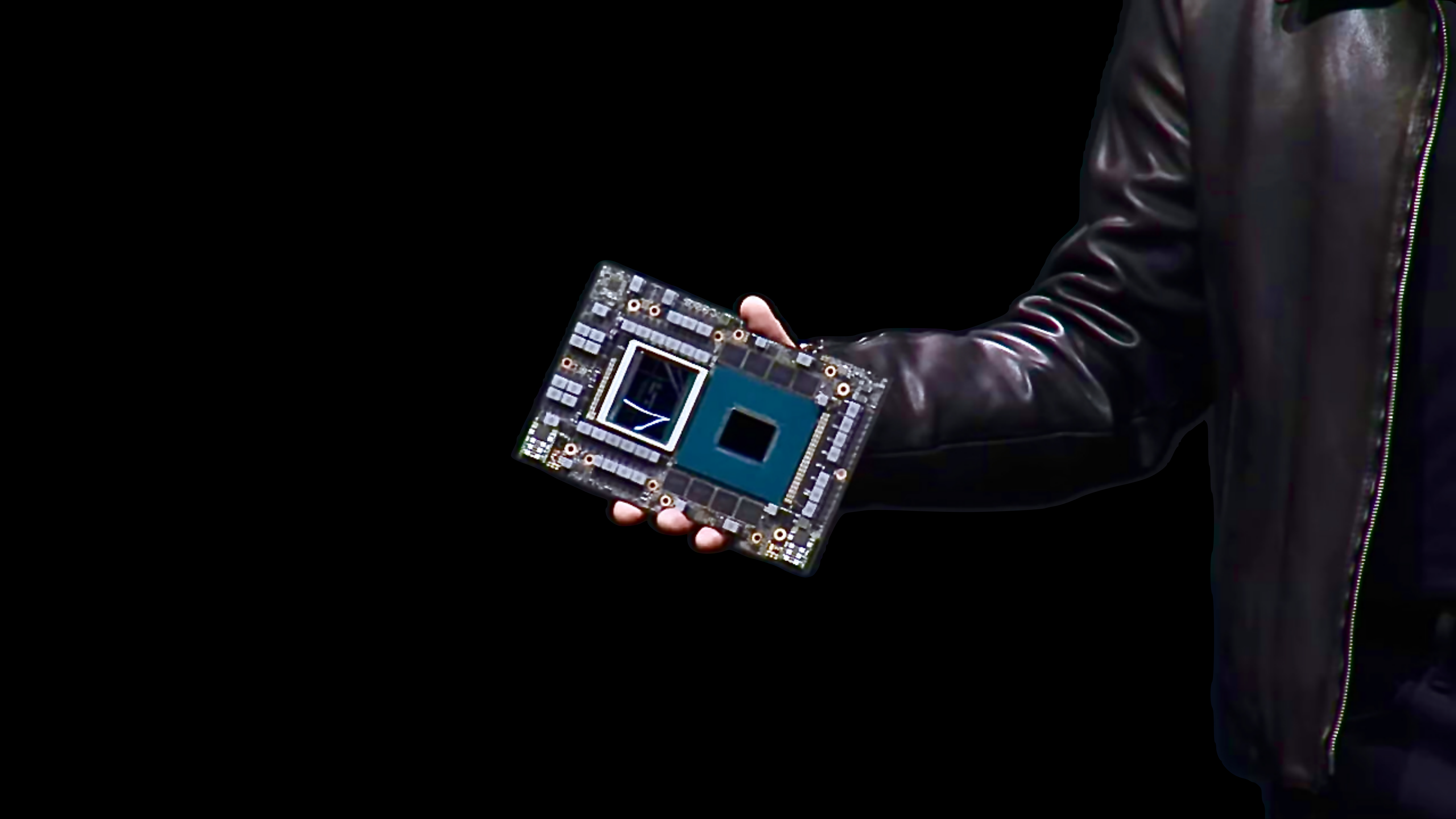
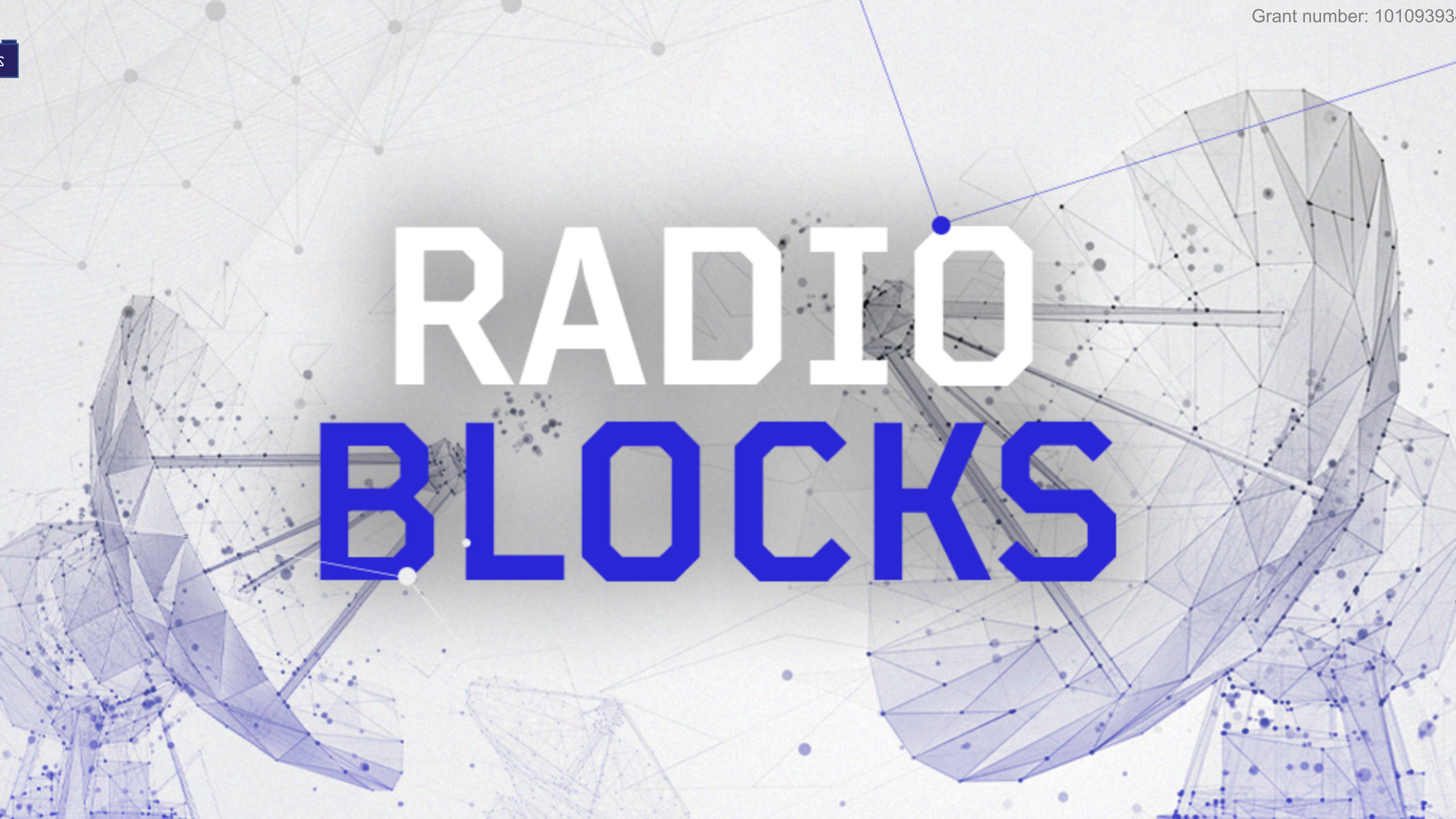



Grant number: 10109393
RADIO
BLOCKS

# RADIOBLOCKS goals

- Building blocks suitable for multiple facilities
- Joint effort to solve common problems
- Enabling new scientific discoveries in mid- and long-term
  - **Sensitivity**
  - **Bandwidth**
  - **Field-of-view**
- Keeping EU at the front in radio technology developments

Address the ***whole*** signal chain from analog to post-processing

# The RADIOBLOCKS project contribution to the VLBI of the future

Marjolein Verkouter (JIVE) for:

de Vicente P., Yebes Observatory (IGN), **Kramer C.**, Institute de Radioastronomie Millimetrique,

**Wieching G.**, Max Planck Institut fuer Radioastronomie**, Romein J.**, ASTRON, **Bemmel I. v**, ASTRON,

**Beswick R.**, University of Manchester, **Verkouter M.**, JIVE, **Attema-van Waas R.**, ASTRON, **Słowikowska A.**, JIVE, **Cimo G.**, JIVE

# RADIOBLOCKS partners

JIVE
ASTRON
ESO
CSIC
Fraunhofer IAF
LOFAR
iram

university of groningen
TU Delft
Universiteit Leiden
VENTSPILS AUGSTSKOLA
université de BORDEAUX

SDU
INAF ISTITUTO NAZIONALE DI ASTROFISICA
l'Observatoire de Paris
Radboud Universiteit
Hes·so
EPFL
KASI Korea Astronomy and Space Science Institute

MANCHESTER 1824 The University of Manchester
UNIVERSITY OF OXFORD
UK Research and Innovation
SKAO
SIOUX TECHNOLOGIES
Lytid
TTI

First time that **companies** participate in these type of projects. Required by the EU

# RADIOBLOCKS partners

First time that **companies** participate in these type of projects. Required by the EU

# Project in a nutshell

EU INFRA-TECH (*Horizon Europe*)
**March 2023 to March 2027**

**24 Beneficiaries of the EU grant: 9M€**
**8 Associate non-EU partners: 3M€**

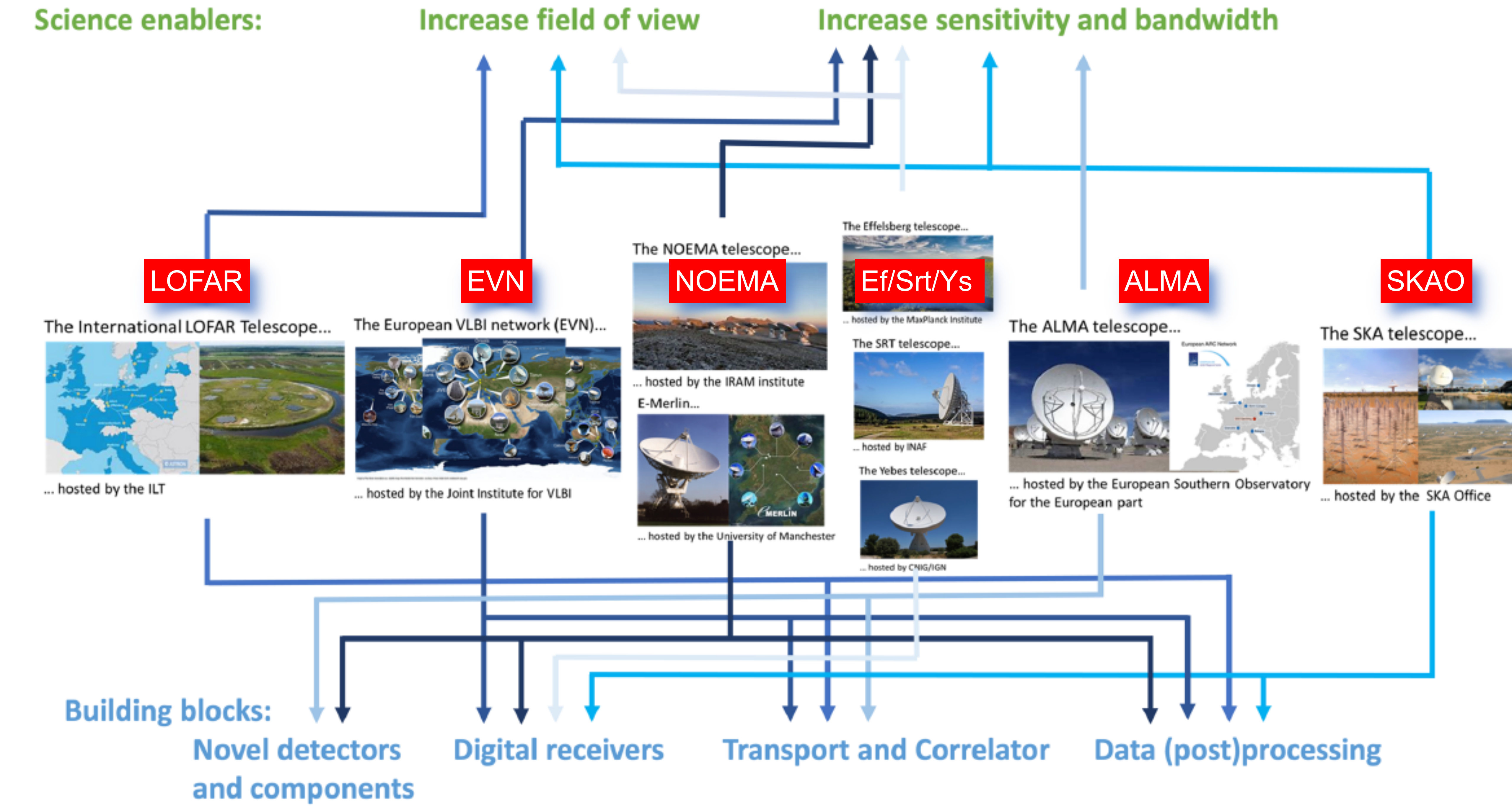
32 partners from 12 countries
(incl. ESO and SKAO)

