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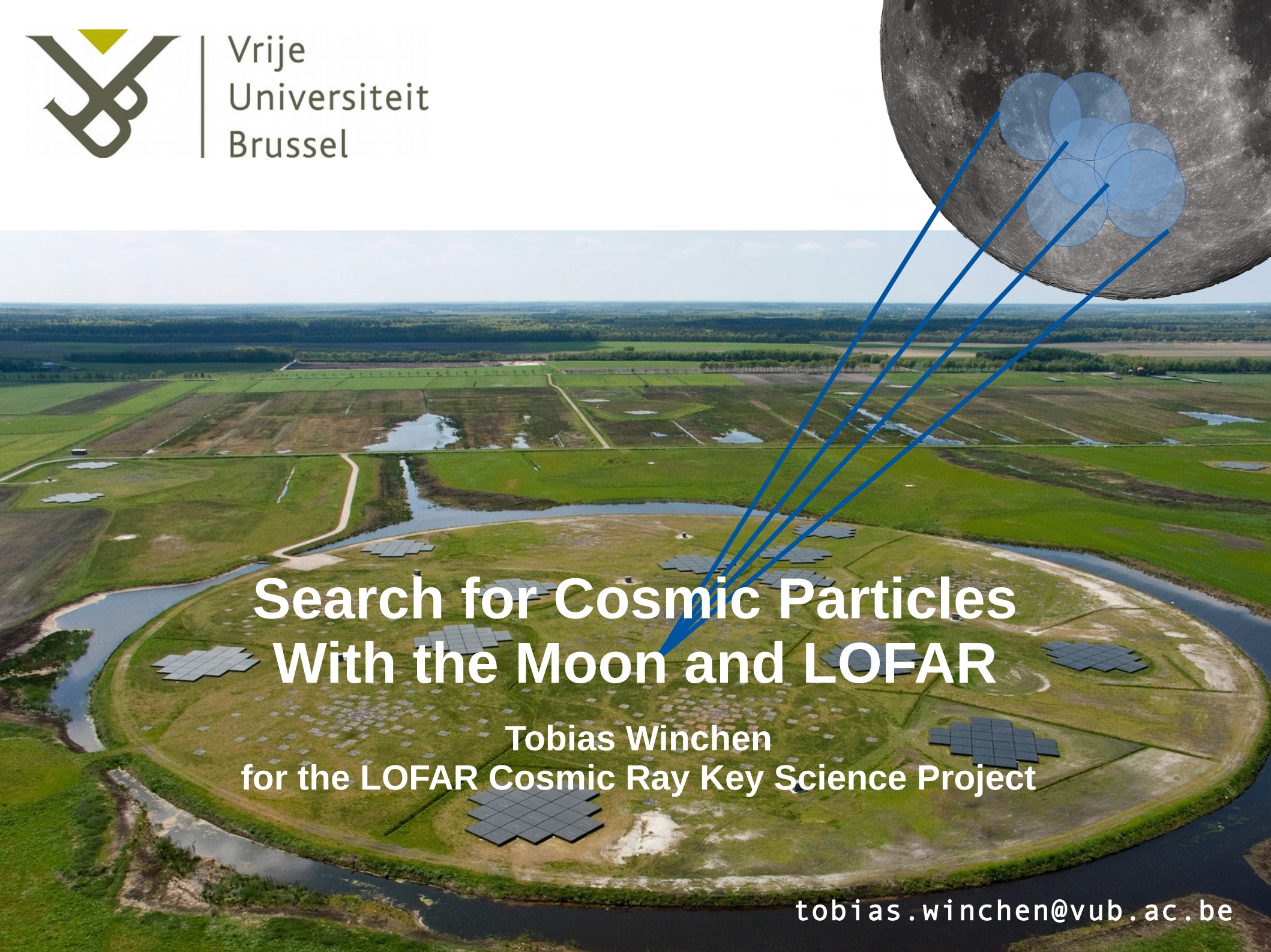

Search for Cosmic Particles With the Moon and LOFAR

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for the LOFAR Cosmic Ray Key Science Project

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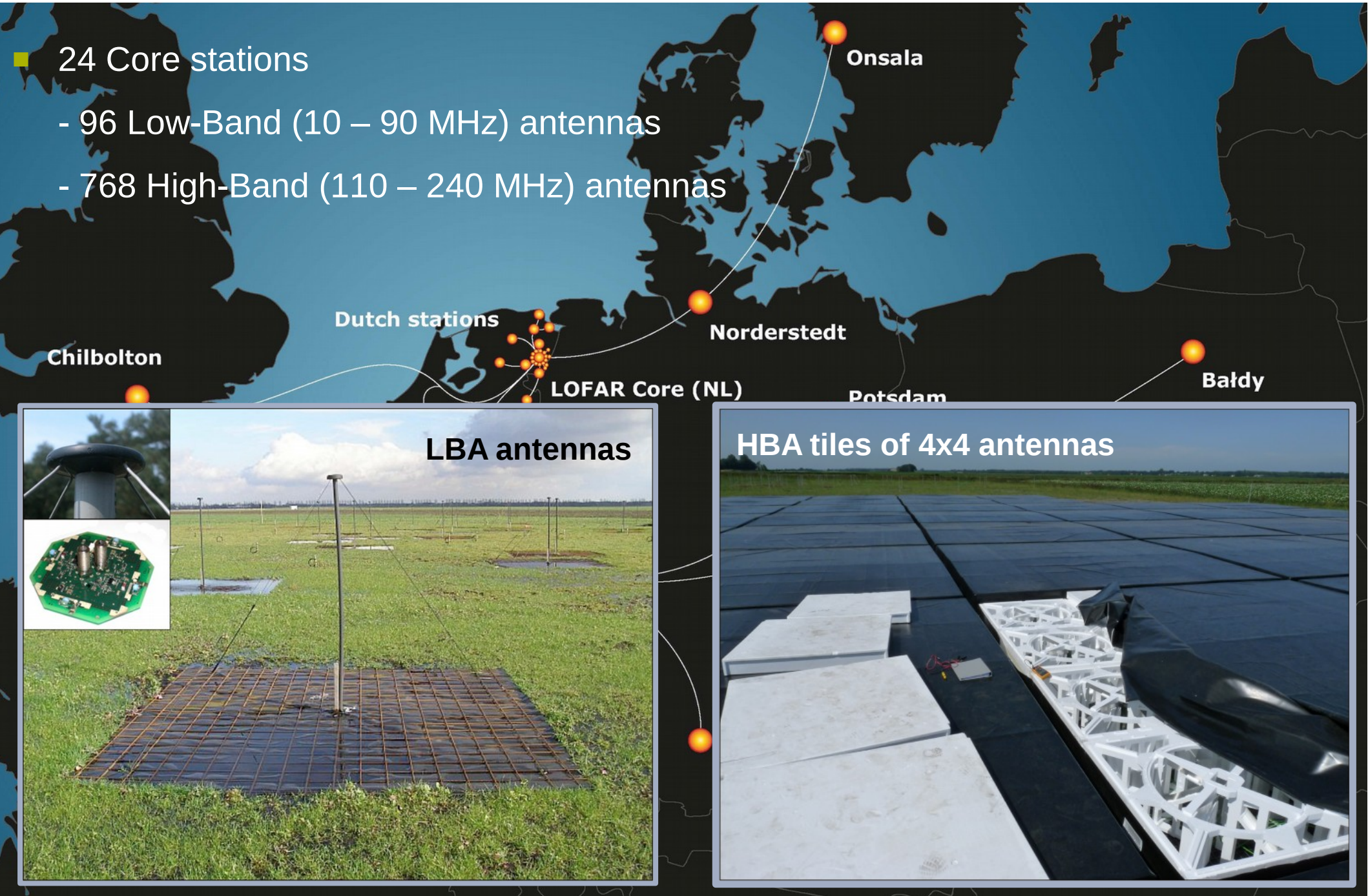
The **LO**w **F**requency **AR**ray

