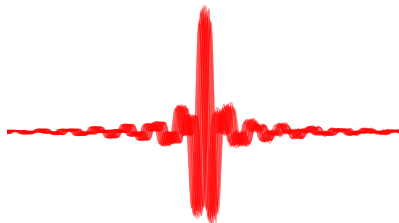
- ▶ Measure signal  $S_i(t)$  at antenna  $\vec{a}_i$

- ▶ Calculate light travel time

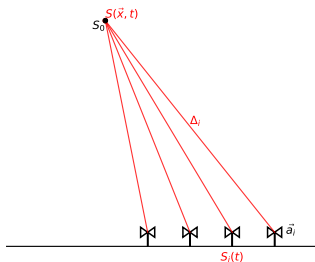
$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i|}{c} n_{eff}$$

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$$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$



# Radio Interferometry: Concept



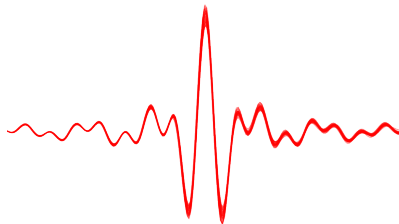
- ▶ Measure signal  $S_i(t)$  at antenna  $\vec{a}_i$

- ▶ Calculate light travel time

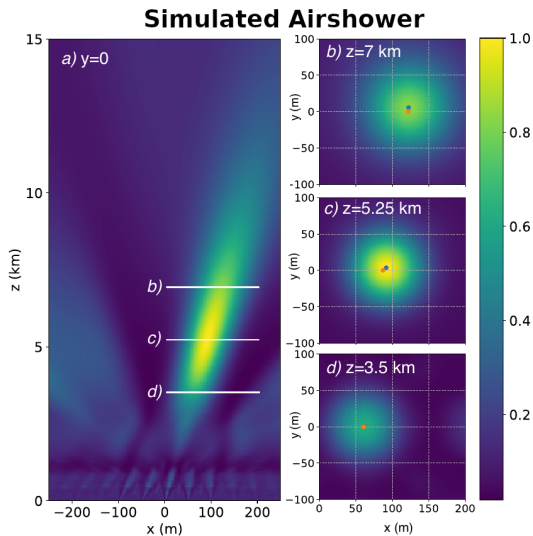
$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i|}{c} n_{eff}$$

- ▶ Sum waveforms accounting for time delay

$$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$

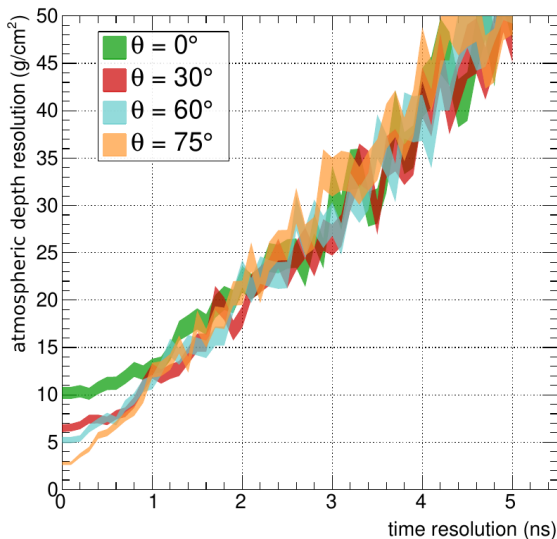


# Radio Interferometry: Image



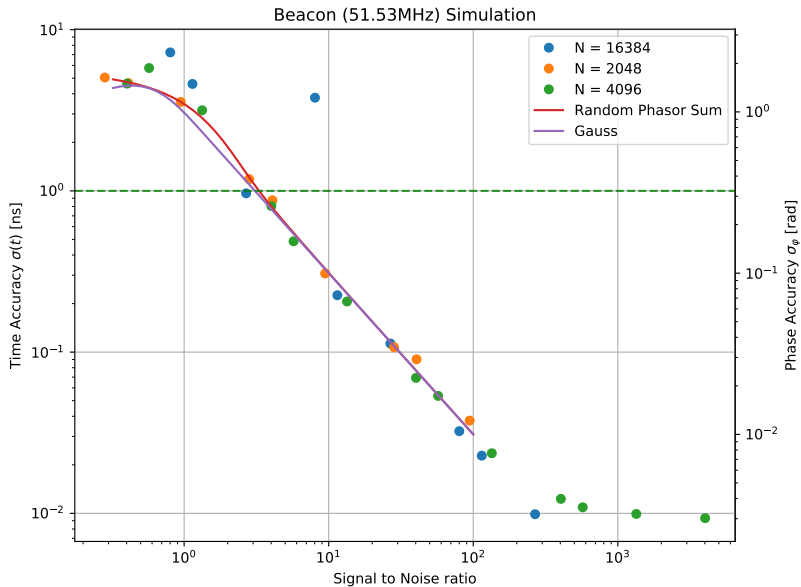
4. arXiv: 2006.10348 [astro-ph.HE]