1187 person months

Grant number: 101093934

# Project in a nutshell

1. Project management
2. Novel detectors and components
3. Digital receivers
4. Data transport and correlation
5. Data processing

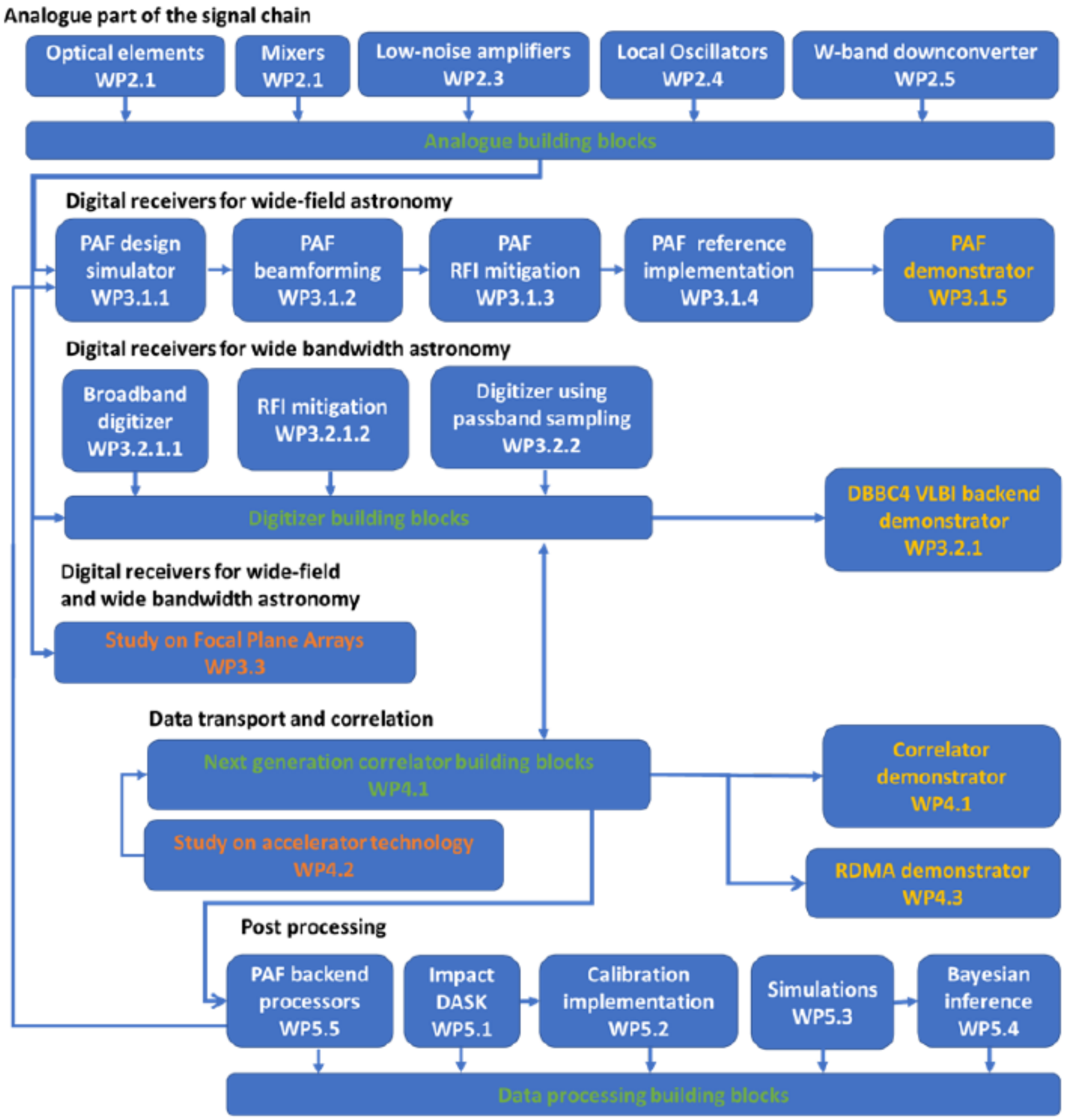


Science enablers:
Increase field of view
Increase sensitivity and bandwidth
LOFAR
The International LOFAR Telescope...
... hosted by the ILT
EVN
The European VLBI network (EVN)...
... hosted by the Joint Institute for VLBI
The NOEMA telescope...
NOEMA
... hosted by the IRAM institute
E-Merlin...
... hosted by the University of Manchester
The Effelsberg telescope...
Ef/Srt/Ys
... hosted by the MaxPlanck Institute
The SRT telescope...
... hosted by INAF
The Yebes telescope...
... hosted by CNIG/IGN
ALMA
The ALMA telescope...
... hosted by the European Southern Observatory for the European part
SKAO
The SKA telescope...
... hosted by the SKA Office
Building blocks:
Novel detectors and components
Digital receivers
Transport and Correlator
Data (post)processing

# RADIOBLOCKS for the VLBI of the future

Not *specifically* designed for VLBI: but for
**single dish, connected interferometry** *and* **VLBI**.

| | |
|---|---|
| • **RFI**: resilience & mitigation | WP2, 3 |
| • Larger **bandwidth** | WP2, 4, 5 |
| • **Sensitivity** | WP2, 4, 5 |
| • Wide **field-of-view** | WP4 |
| • **FP Arrays** (field of view & high prec. astrometry) | WP2, 3, 5 |
| • Early **digitization** (close to the frontend) | WP3 |



Analogue part of the signal chain
Optical elements WP2.1
Mixers WP2.1
Low-noise amplifiers WP2.3
Local Oscillators WP2.4
W-band downconverter WP2.5
Analogue building blocks
Digital receivers for wide-field astronomy
PAF design simulator WP3.1.1
PAF beamforming WP3.1.2
PAF RFI mitigation WP3.1.3
PAF reference implementation WP3.1.4
PAF demonstrator WP3.1.5
Digital receivers for wide bandwidth astronomy
Broadband digitizer WP3.2.1.1
RFI mitigation WP3.2.1.2
Digitizer using passband sampling WP3.2.2
Digitizer building blocks
DBBC4 VLBI backend demonstrator WP3.2.1
Digital receivers for wide-field and wide bandwidth astronomy
Study on Focal Plane Arrays WP3.3
Data transport and correlation
Next generation correlator building blocks WP4.1
Correlator demonstrator WP4.1
Study on accelerator technology WP4.2
RDMA demonstrator WP4.3
Post processing
PAF backend processors WP5.5
Impact DASK WP5.1
Calibration implementation WP5.2
Simulations WP5.3
Bayesian inference WP5.4
Data processing building blocks

RADIOBLOCKS key ideas

**Focal Plane Arrays** require:

- Compactness (= better integration of OMTs, mixers, LNAs)
- Easier and faster manufacturing
- DC power (less dissipation = lower load for cryogenic cooler)
- uW power (higher LO power needed to feed all pixels)

**Larger bandwidth** & **larger arrays**

- Generate larger volumes of data

**Digitization** starting closer to frontend

- Phased Array Feeds.
- Data filtering & no frequency dependent power loss for downconverted signals

# WP1 Project management

*"Effective, transparent and pro-active management which guarantees the smooth implementation of the financial, administrative and technical activities into the project"*

Coordinator: Aga Słowikowska (JIVE)
Management Team:
Giuseppe Cimo' (PM), Arpad Szomoru, Aukelien van den Poll

3 periodic reports (months 12, 30 & 48)
21 milestone reports
23 deliverables

# WP2 Novel detectors & components

*“Developing key components for future sensitive, wideband receivers for European research infrastructures”*

Analogue parts of the signal chain

Coordinated by Carsten Kramer (IRAM)

16 institutes & ***companies***:

IRAM, Fraunhofer – IAF, ESO, GARD, UOXF, MPG, RUG, UKRI, TUD, UNIMAN, CNIG, UCO, INAF, OBSPARIS, HES-SO, ***Lytid, TTI-Norte, RUAG***

# WP2 Tasks

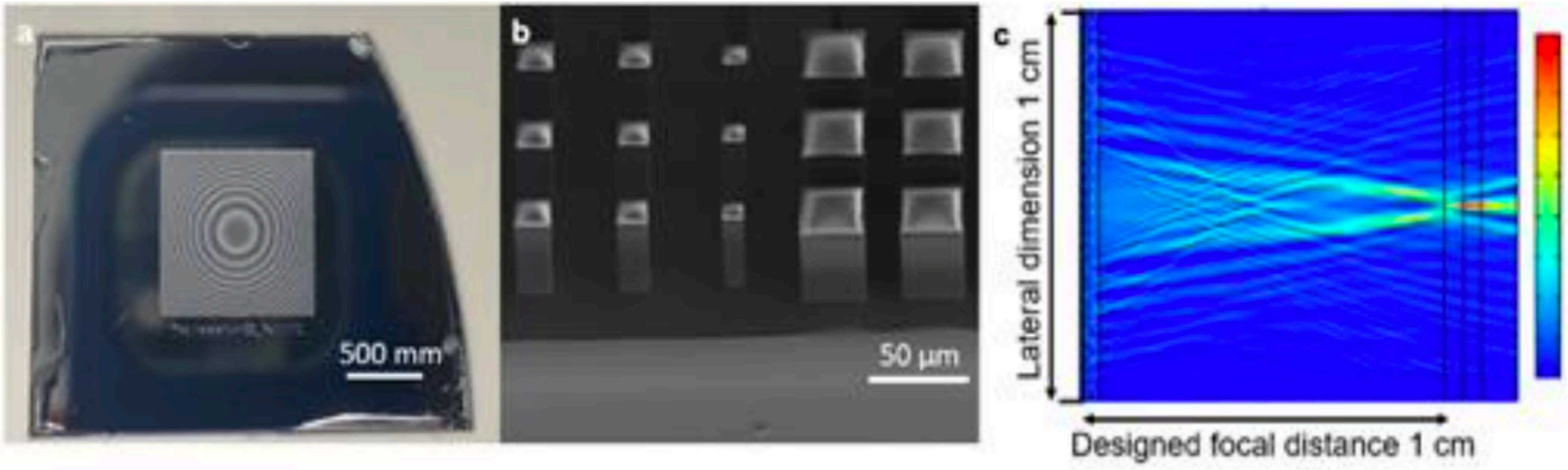
- (Task 2.1.1) RF windows, lenses, filters
  - Development of wideband nearly reflectionless flat lenses

