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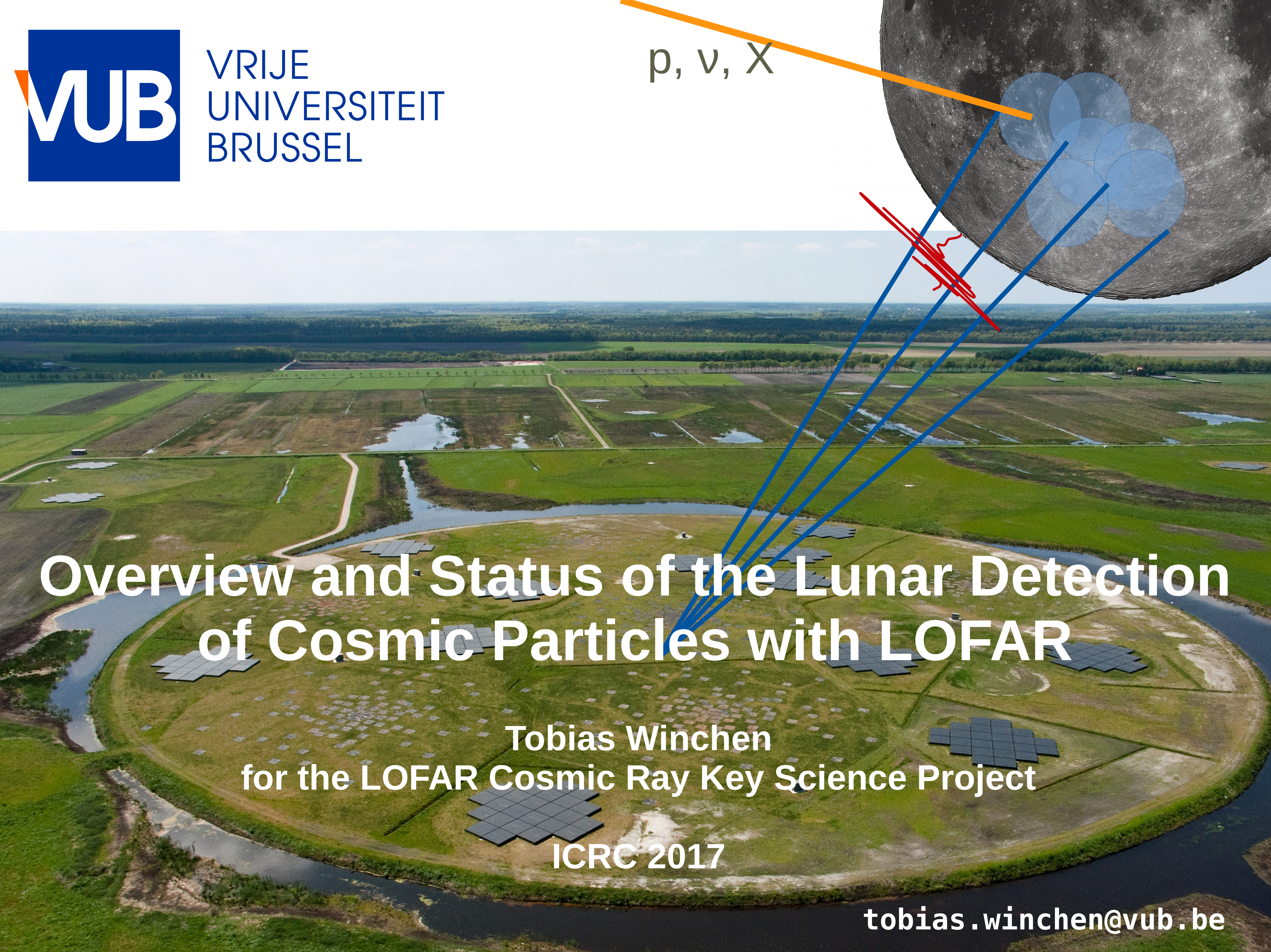

Overview and Status of the Lunar Detection of Cosmic Particles with LOFAR

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for the LOFAR Cosmic Ray Key Science Project

ICRC 2017

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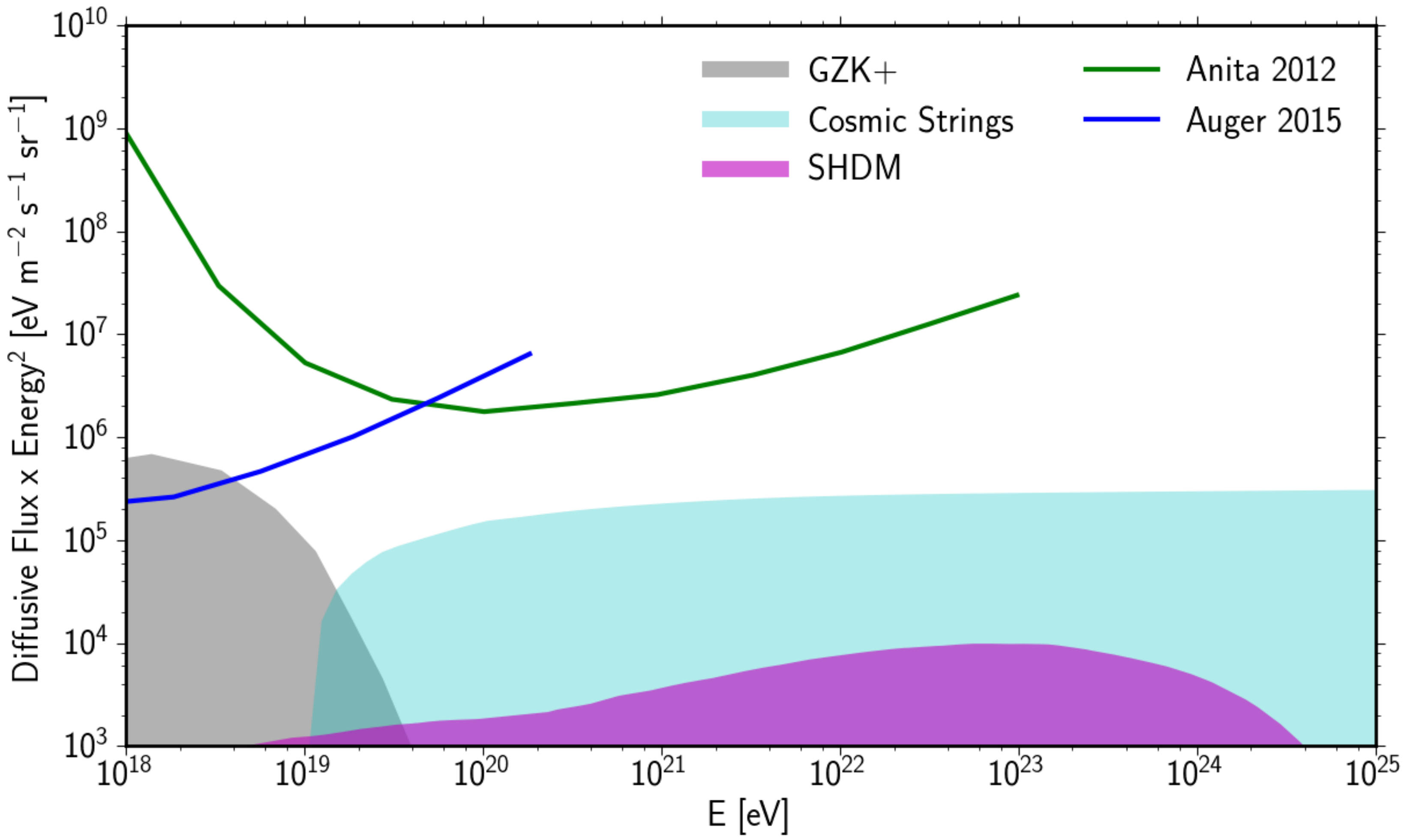
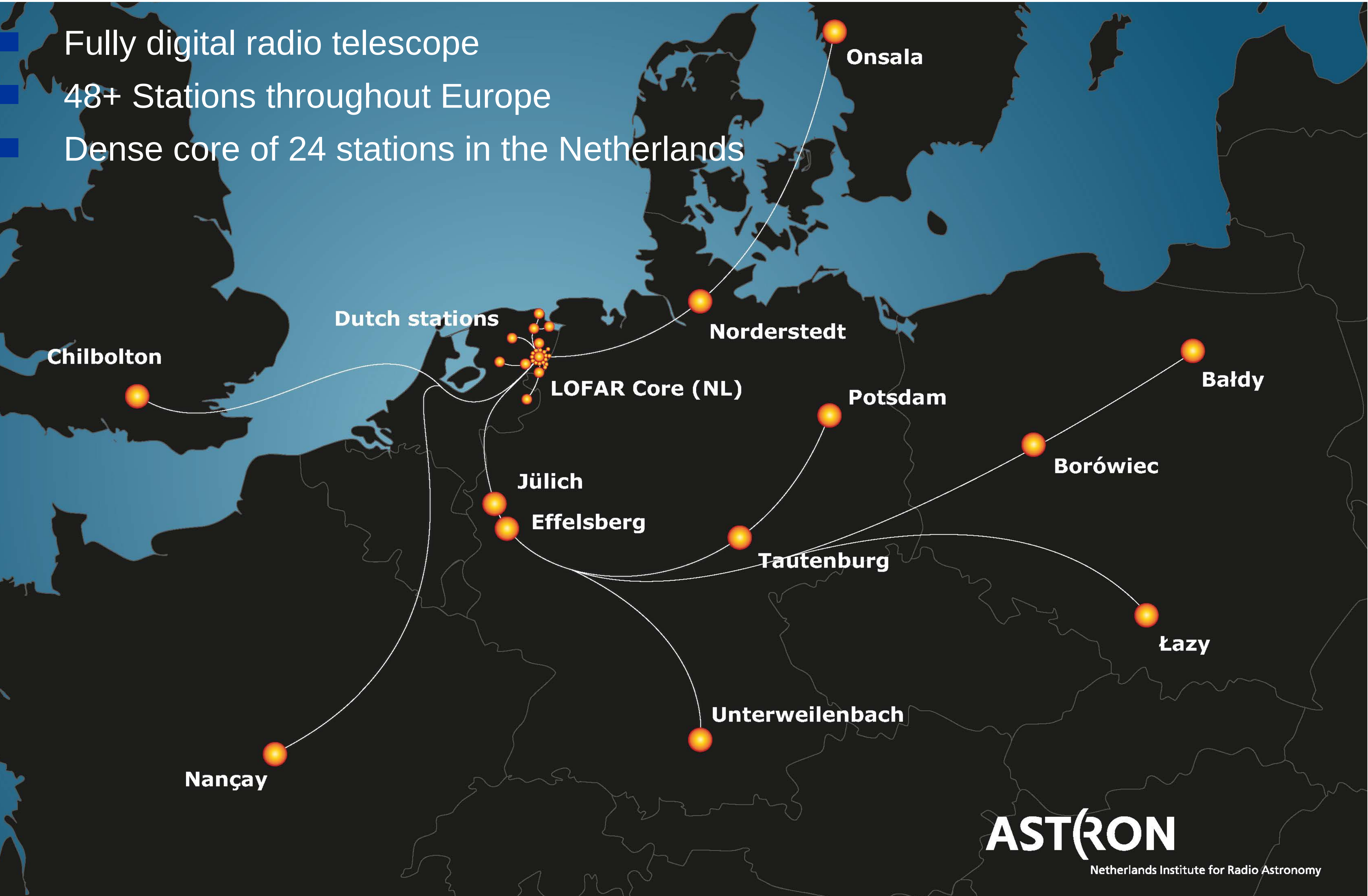
Search for High Energy Neutrinos



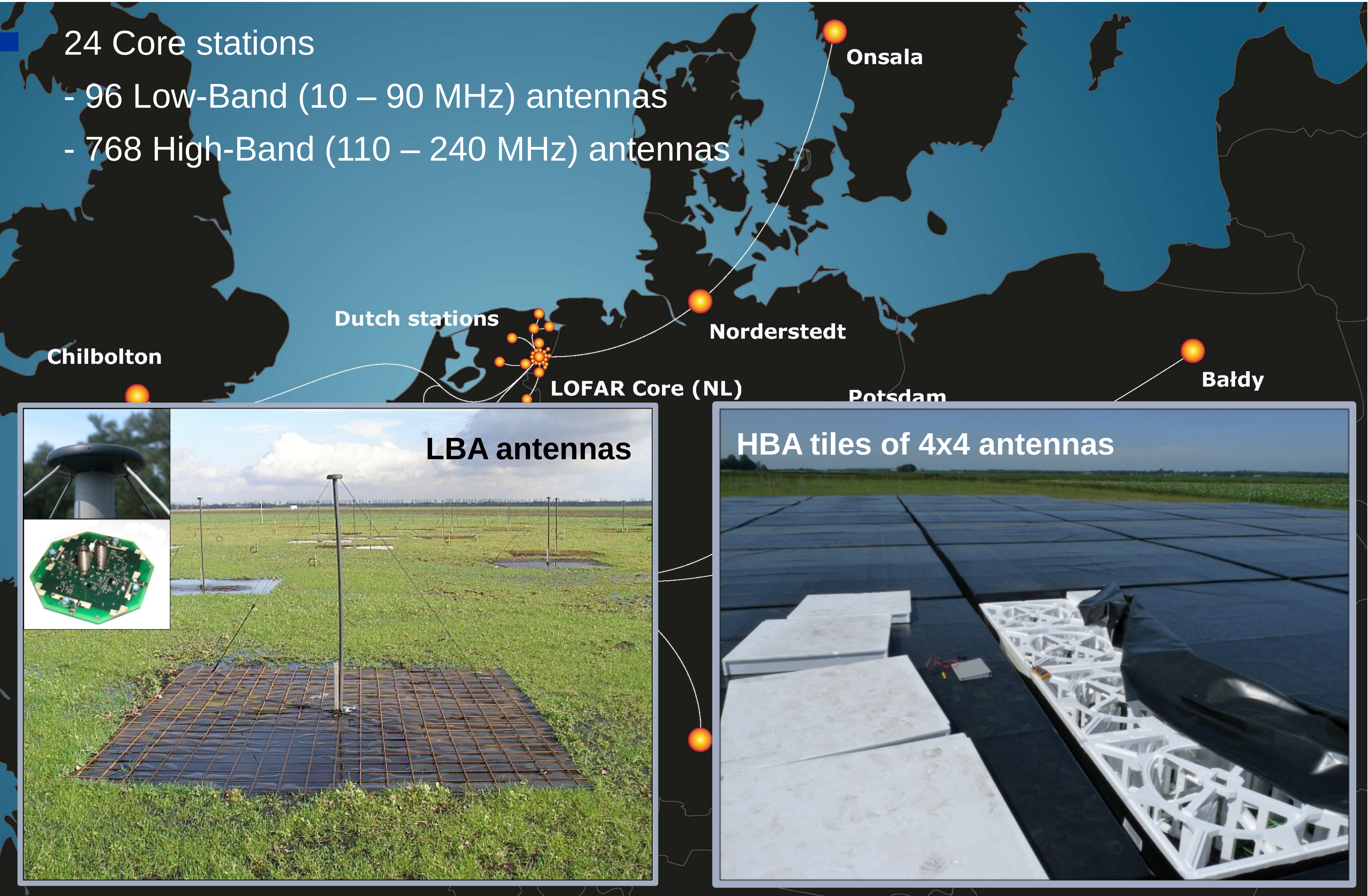
The LOw Frequency ARray

- Fully digital radio telescope
- 48+ Stations throughout Europe
- Dense core of 24 stations in the Netherlands



