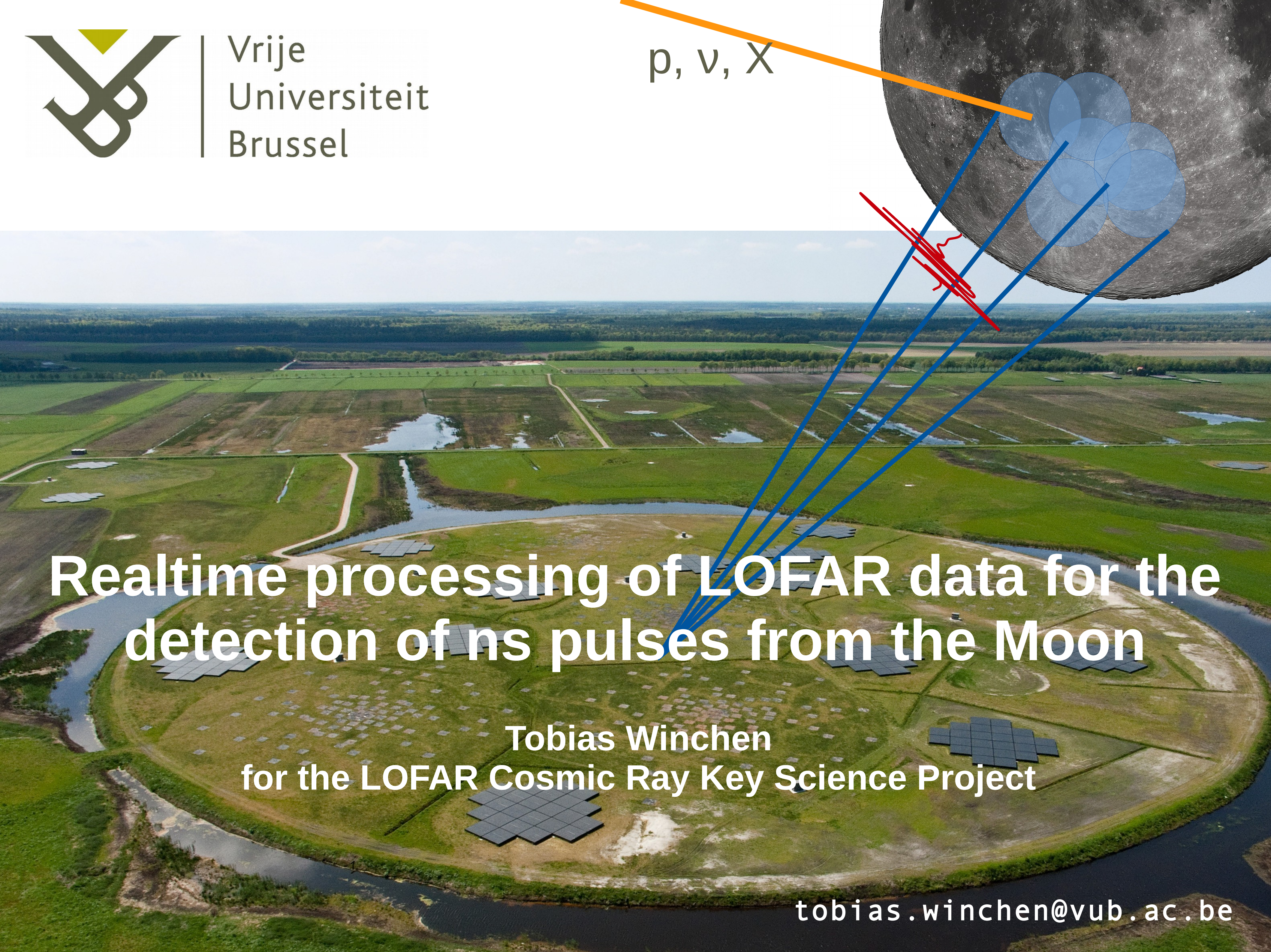

Realtime processing of LOFAR data for the detection of ns pulses from the Moon

Tobias Winchen
for the LOFAR Cosmic Ray Key Science Project

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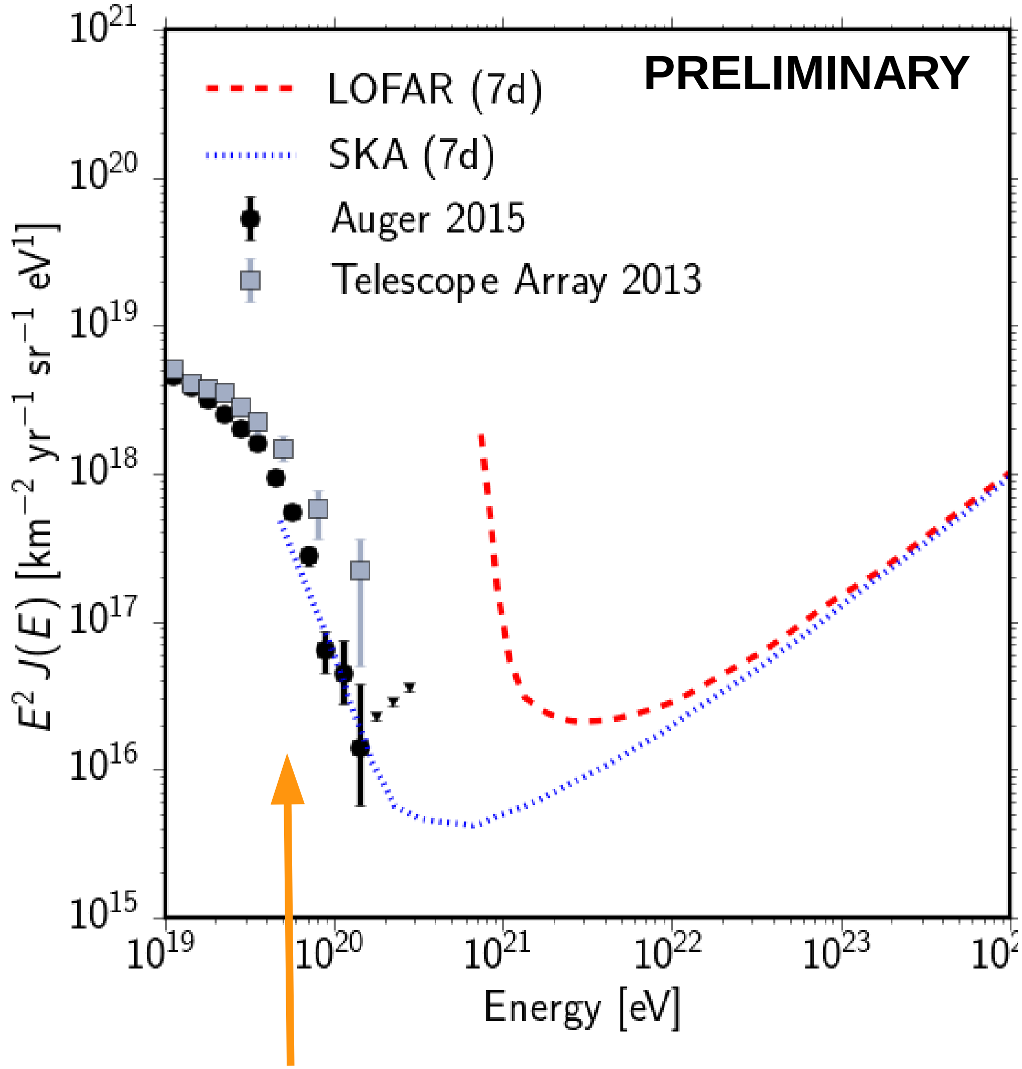
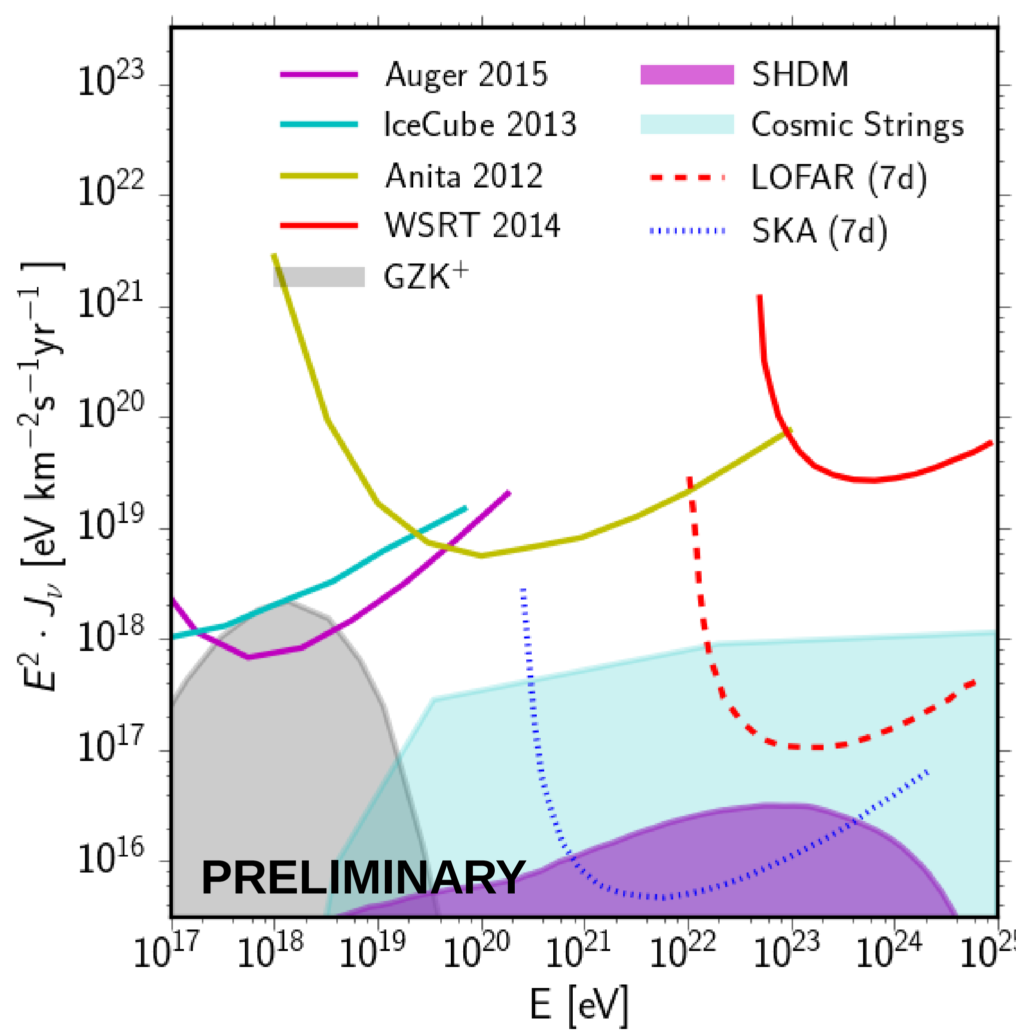
Search for Particles on ZeV* Scale