- (Task 2.1.2) Orthomode-Transducers
  - Waveguide and planar technology from 100 GHz to 650 GHz
  - Planar technology to reduce size (improved integration)

- (Task 2.1.3) Horns
  - High performance corrugated horns: difficult to mass produce
  - Silicon micromachining: new technology for easier manufacturing

Focal Plane Arrays

100 – 600 GHz




Metalens (TUD)

Si nanopillars (at 30deg)

Simulation of finite element focussing effect

# WP2 Tasks

- (Task 2.2) SIS mixers
  - Expanding RF and IF bandwidth
  - Exploring new materials (AlN…)

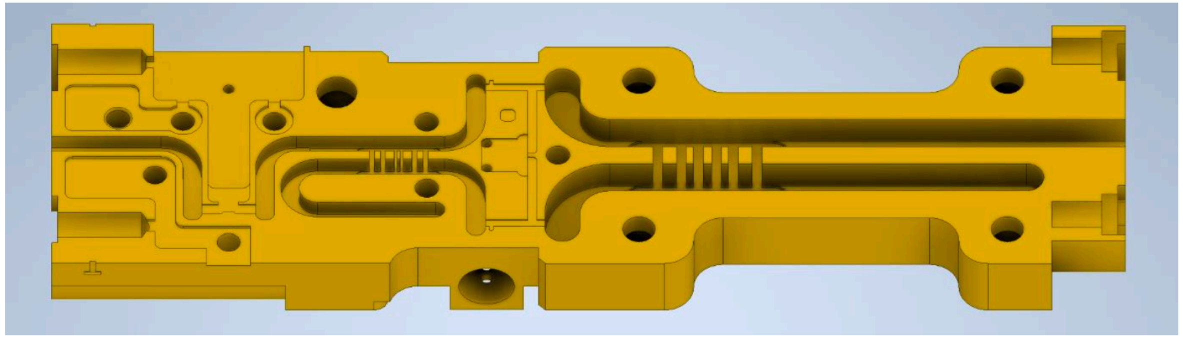
- (Task 2.3) LNAs:
  - RF LNAs: 67 - 150 GHz integrated IF mixers
  - IF LNAs:
    - Bandwidth expansion up to 30 GHz
    - Different technologies to improve sensitivity (mHEMT MMICs, Inp HEMT, superconductive parametric amplifiers)

Sensitivity

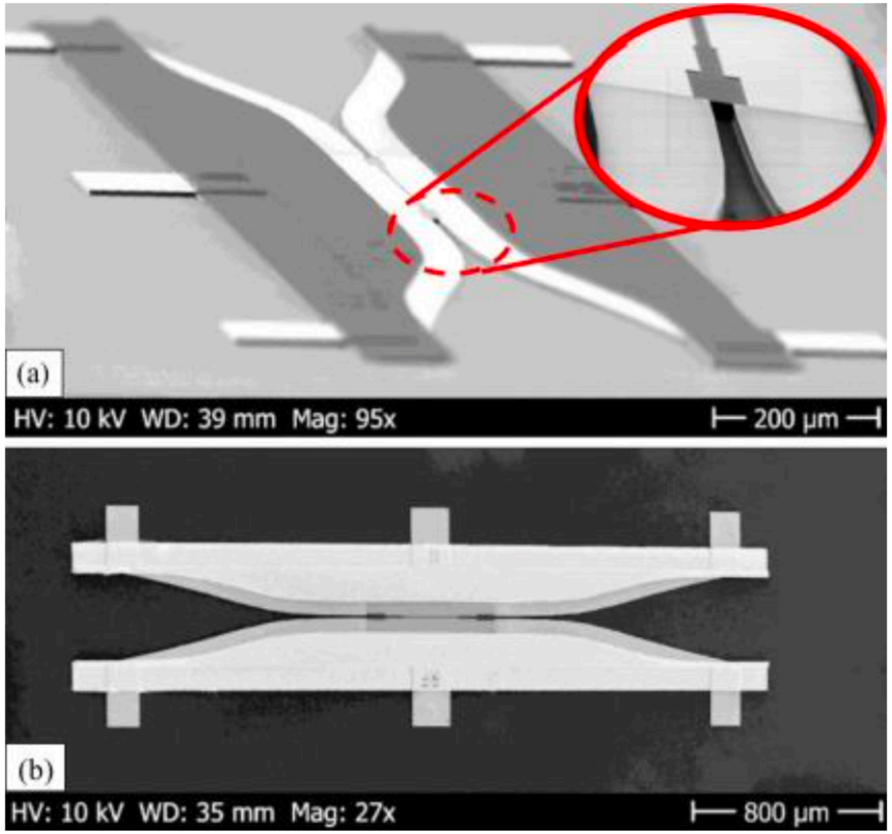
Bandwidth

Focal Plane Arrays

67 – 345 GHz



RF LNA: CAD design of integration of LNA and SHIRM using a W-band hybrid coupler




Ultra-wide band waveguide to slotline transition

# WP2 Tasks

- (Task 2.4) Local Oscillators:
  - Up to 345 GHz
  - Increasing power and efficiency
- (Task 2.5) W-Band downconverter modules
  - MMIC+LOs (67 – 116 GHz)
- (Task 2.6) Tunable filters
  - Before the LNAs to reject RFI

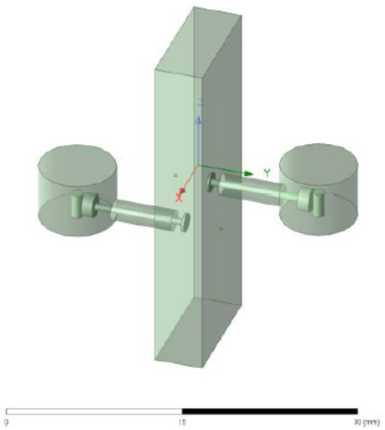
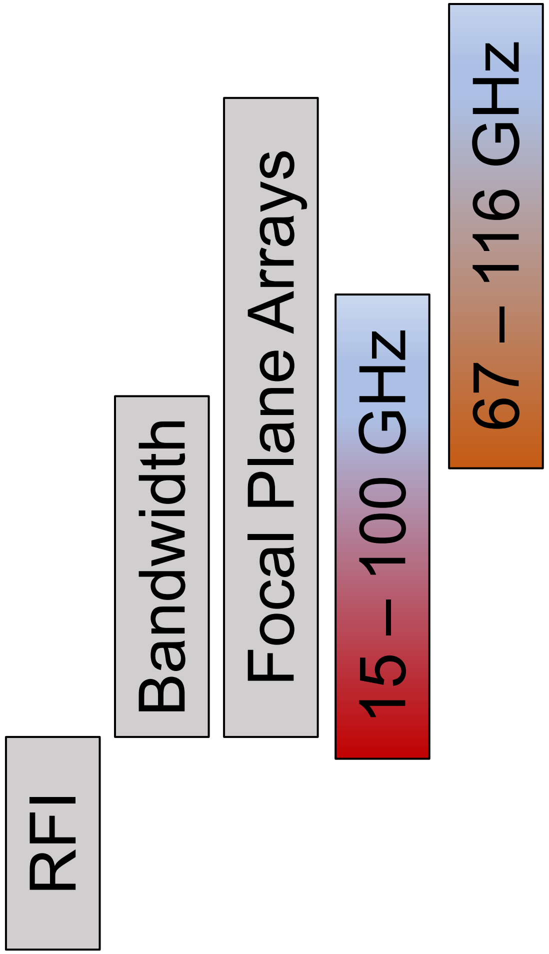


*Figure 9 Two cavity filter.*



# WP3 Digital receivers

*"Deployment of state-of-the art digital technology to improve system temperature, bandwidth and field-of-view"*

Coordinated by Gundolf Wieching (MPG)

6 institutes & ***companies***:

MPG, RUG, UNIMAN, INAF, HES-SO, ***RUAG***

Grant number: 101093934

# WP3 Task 3.1 (wide field)

- (Task 3.1.1) PAF Design Simulator Wide-field astronomy
  - Simulate the effect of RFI-sources & instrumental misbehaviour
  - Already available in MPIfR Github

- (Task 3.1.2) Novel Beamforming technology on RFSoC
  - Characterize the RFSoC (FPGA) performance for PAF systems and design and build a prototype beamformer

- (Task 3.1.3) PAF-RFI mitigation and adaptive beamforming methods
  - Adaptive filtering, generalised adaptive beamforming strategies and software for use on arbitrary phased array feeds

Phased Array Feeds

# WP3 Task 3.1 (wide field)

- (Task 3.1.4) PAF Reference implementation
  - Simulate the sky as seen by a target PAF design and use it as a digital signal processing reference.

- (Task 3.1.5) Demonstrator
  - Provide the 100m Effelsberg CryoPAF (conveniently modified) as a demonstrator platform for tasks 3.1.2, 3.1.3 and 5.5

Phased Array Feeds

# WP3 Task 3.2 (wide BW)

- (Task 3.2.1) DBBC4 VLBI backend demonstrator
  - Hardware developments for a high performance VLBI backend prototype
  - BW: 256 GHz, output 1 Tb/s (2 bits)

- (Task 3.2.2) DiFrEnd28 Broadband digitizer
  - Direct digitization and formatting of 2 analogue 28 GHz BW inputs.

- (Task 3.2.3) RFI-Mitigation: A-EYE Artificial Intelligence Controller
  - AI techniques for allowing near-realtime recognition and mitigation (Multi CPU FPGA)

RFI

Early digitization

Grant number: 101093934

# WP3 Task 3.2 (wide BW)

- (Task 3.2.4) Digitizer using passband sampling
  - Alternative technology to wide-bandwidth digitizer (10 bits)
  - Applicable to SKA band 6: 14-25 GHz, expandable to 40 GHz.
  - Potential VLBI in 35-40 and 35-50 GHz bands
- (Task 3.3) Multi-pixel astronomy via Focal Plane Arrays
  - Wide-field wide-band radio astronomy at high-frequencies
  - Multiple beams on the sky via mechanical components

Early digitization

Focal Plane Arrays

# WP4 Data transport and correlation

*"to deliver a collection of efficient, and/or high-performance signal processing building blocks exploiting commercially available hardware accelerator platforms"*

John Romein & Ilse v. Bemmel (ASTRON)