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

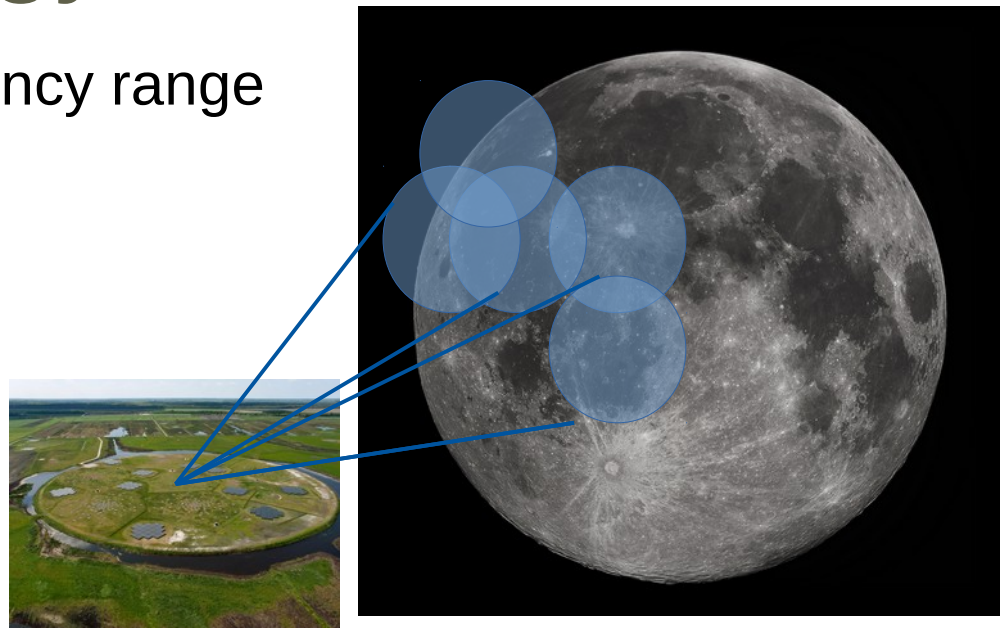
The **LO**w **F**requency **AR**ray

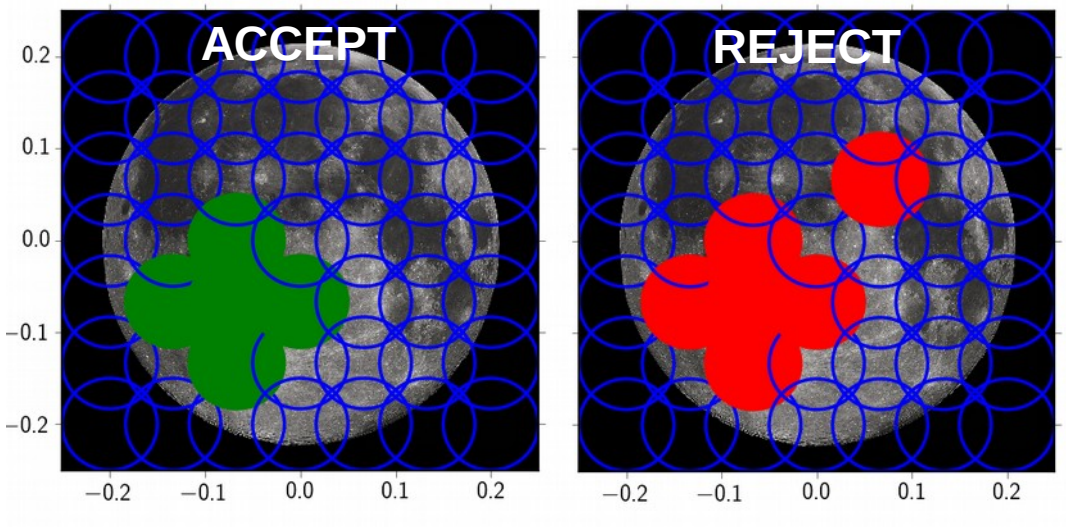
- 24 Core stations
  - 96 Low-Band (10 – 90 MHz) antennas
  - 768 High-Band (110 – 240 MHz) antennas



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





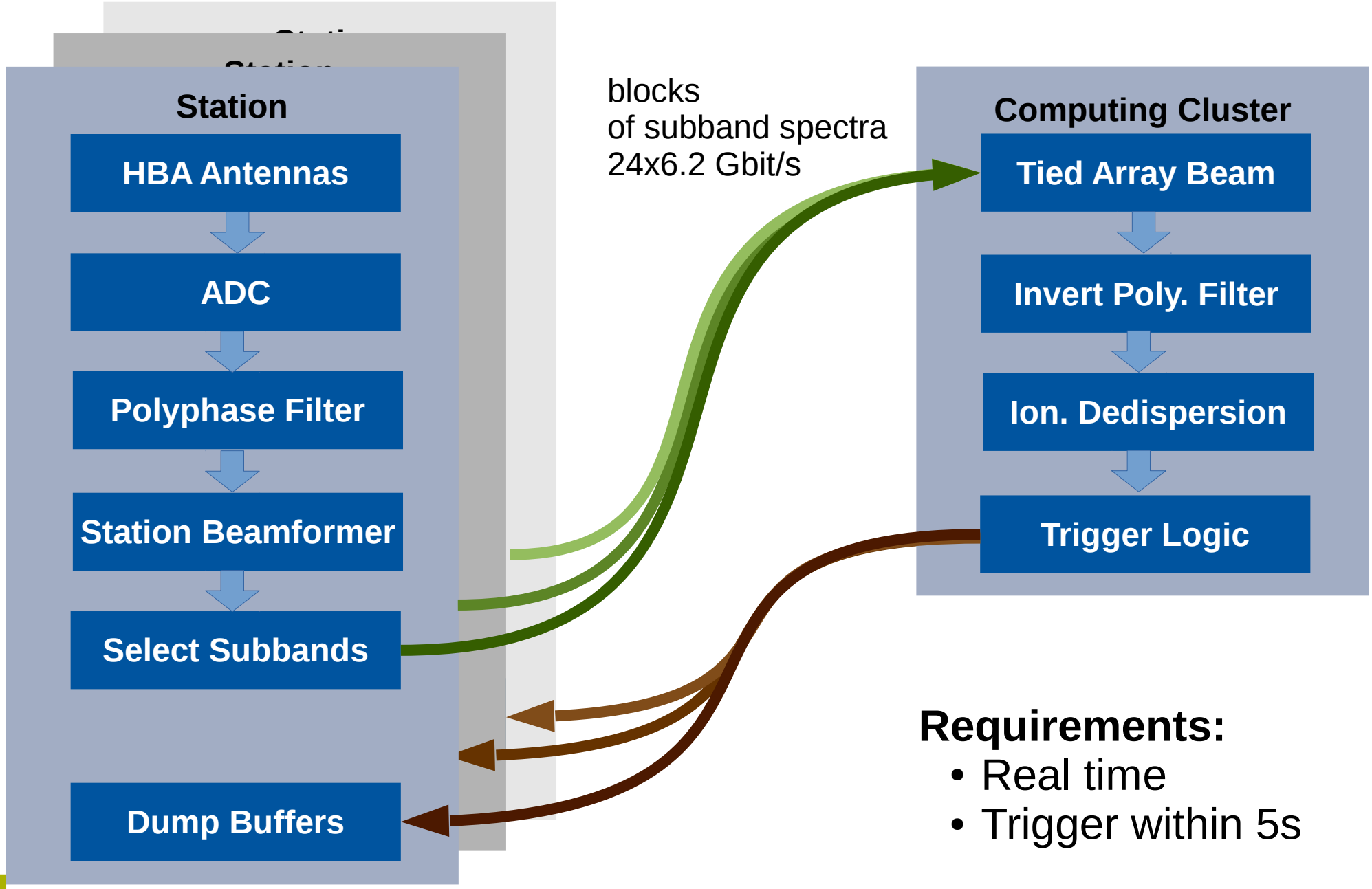
Challenges

- Data rate 0.8 GiB/s per station/beam

  → Trigger required

- LOFAR designed to integrate flux
  - Reconstruct time series from filtered signal for trigger
  - Use buffered traces for analysis

Online Data Analysis



Requirements:

- Real time
- Trigger within 5s

Signal Filtering @ LOFAR

- Decompose signal into subbands
- Example signal 16 184 samples

  White noise

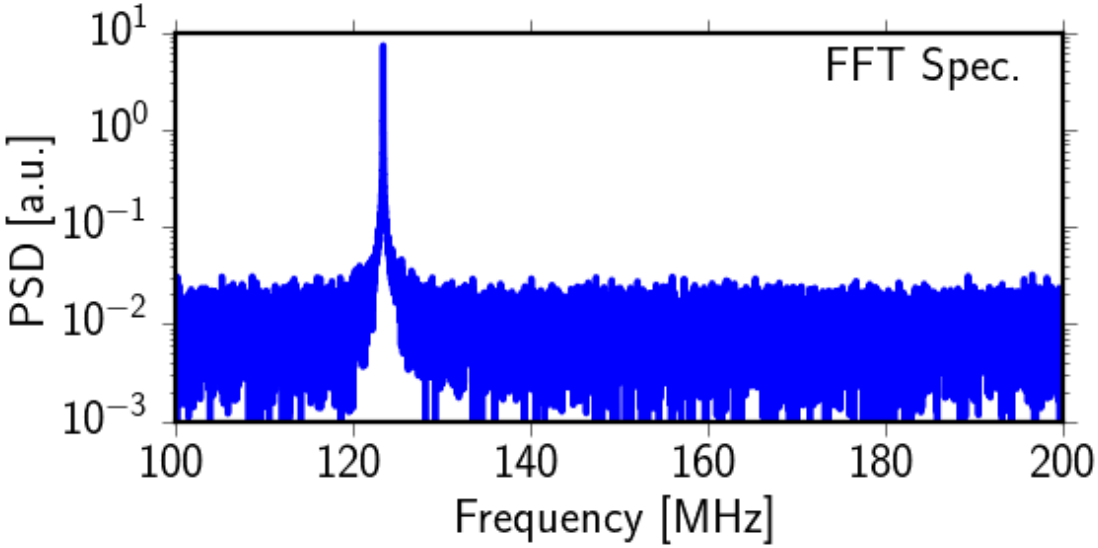
  Transmitter: 123.42 MHz

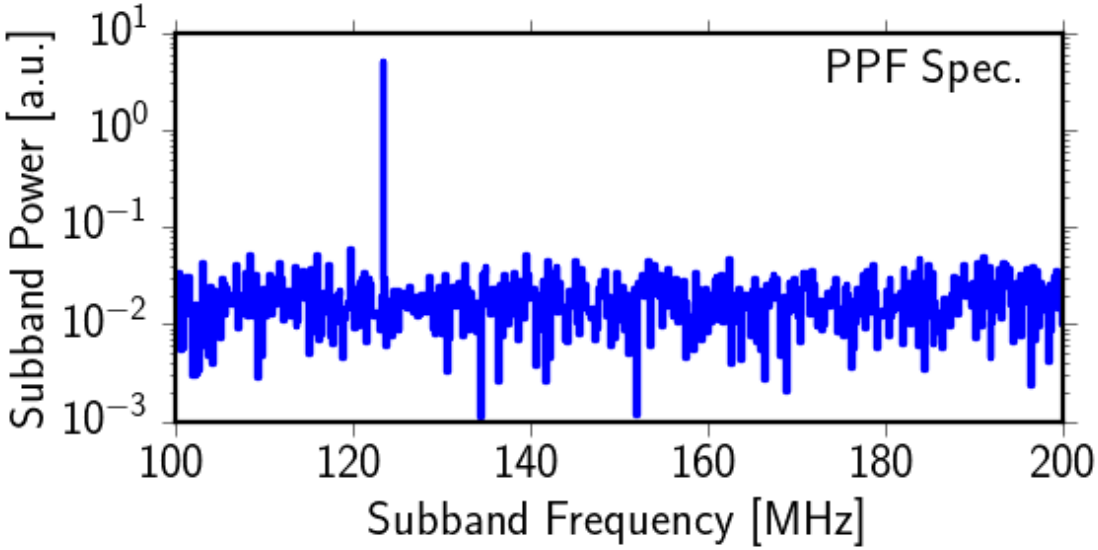
  Sampling freq. 200MHz
- FFT signal is smeared out over neighboring frequencies
- Efficient filtering with PPF

  + avoids smearing

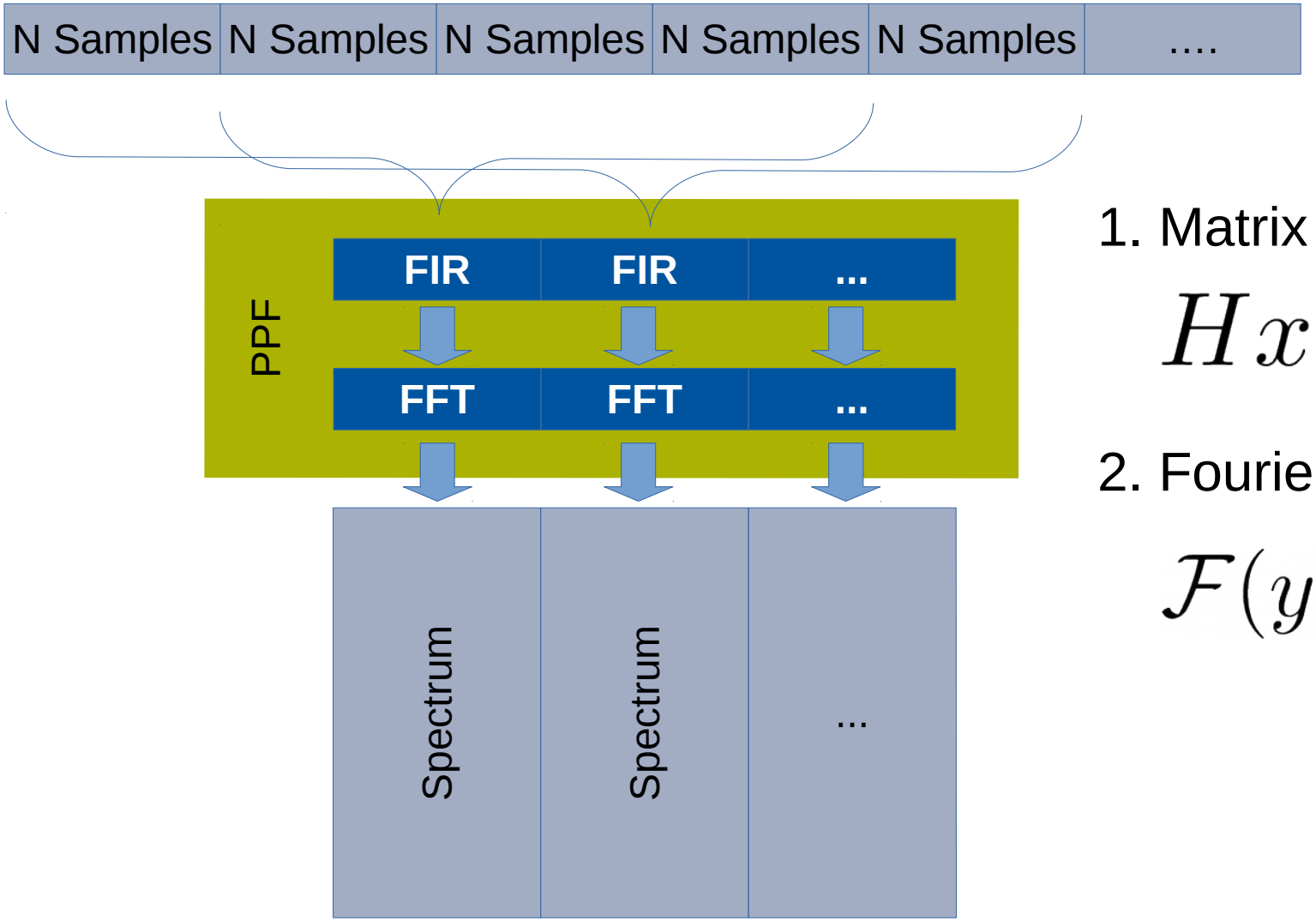
  - Reduces time resolution

  from 5 ns to ~5 us





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)