The LOw Frequency ARray

- 24 Core stations
  - 96 Low-Band (10 – 90 MHz) antennas
  - 768 High-Band (110 – 240 MHz) antennas



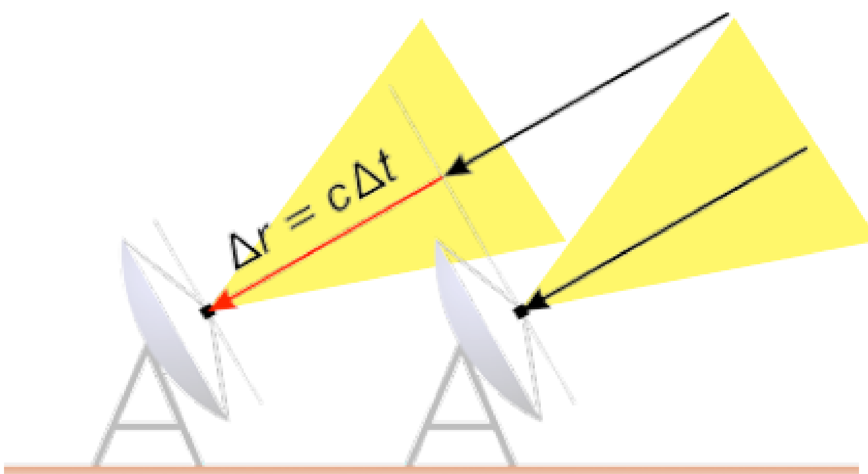
A Fully Digital Radio Telescope

Conventional radio telescope:

Mechanically point (few) directional antennas into observing direction + combine signals

Observe only one direction at a time

Nancay Radioheliograph, 2009

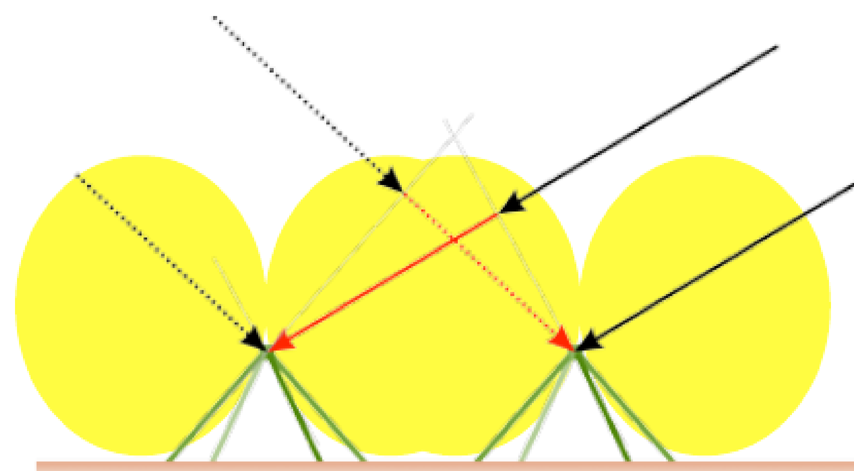


Digital radio telescope:

Many omni-directional antennas digitally combine signals according to direction

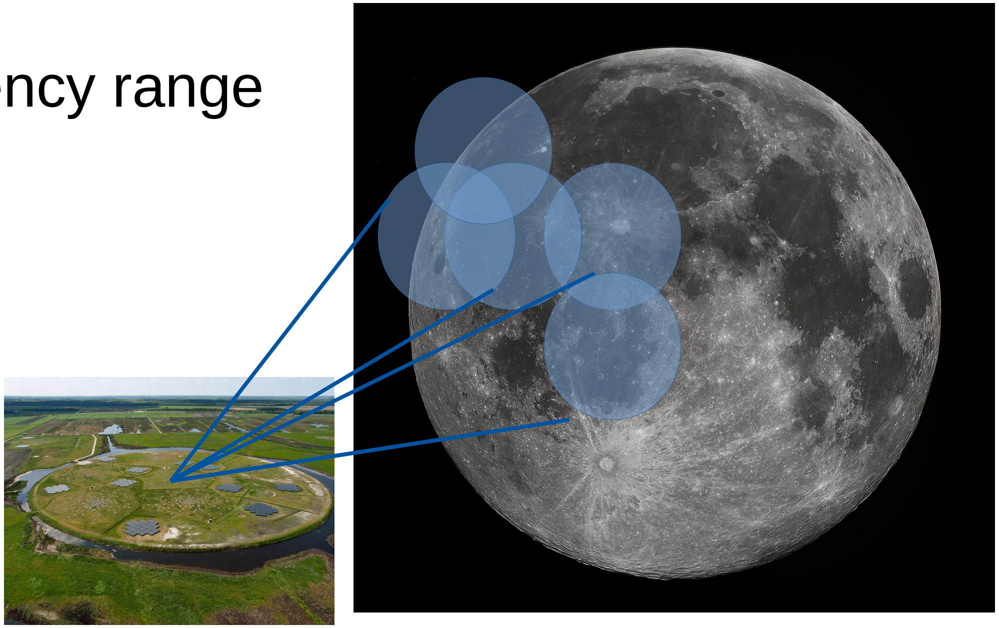
Observe multiple directions simultaneously

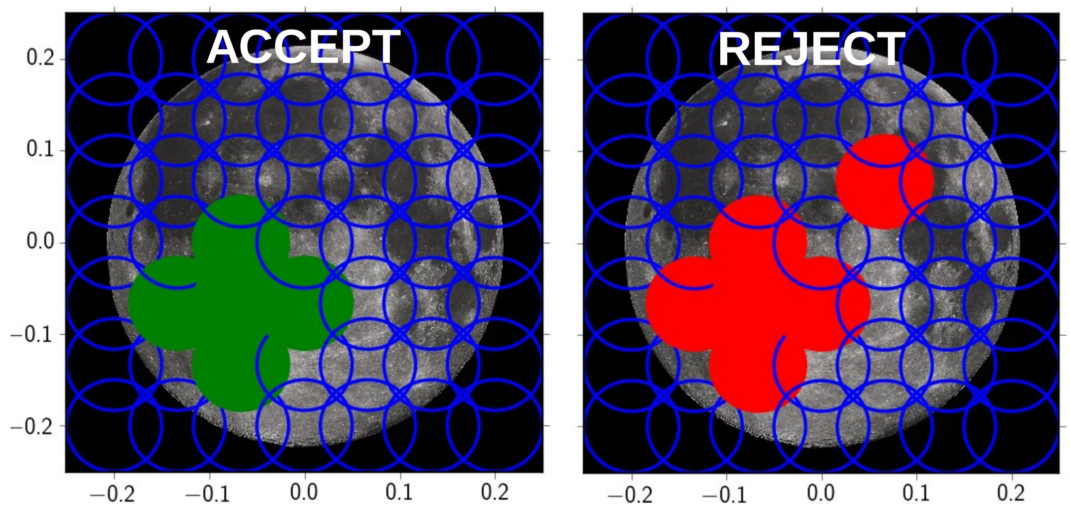
LOFAR Core, 2012



Observation Strategy

- HBA Antennas have optimal frequency range
- Form multiple beams on the Moon
- Search for ns pulses in time-series
- Anti coincidence to suppress RFI
- Analyze Faraday rotation and dispersion to check lunar origin



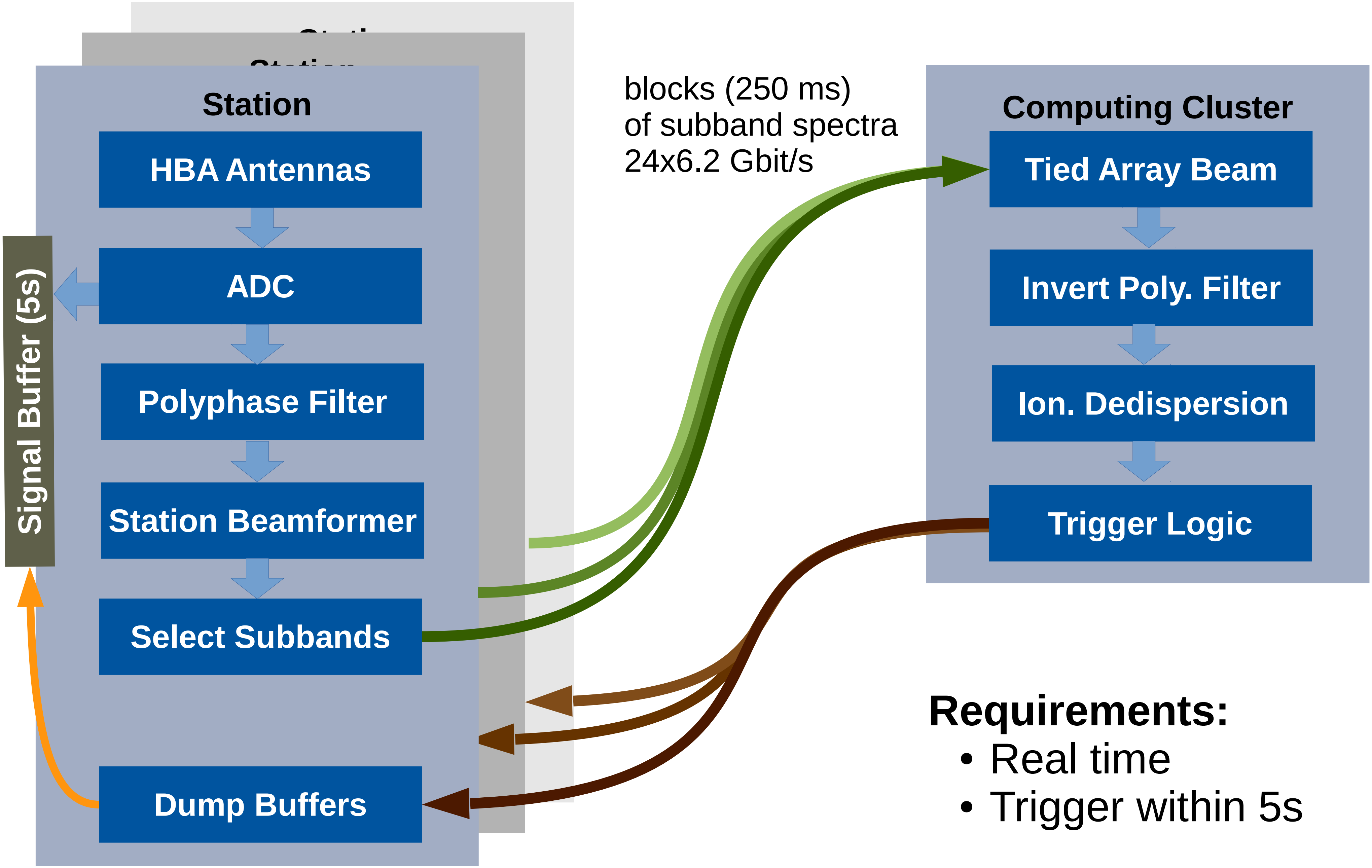


Challenge:

LOFAR designed to integrate flux, user access only to processed signal

- Reconstruct ns time series from processed signal for trigger
- Use buffered traces for analysis

Online Data Analysis



Requirements:

- Real time
- Trigger within 5s

Inversion of Polyphase Filter

- Filter to decompose signal into subbands
- FFT signal is smeared out over neighboring frequencies
- Efficient filtering with PPF