# Radio Interferometry: Xmax Resolution vs Timing Resolution

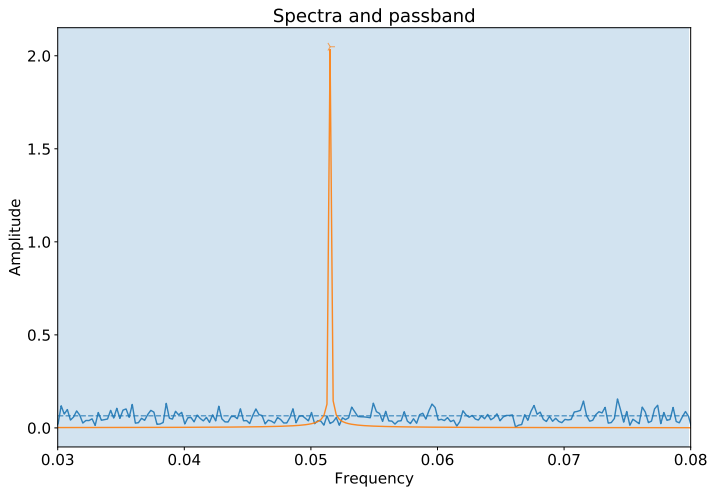


4. arXiv: 2006.10348 [astro-ph.HE]