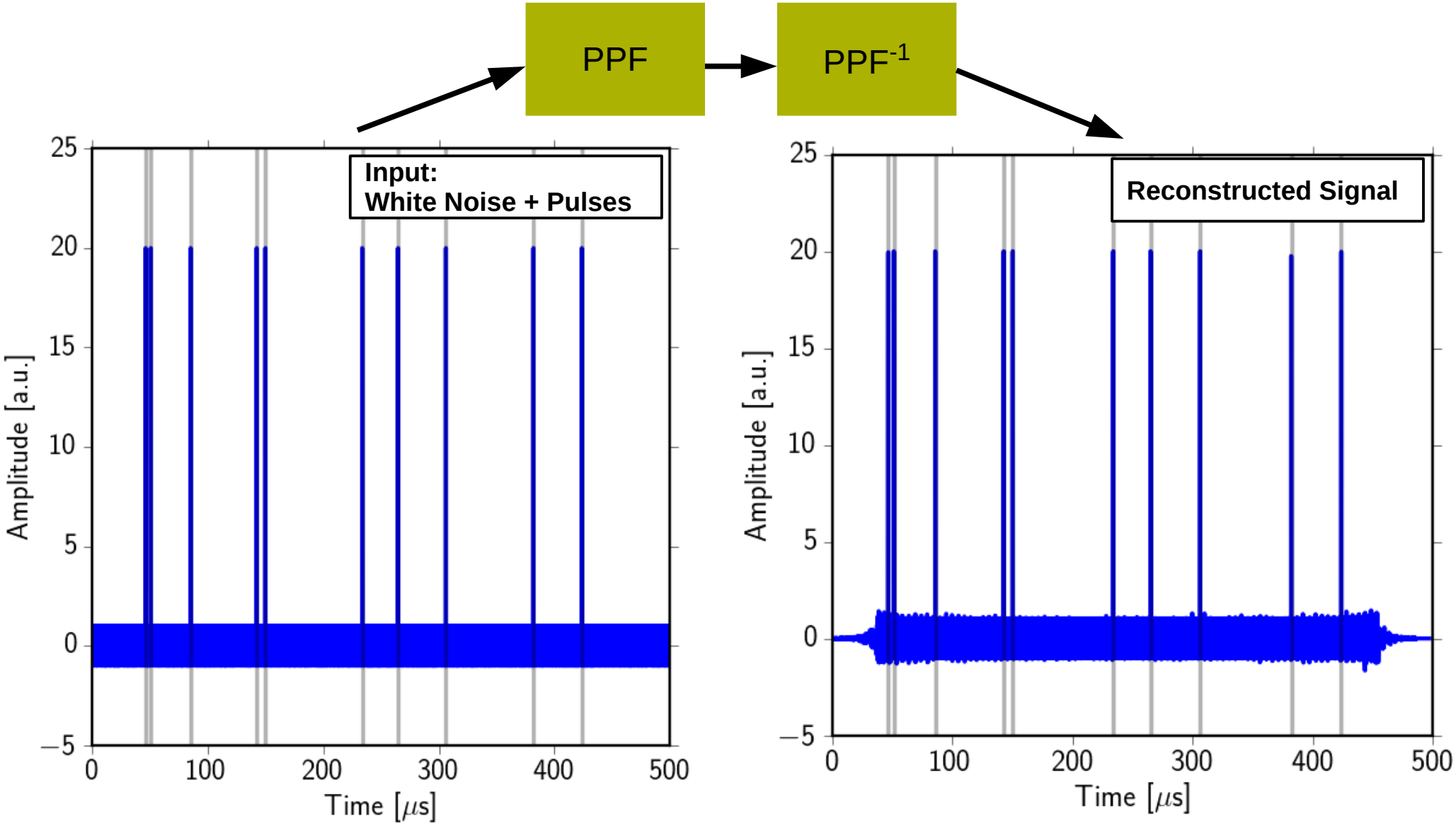
- Robust approach: Solve linear system

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

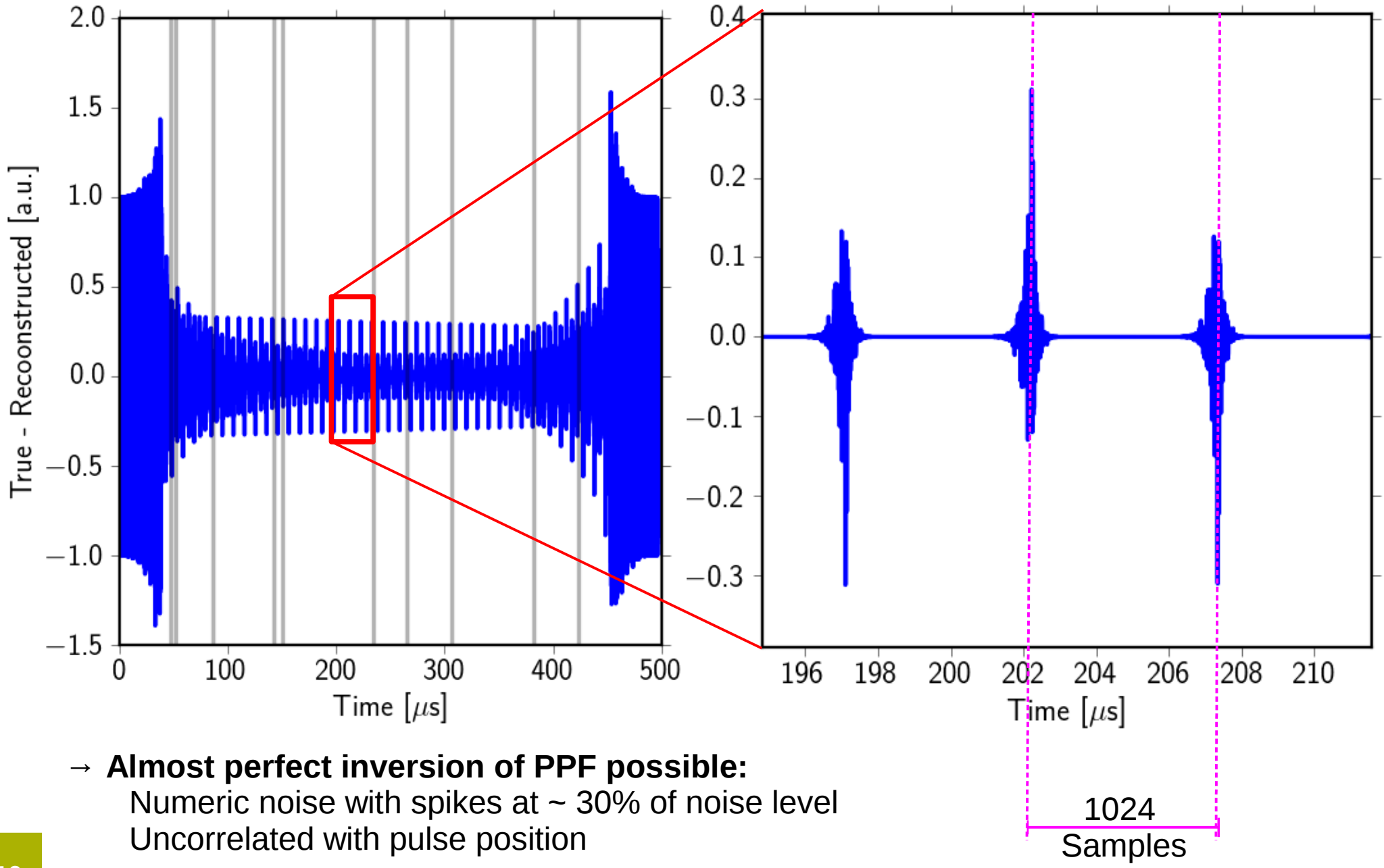
using iterative least squares (LSMR)

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

PPF^{-1} Example



Accuracy of PPF Inversion



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

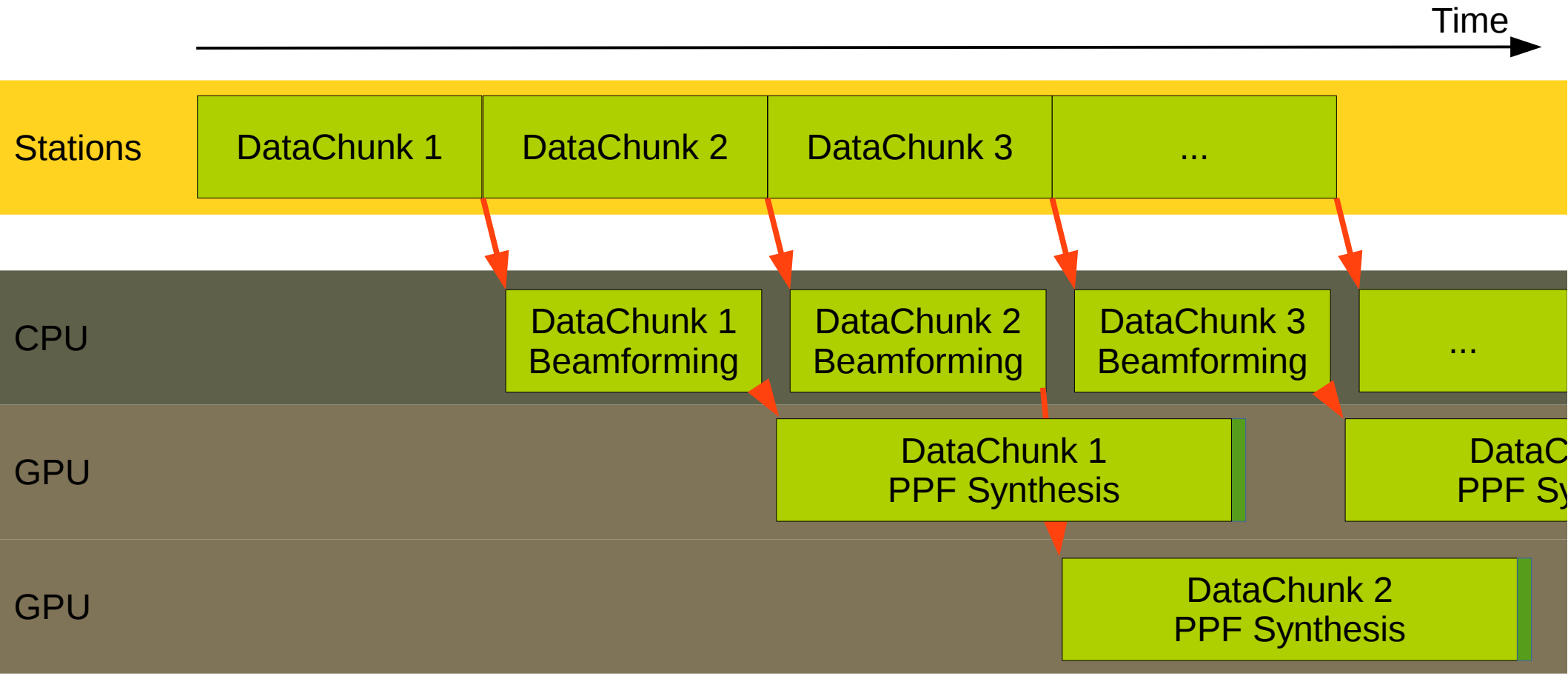
Numeric noise with spikes at ~ 30% of noise level