COSMIC RAYS



COSMIC NEUTRINOS



Less than 1 particle per km^2 and century

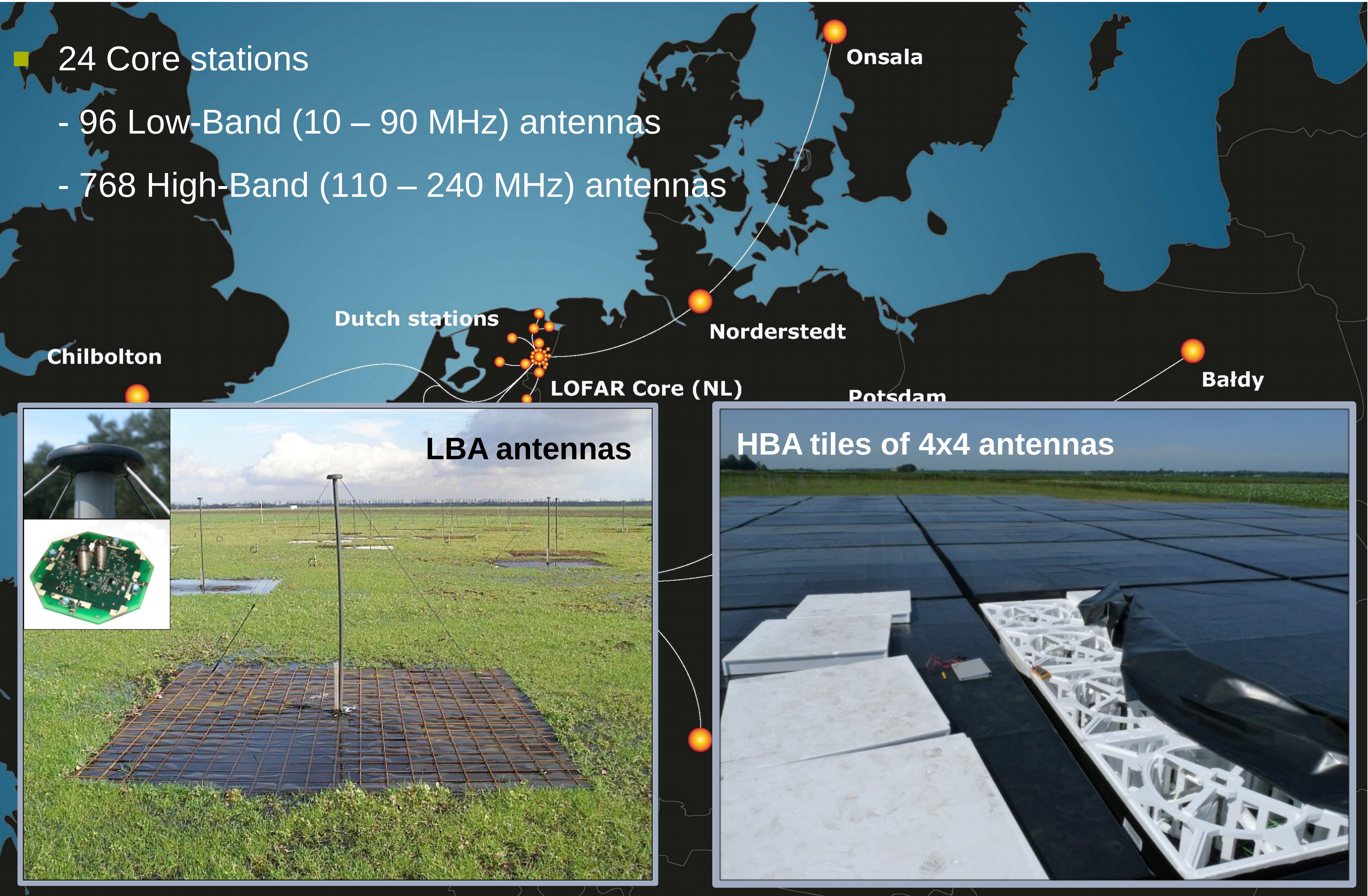
* 1 ZeV = 10^{21} eV

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

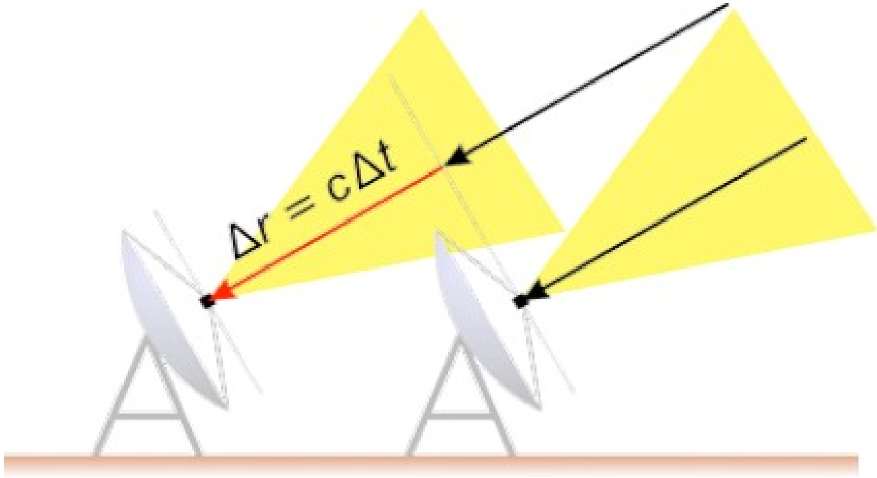


A Fully Digital Radio Telescope

Conventional radio telescope:

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

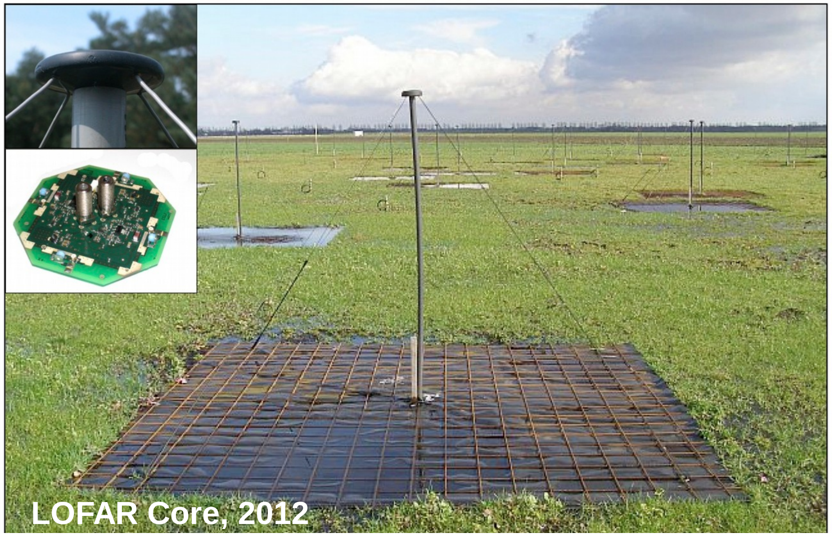
Observe only one direction at a time

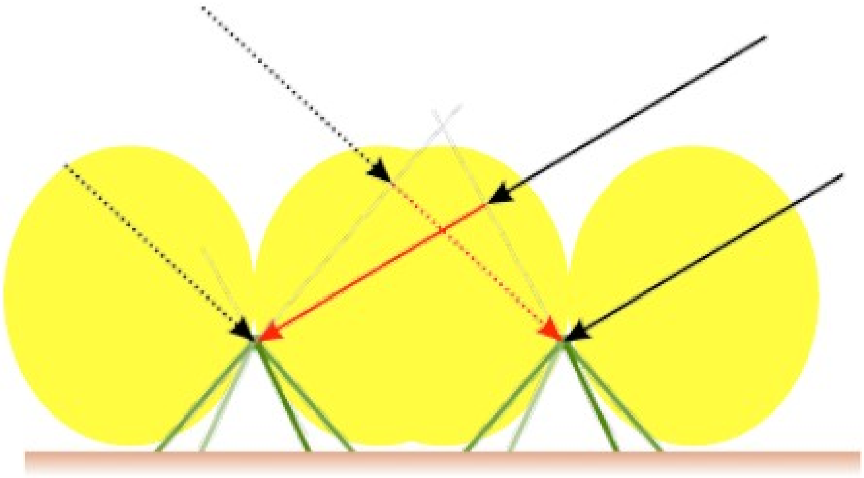


Digital radio telescope:

Many omni-directional antennas digitally combine signals according to direction

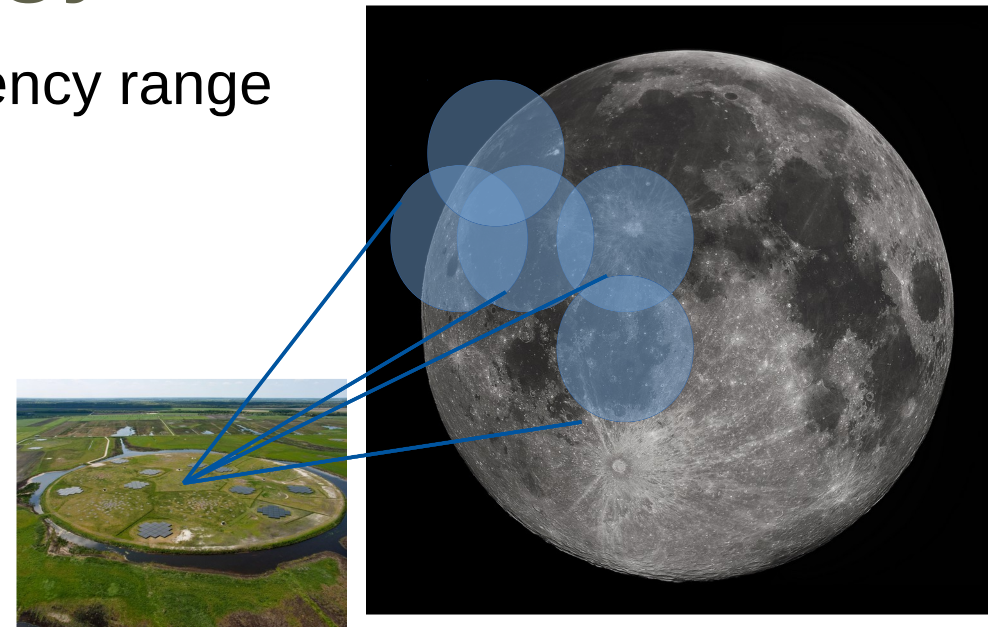
Observe multiple directions simultaneously

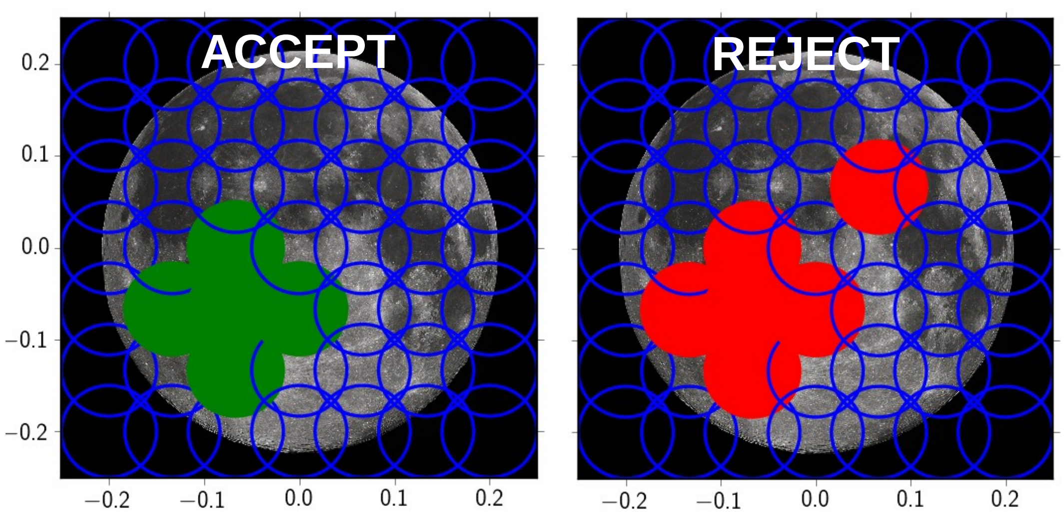




Observation Strategy

- 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



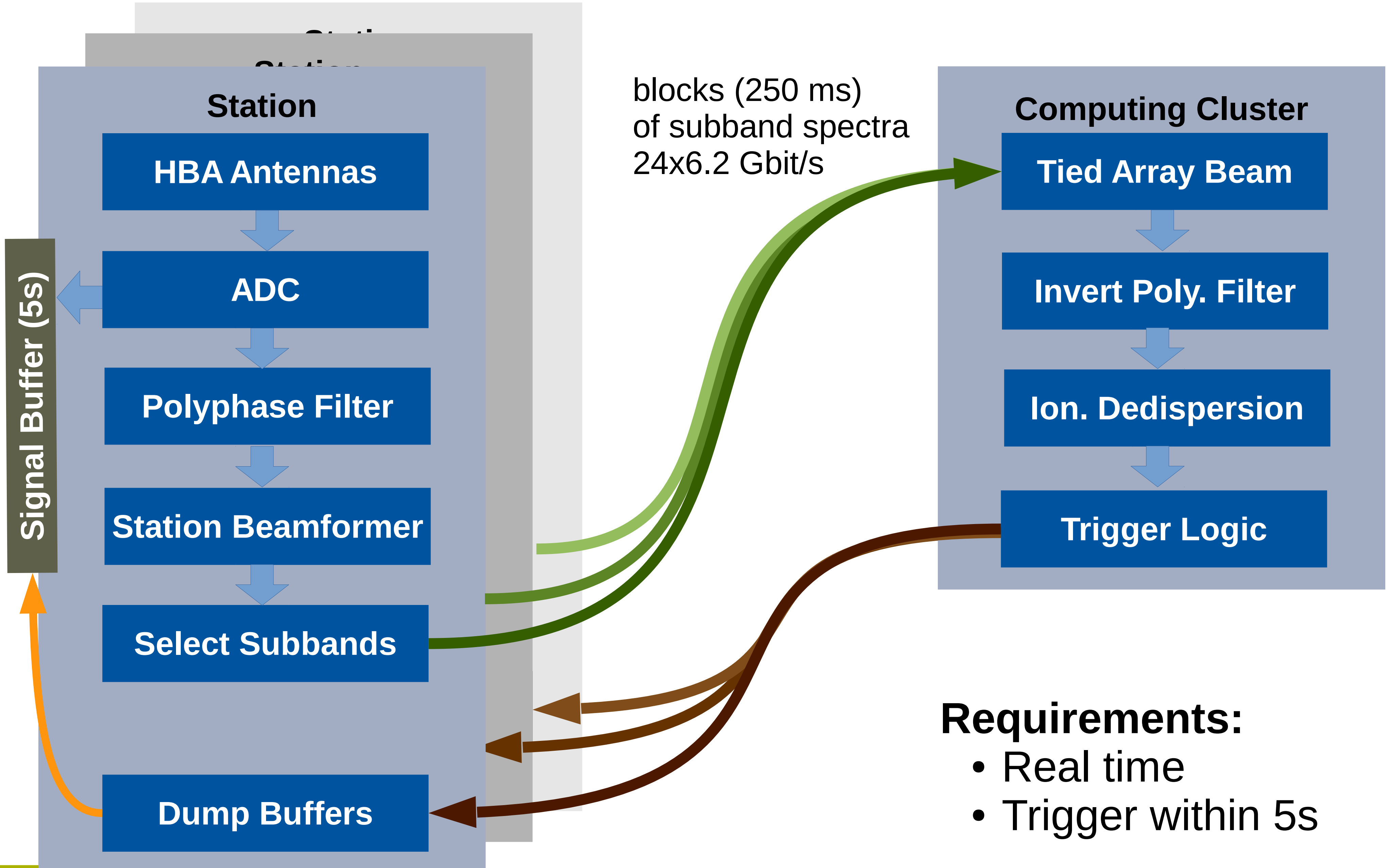


Challenge:

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

Step 1: Beamforming

- Digitally point antenna by time delay stacking of signal
- Efficiently done in frequency domain:

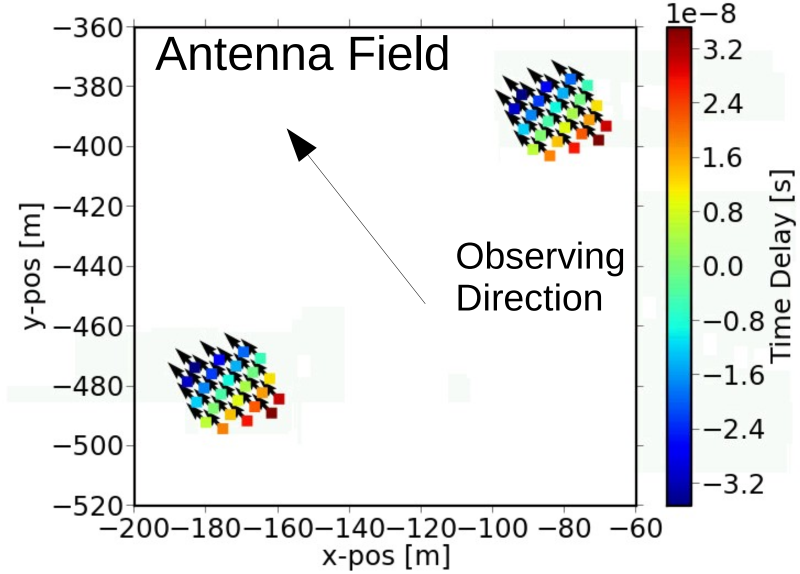
$$x_i^{\mathrm{Beam}}(\omega_i) = \sum_{k}^{\mathrm{Antennas}} x_i(\omega_i) e^{i\omega_i \Delta t_k}$$