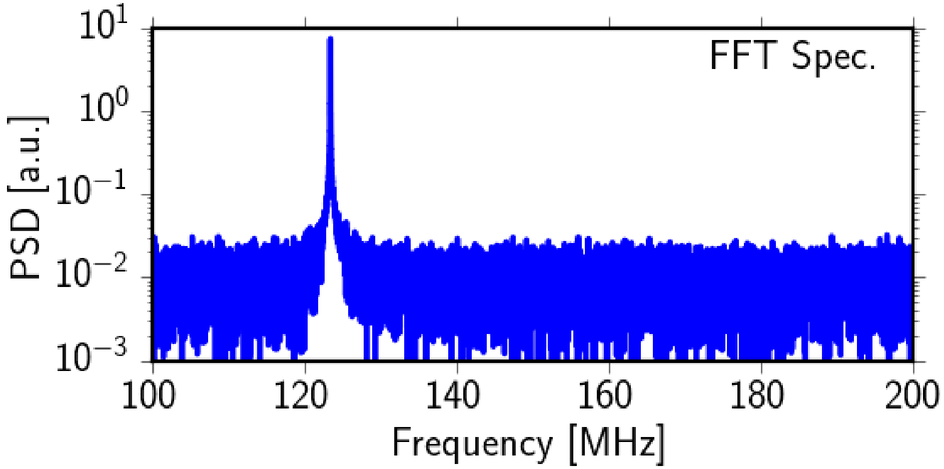
  + avoids frequency smearing

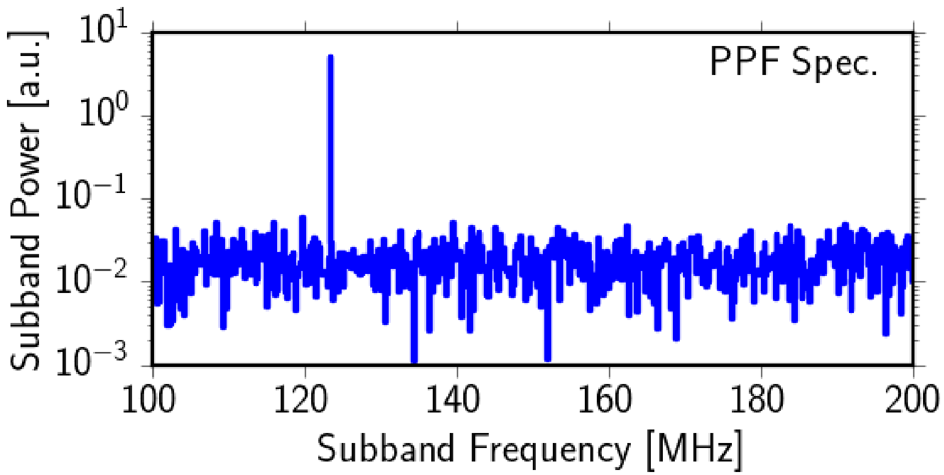
  - Reduces time resolution

  from 5 ns to ~5 us
- Inversion with small error possible,

  but computationally intensive:

  O(1000) GFLOP / s / beam
- As much computing power as possible needed for dedispersion + trigger



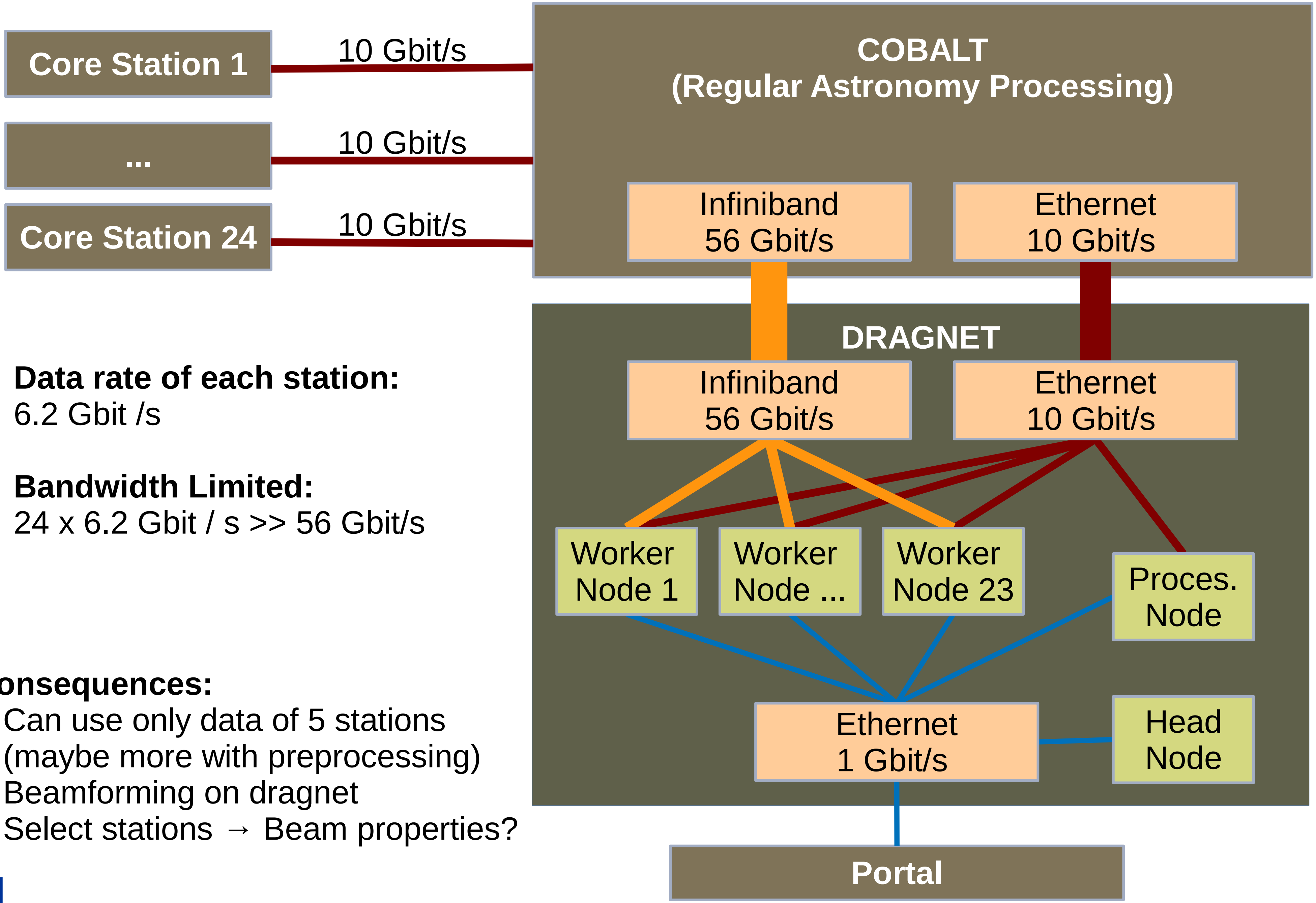


Not available on regular system,

requires additional computing power

- Use DRAGNET, CPU/GPU cluster for pulsar searches

LOFAR Network



Data rate of each station:
6.2 Gbit /s

Bandwidth Limited:
24 x 6.2 Gbit / s >> 56 Gbit/s

Consequences:

- Can use only data of 5 stations (maybe more with preprocessing)
- Beamforming on dragnet
- Select stations → Beam properties?

Station Selection

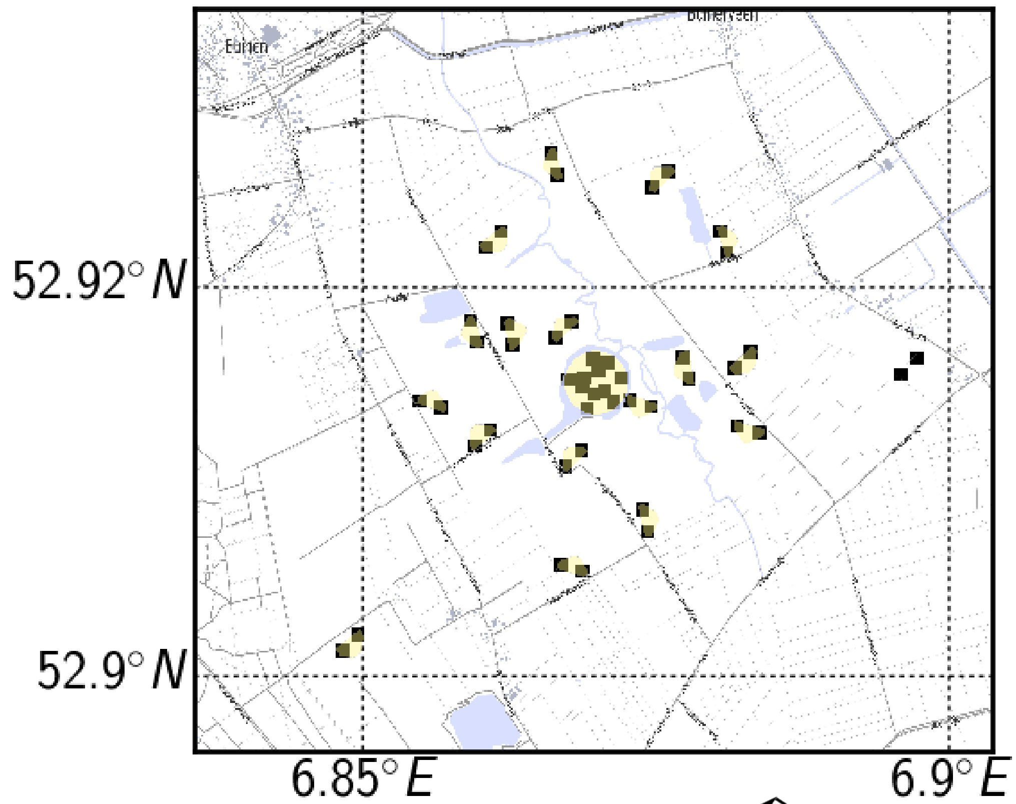
- 5 out of 48 combinations
  1712304 combinations
- Preselect interesting combinations
  - Unfiorm distribution of baselengths

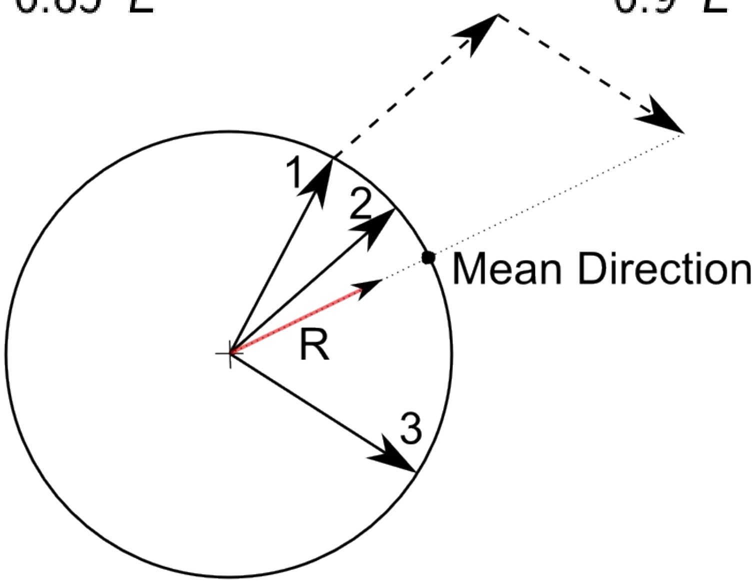
    - use KS Distance
  - Uniform distribution of directions of baselength

    - use Length of the Resultant R
  - Uniform distribution of direction of stations