Uncorrelated with pulse position

Performance Prototype Pipeline

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

Prototype implementation on Nijmegen cluster
CPU: Xeon-2660 (2012)
GPU: M2090



DRAGNET Cluster

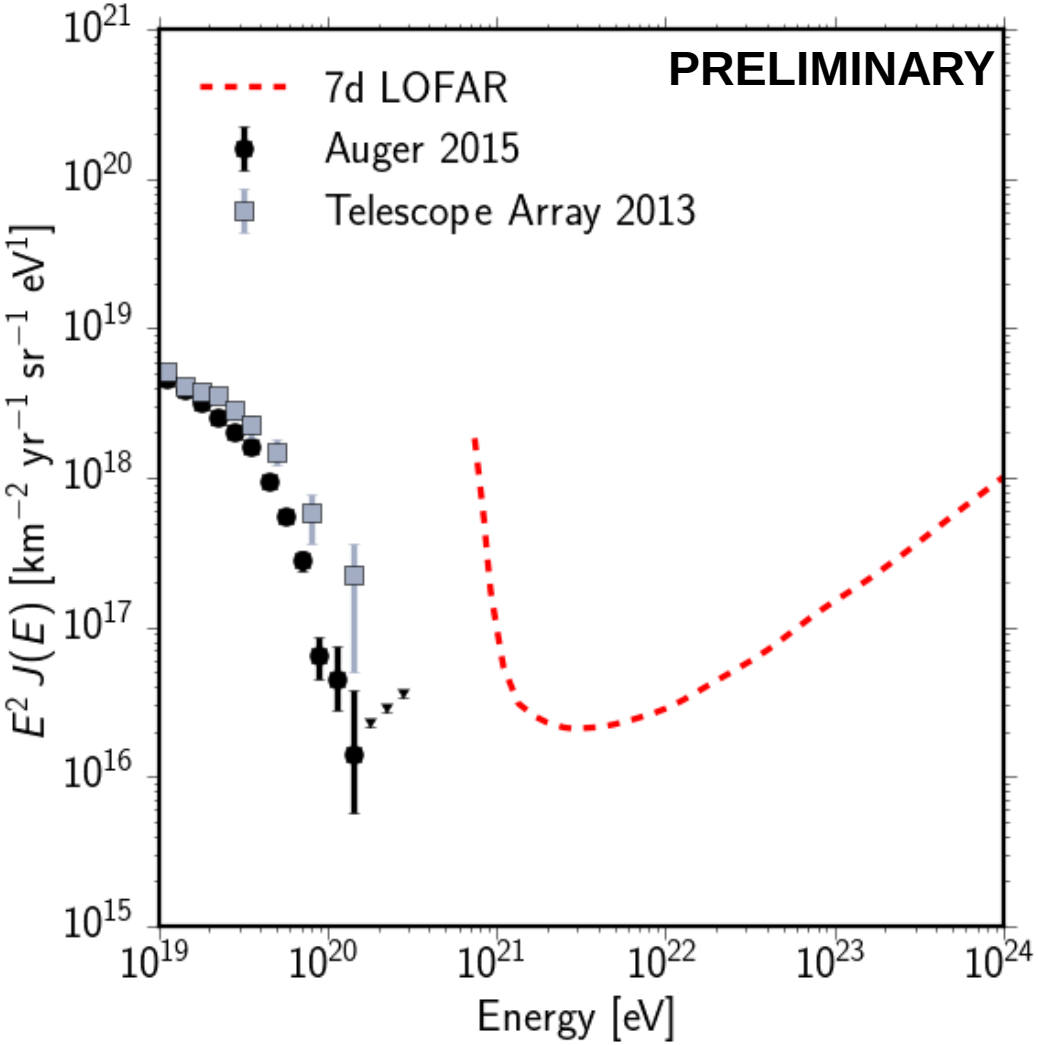
- Designed for Pulsar searches (J. Hessels et al.)
  - 23 worker nodes
    - 16 CPU cores (2x Xeon E5-2630v3 (2014))
    - 128 GiB ram
    - 4x TitanX GPU
    - 56 Gbit/s Infiniband connection to LOFAR

    = 92 High-End GPUs + CPUs ; 0.5 PetaFLOPs
- Estimate based on prototype implementation:
  - 2 beams per node,
  - Computing power allows 46 beams total:

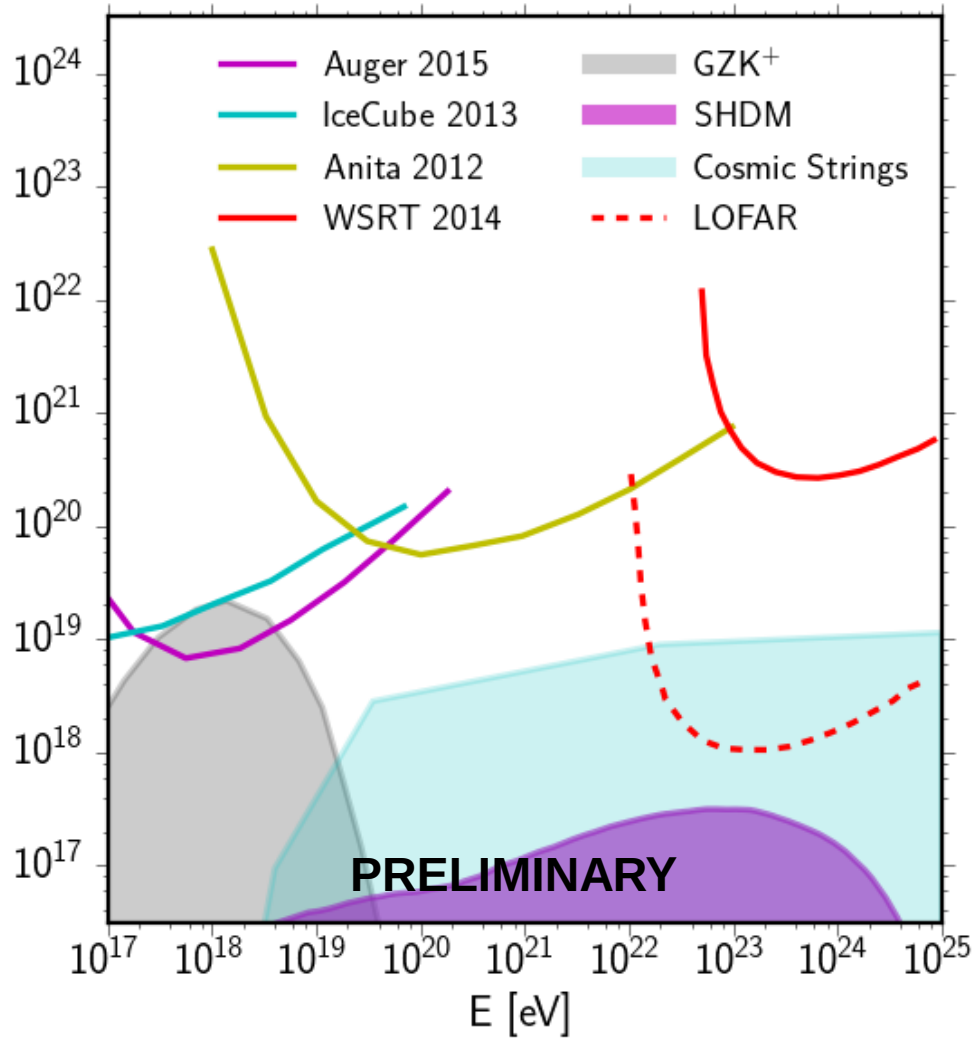
    → **Full coverage of the moon with .1 deg beams possible**