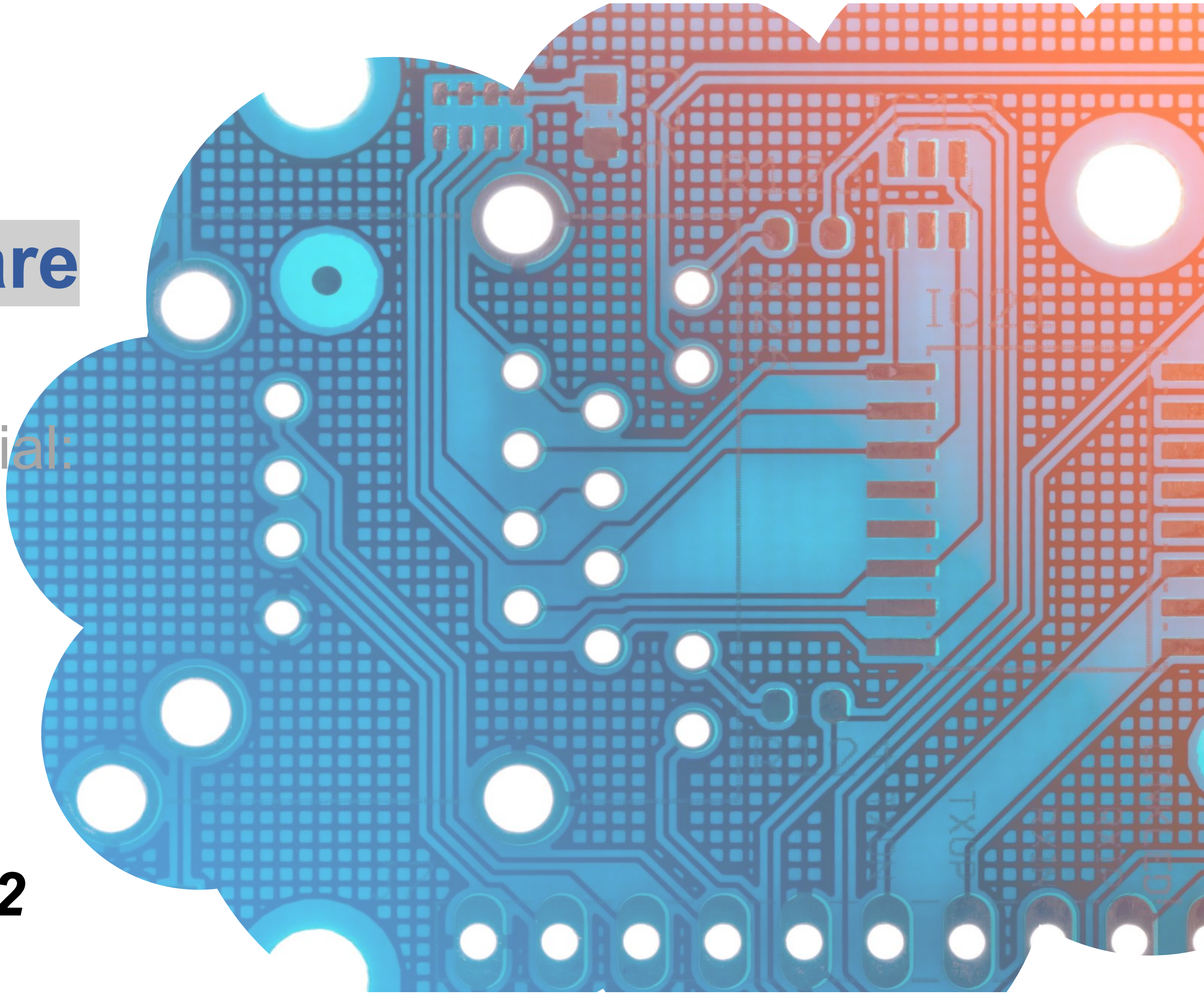
9 institutes & ***companies***:

ASTRON, JIV-ERIC, ESO, VENTSPILS, UBx, ***Sioux***, ~~KASI~~, NAOJ, UNIMAN

Grant number: 101093934

# Objectives and goals

**Boost efficiency by exploiting commercially available hardware**



This will lead to increased science potential:

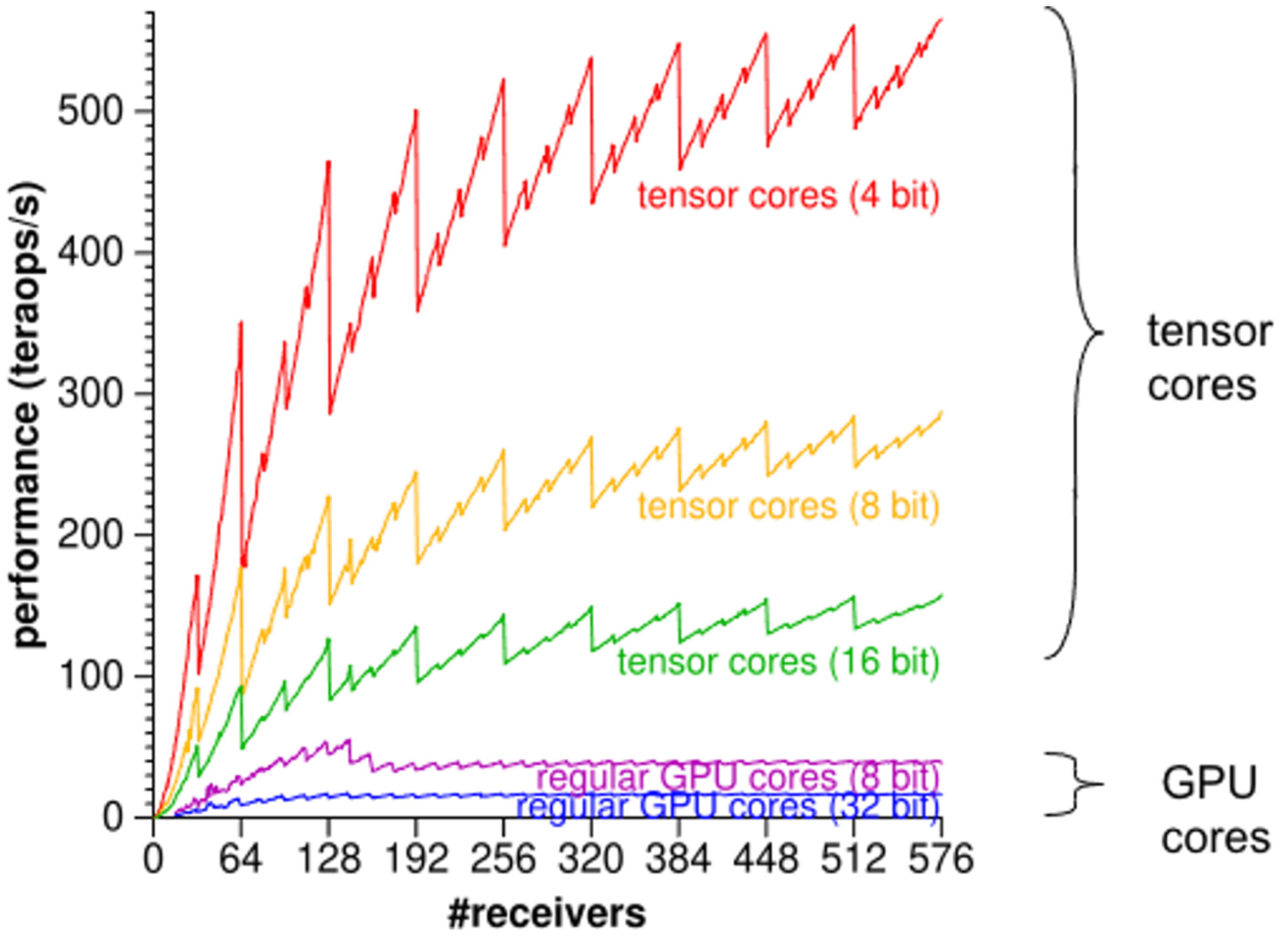
- Higher sensitivity (more bandwidth)
- Larger field-of-view
- Sustainable systems

*Of **interest** for e.g. **ALMA, EVN, LOFAR2***

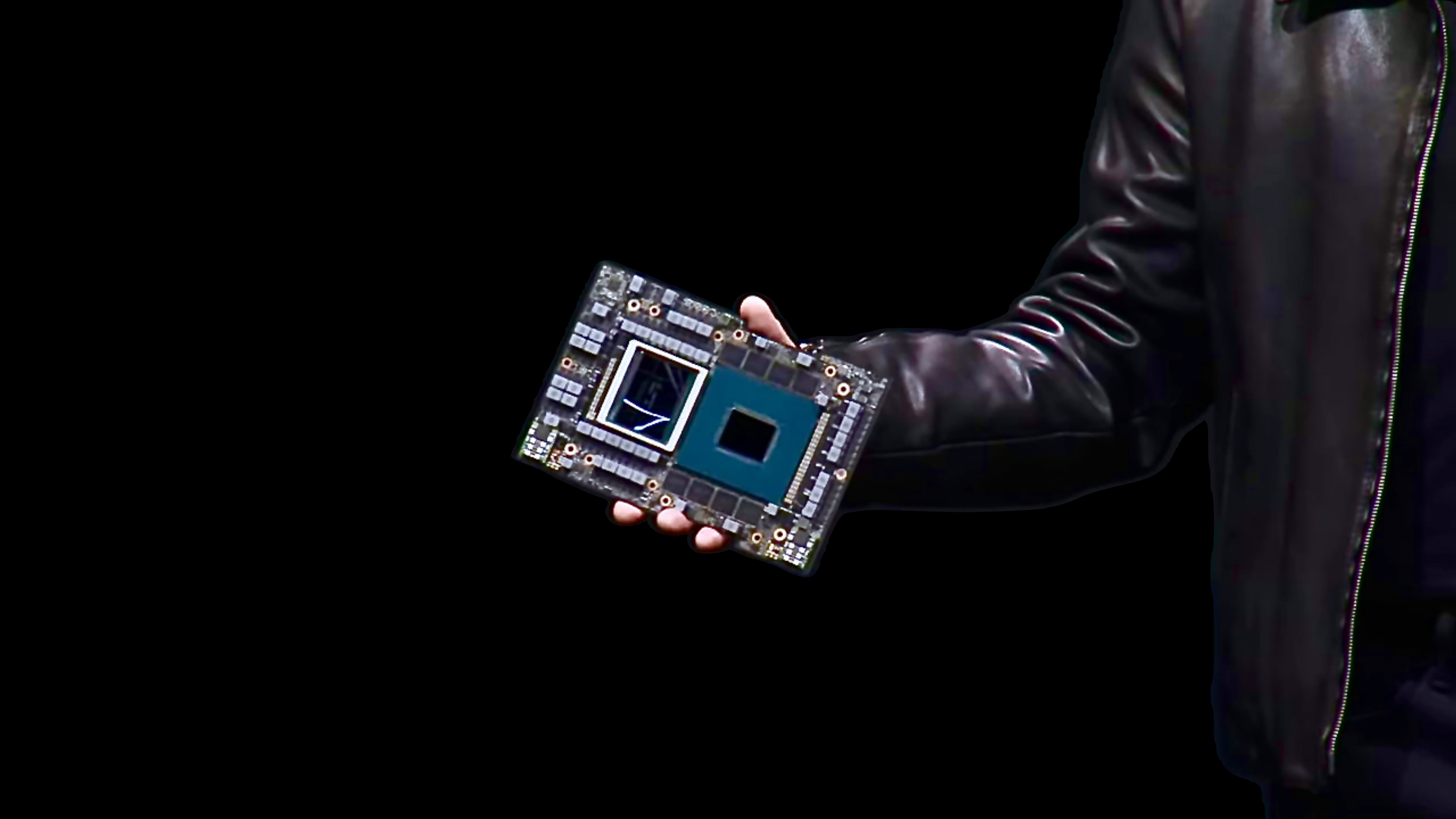
# Tasks

1. Next generation correlators building blocks: TensorCore
2. Accelerator research report: exploring alternative HPC tech
3. High-speed data transport development: moving to >100Gb/s