Complex multiplication and summation of traces

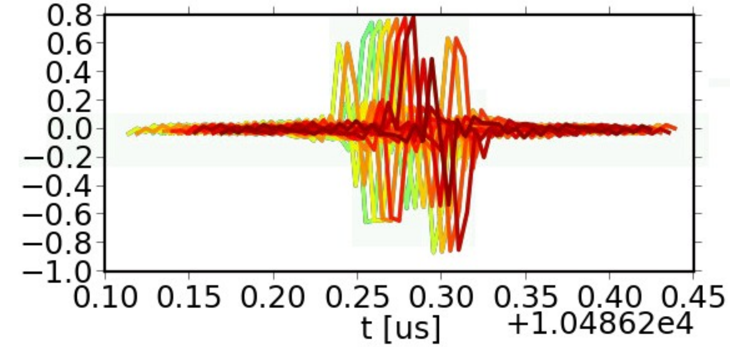
- Signal from 24 stations with 8 FLOP / 8 byte:

~ 40 GFLOP / s / Beam

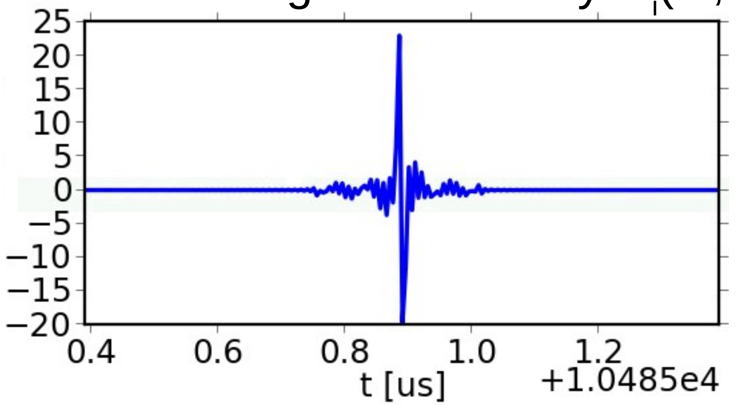
- Few computations per byte; here best done on CPU to reduce transfer costs



Pulse from direction (Θ, Φ) in individual antennas



Summed signal with delays t_i(Θ, Φ)



Step 2: 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

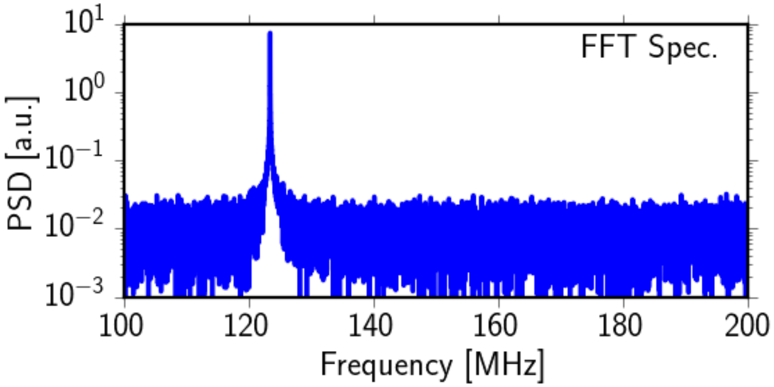
  - Reduces time resolution

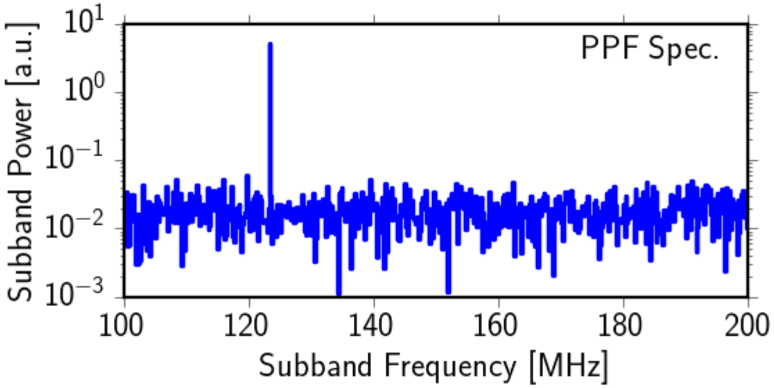
  from 5 ns to ~5 us
- Inversion with small error possible:
  - Inverse FFT $\mathcal{F}^{-1}(\tilde{y}) = y$
  - Solving sparse linear system

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

    every 250 ms with

    x ~ 5 000 000 elements



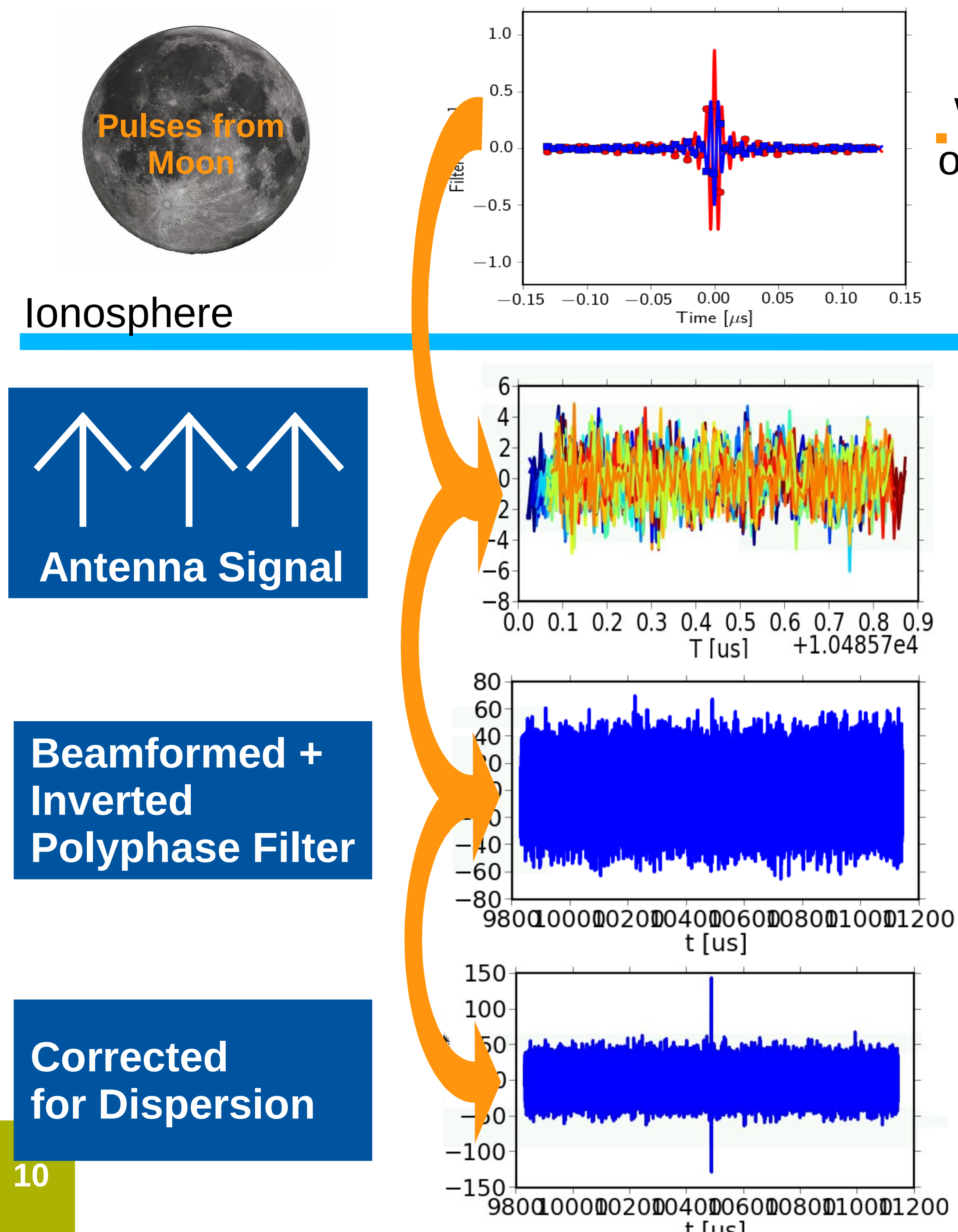


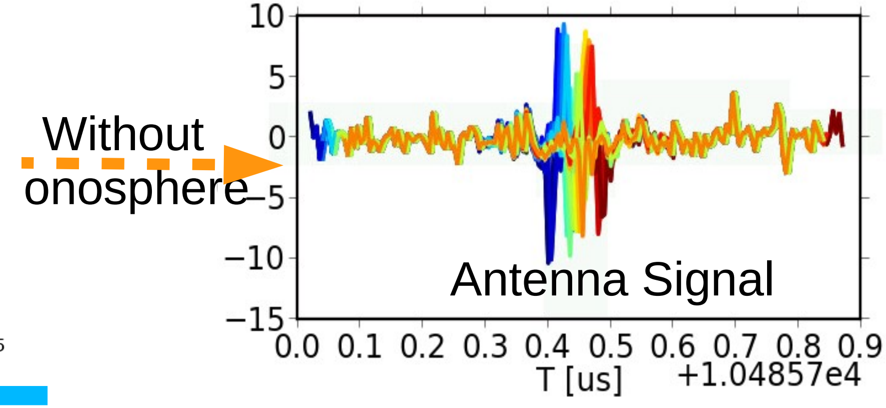
Iterative LSMR Algorithm

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

O(100) GFLOP/s per iteration
Tests ~ 25 iterations,
=> O(1000) GFLOP/s / beam

Step 3: Ionospheric Dedispersion





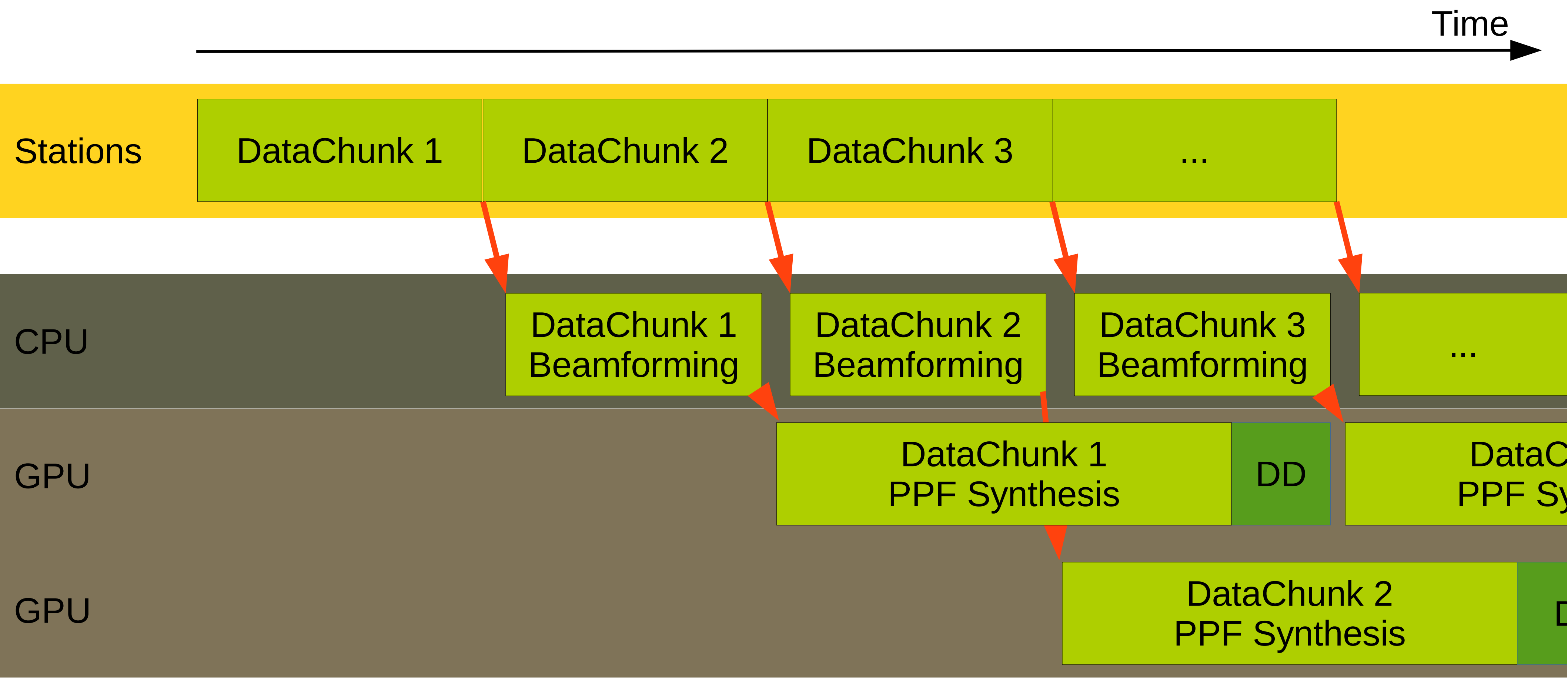
- EM Pulse from Moon pass through Ionosphere
- Frequency dependent dispersion
- Dispersion depends on electron content of ionosphere (STEC)
- Dedispersion
  - Complex Multiplication and summation on Beam in Fourier Space + FFT