Sensitivity Optimization

COSMIC RAYS

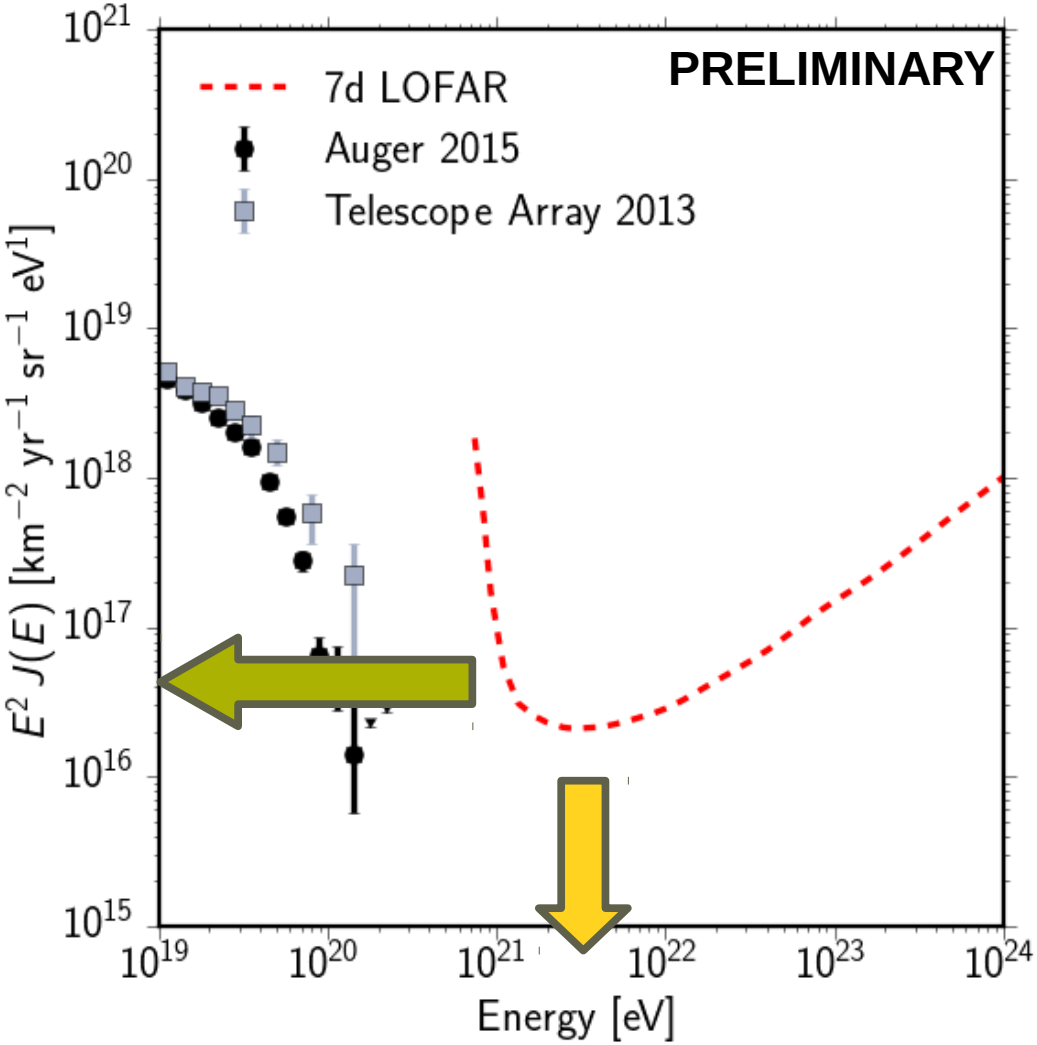


NEUTRINOS



Sensitivity Optimization

COSMIC RAYS



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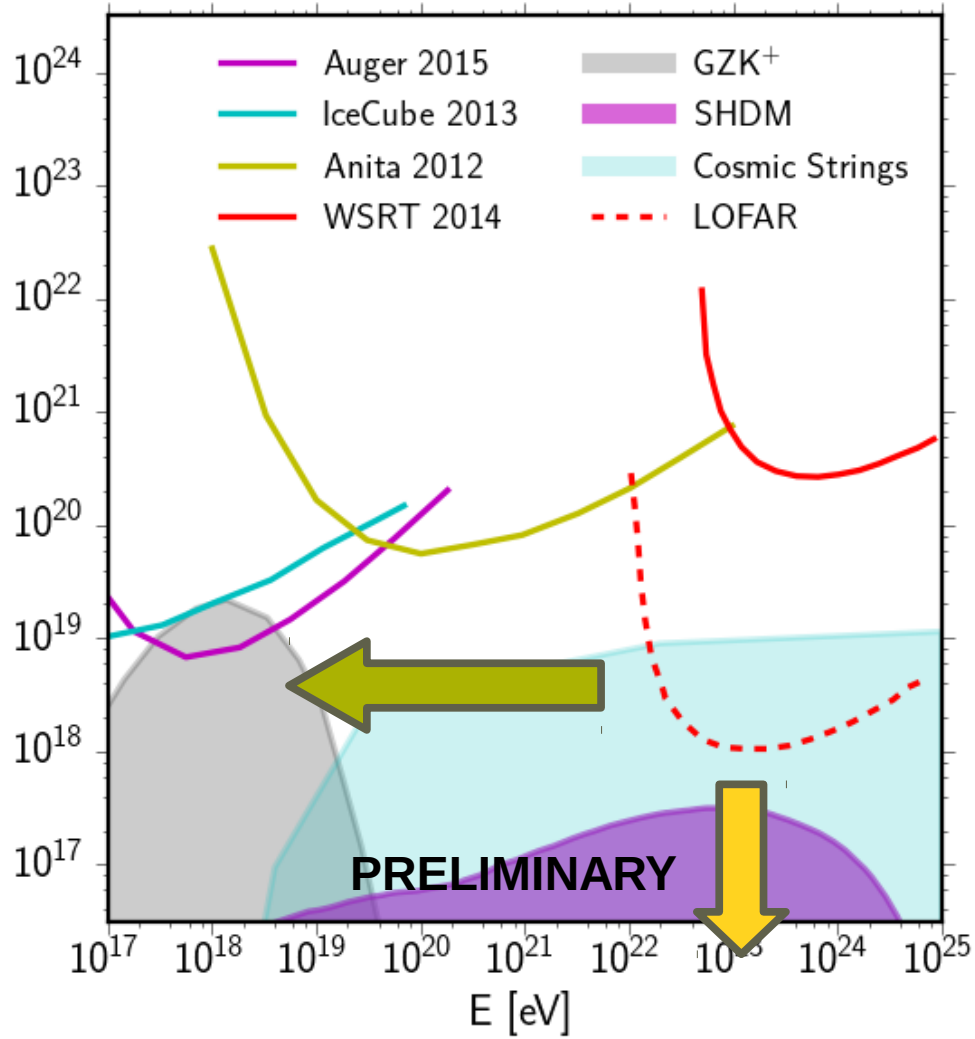

Energy Threshold:
- Number of Stations
- Shape of beams
- ...

Sensitivity:
- Number of Beams
- Observation Time
- ...

Conclusions

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- LOFAR High-Band antennas optimal for lunar Askaryan
- Online analysis requires inversion of polyphase filter
  - Inverse almost perfect: Regular spikes at ~30% noise level
  - Computationally expensive
- DRAGNET GPU/CPU cluster available
- First test-run in preparation
- Next talk by Sander ter Veen:

  Trigger strategies, TEC measurements, offline processing, ...