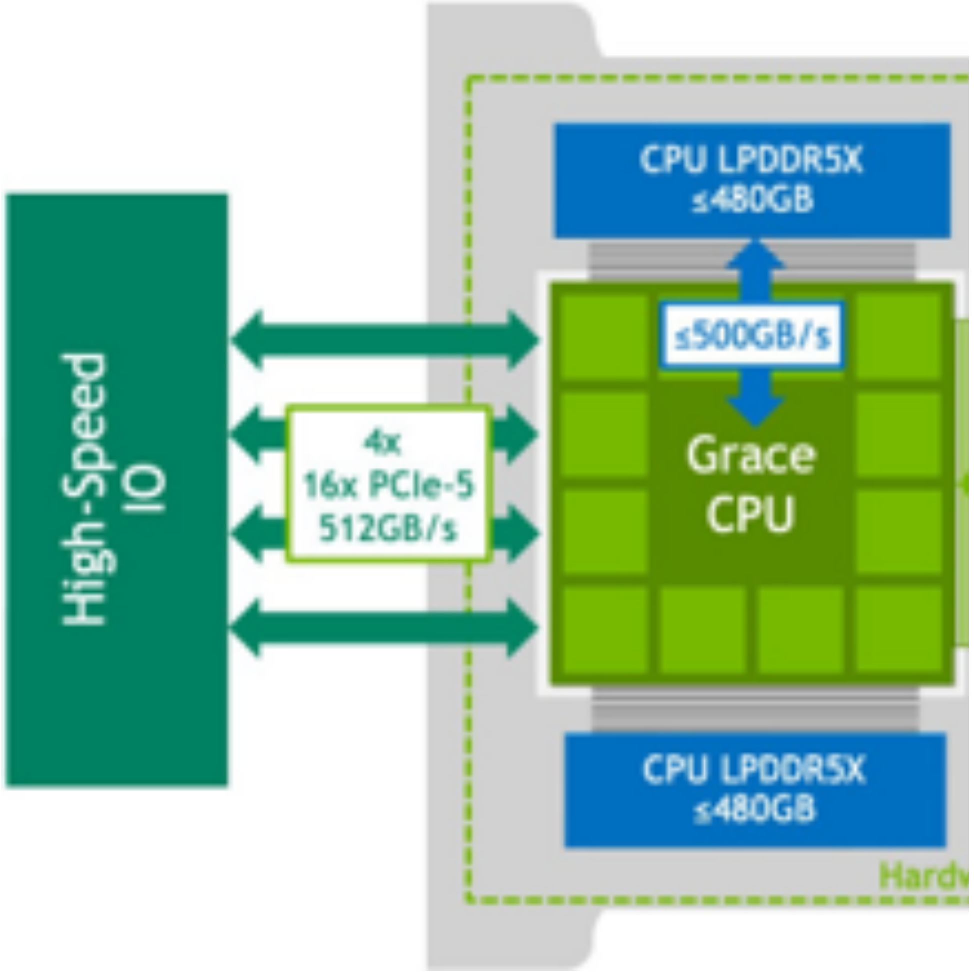
# Current status: TensorCore correlator



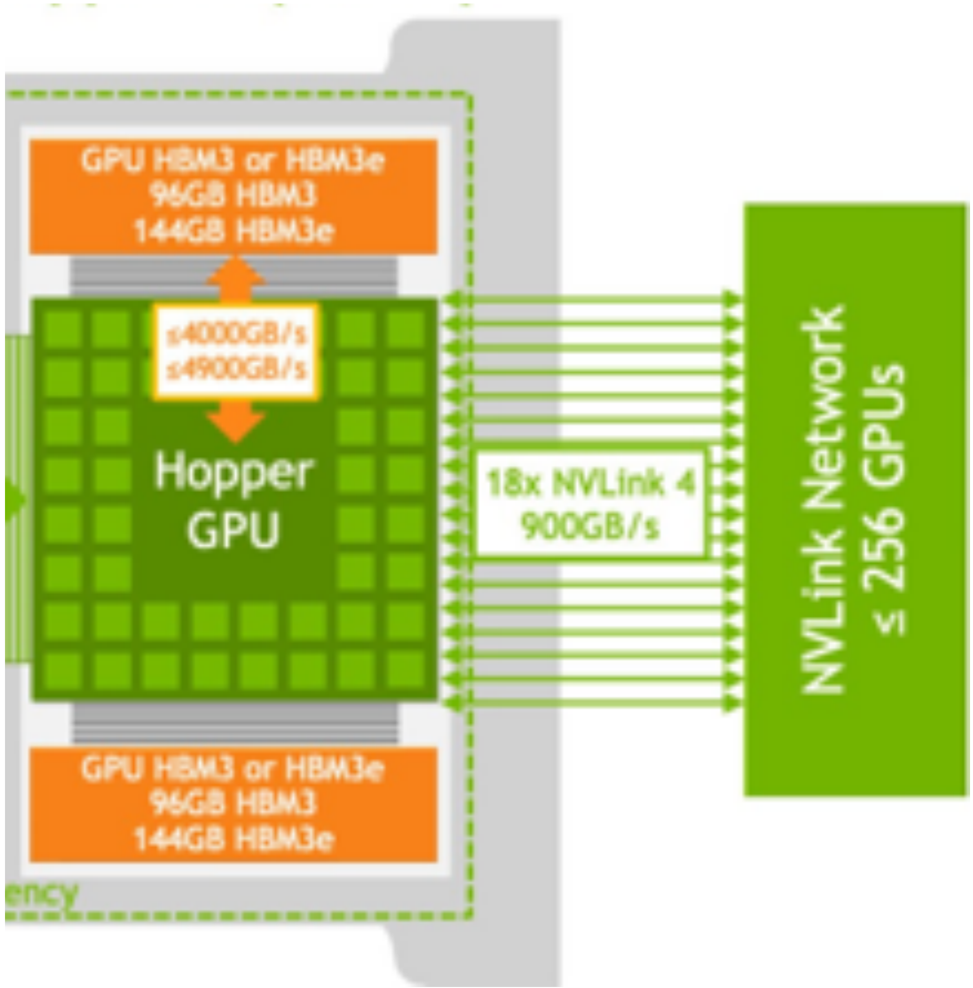

NVIDIA A100 PCIe 40GB



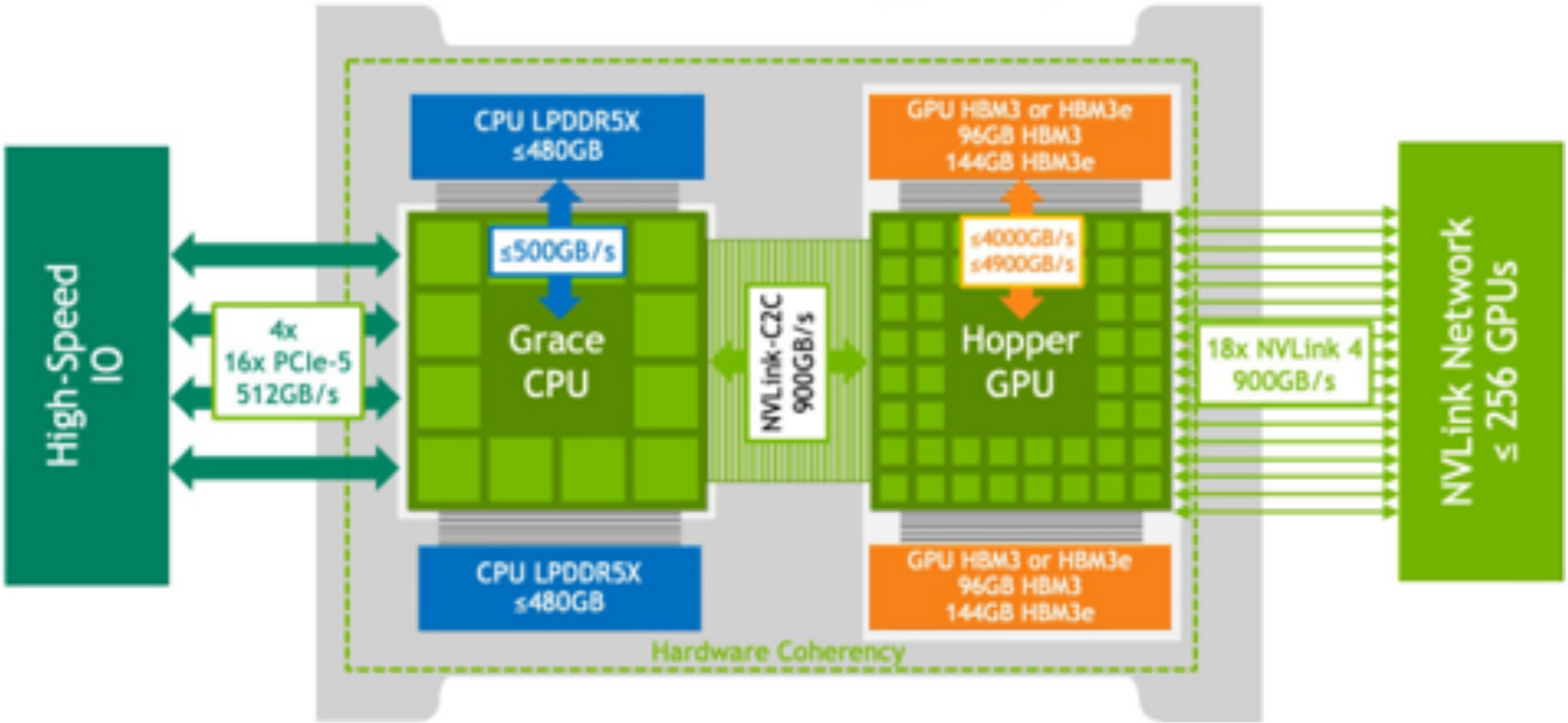
the NVIDIA© Grace Hopper™ SuperChip

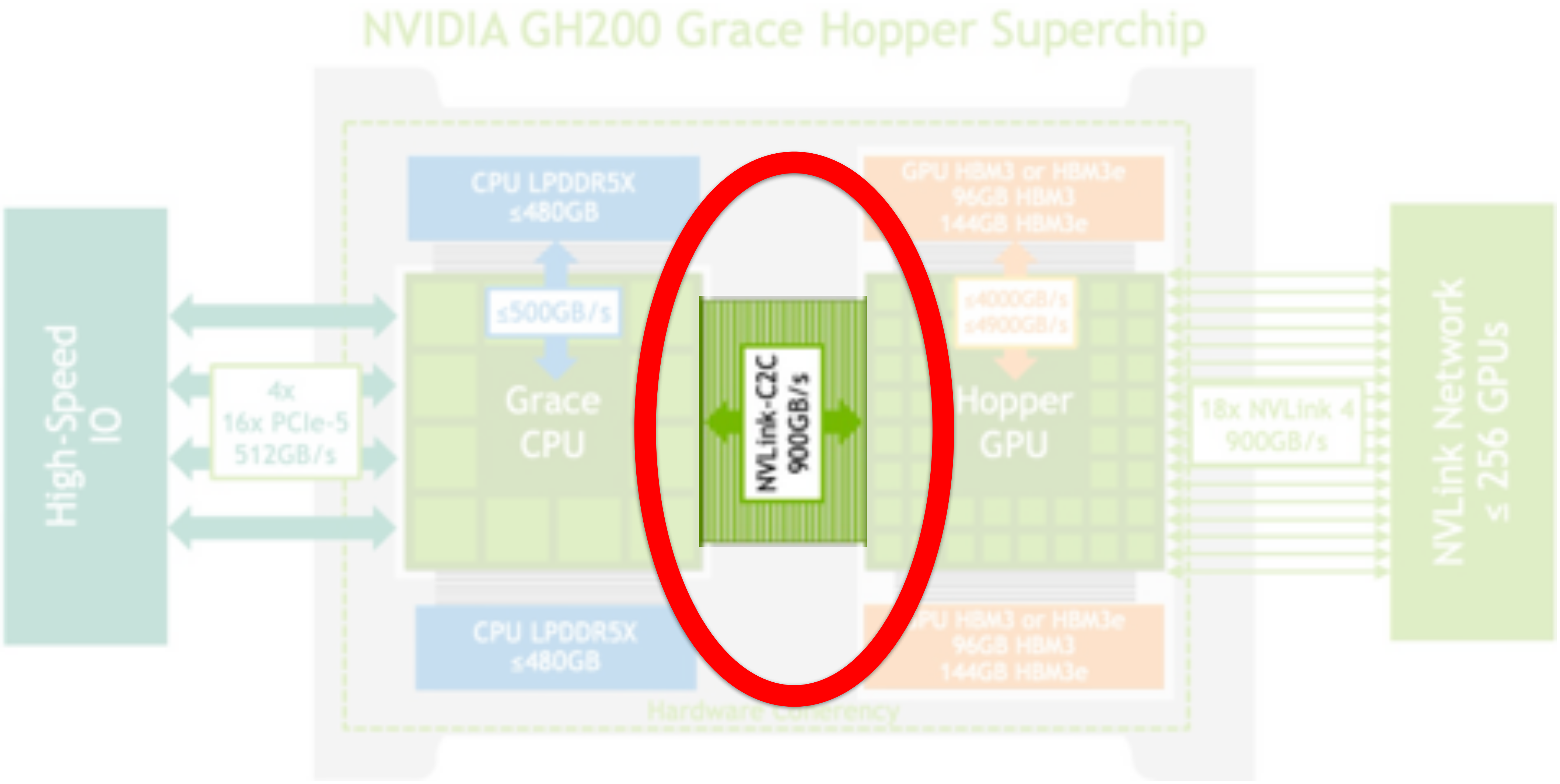


High-Speed IO
4x 16x PCIe-5 512GB/s
CPU LPDDR5X ≤480GB
≤500GB/s
Grace CPU
CPU LPDDR5X ≤480GB