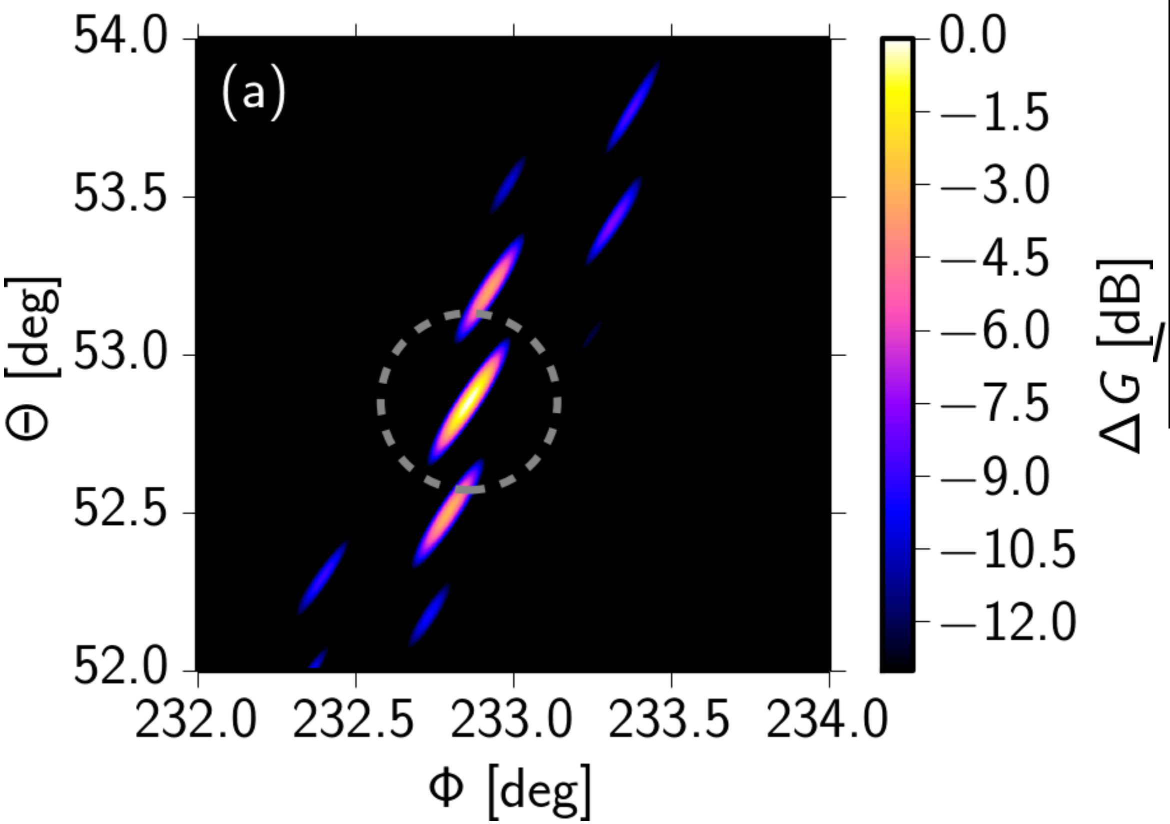
    - use Length of the Resultant R

$$R = \frac{1}{N} \left| \sum v_i \right|$$

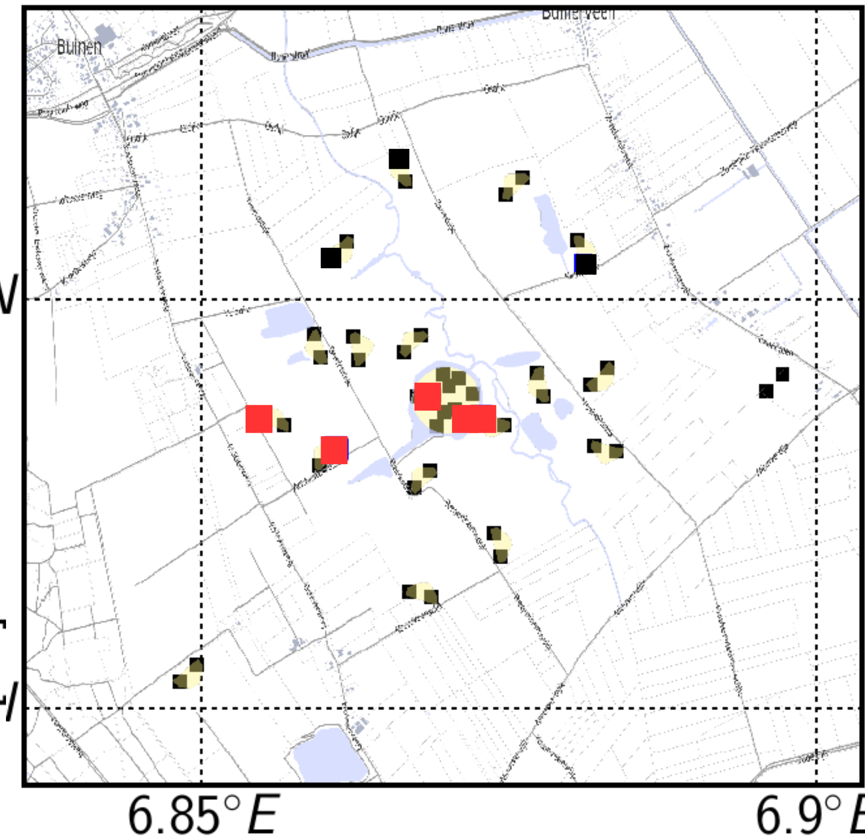




Station Selection: Bad Combination

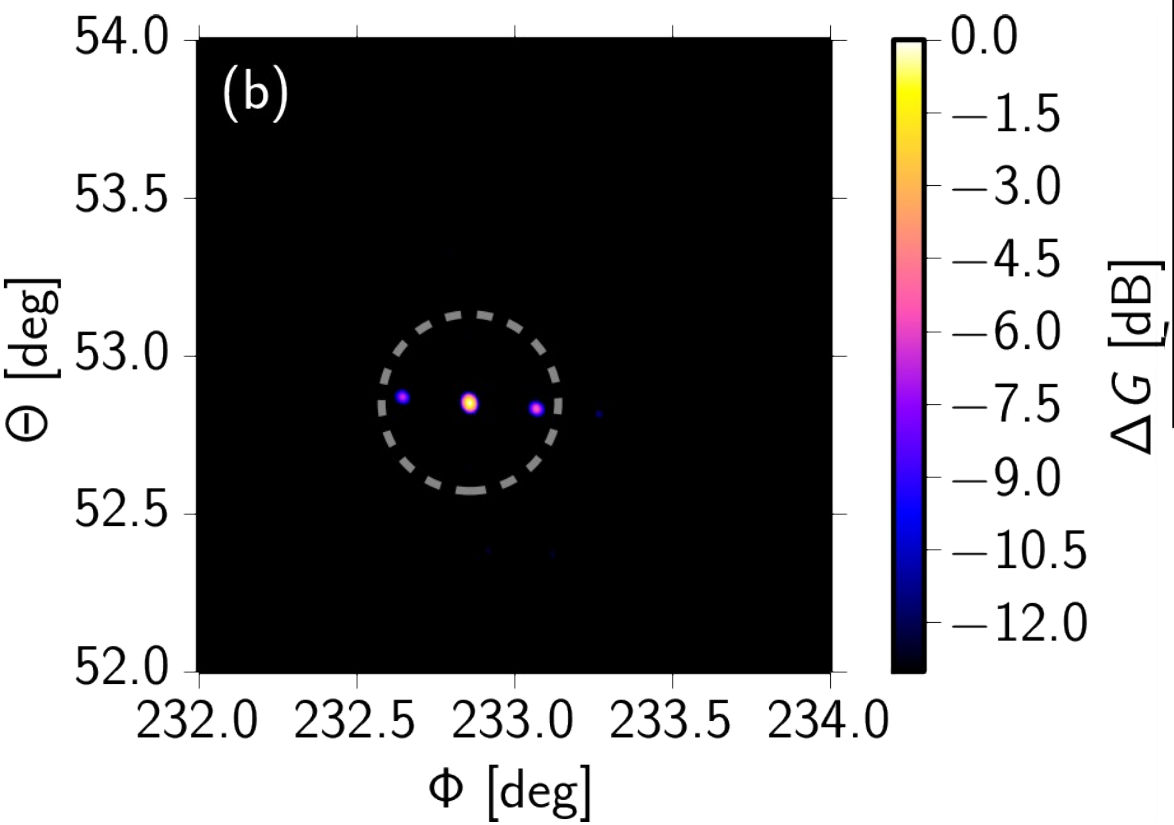


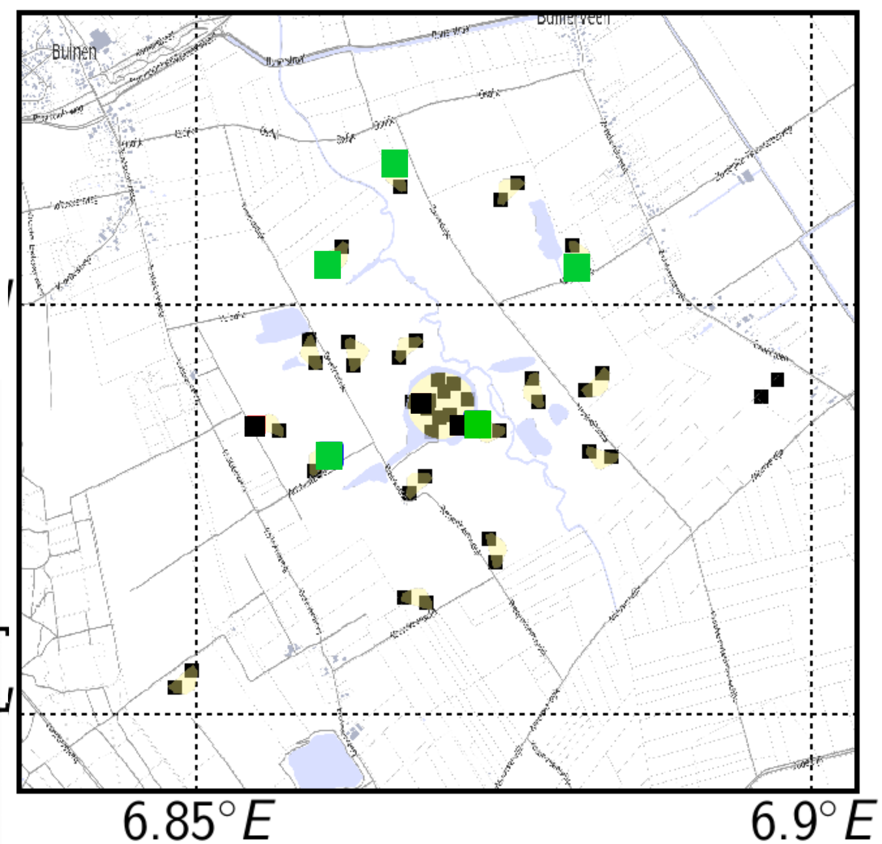
- Elongated beam
- Many sidelobes
- Sidelobes not on moon



- Good distribution of baselengths
- Bad distribution of directions

Preliminary
Station Selection



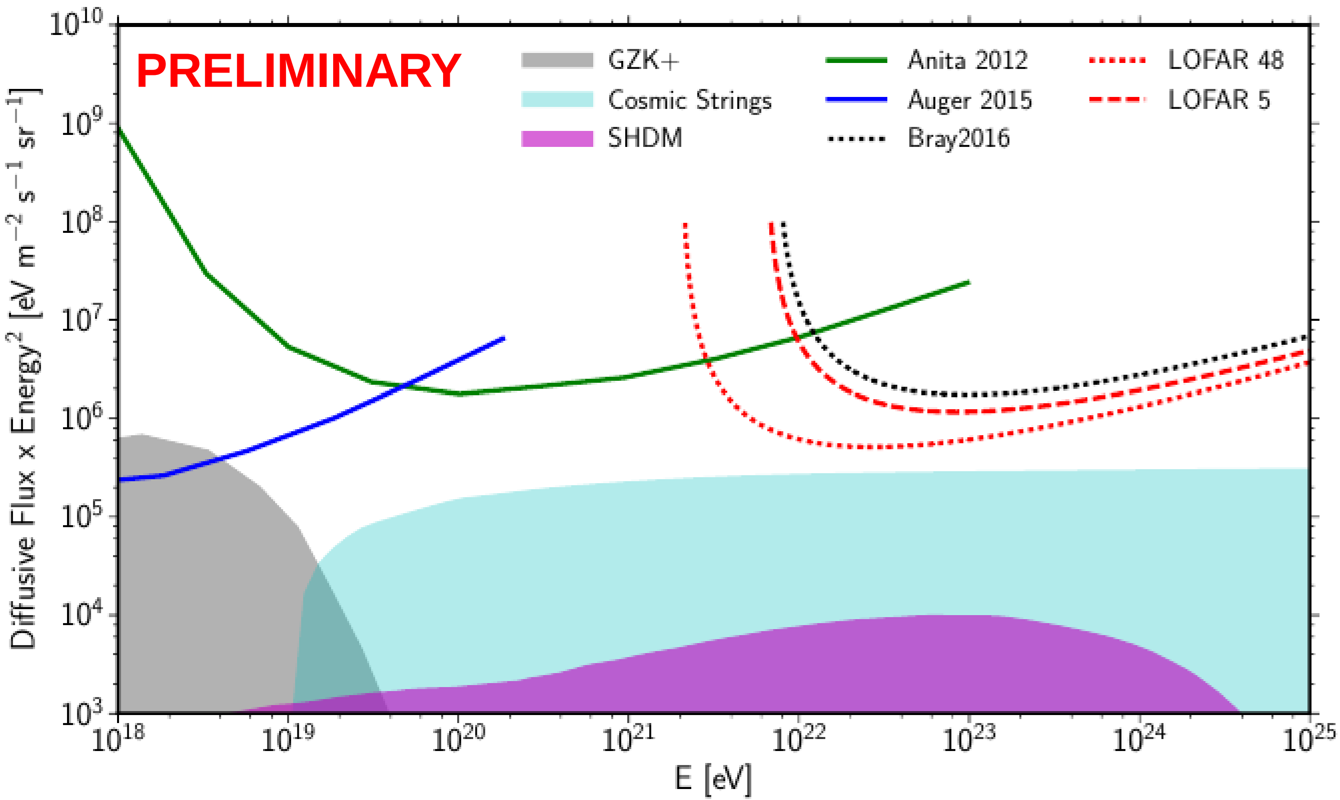


- Good distribution of baselengths
- Good distribution of directions

+ Symmetric beam
+ Few sidelobes
+ Sidelobes focussed and on the moon

Consequences for Sensitivity

Based on semi-analytical calculations (Gayley2009)



Bray 2014

- 48 stations
- Bandwidth
- Trigger threshold 12s

Update (2017)

- 5 Stations
- Bandwidth
- Trigger threshold 6s

Caution:

- Semi - Analytical calculation underestimates sensitivity for frequencies below ~GHz
- Assumes simple threshold trigger – trigger-level suppression of noise to increase sensitivity
- Full simulation needed for reliable estimation of sensitivity

Conclusions

- Search Cosmic Particles on ZeV scale via Lunar-Askaryan-Effect with LOFAR (and SKA in future)
- Analysis + Simulation software ready
  - PPF Inversion
  - Dedispersion
  - Beamforming
- Preliminary design choices of station selections, etc.
- Detailed simulations of experiment ongoing → sensitivity?
- First commissioning data taken in June (analysis ongoing)
- **First run: 2017? 2018!**