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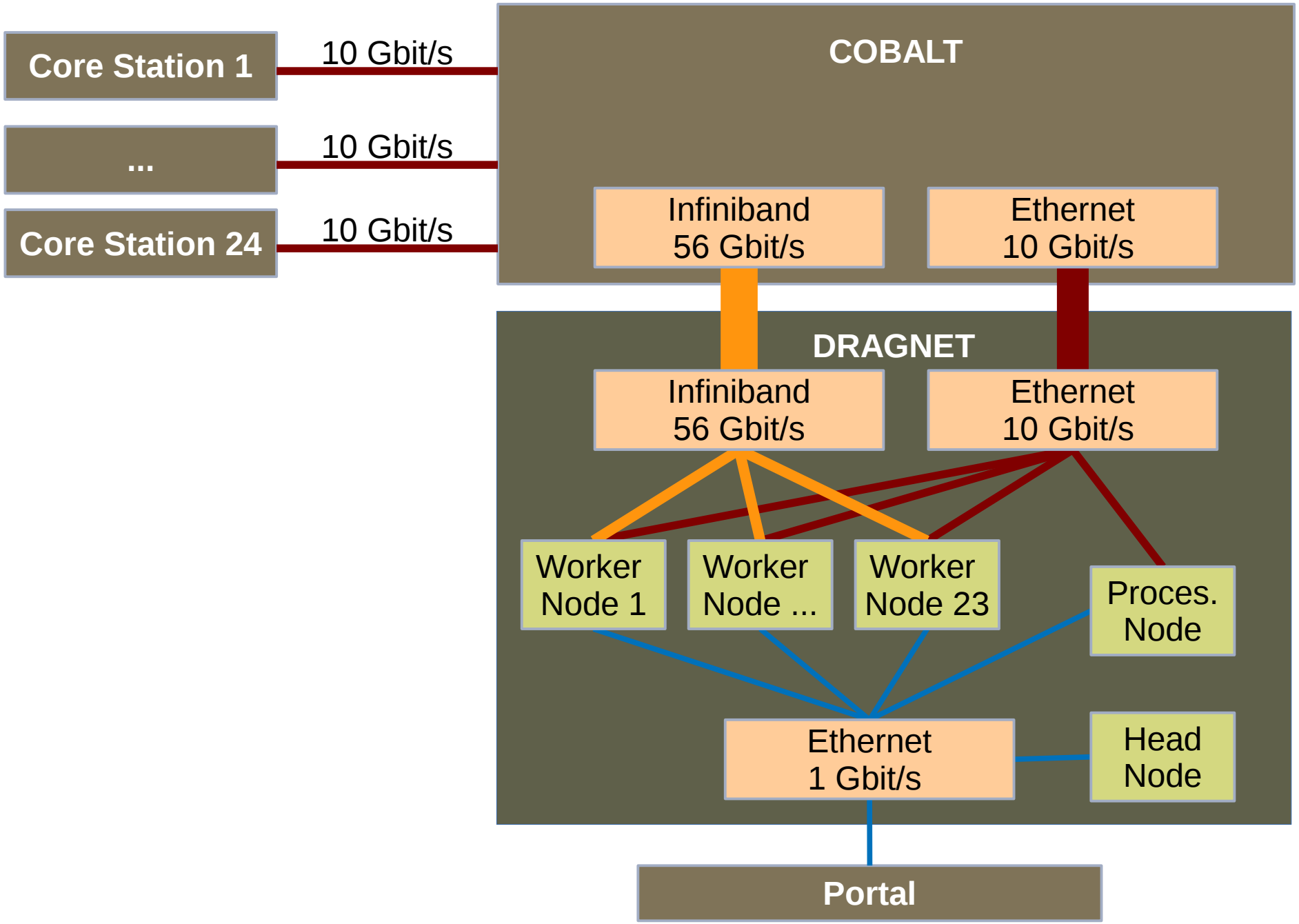
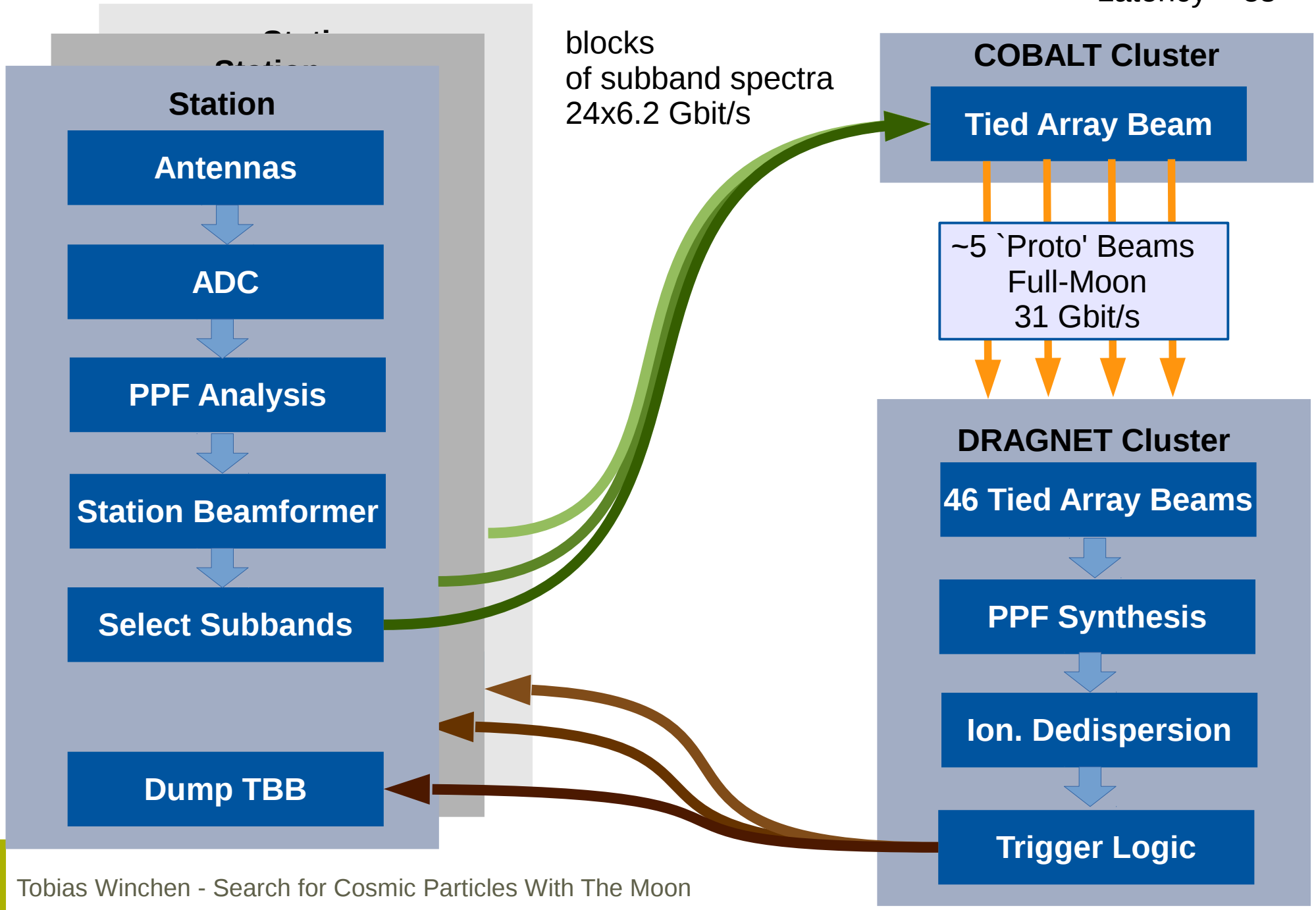
Backup