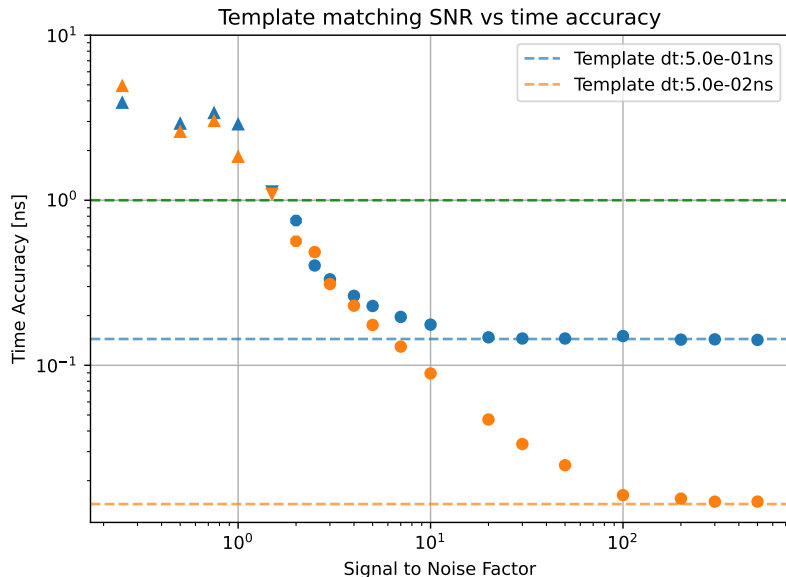
# Sine wave: Accuracy



## Sine wave: SNR



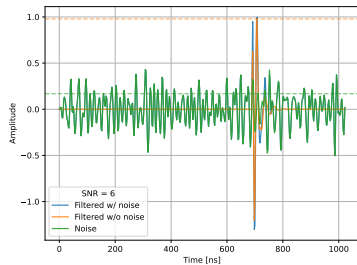
# Pulse Template



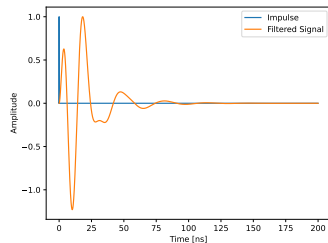


# Pulse Template: SNR

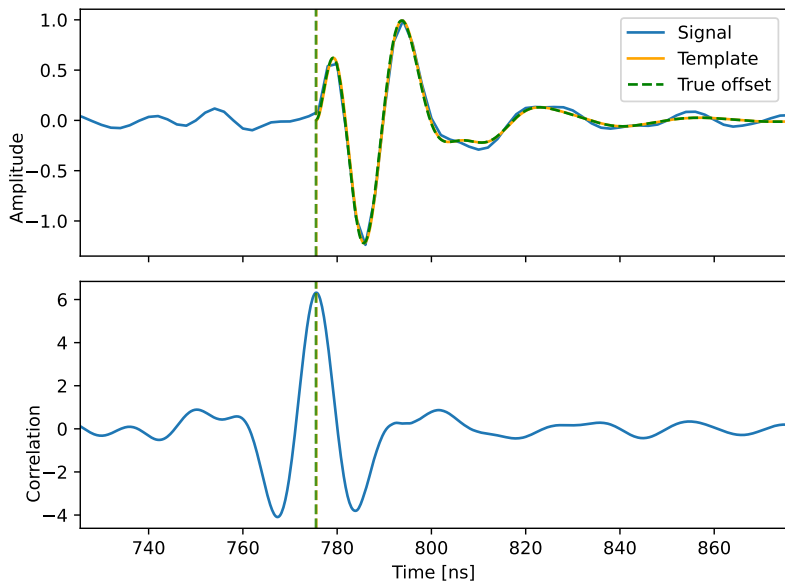
## Signal to Noise



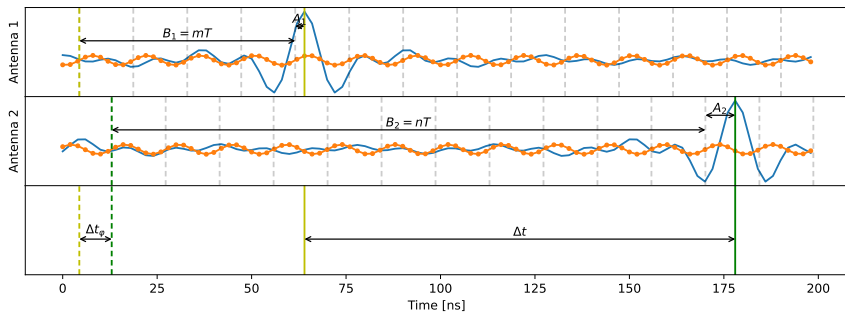
## Impulse Response



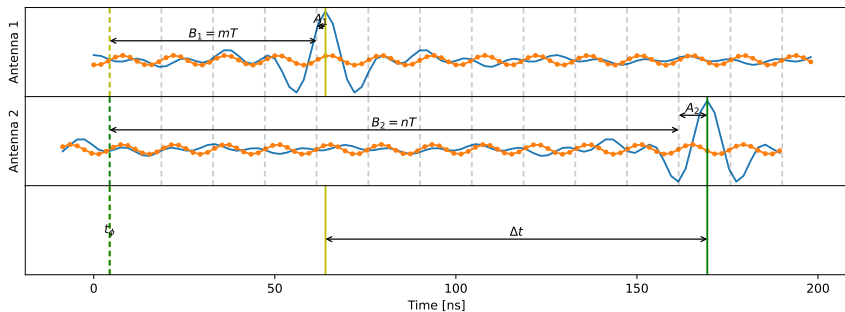