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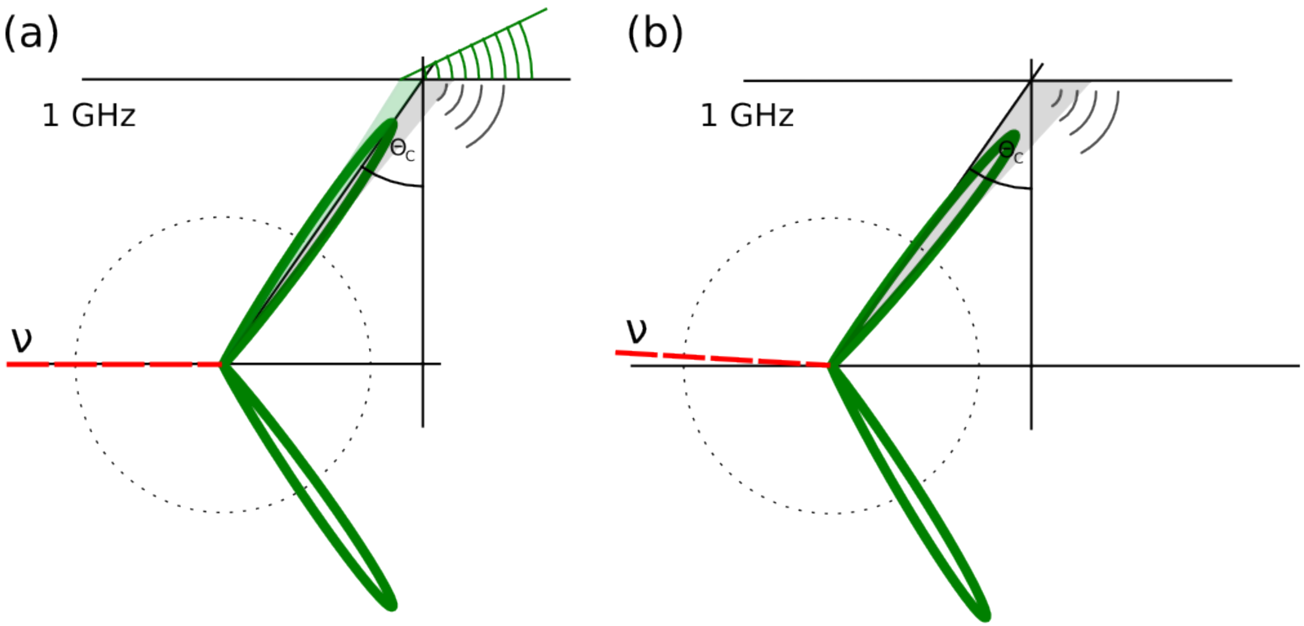
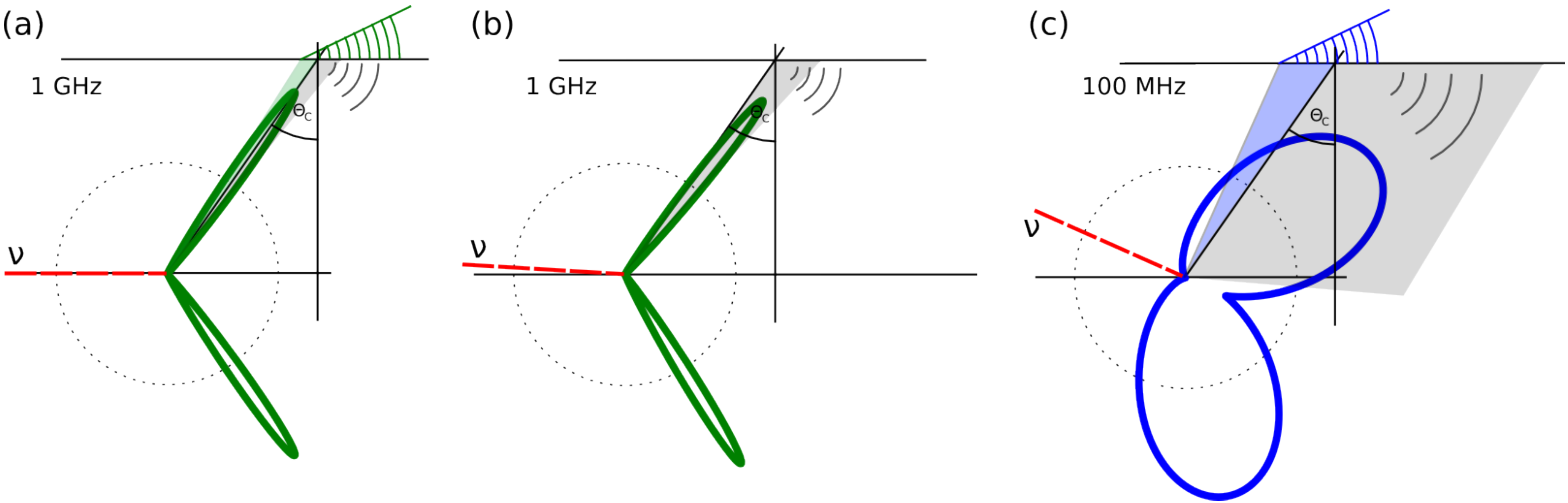
Backup

Pulse Reflected at High Frequencies



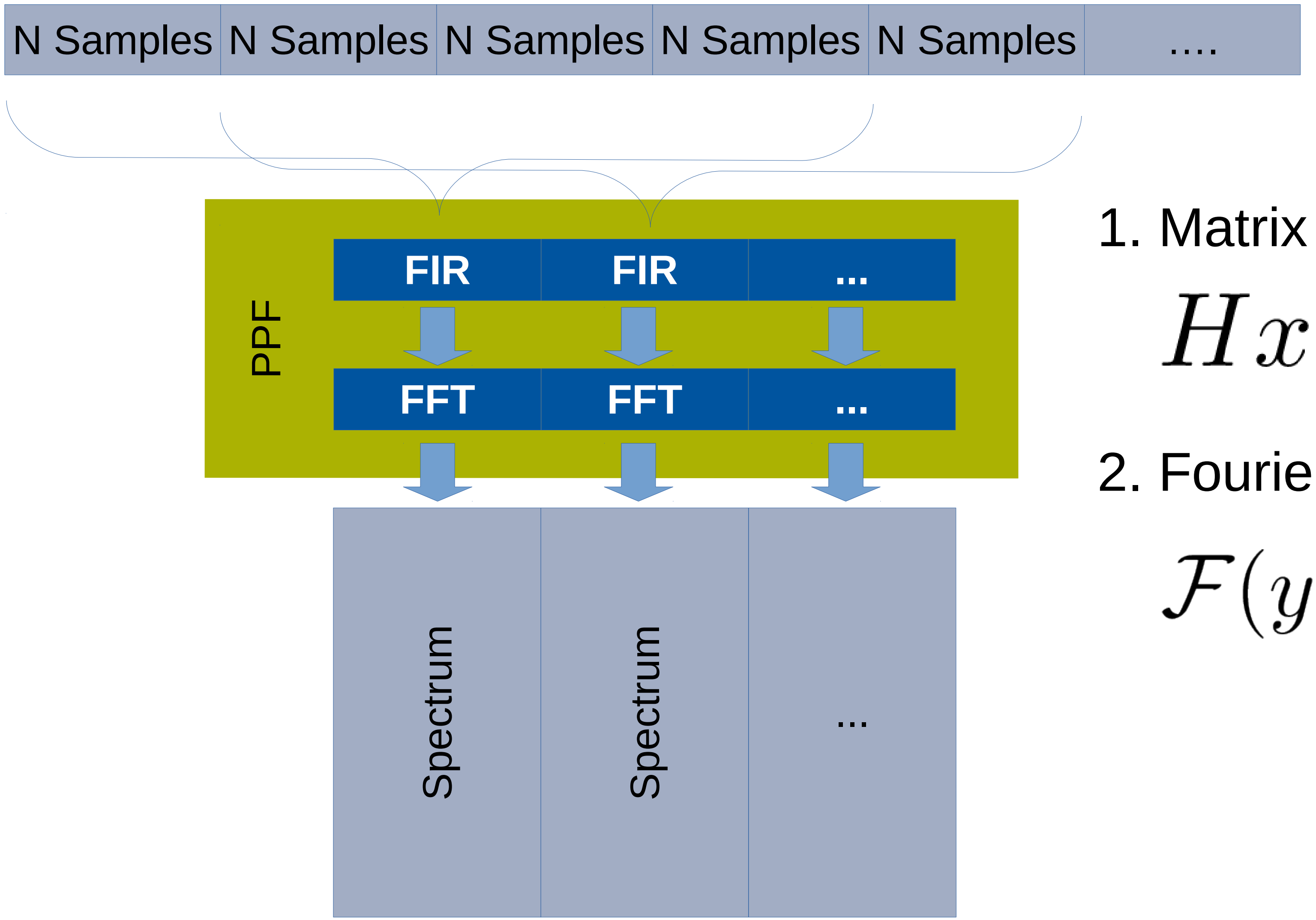
- Radiation emitted in Cherenkov cone
- Cherenkov angle == Angle of total reflection
- Upgoing shower required / rely on surface roughness

Pulse Escapes at Low Frequencies



- Cherenkov cone is broader at low frequencies
- Also downgoing showers detectable
- Optimum in 100 - 200 MHz range (Scholten et al. 2006)

Polyphase Filter



1. Matrix product

$$Hx = y$$

2. Fourier transformation

$$\mathcal{F}(y) = \tilde{y}$$

Inverse Polyphase Filter (PPF^{-1})

$$\mathcal{F}^{-1}(\tilde{y}) = y$$

- Direct inversion of FIR filter

$$H^{-1}y = \hat{x}$$

Inverse does not exists as H is not square

- Approximate inverse

$$Gy \approx \hat{x} \qquad GH \approx I$$

Supposed to be numerically unstable / produces artifacts (spikes)