    ~ 27 GFLOP/s / beam
- STEC not known exactly →

  Test as many STEC-Values as possible

Performance Prototype Pipeline

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



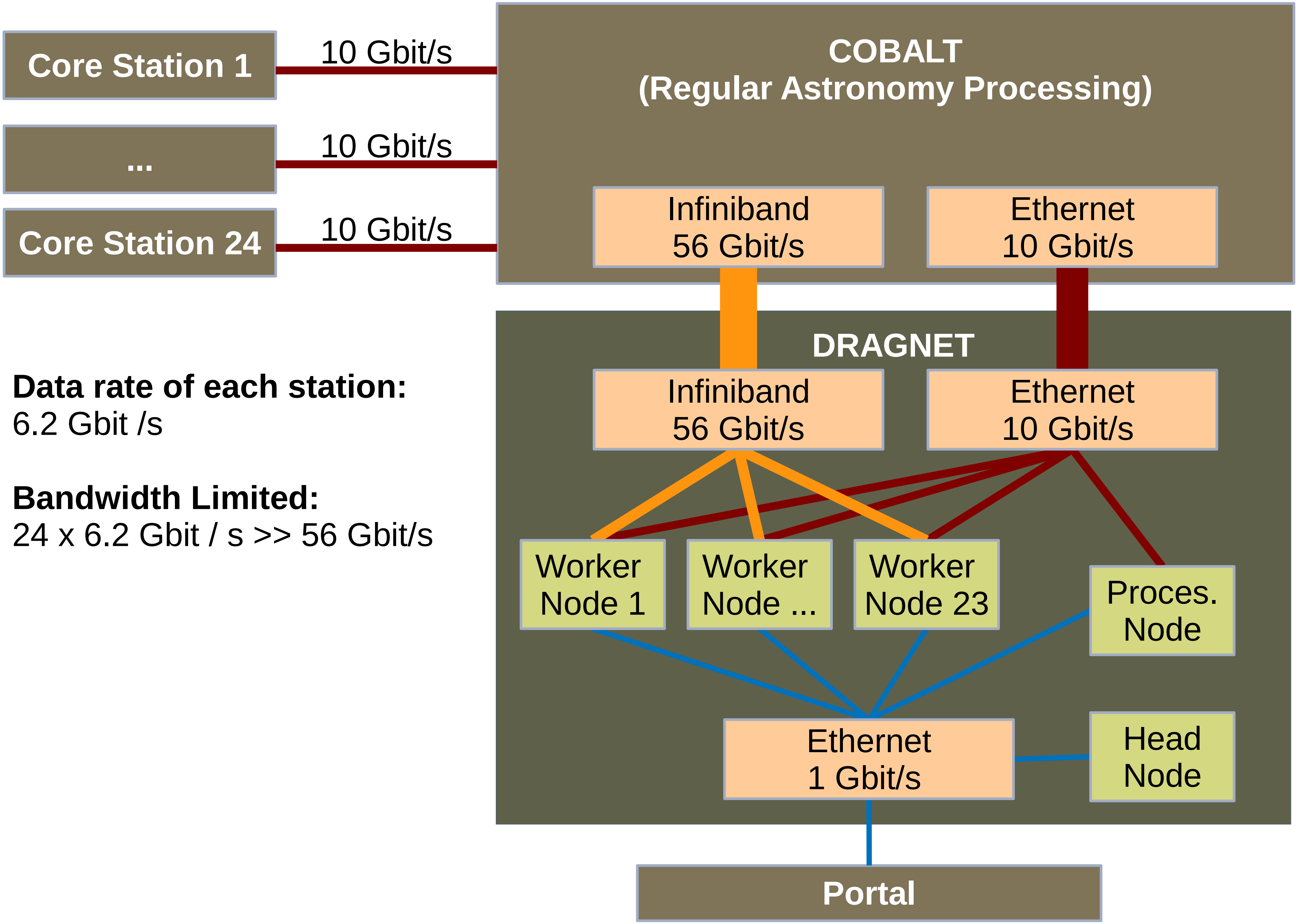
DRAGNET Cluster

- 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**

LOFAR Network



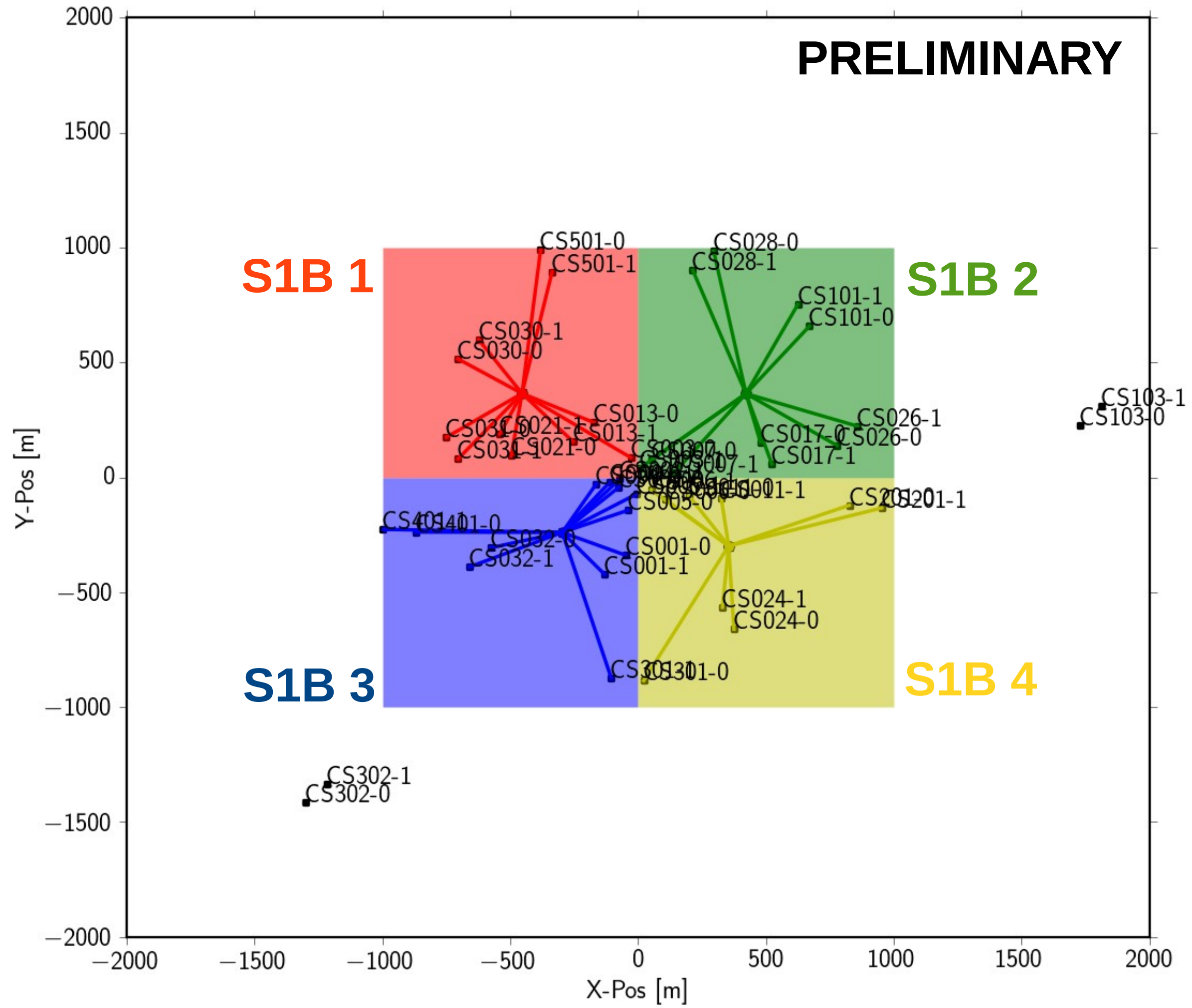
Data rate of each station:
6.2 Gbit /s

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

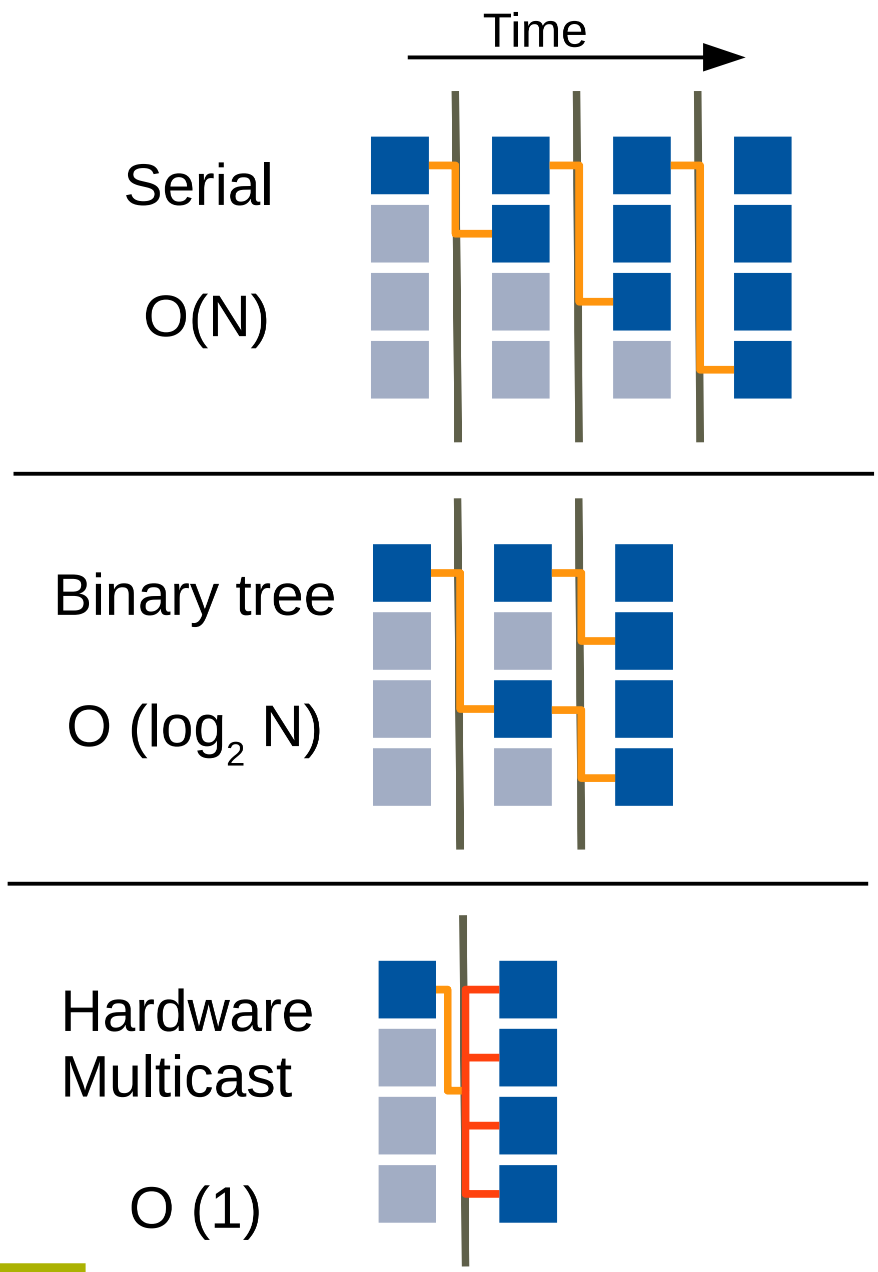
2 Stage Beamforming

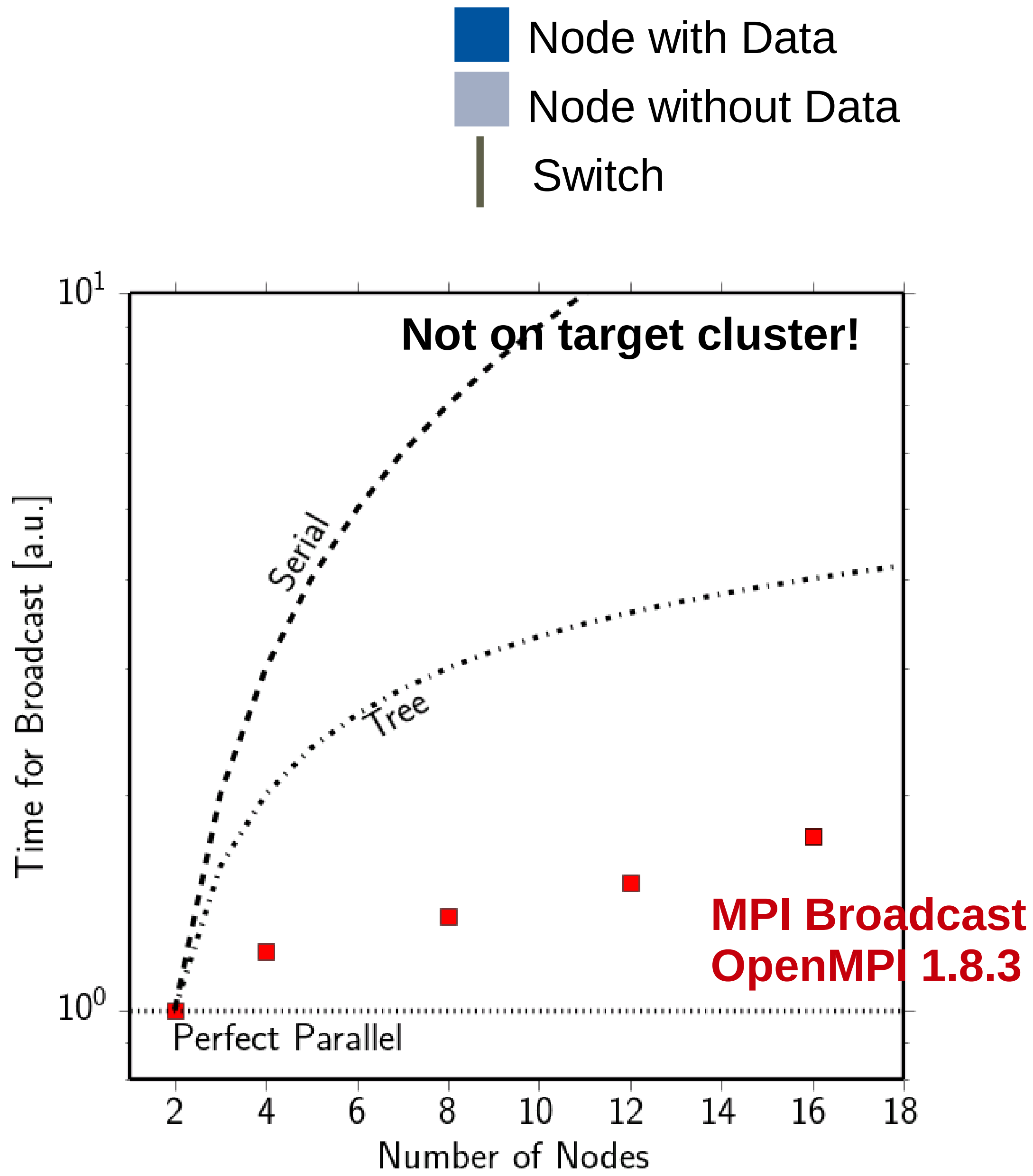
- Combine multiple stations into windows of `virtual antennas'
- Limit on spacing as every Stage-1 beam has to cover full moon
- Loss of 2 stations →
  - ~ 8% reduction in sensitivity
- Inhomogeneous sensitivity
- 4 `Stage-1 beams'
- Real time access known to work for 7 beams,

  but here each beam has to be distributed on all 23 nodes



Data Broadcast





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

Analysis and Simulation Software

Data Container

DataChunk
Holds trace on GPU and CPU
(Lazy update)