## Pulse Template: Timing



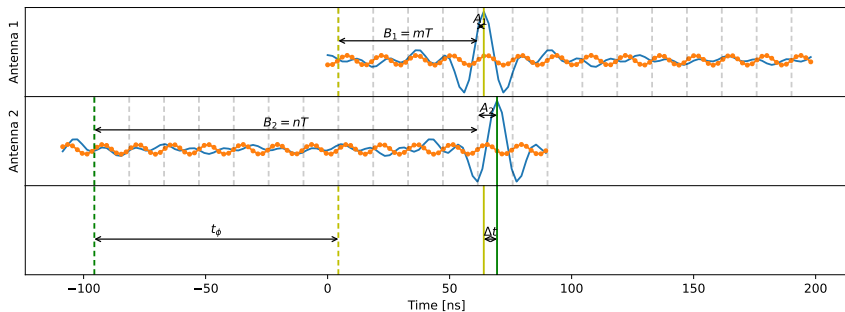
# Short period beacon synchronisation



# Short period beacon synchronisation

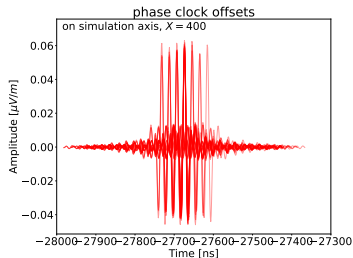


# Short period beacon synchronisation

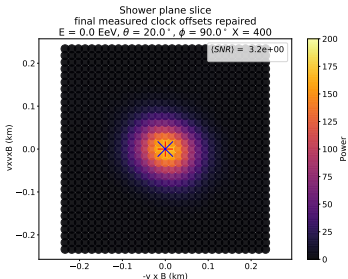
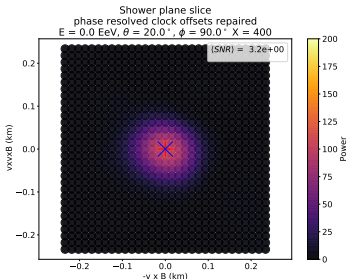
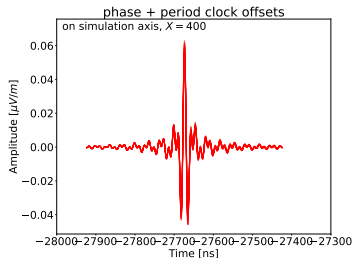