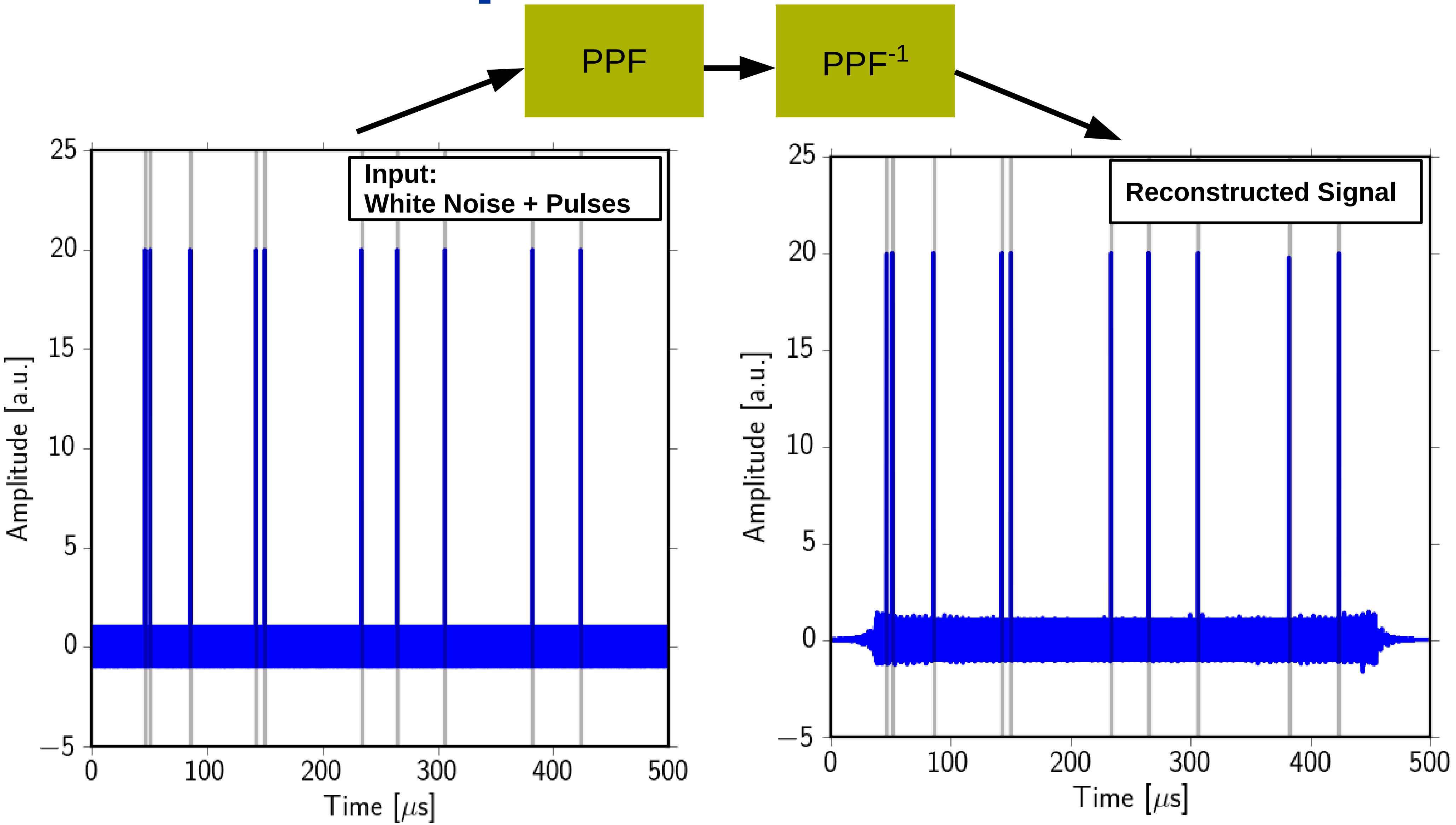
- Robust approach: Solve linear system

$$H\hat{x} = y$$

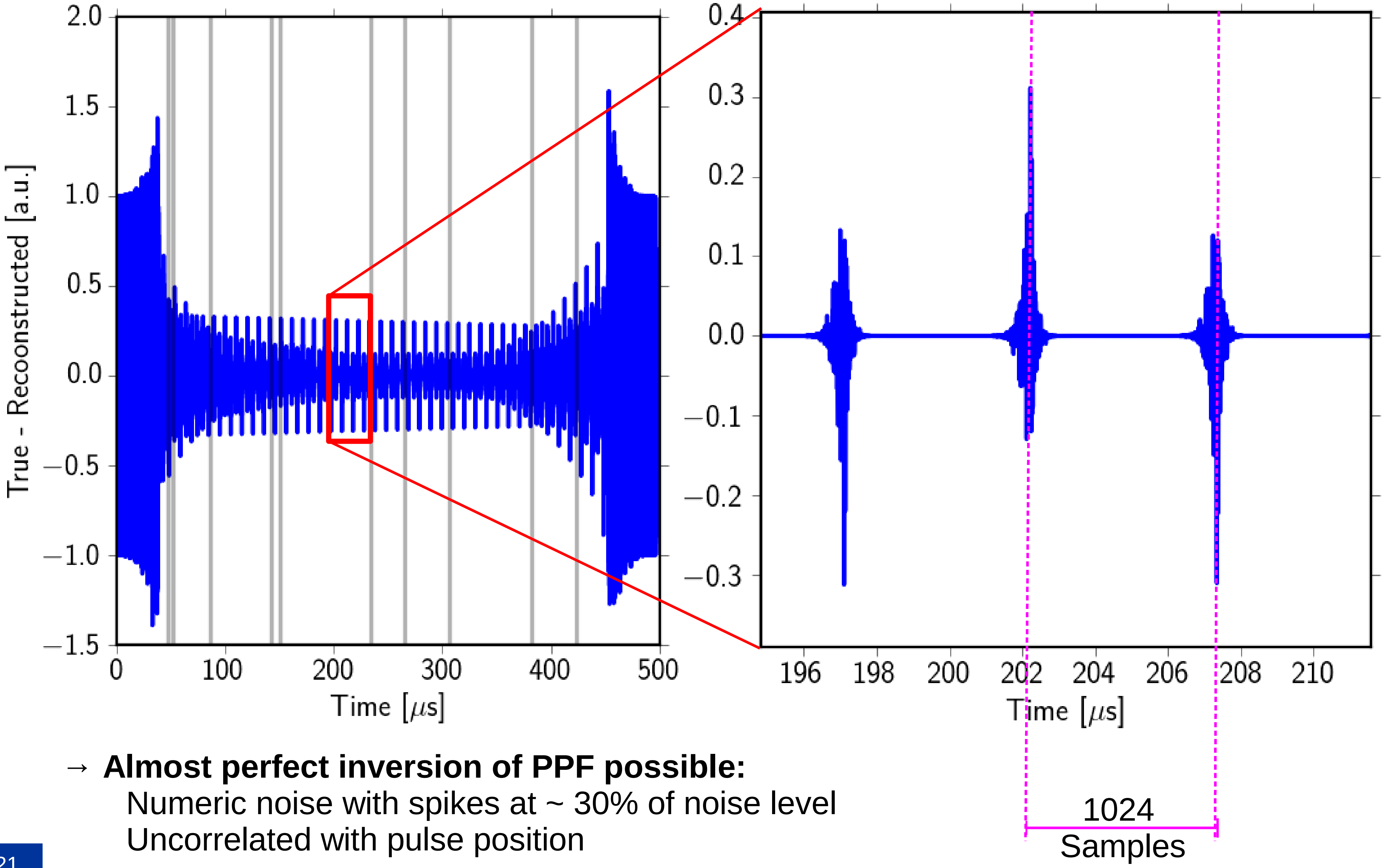
using iterative least squares (LSMR)

$$\min_{\hat{x}} ||H\hat{x} - y||$$

PPF^{-1} Example



Accuracy of PPF Inversion



→ **Almost perfect inversion of PPF possible:**

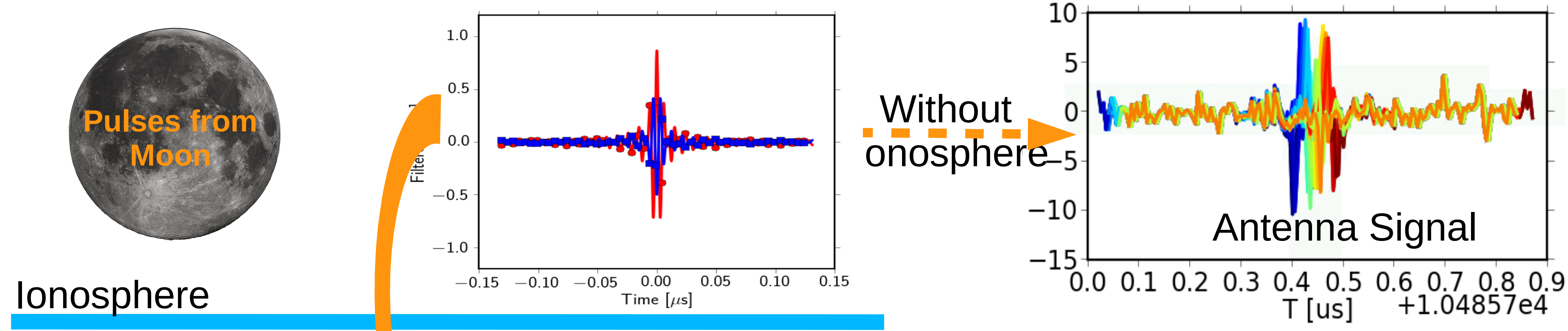
Numeric noise with spikes at ~ 30% of noise level

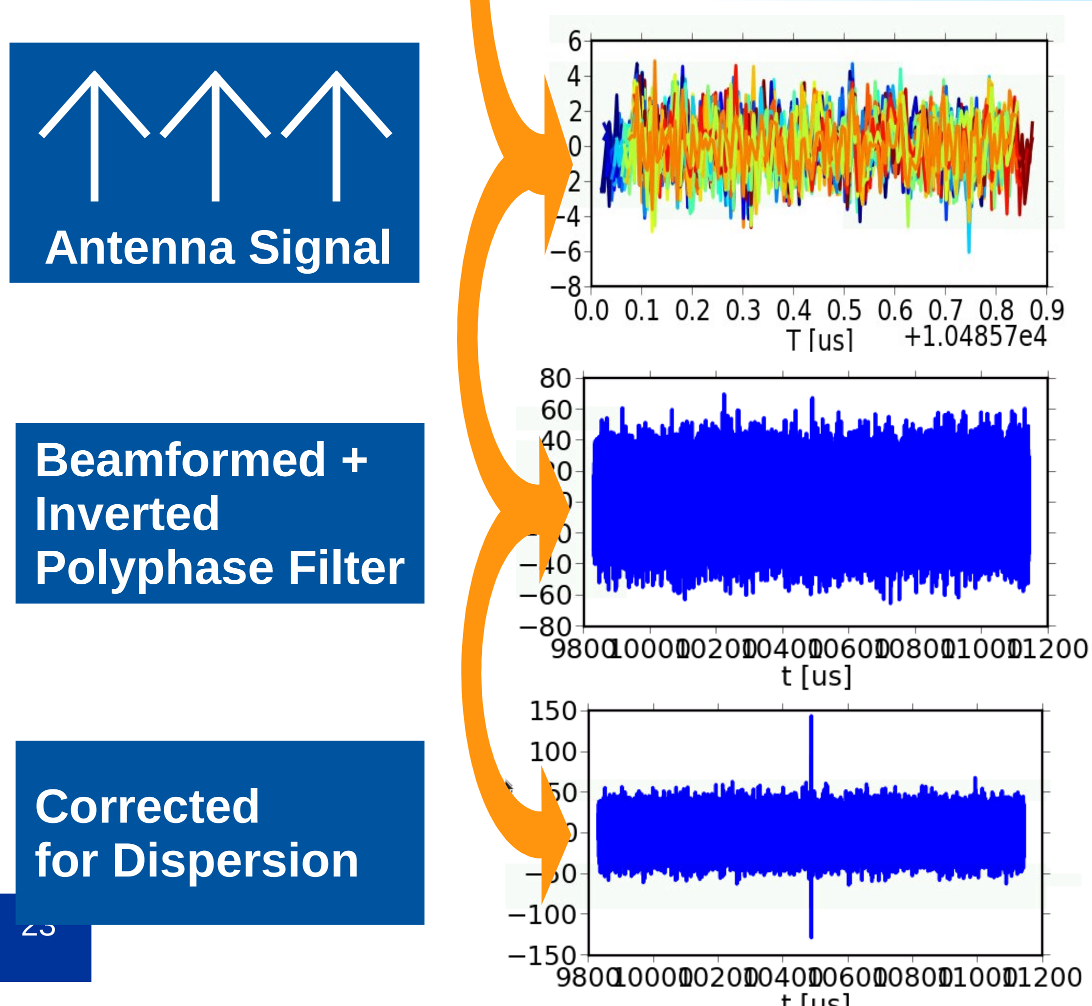
Uncorrelated with pulse position

Dispersion

- Frequency dependent time delay of pulse due to free electrons in ionosphere
- Frequency dependent time delay
- Typical values 5 - 100 TECU
  > 500 ns delay between 100 MHz and 200 MHz

Ionospheric Dedispersion





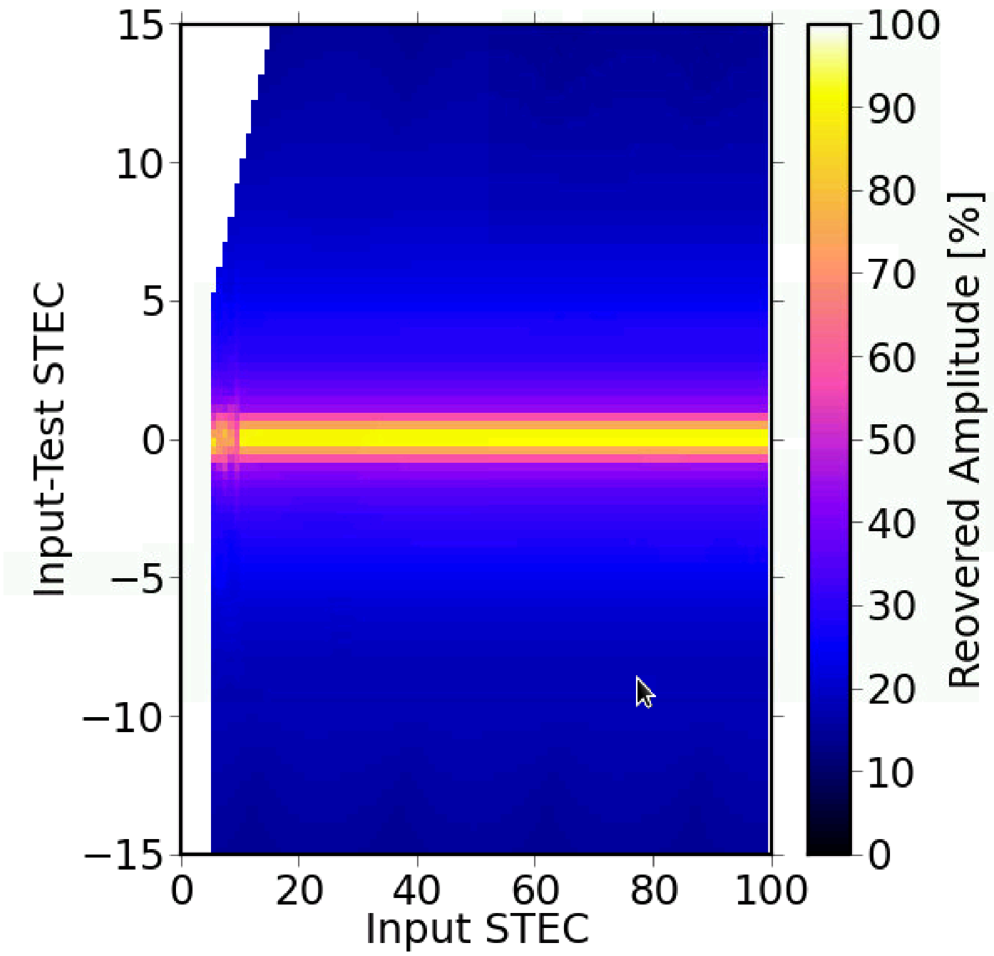
- EM Pulse from Moon pass through Ionosphere
- Frequency dependent dispersion
- Dispersion depends on electron content of ionosphere (STEC)