DataState:
Time Domain
Freq. Domain
PPF Filtered

Beam Config

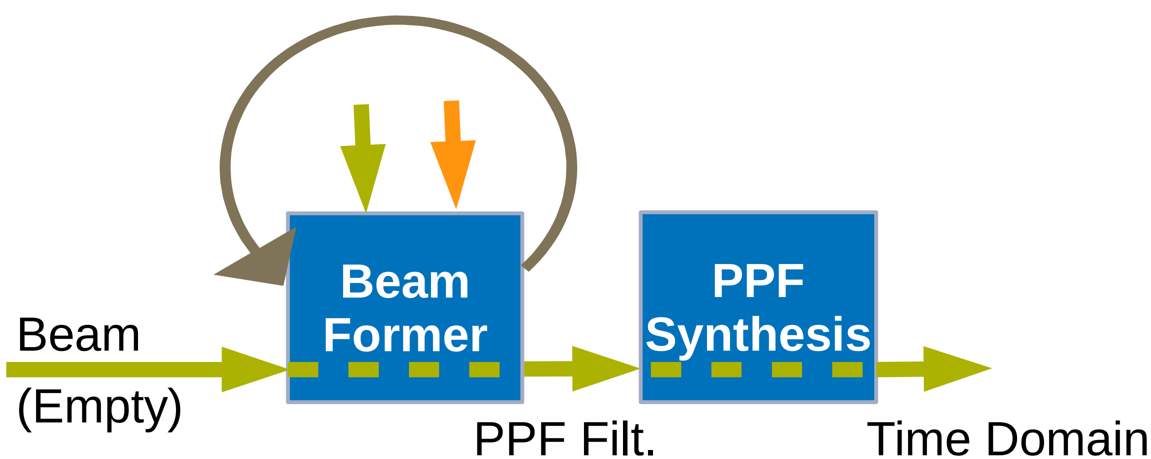
Detector Layout

Modules for Processing Steps
Operate on one DataChunk
(Additional as input)

Beam Former | **PPF Synthesis** | **PPF Analysis** | **Antenna** | **...**

Pipeline from Modules
- Simulation Pipeline
- Online Analysis Pipeline
- Offline Analysis Pipeline

Technology Used:
Modules: C++ / CUDA
Pipeline: Python
+ Numpy Interface
OpenMPI



Conclusions

- Search Cosmic Particles on ZeV scale via Lunar-Askaryan-Effect with LOFAR (and SKA in future) to determine cosmic ray origin and test new physics scenarios
- Radio Telescopes are designed to integrate signal, not to analyze ns time traces
- Recovery of ns time resolution possible in realtime with DRAGNET GPU/CPU cluster
- Working prototype for Online + Simulation software

  (CUDA, MPI, Python Interface)
- Now: Simulation studies to determine and optimize sensitivity
- First run next year

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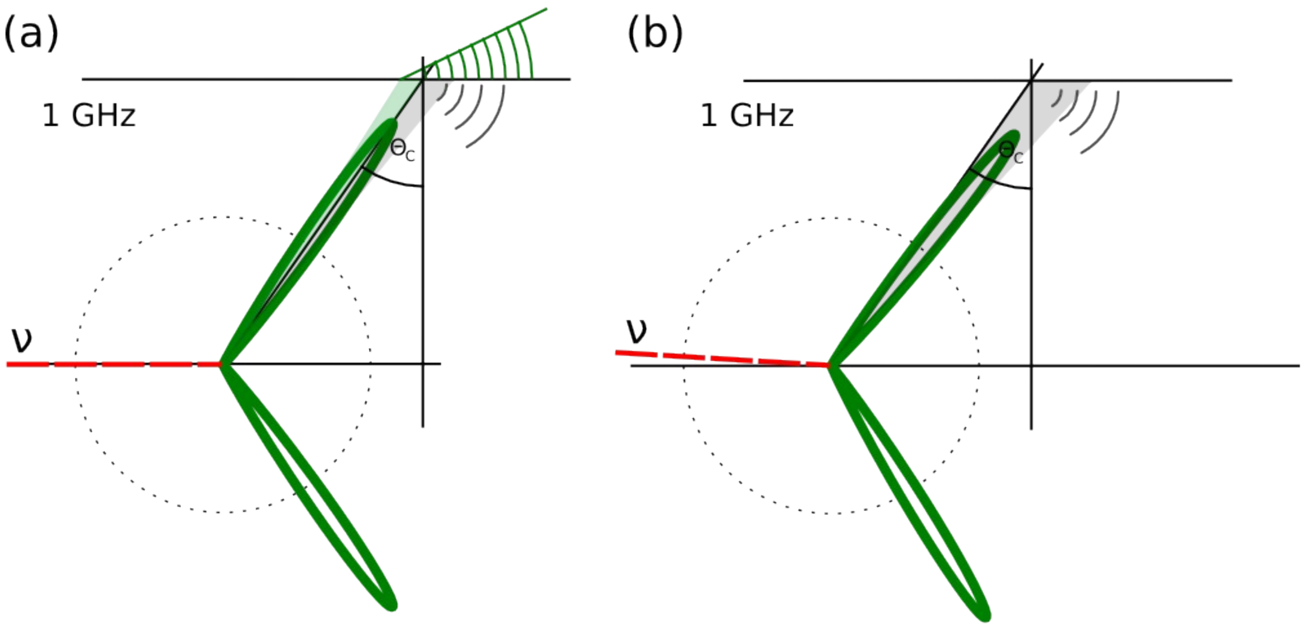
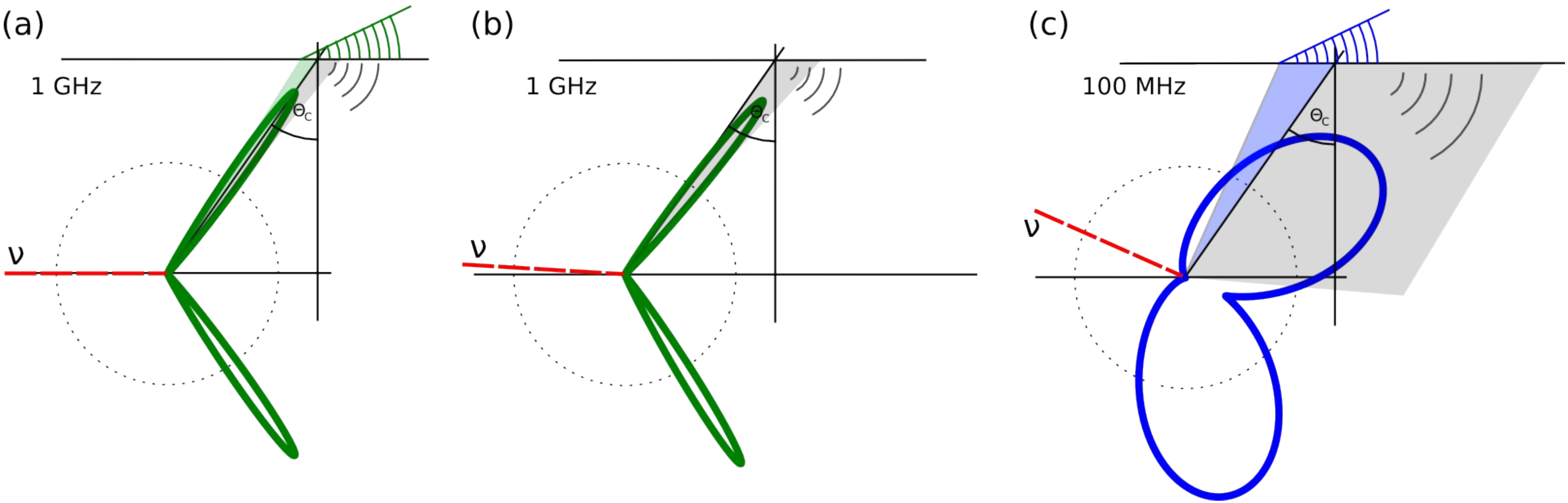
Backup

Pulse Reflected at High Frequencies



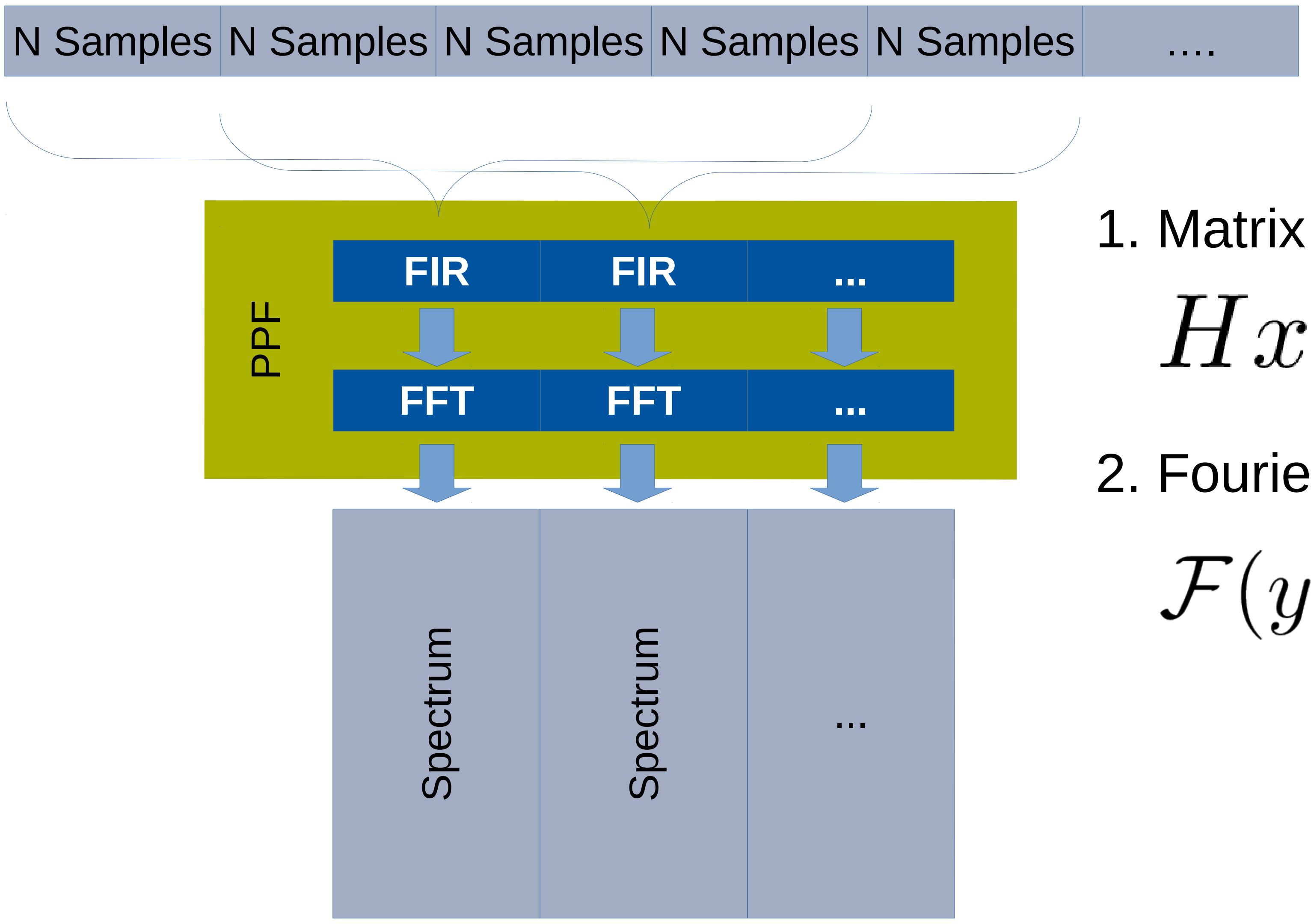
- Radiation emitted in Cherenkov cone
- Cherenkov angle == Angle of total reflection
- Upgoing shower required / rely on surface roughness

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)