LOFAR Network

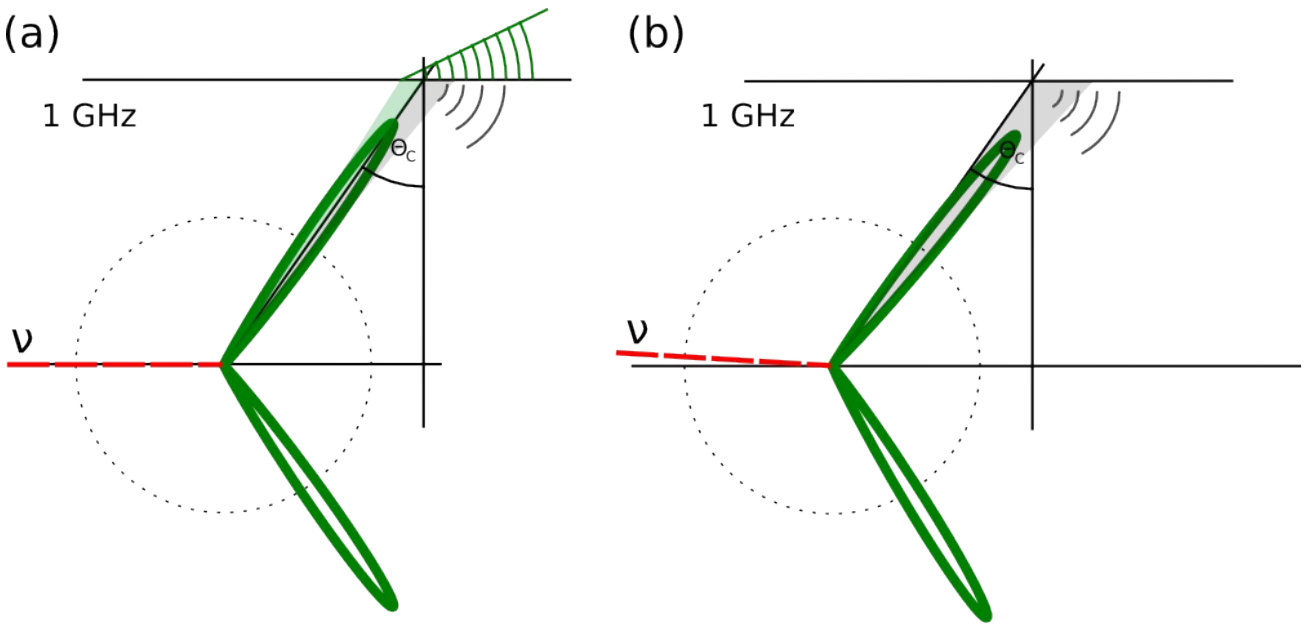


2 Step Online Processing

Requirements:
- Real time
- Latency < 5s

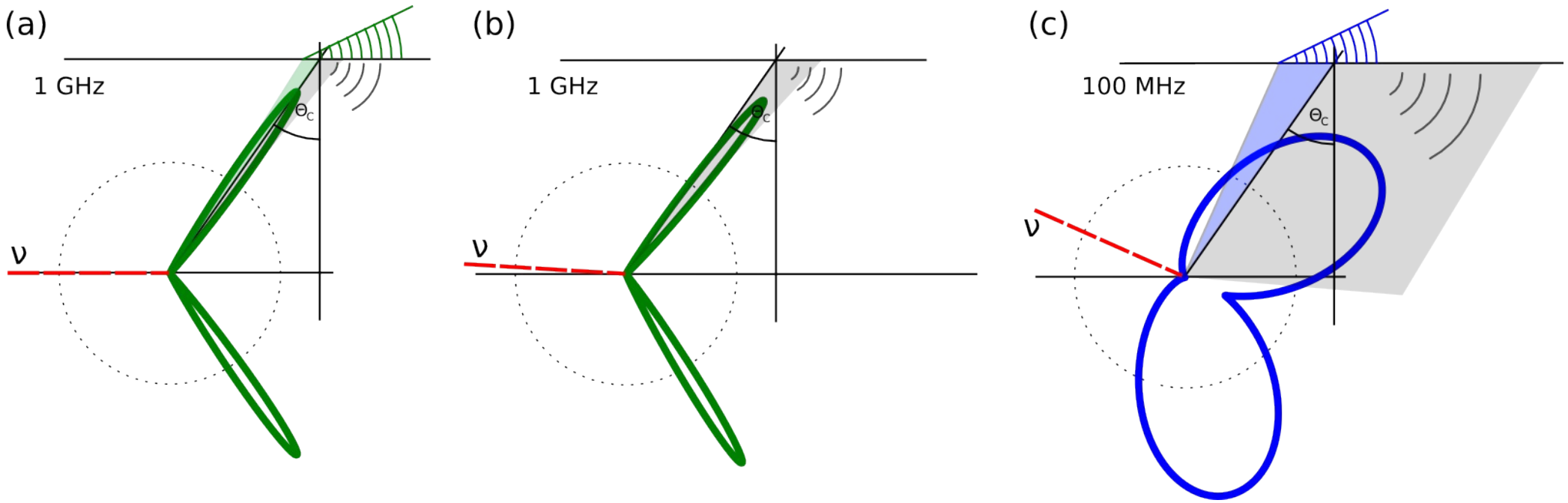


Pulse Reflected at High Frequencies



- 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)

Dispersion

- Frequency dependent time delay of pulse due to free electrons in ionosphere
- Frequency dependent time delay

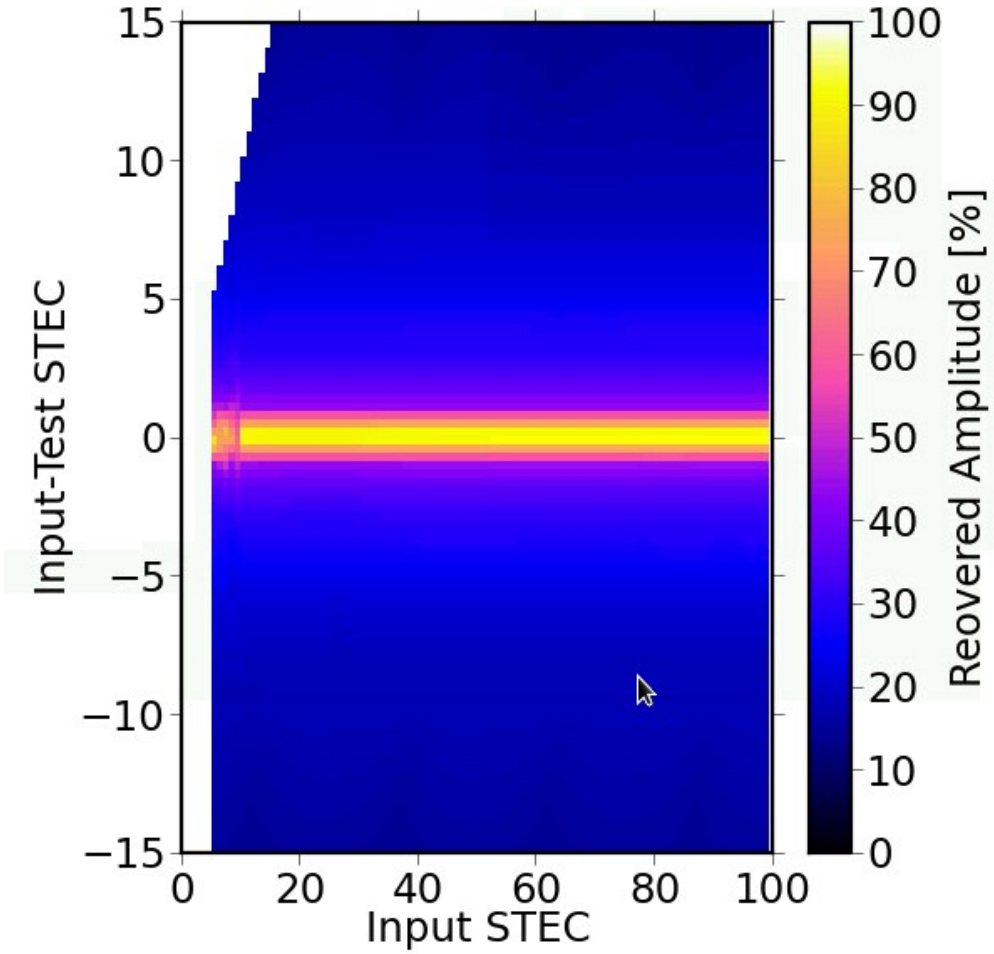
$$\Delta t(\nu) = 1.34 \frac{STEC}{\mathrm{TECU}} \left(\frac{\nu}{\mathrm{Hz}}\right)^{-2} \mathrm{s}$$

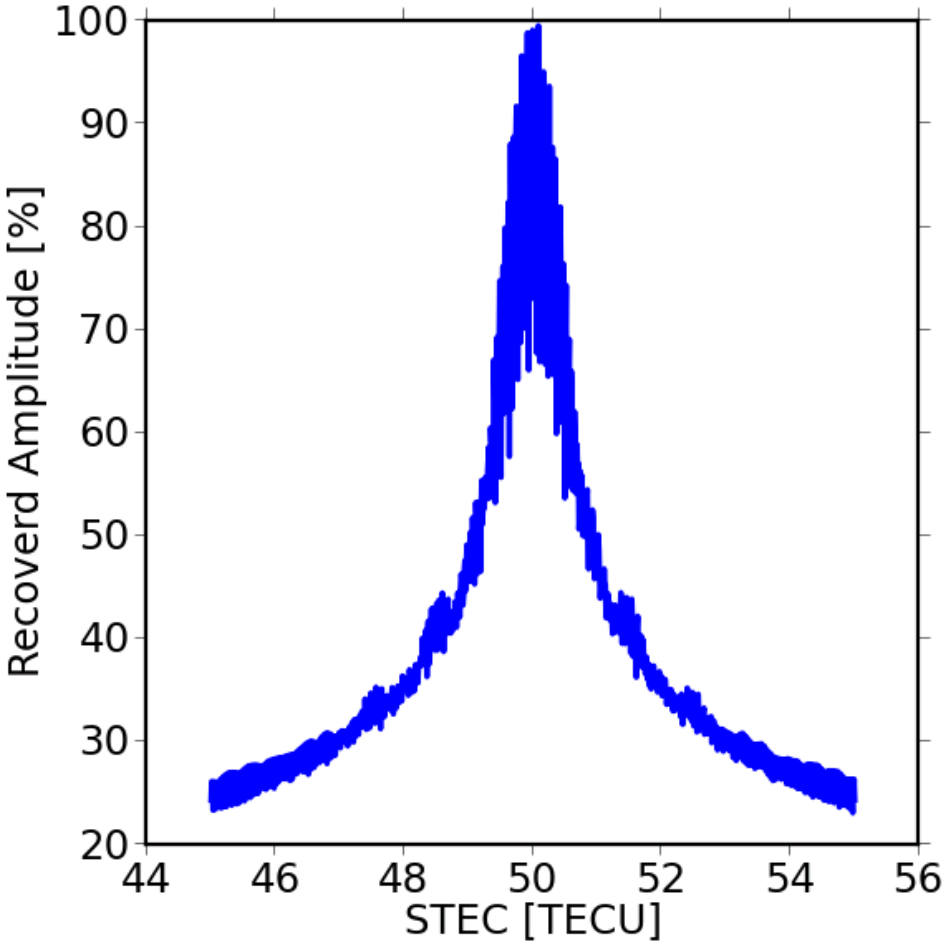
STEC: Standard electr. content
1 TECU = 10^{16} electrons / m^2

- Typical values 5 - 100 TECU

  > 500 ns delay between 100 MHz and 200 MHz

Dedispersion





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