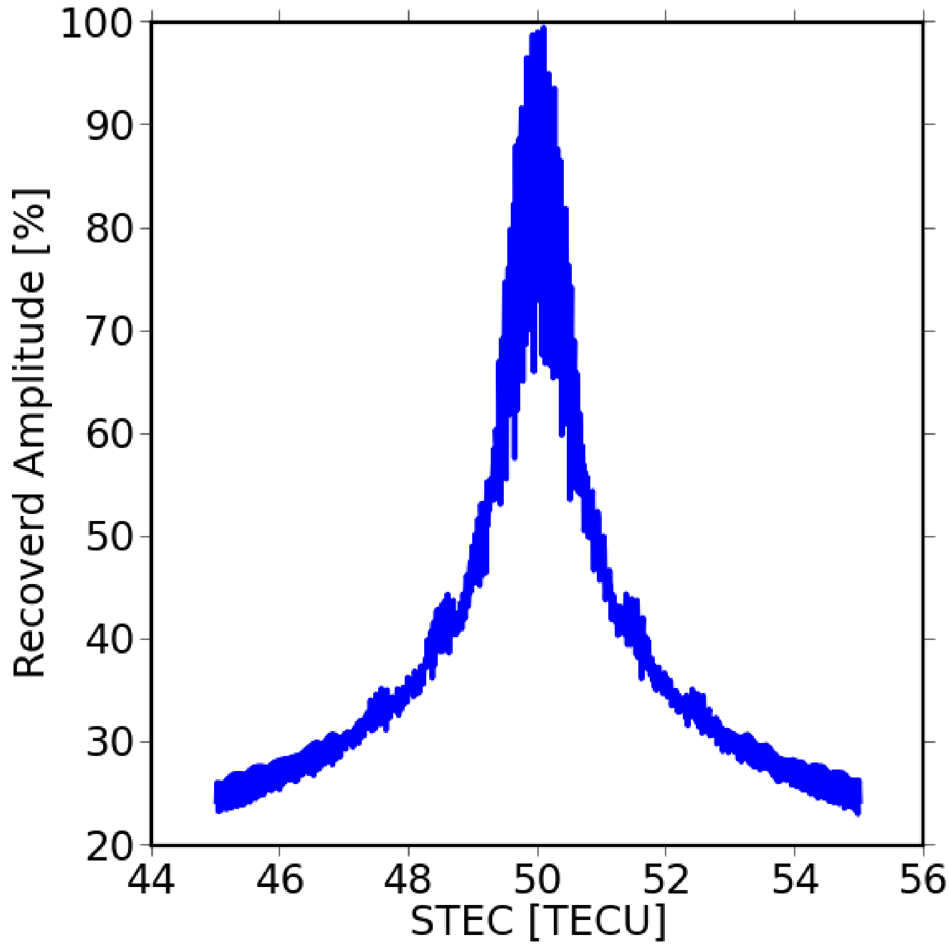
$$\Delta t(\nu) = 1.34 \frac{STEC}{\mathrm{TECU}} \left(\frac{\nu}{\mathrm{Hz}}\right)^{-2} \mathrm{s}$$

1 TECU = 10^{16} electrons / m^2

- STEC not known exactly →
  Test as many STEC-Values as possible

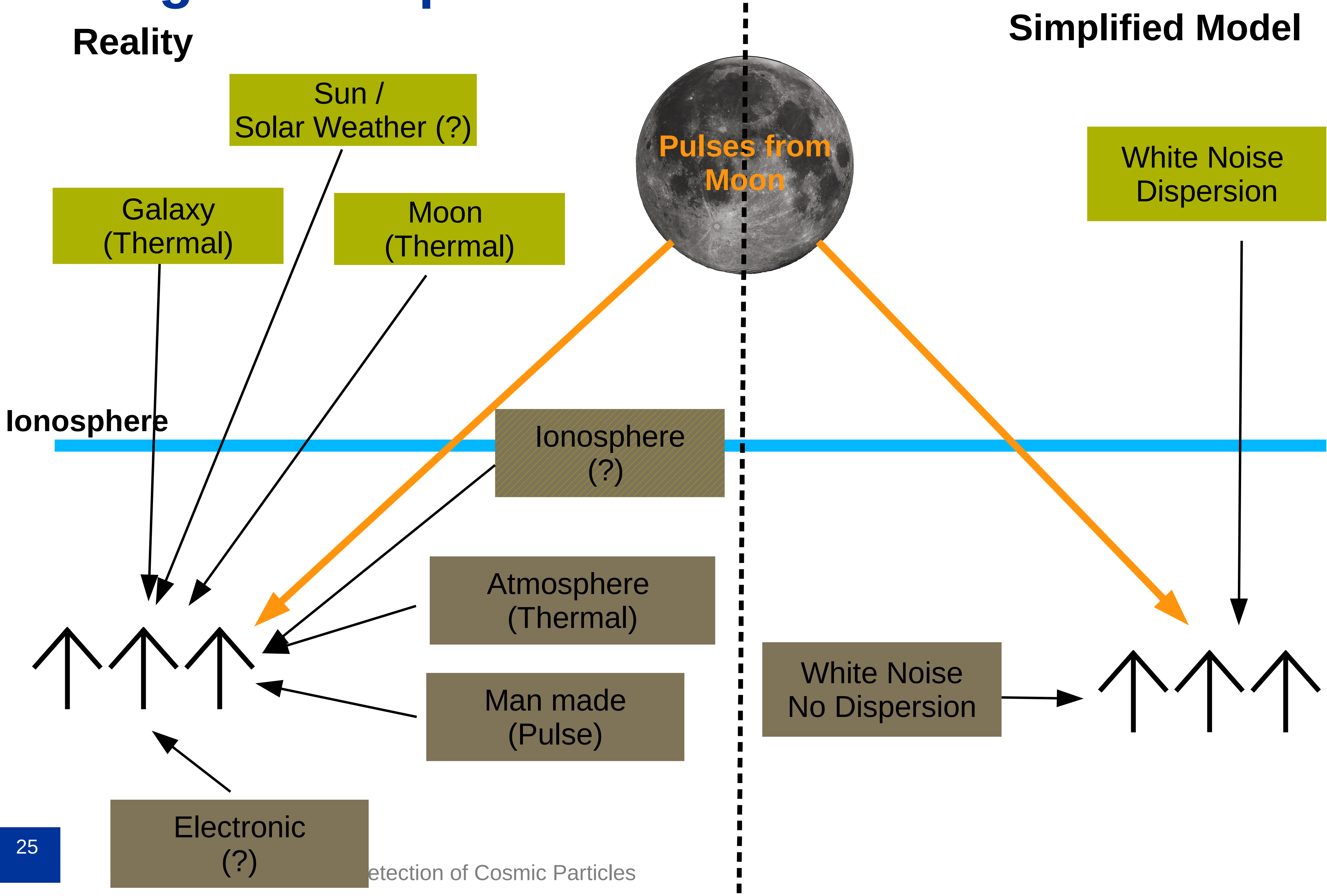
Dedispersion





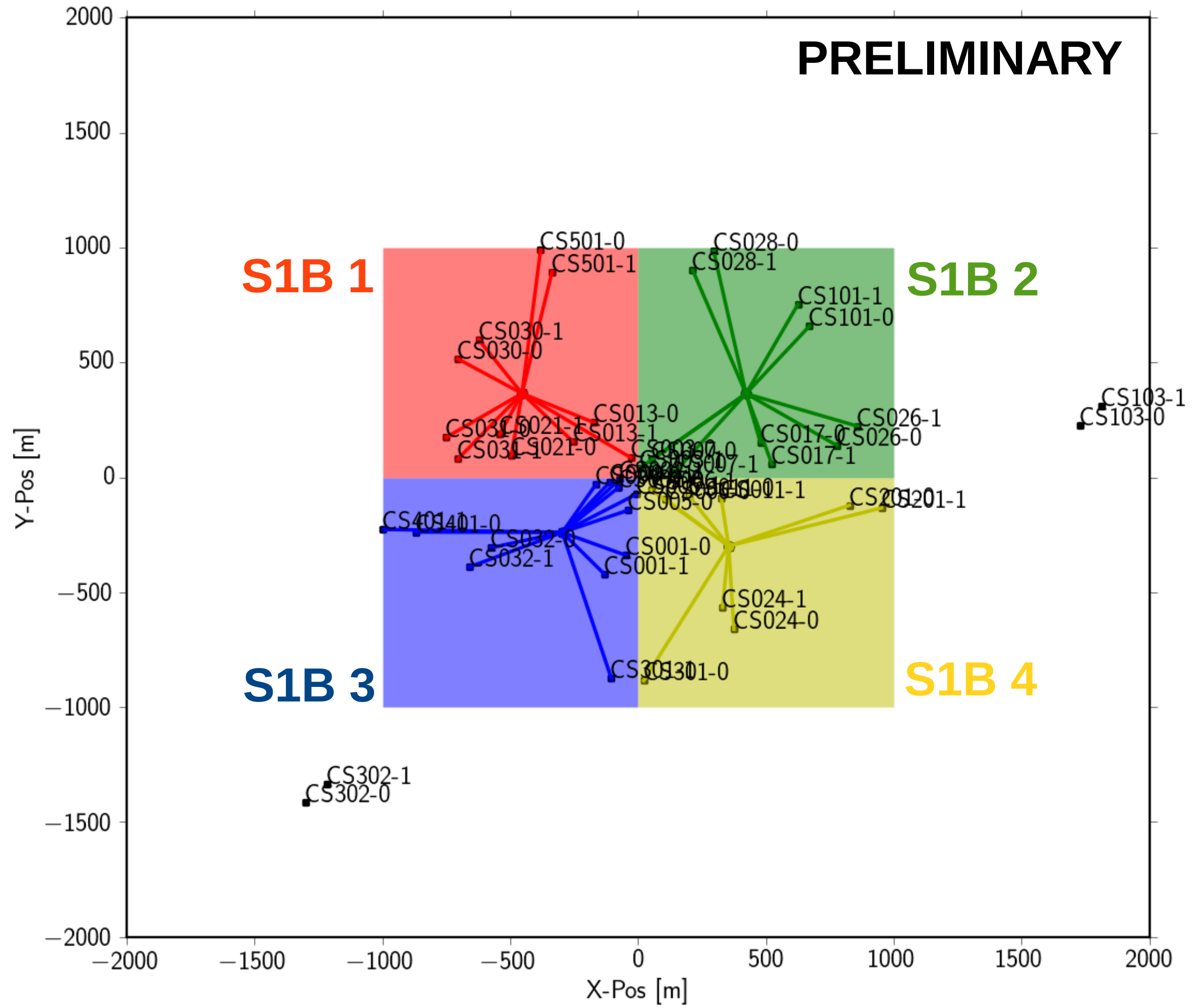
Recovery of 99% of amplitude possible
PPF results in 30% fluctuations with small TEC values → need to scan multiple TEC values

Signal Components



2 Stage Beamforming

- Combine multiple stations into windows of `virtual antennas'
- Limit on spacing as every Stage-1 beam has to cover full moon
- Loss of 2 stations →
  - ~ 8% reduction in sensitivity
- Inhomogeneous sensitivity
- 4 `Stage-1 beams'
- Real time access known to work for 7 beams, but here each beam has to be distributed on all 23 nodes



DRAGNET Cluster

- Designed for Pulsar searches with LOFAR

  (J. Hessels et al., Amsterdam)

  - 23 worker nodes
    - 16 CPU cores (2x Xeon E5-2630v3 (2014))
    - 128 GiB ram
    - 4x TitanX GPU
    - 56 Gbit/s Infiniband connection to LOFAR

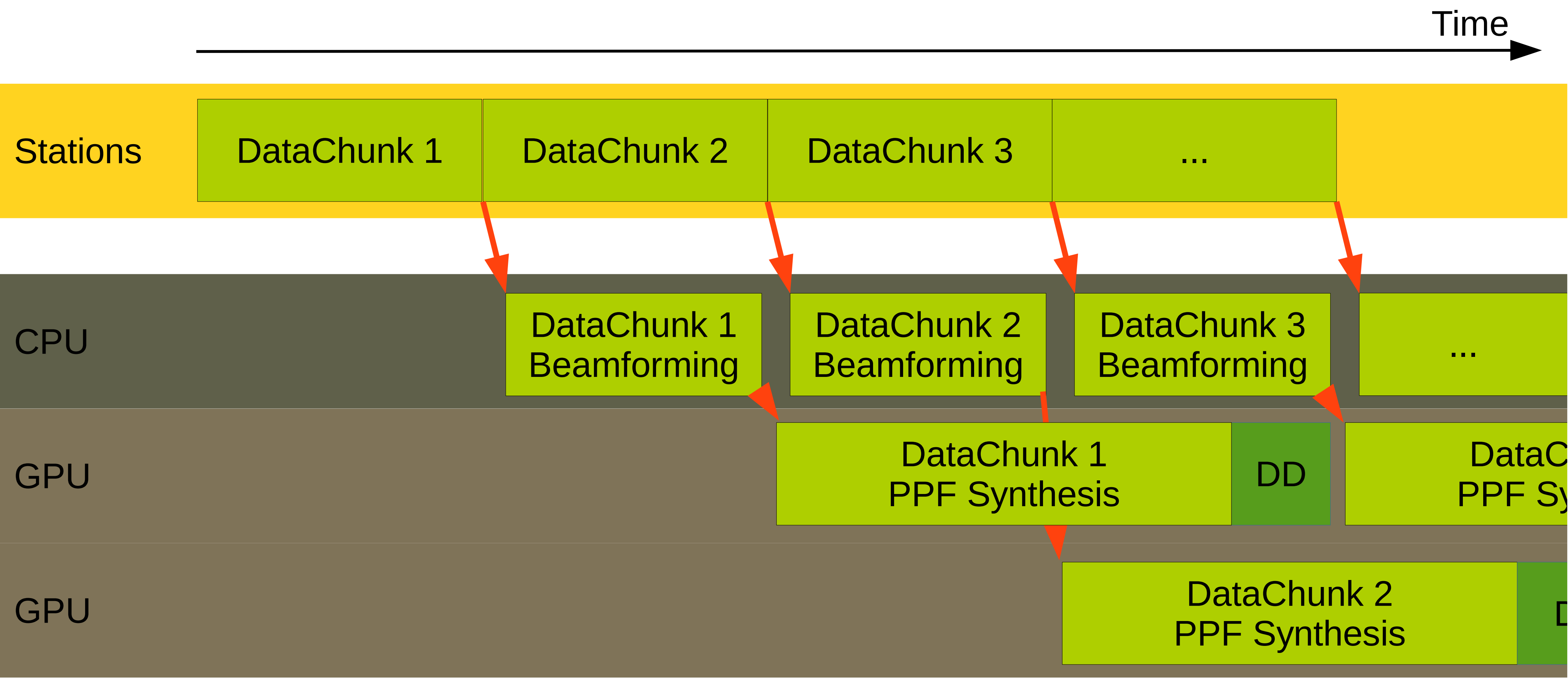
  = 92 High-End GPUs + CPUs ; 0.5 PetaFLOP/s