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

Signal Filtering @ LOFAR

- Decompose signal into subbands
- Example signal 16 184 samples

  White noise

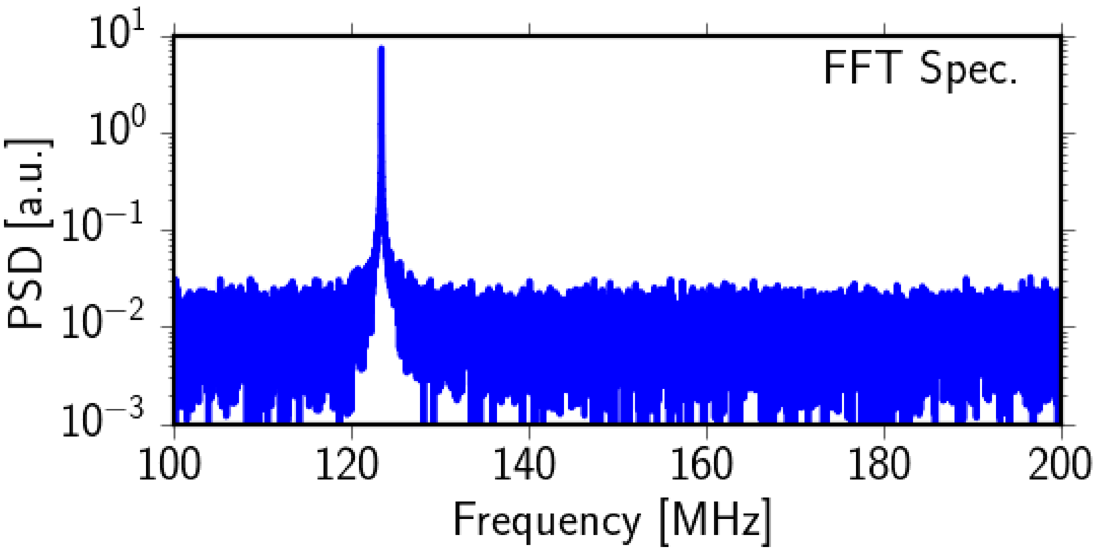
  Transmitter: 123.42 MHz

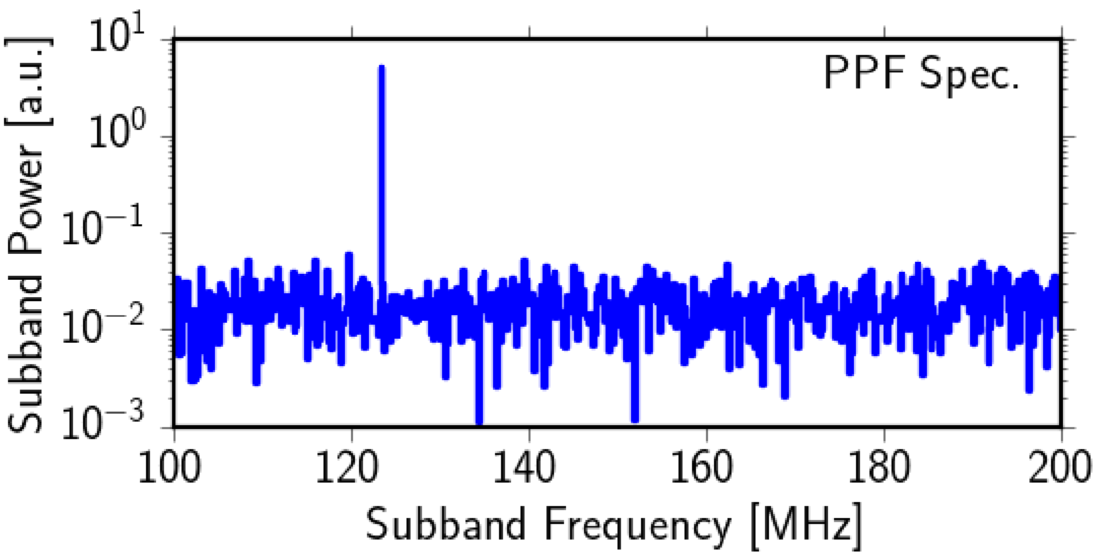
  Sampling freq. 200MHz
- FFT signal is smeared out over neighboring frequencies
- Efficient filtering with PPF

  + avoids smearing

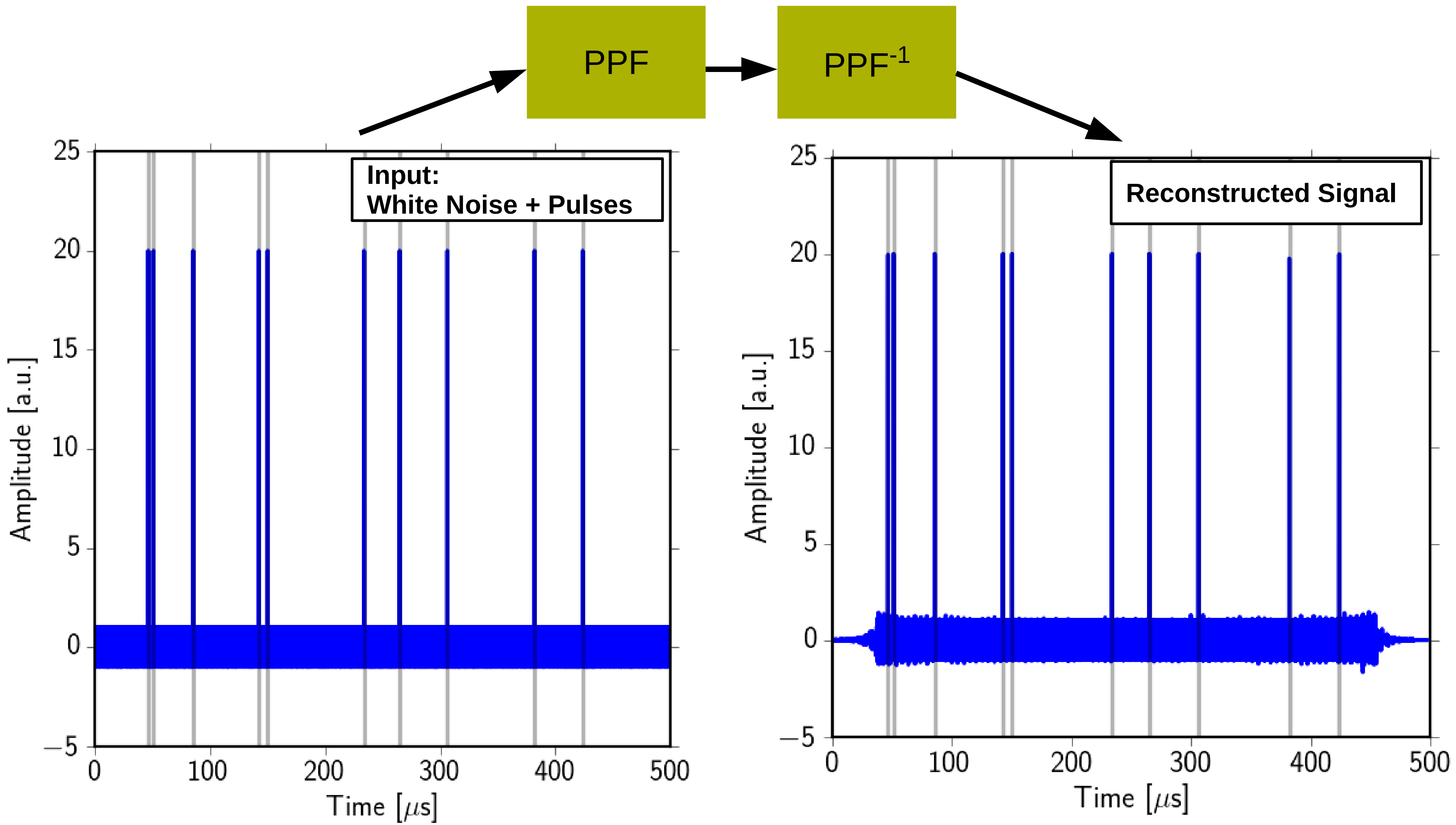
  - Reduces time resolution

  from 5 ns to ~5 us

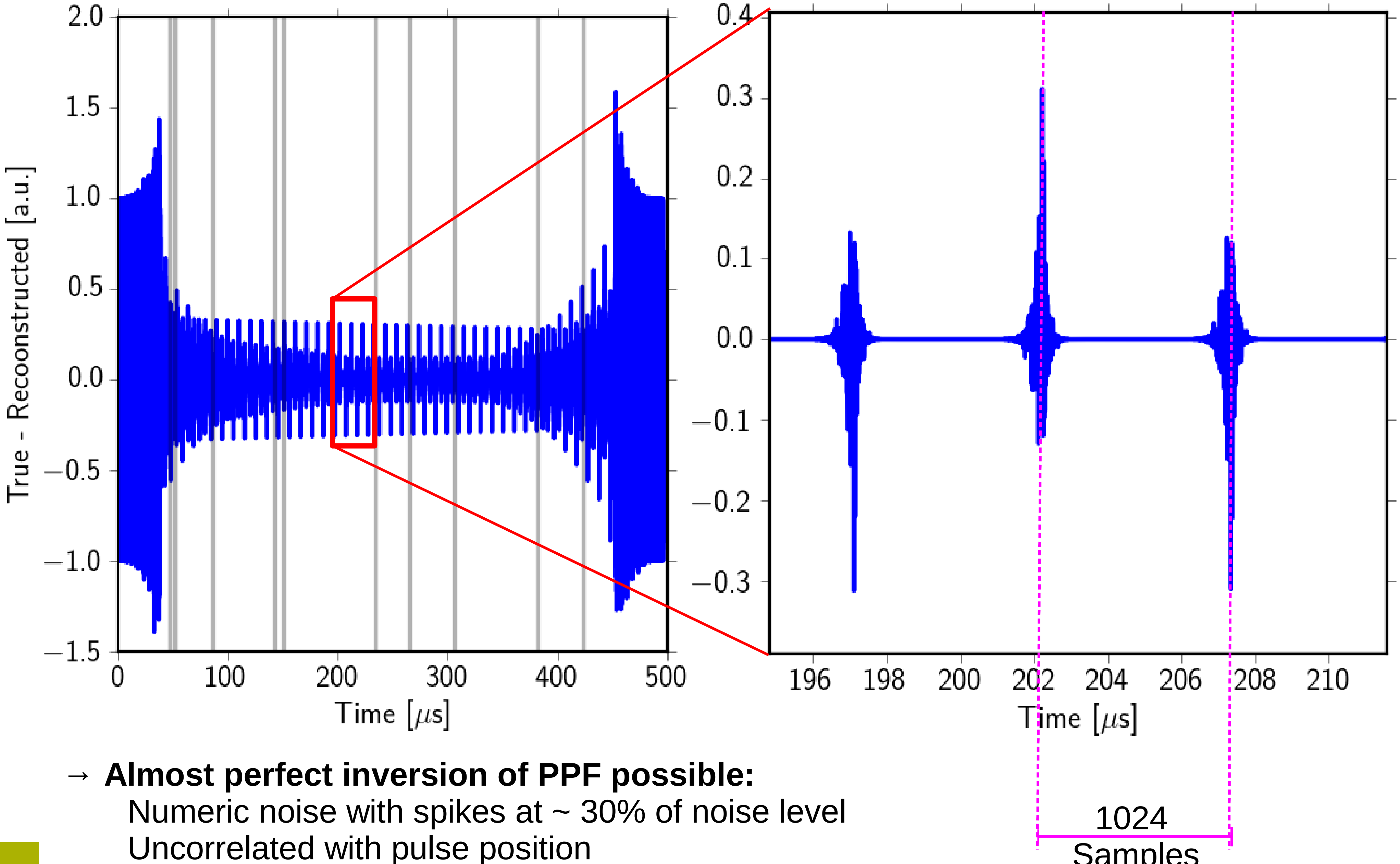




PPF^{-1} Example



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

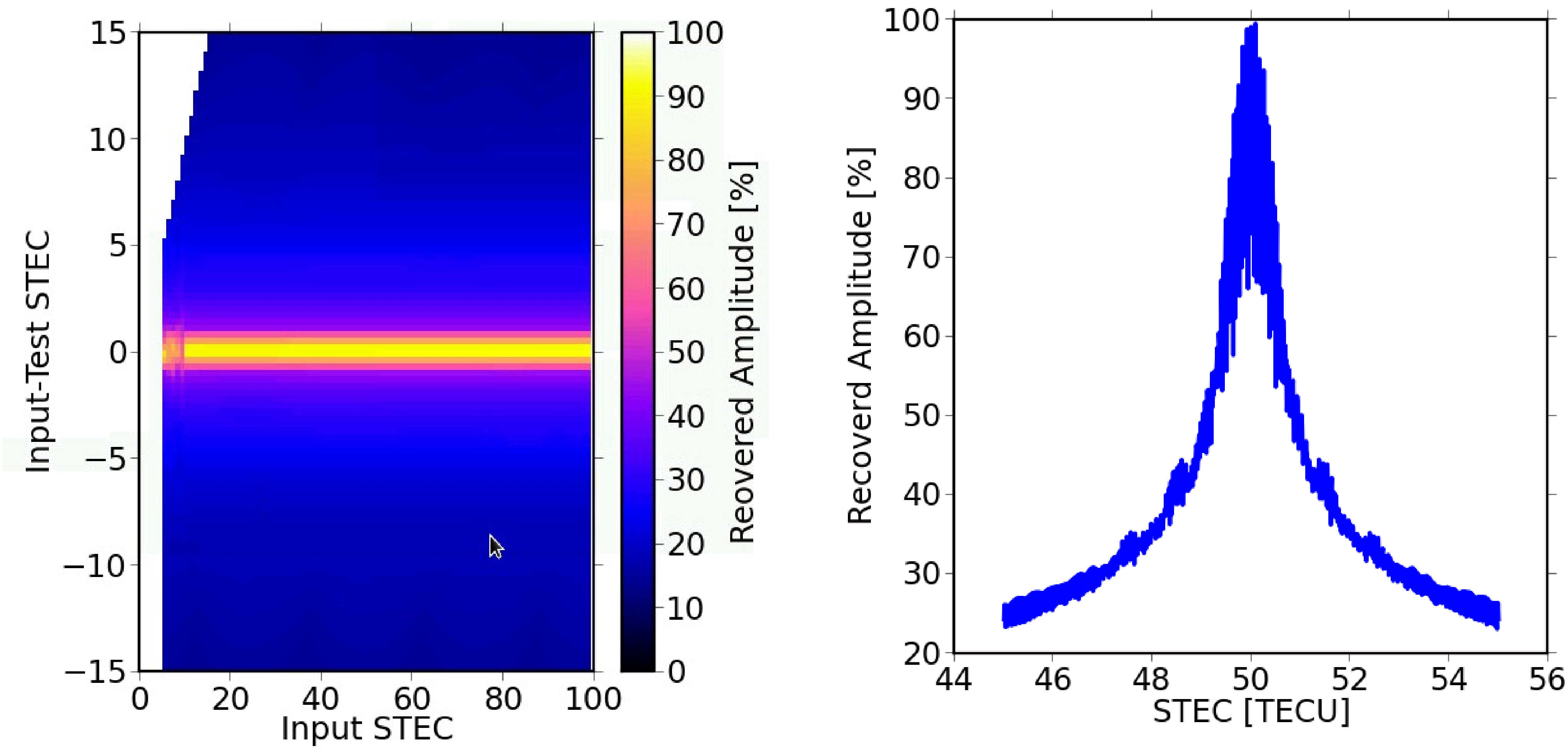
$$\Delta t(\nu) = 1.34 \frac{STEC}{\mathrm{TECU}} \left(\frac{\nu}{\mathrm{Hz}}\right)^{-2} \mathrm{s}$$