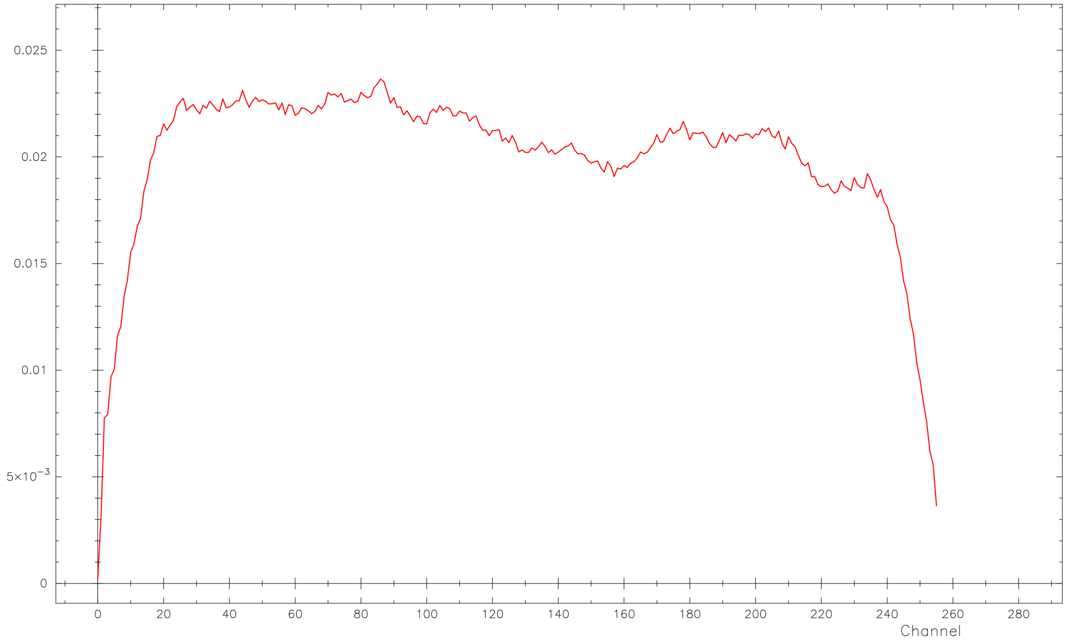

GPU HBM3 or HBM3e
96GB HBM3
144GB HBM3e
≤4000GB/s
≤4900GB/s
Hopper
GPU
18x NVLink 4
900GB/s
NVLink Network
≤ 256 GPUs
GPU HBM3 or HBM3e
96GB HBM3
144GB HBM3e

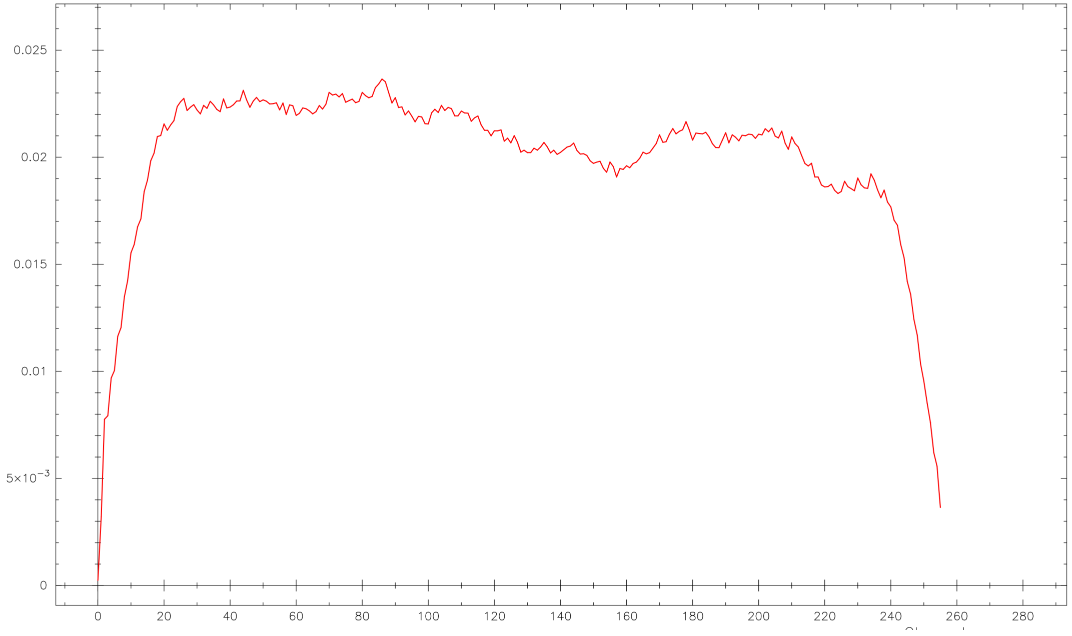
# NVIDIA GH200 Grace Hopper Superchip



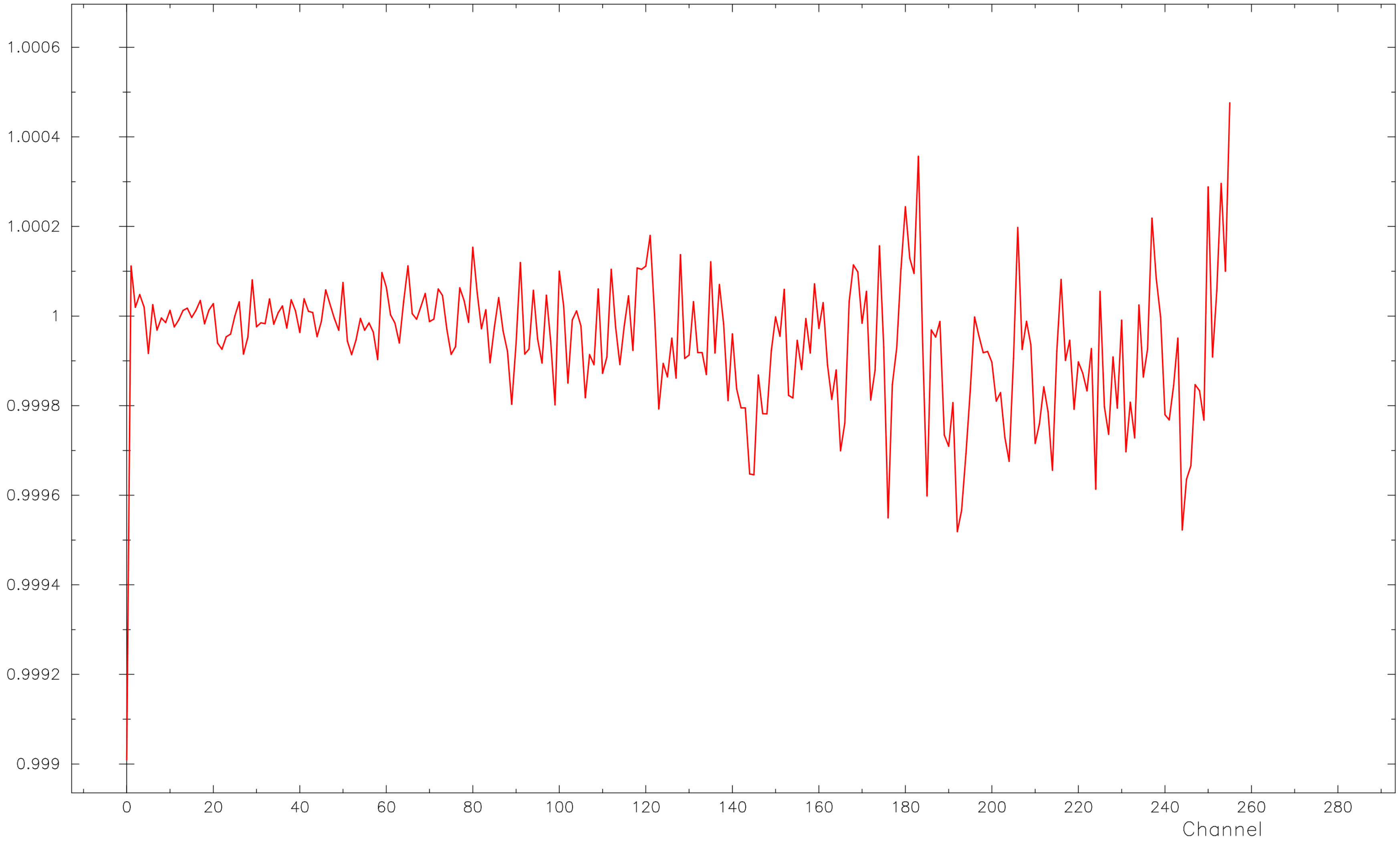

NVIDIA GH200 Grace Hopper Superchip
CPU LPDDR5X
≤480GB
GPU HBM3 or HBM3e
96GB HBM3
144GB HBM3e
High-Speed
IO
4x
16x PCIe-5
512GB/s
≤500GB/s
Grace
CPU
NVLink-C2C
900GB/s
Hopper
GPU
18x NVLink 4
900GB/s
NVLink Network
≤ 256 GPUs
CPU LPDDR5X
≤480GB

**Effelsberg-Onsala** baseline
cross-correlation bandpass (**N22L3**)

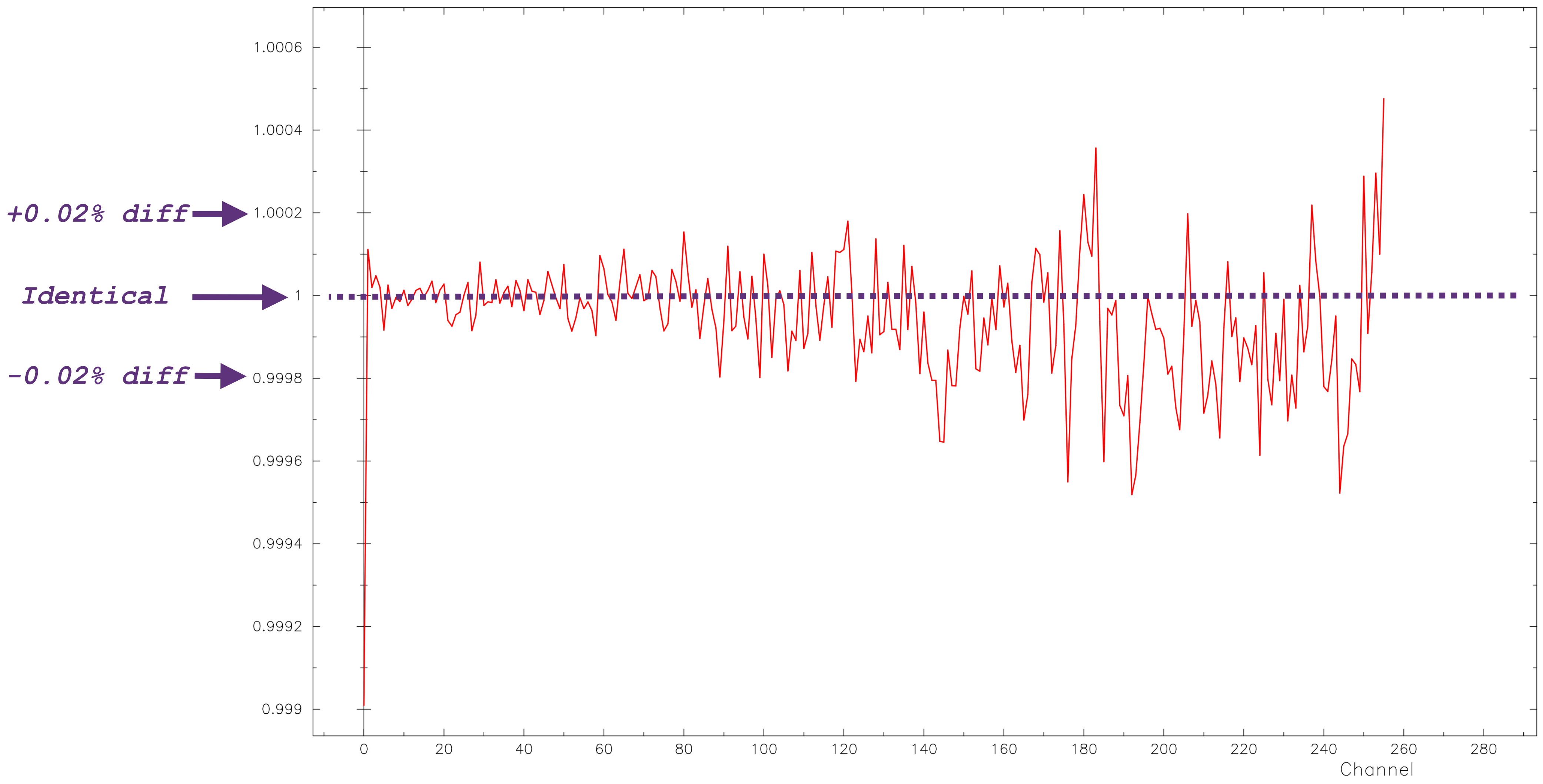



SFXC(CPU) SFXC(GPU)