- Estimate based on prototype implementation:
  - 2 beams per node,
  - Computing power allows 46 beams total:

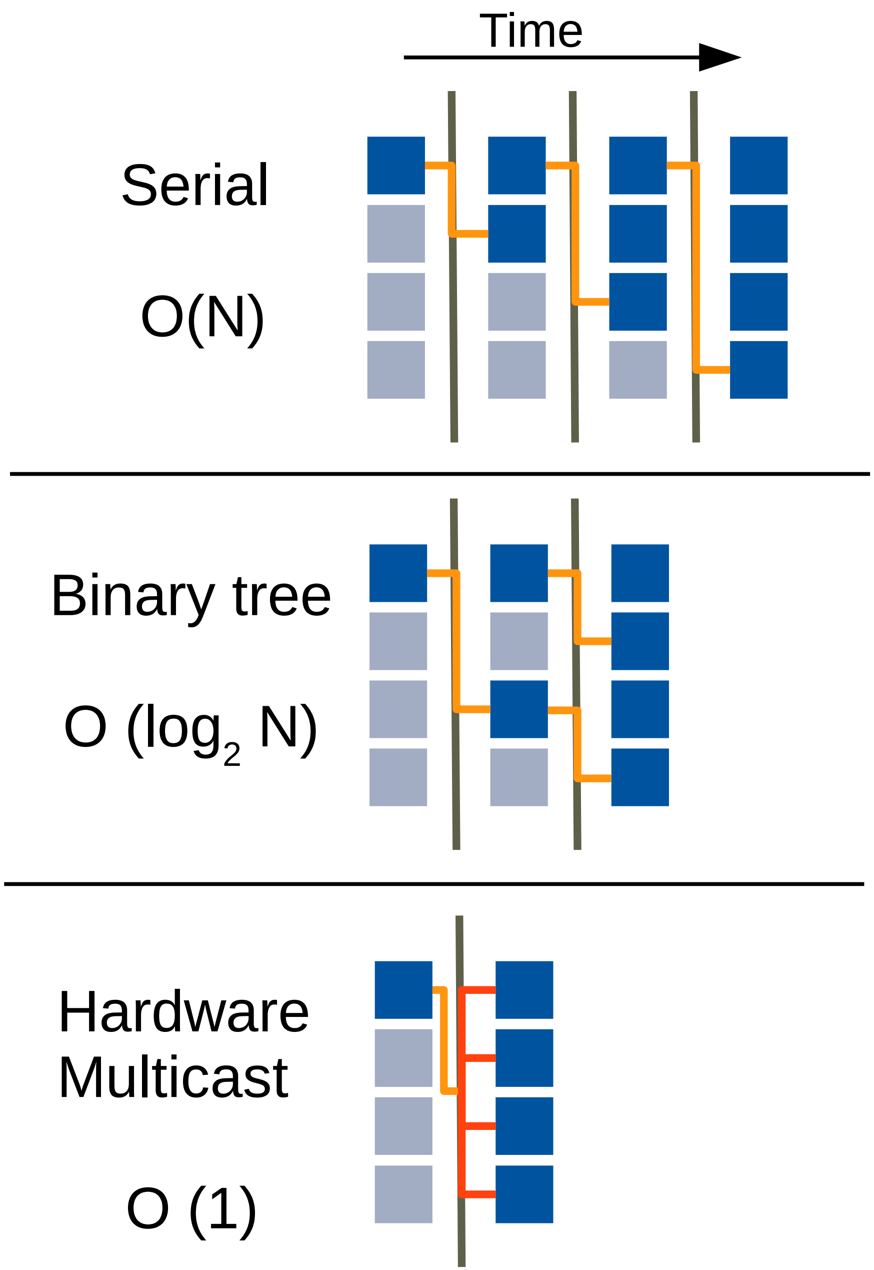
  → **Full coverage of the Moon with .1 deg beams possible**

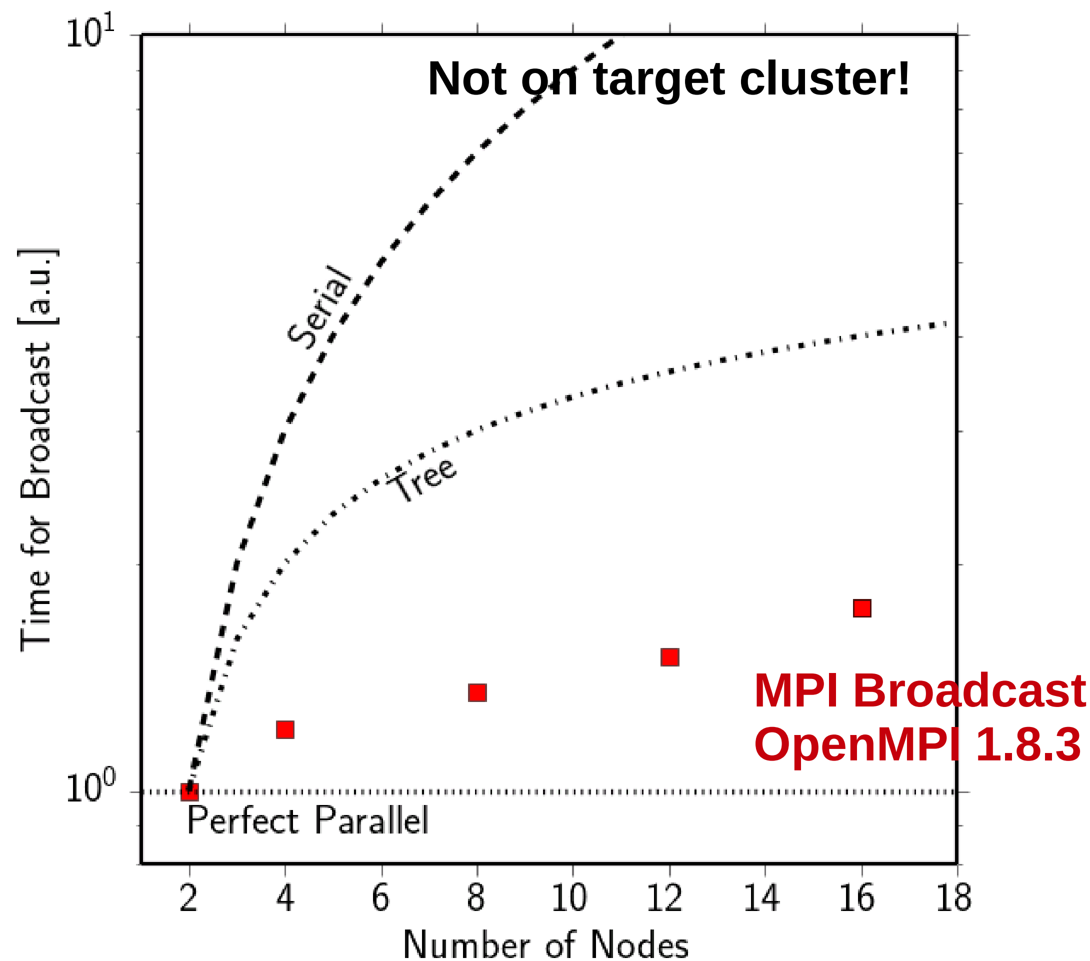
Performance Prototype Pipeline

- Beamforming : CPU
- PPF Synthesis : GPU (160% Realtime)
- Dedispersion : GPU



Data Broadcast

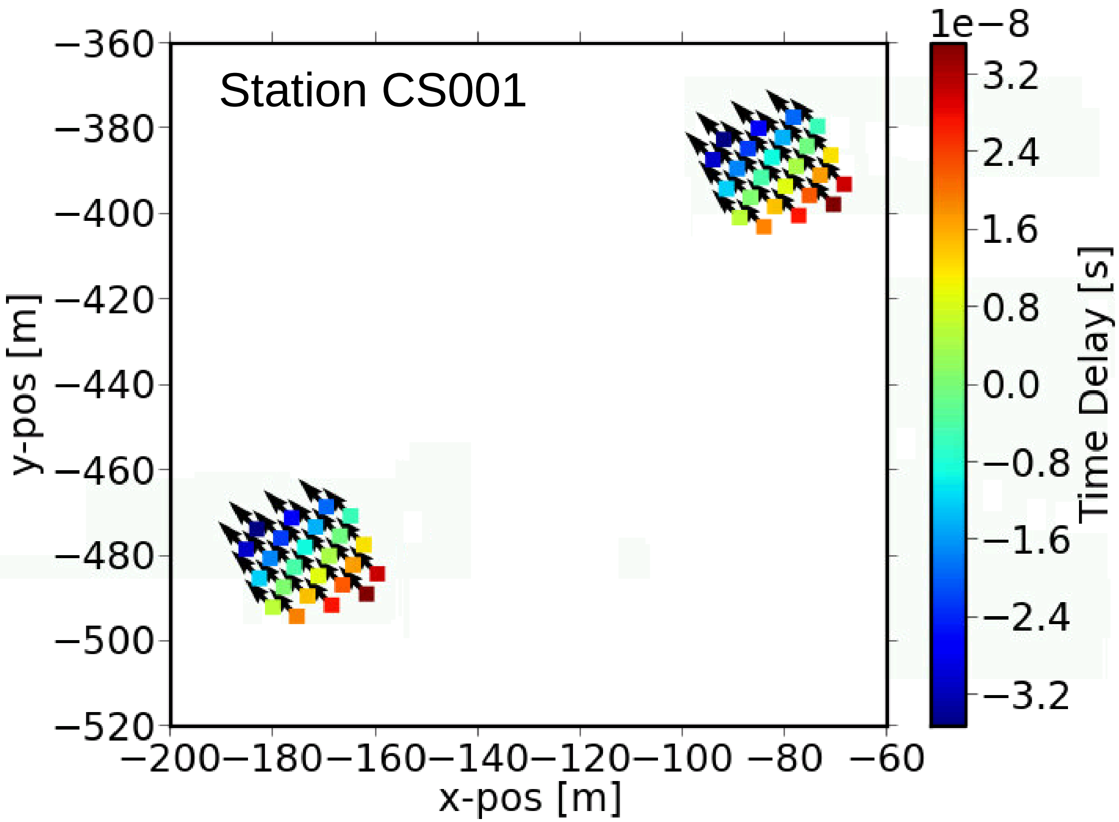


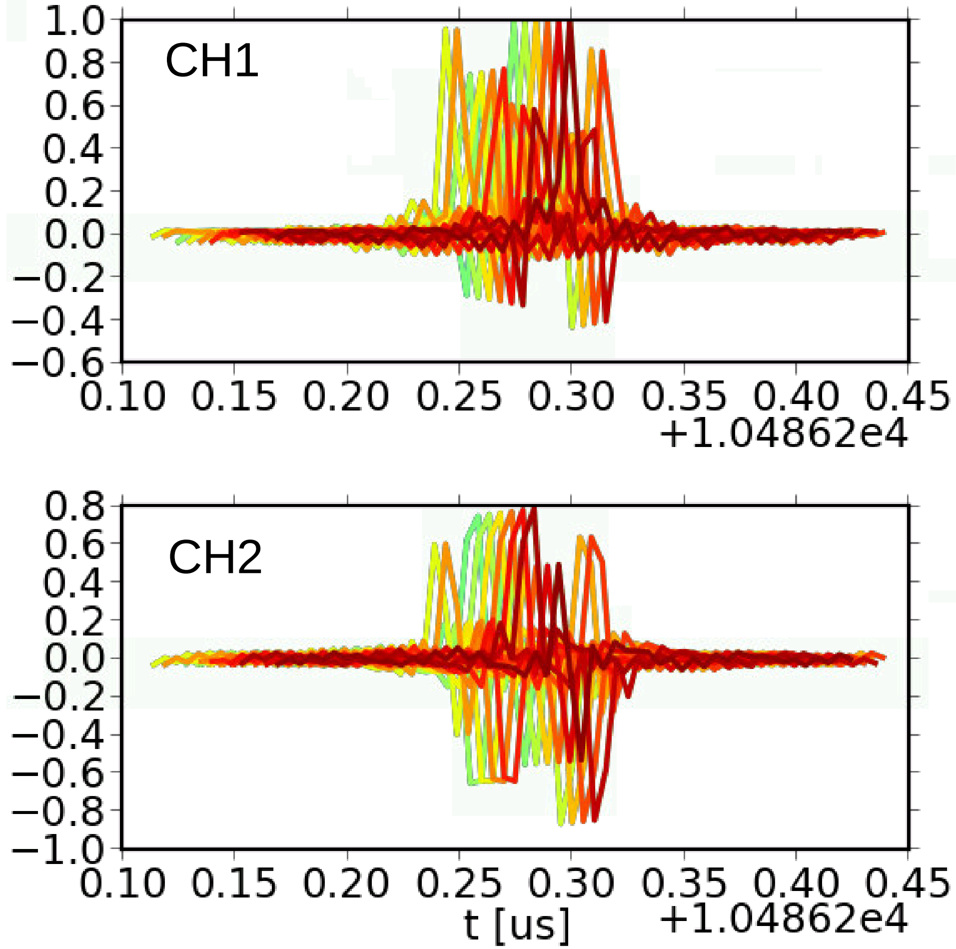


Alternative Options:
- Calculate multiple beams per node
- Reduce number of signal channels
- (Additional Hardware)

Beamforming Single HBA station

- Bandwidth limited delta pulse
  (30 deg rotated in phase)
- Start randomly shifted by 0.5 – 5000 pico seconds (1/10000 of sampling interval)





Pulse from direction (-1,1,1)

Beamformed Pulse

- PPFAnalysis → Beamformer → PPFSynthesis