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

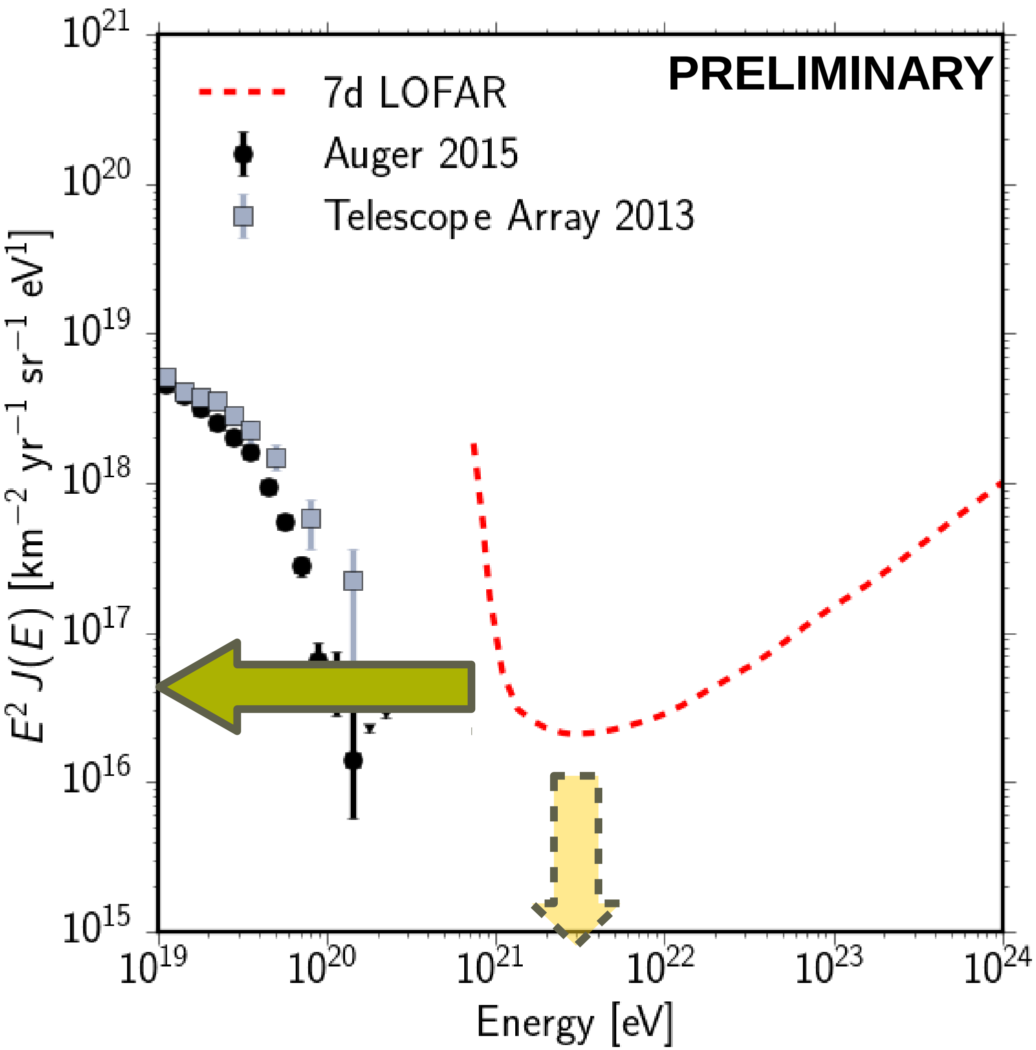


Recovery of 99% of amplitude possible

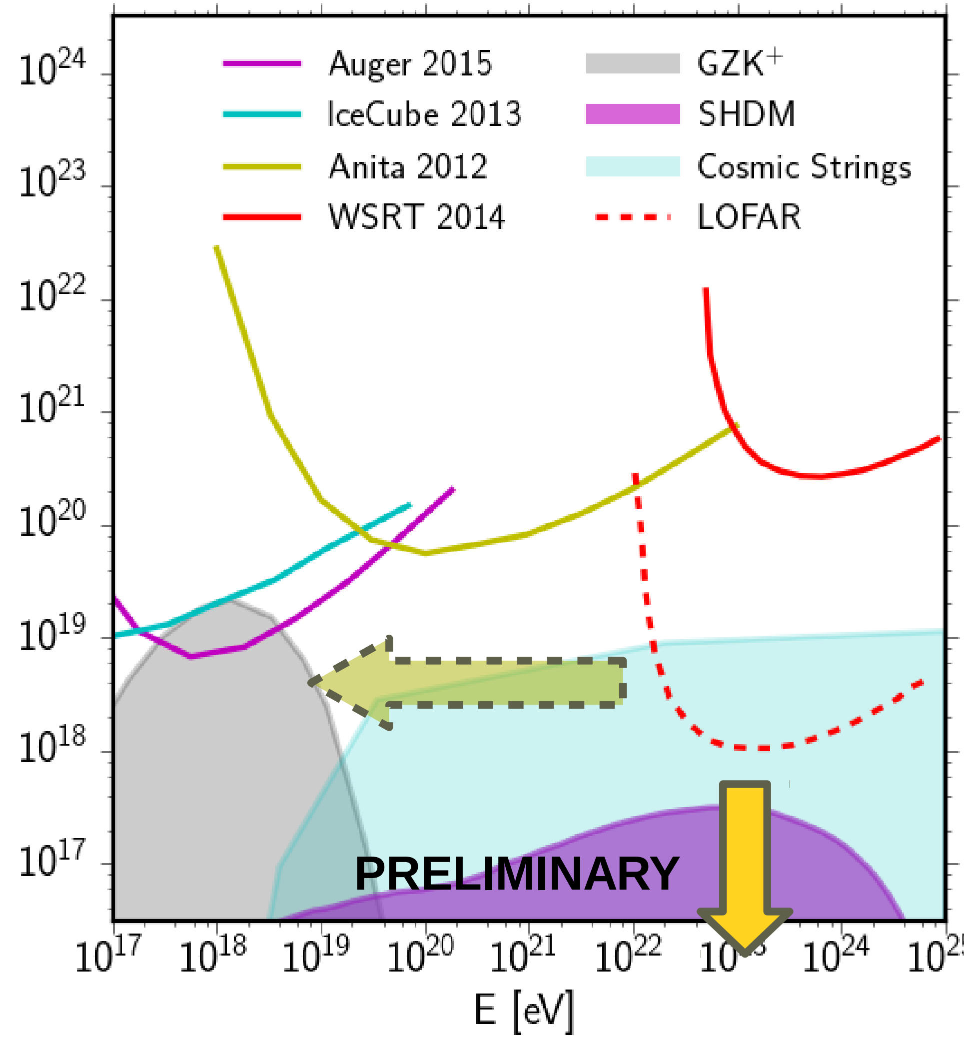
PPF results in 30% fluctuations with small TEC values → need to scan multiple TEC values