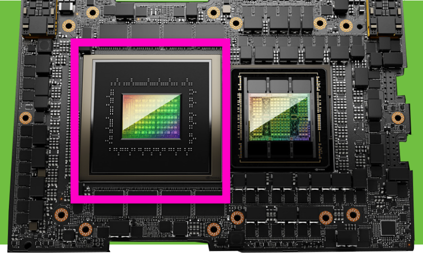



GPU/CPU bandpass ratio - a small scaling issue (under investigation)

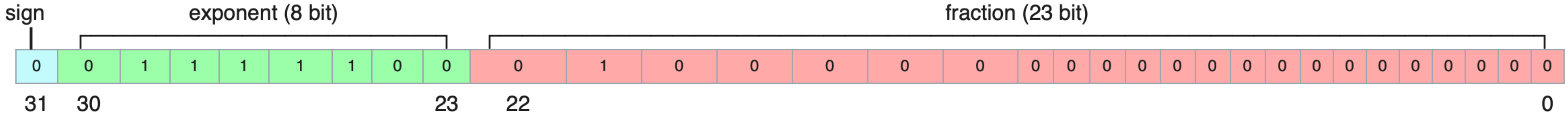



GPU/CPU bandpass ratio - a *very* small scaling issue (under investigation)

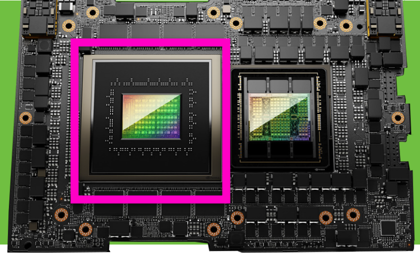
# Grace ARM64 CPU



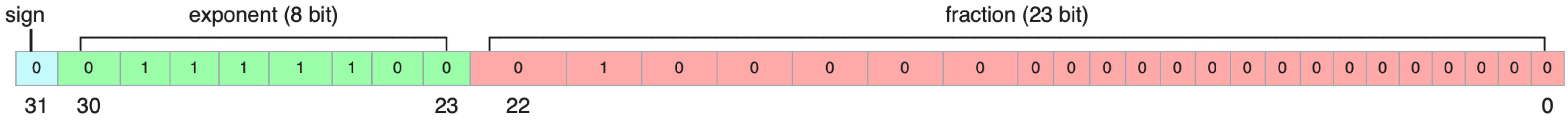
**IEEE 754 single-precision 32-bit float**



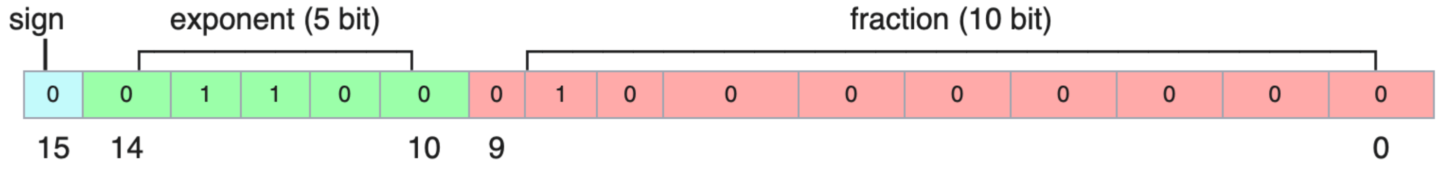
# Grace ARM64 CPU



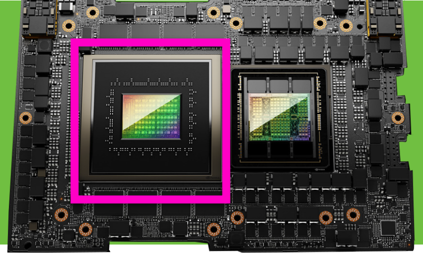
**IEEE 754 single-precision 32-bit float**