# Time resolving short period beacon: phase vs full

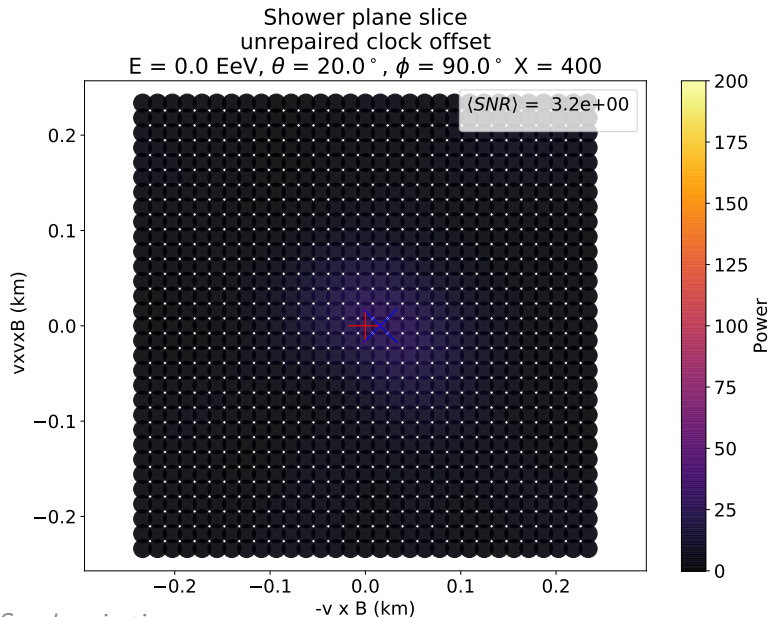
## Phase reparation



## Phase + Period reparation

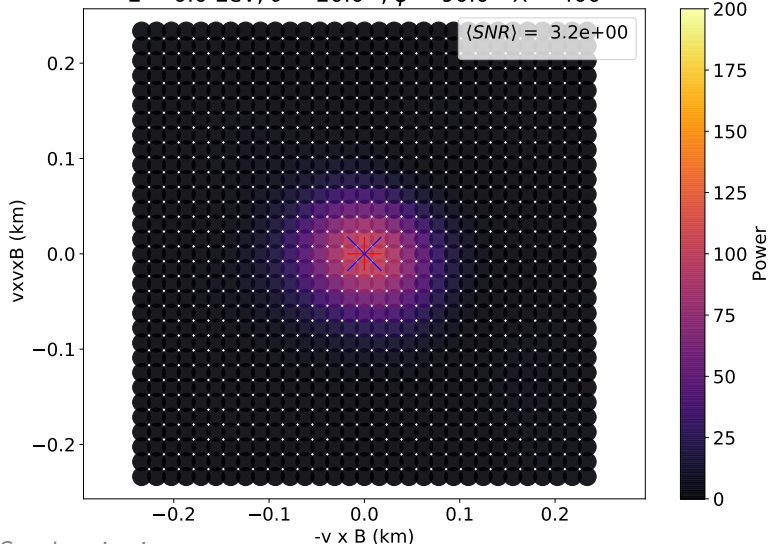


# Time resolving short period beacon



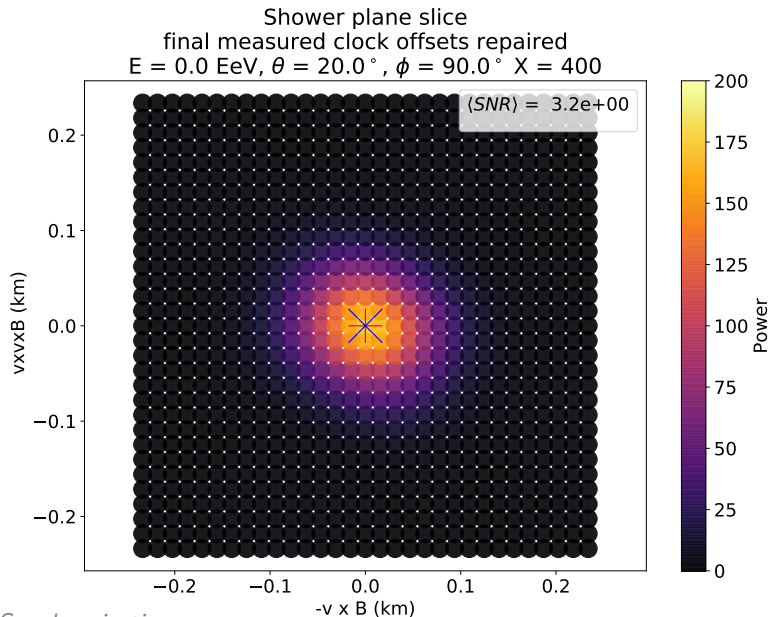
# Time resolving short period beacon

Shower plane slice  
phase resolved clock offsets repaired  
 $E = 0.0$  EeV,  $\theta = 20.0^\circ$ ,  $\phi = 90.0^\circ$   $X = 400$

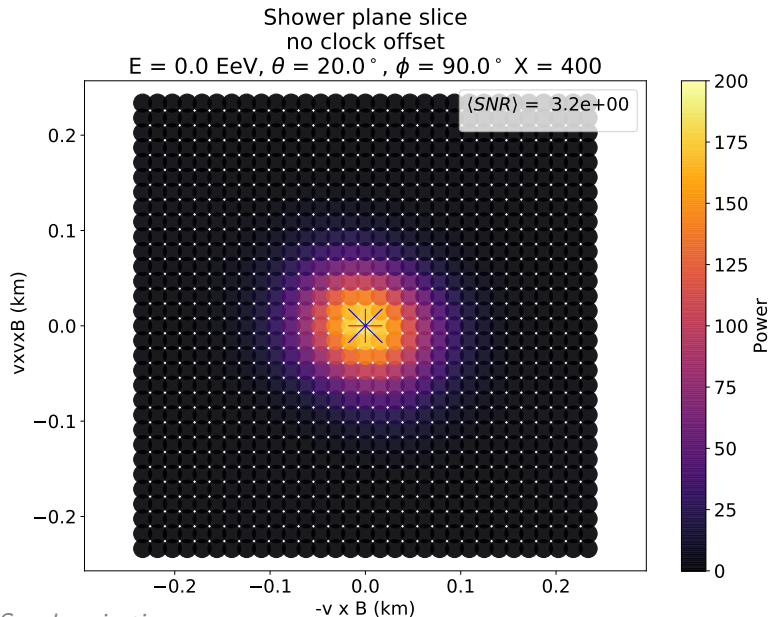




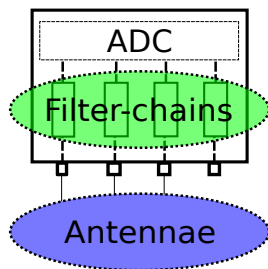
# Time resolving short period beacon



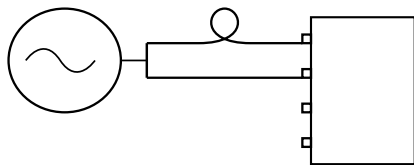
# Time resolving short period beacon



# GNSS clock stability I



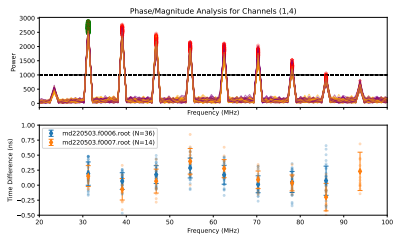
GRAND Digitizer Unit's  
ADC to antennae