Sensitivity Optimization

COSMIC RAYS



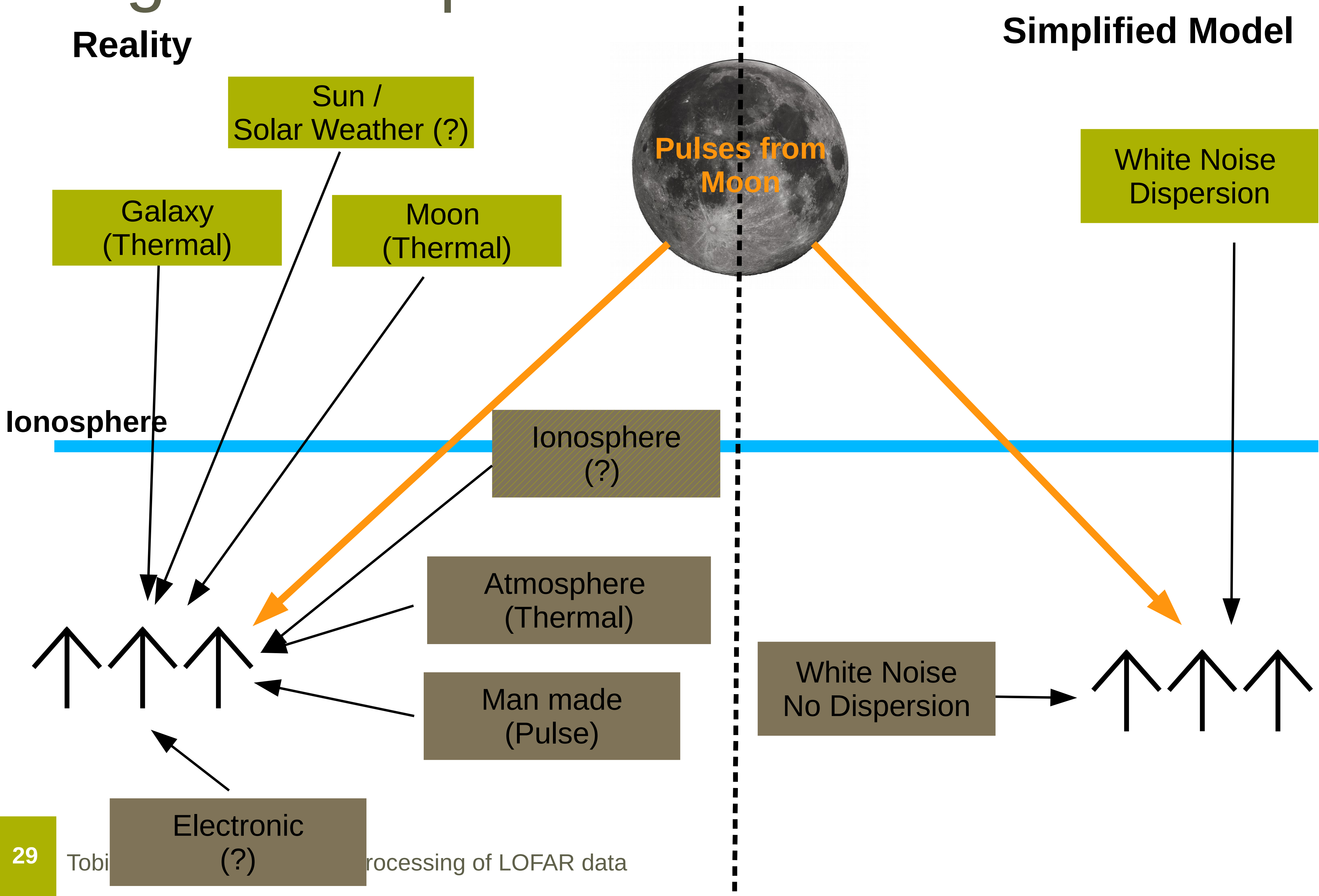
NEUTRINOS



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

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

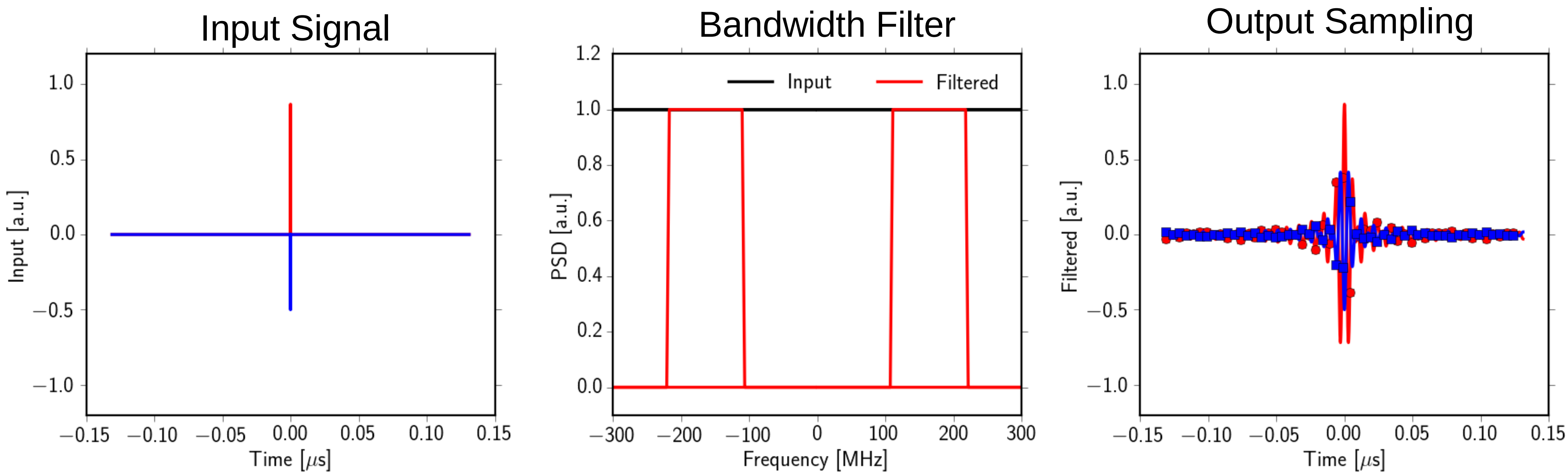
Signal Components



Pulse Simulation

- Bandwidth limited delta pulse

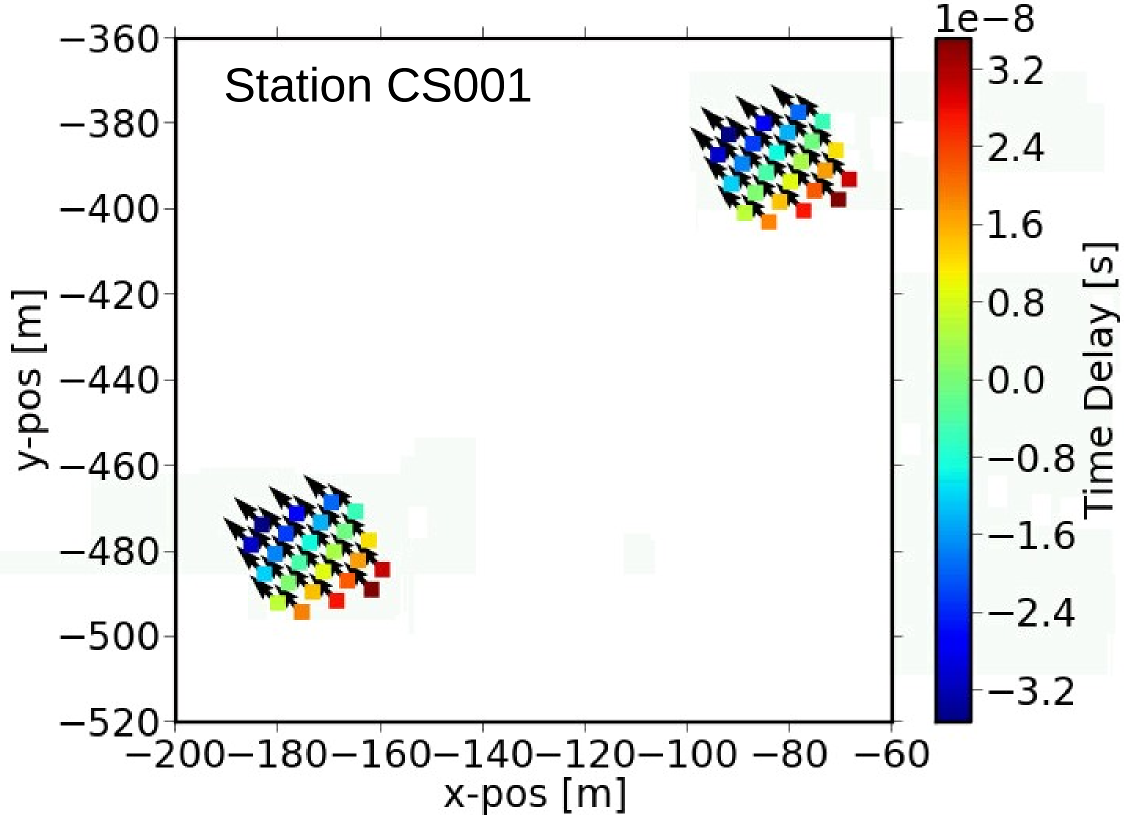
  (30 deg rotated in phase)
- Start randomly* shifted by 0.5 – 5000 pico seconds (1/10000 of sampling intervall)

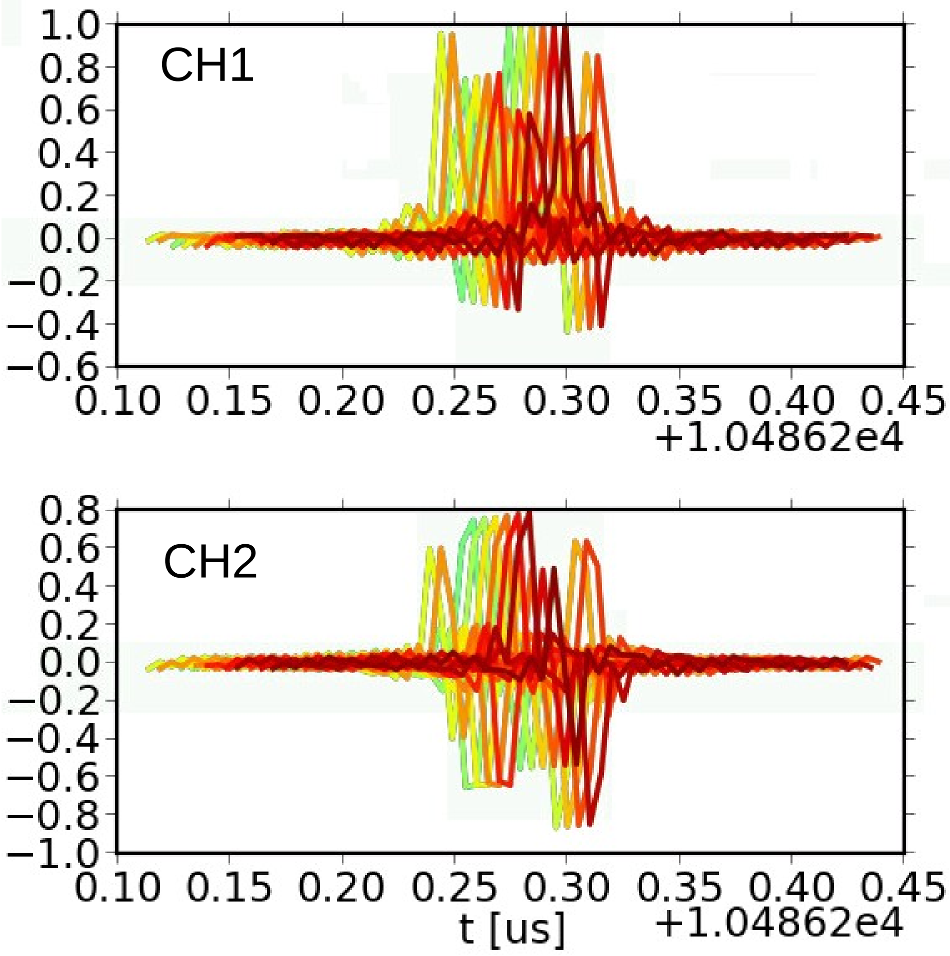


* respectively corrected for individual antenna positions

Beamforming Single HBA station

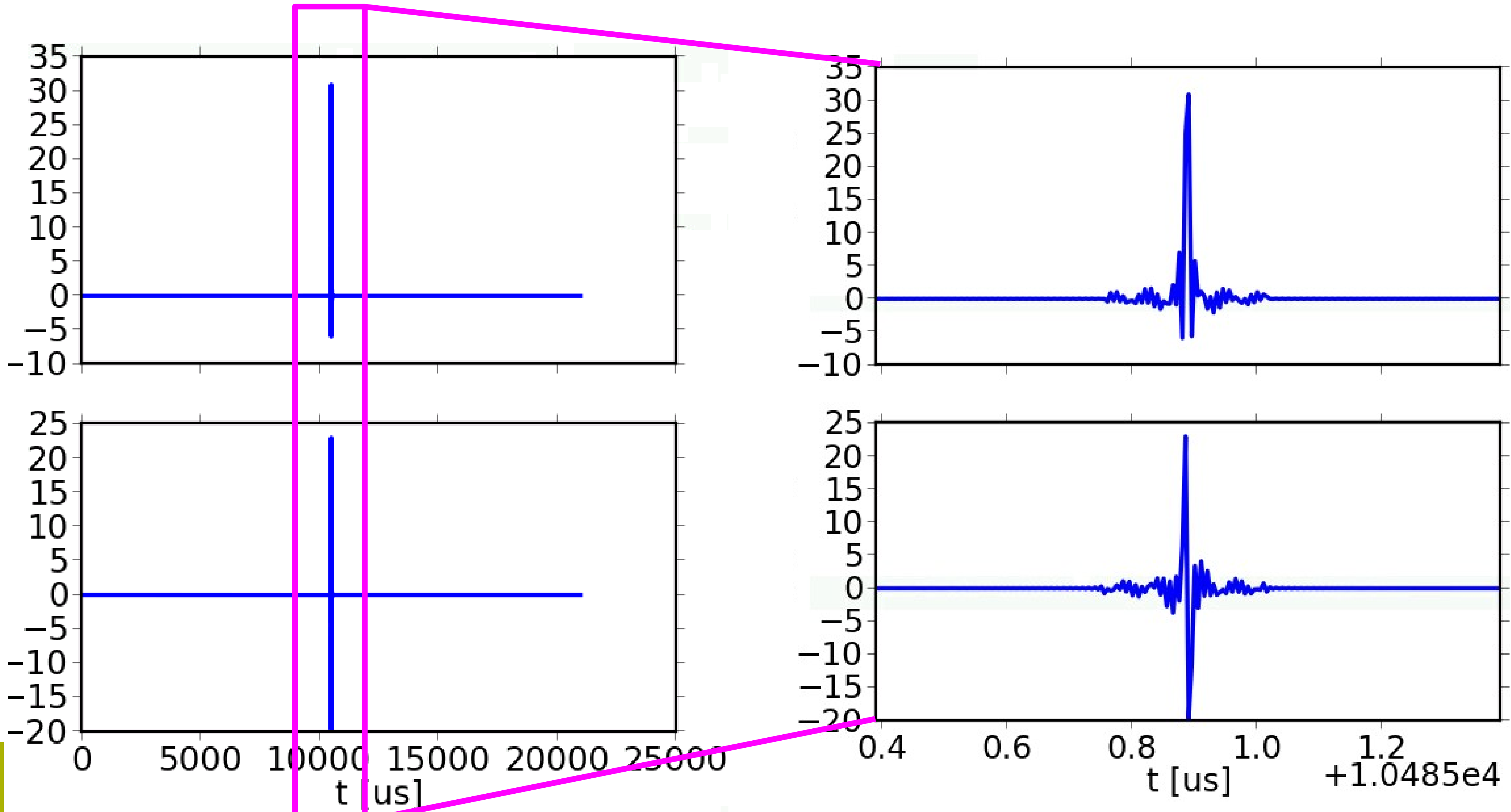
Pulse from direction (-1,1,1)



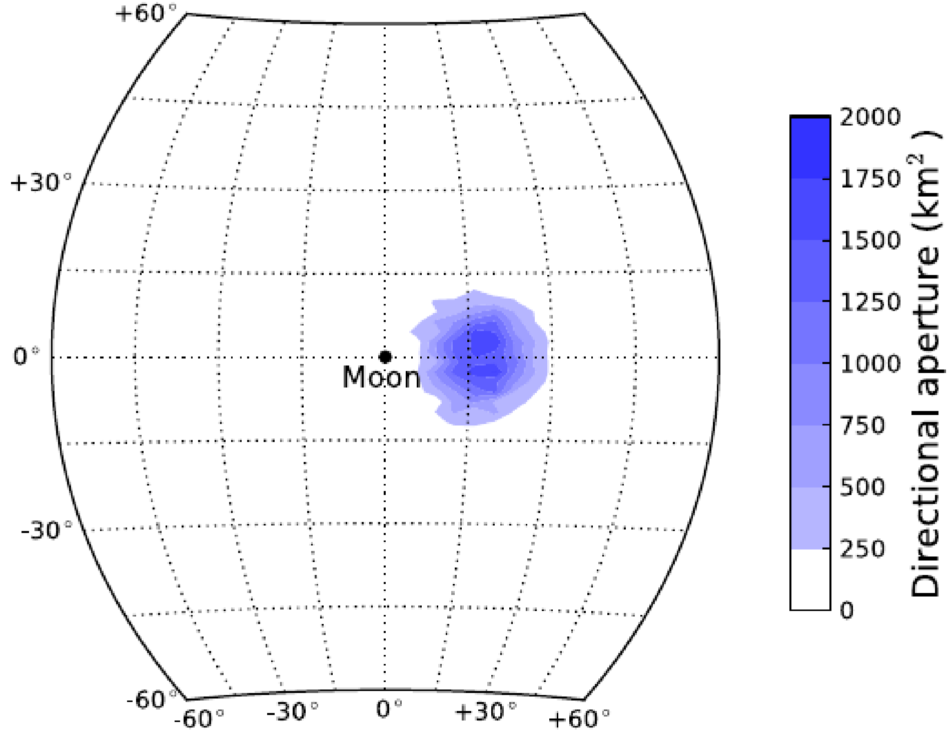


Beamformed Pulse

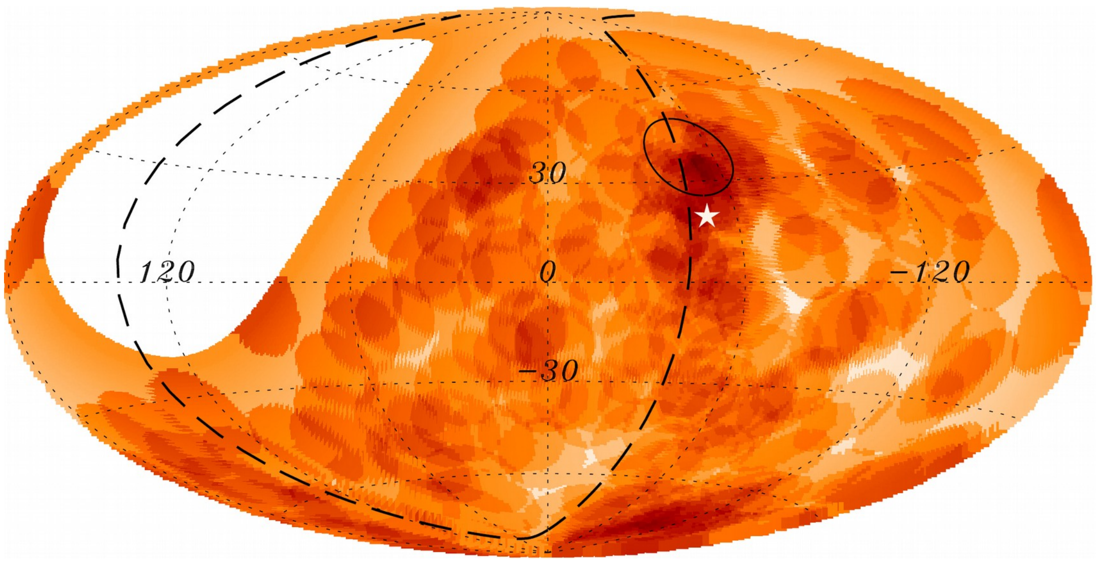
- PPFAnalysis → Beamformer → PPFSynthesis



Angular Resolution of Lunar Mode



Cosmic Ray Excess at 15^{O} scales



Aab et al, ApJ 804 (2015), 15

- Limit observations to rim
- Possible Incident angles yield ~5^{O} resolution
- Explicit reconstruction should do better