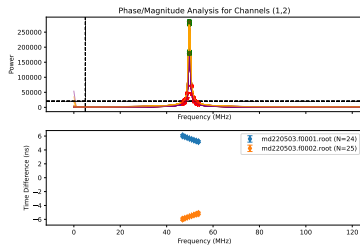
Channel filterchain delay experiment

# GNSS filterchain delay experiment

## Pulse

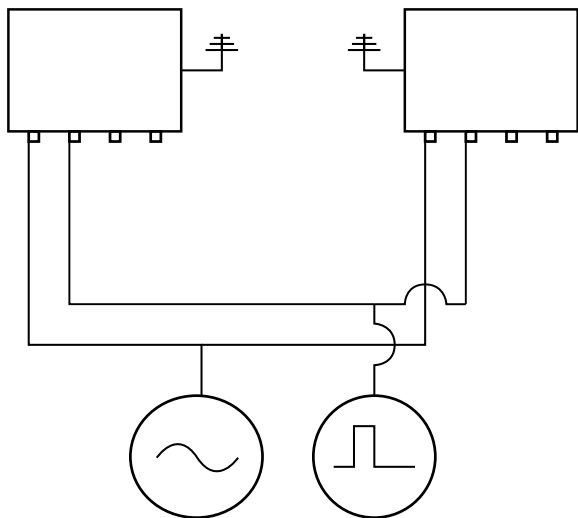


## 50MHz Sinewave



Delay  $\lesssim 150$ ps

## GNSS clock stability II

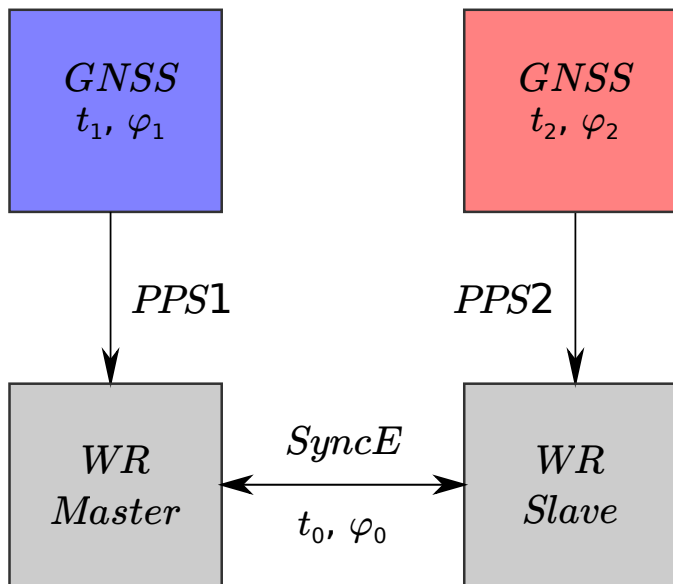


GNSS stability experiment

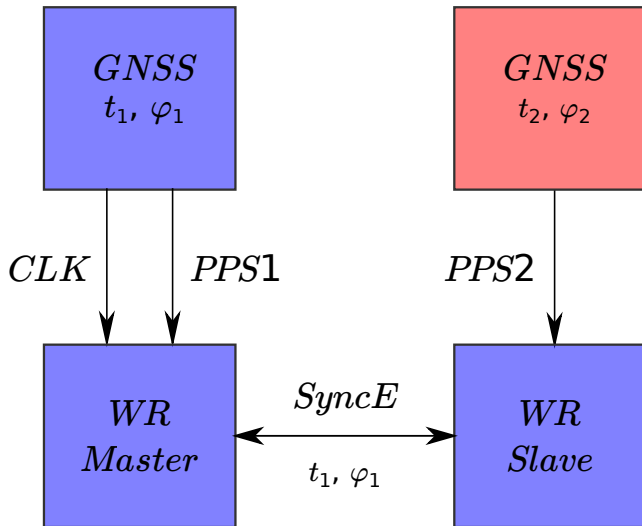
## GNSS clock stability II



## White Rabbit: GNSS

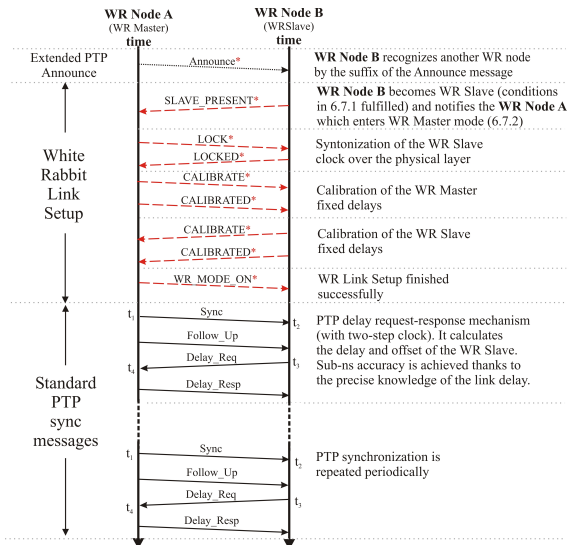


# White Rabbit: GNSS



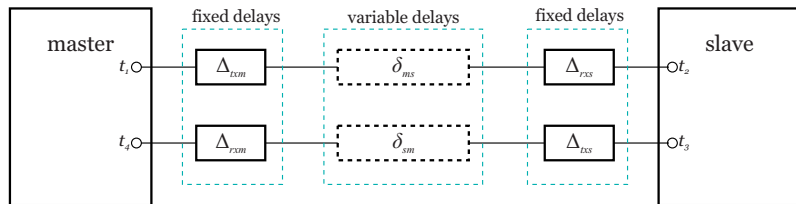


# White Rabbit: Precision Time Protocol



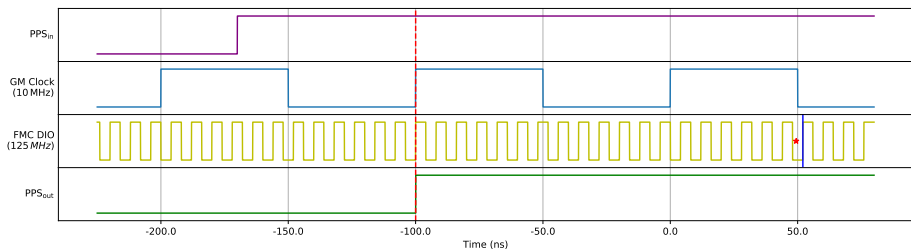
\* WR-related messages described in section 6.5.

# White Rabbit: Delay model



2

# White Rabbit: Clocks Reference



# References I

-  Jaime Álvarez-Muñiz et al. The Giant Radio Array for Neutrino Detection (GRAND): Science and Design. *Sci. China Phys. Mech. Astron.*, 63(1):219501, 2020. DOI: 10.1007/s11433-018-9385-7. arXiv: 1810.09994 [astro-ph.HE].
-  E. Cota, M. Lipiński, T. Włostowski, E. van der Bij and J. Serrano. White Rabbit Specification: Draft for Comments. [www.ohwr.org/attachments/1169/WhiteRabbitSpec.v2.0.pdf](http://www.ohwr.org/attachments/1169/WhiteRabbitSpec.v2.0.pdf), July 2011.
-  Tim Huege. Radio detection of extensive air showers. *Nucl. Instrum. Meth. A*, 876:9–12, 2017. P. Krizan, S. Korpar, G. Hallewell, W. Hofmann and E. Nappi, editors. DOI: 10.1016/j.nima.2016.12.012. arXiv: 1701.02995 [astro-ph.IM].

## References II



Harm Schoorlemmer and Washington R. Carvalho. Radio interferometry applied to the observation of cosmic-ray induced extensive air showers. *Eur. Phys. J. C*, 81(12):1120, 2021. DOI: [10.1140/epjc/s10052-021-09925-9](https://doi.org/10.1140/epjc/s10052-021-09925-9). arXiv: [2006.10348](https://arxiv.org/abs/2006.10348) [astro-ph.HE].



Frank G. Schröder. Radio detection of Cosmic-Ray Air Showers and High-Energy Neutrinos. *Prog. Part. Nucl. Phys.*, 93:1–68, 2017. DOI: [10.1016/j.pnpnp.2016.12.002](https://doi.org/10.1016/j.pnpnp.2016.12.002). arXiv: [1607.08781](https://arxiv.org/abs/1607.08781) [astro-ph.IM].