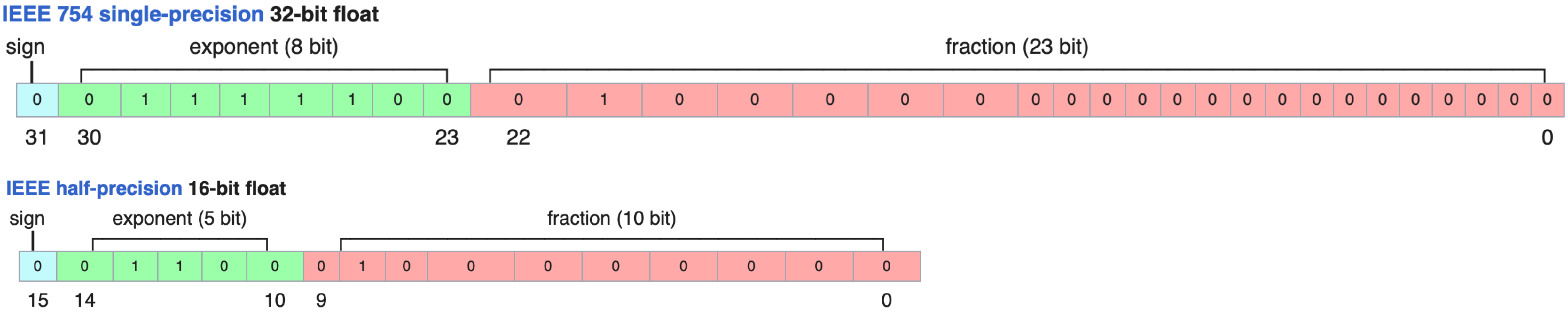



**IEEE half-precision 16-bit float**



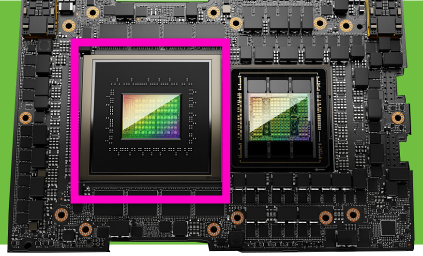
# Grace ARM64 CPU

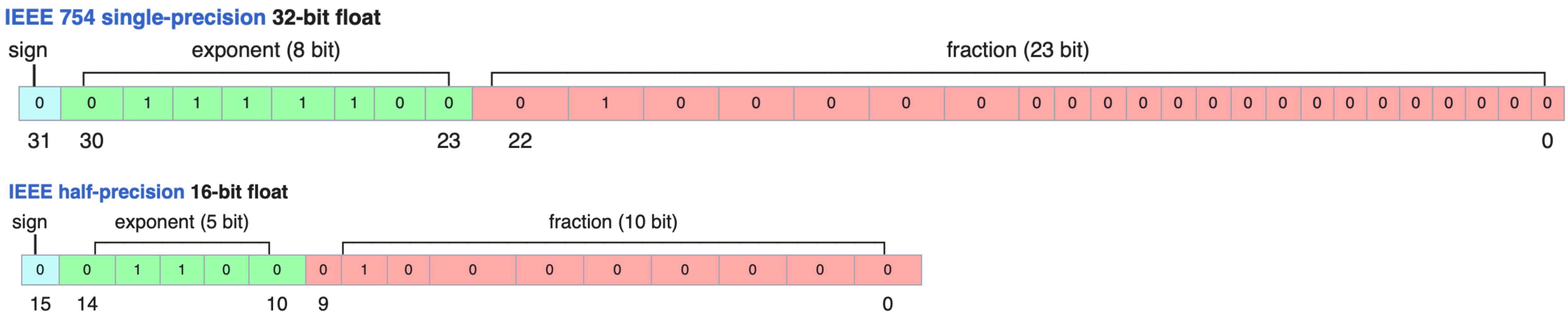





+ slightly faster
+ half the memory usage

# Grace ARM64 CPU

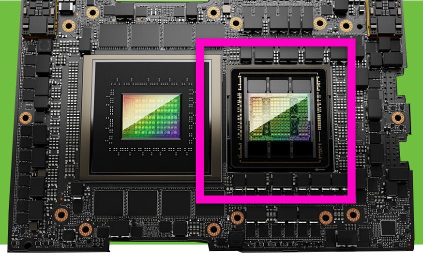


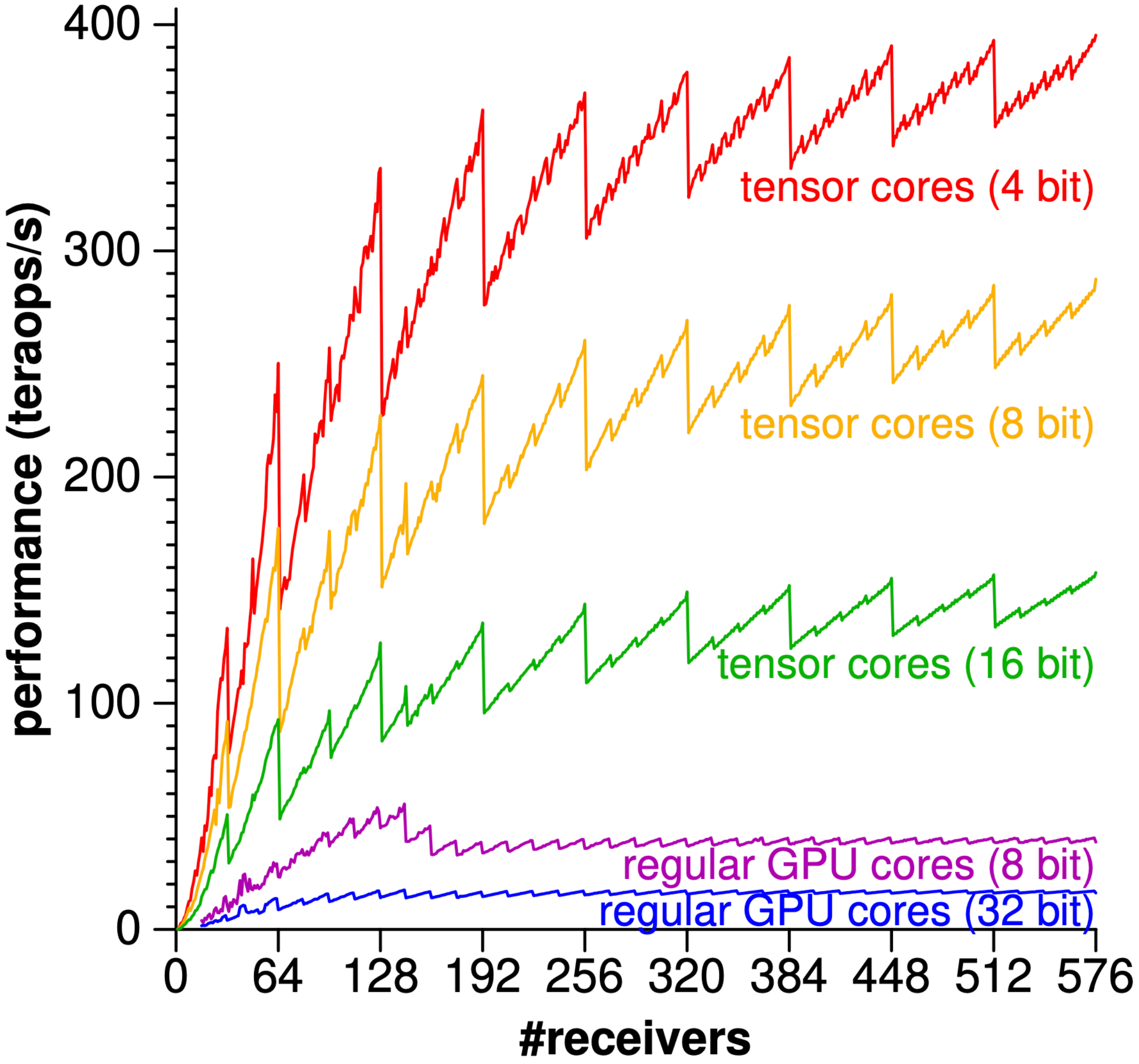



+ slightly faster
+ half the memory usage

- sensitivity loss ~1%

# Hopper GPU



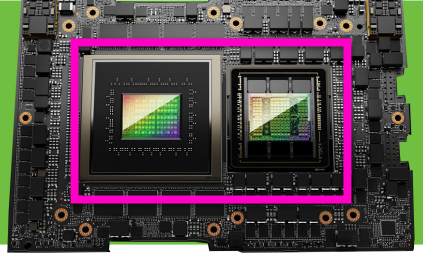


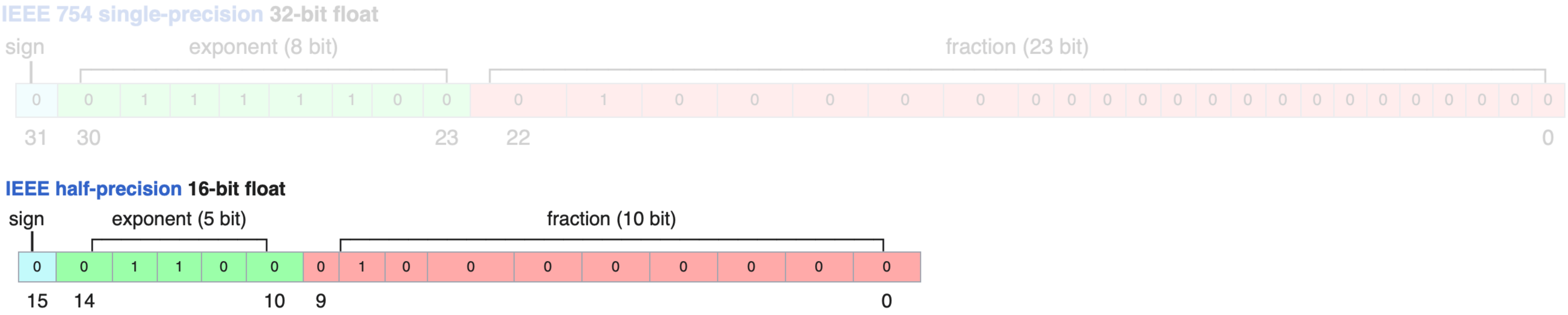

*TensorCore GPU 16-bit float*

*Regular GPU 32-bit float*

*"The Tensor-Core Correlator" Romein, J.*
*https://doi.org/10.1051/0004-6361/202141896*

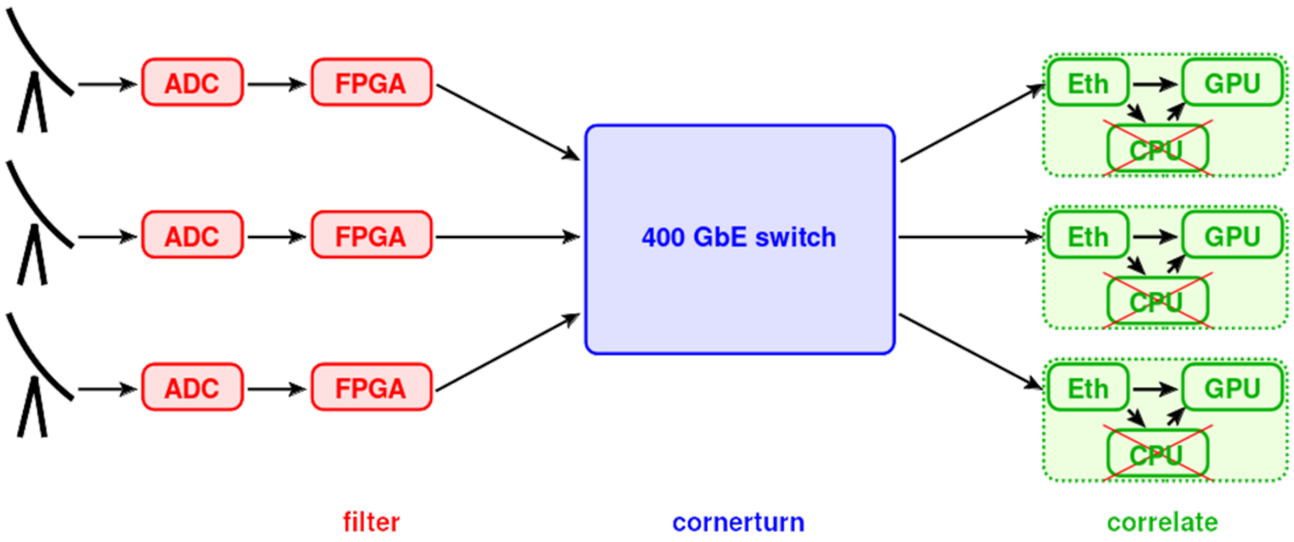
# float16 …





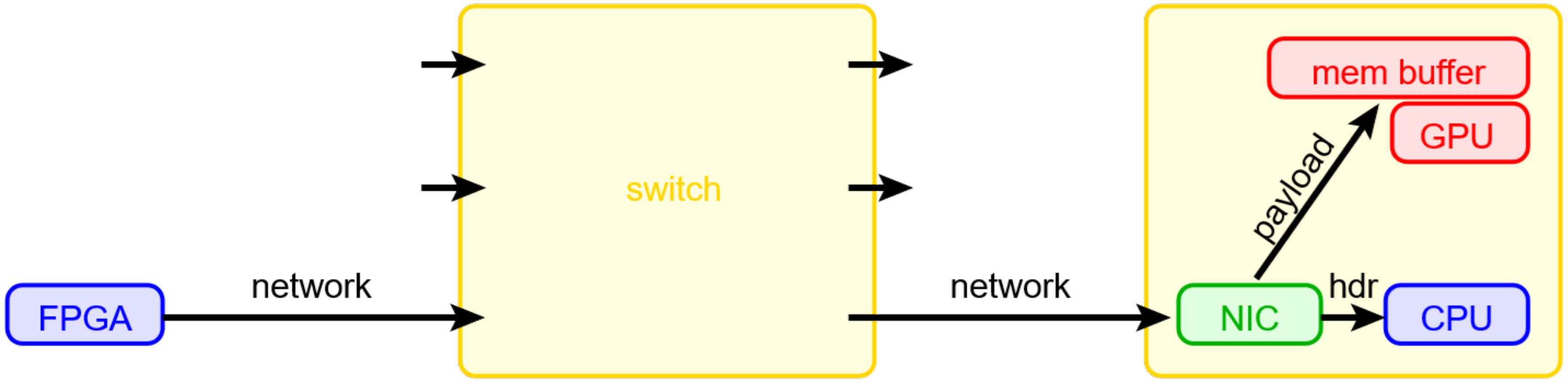

+ Grace CPU: slightly faster
+ both: half the memory usage
+ Hopper GPU: ***extremely*** fast
- sensitivity loss ~1%

# High-speed data transport development




## Exploring 2 methods:

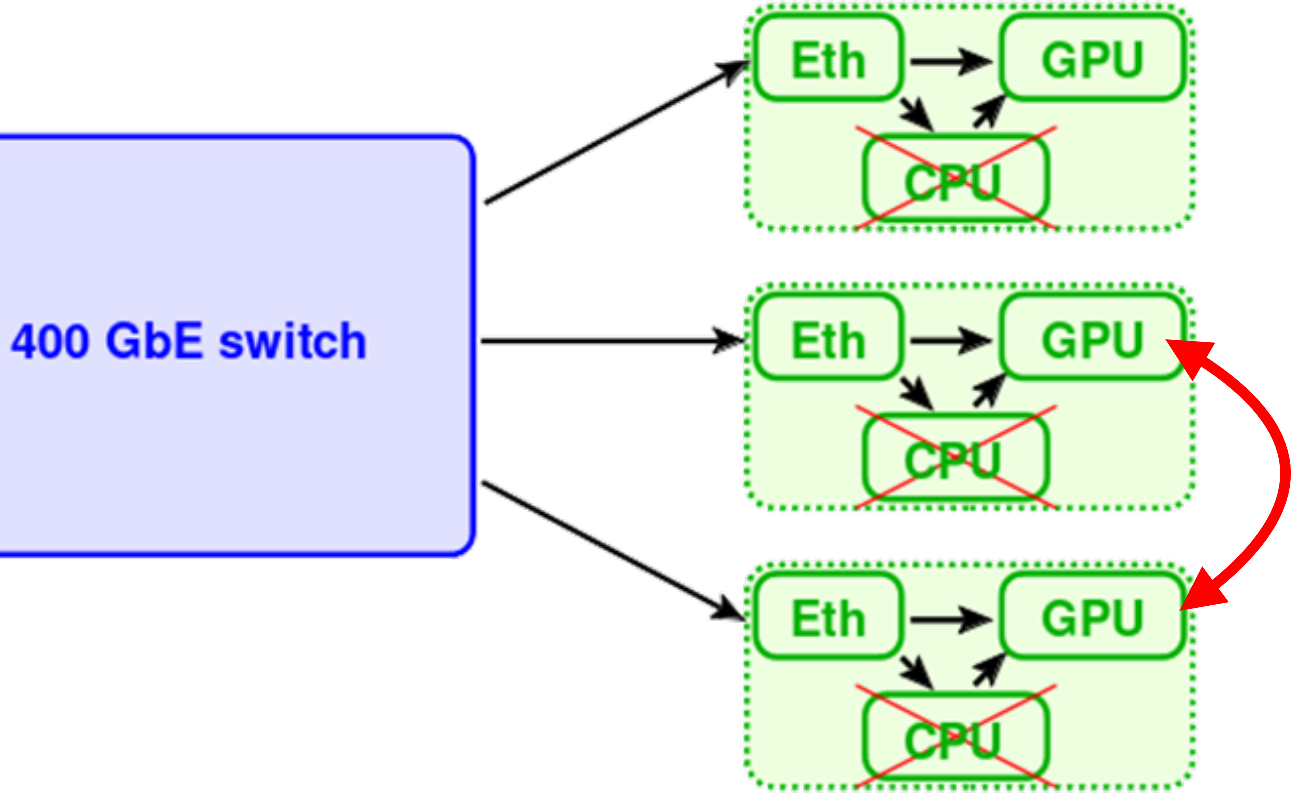
- Hardware based (RDMA)
- Software based (DPDK)



# High-speed data transport development

**Exploring 2 methods:**

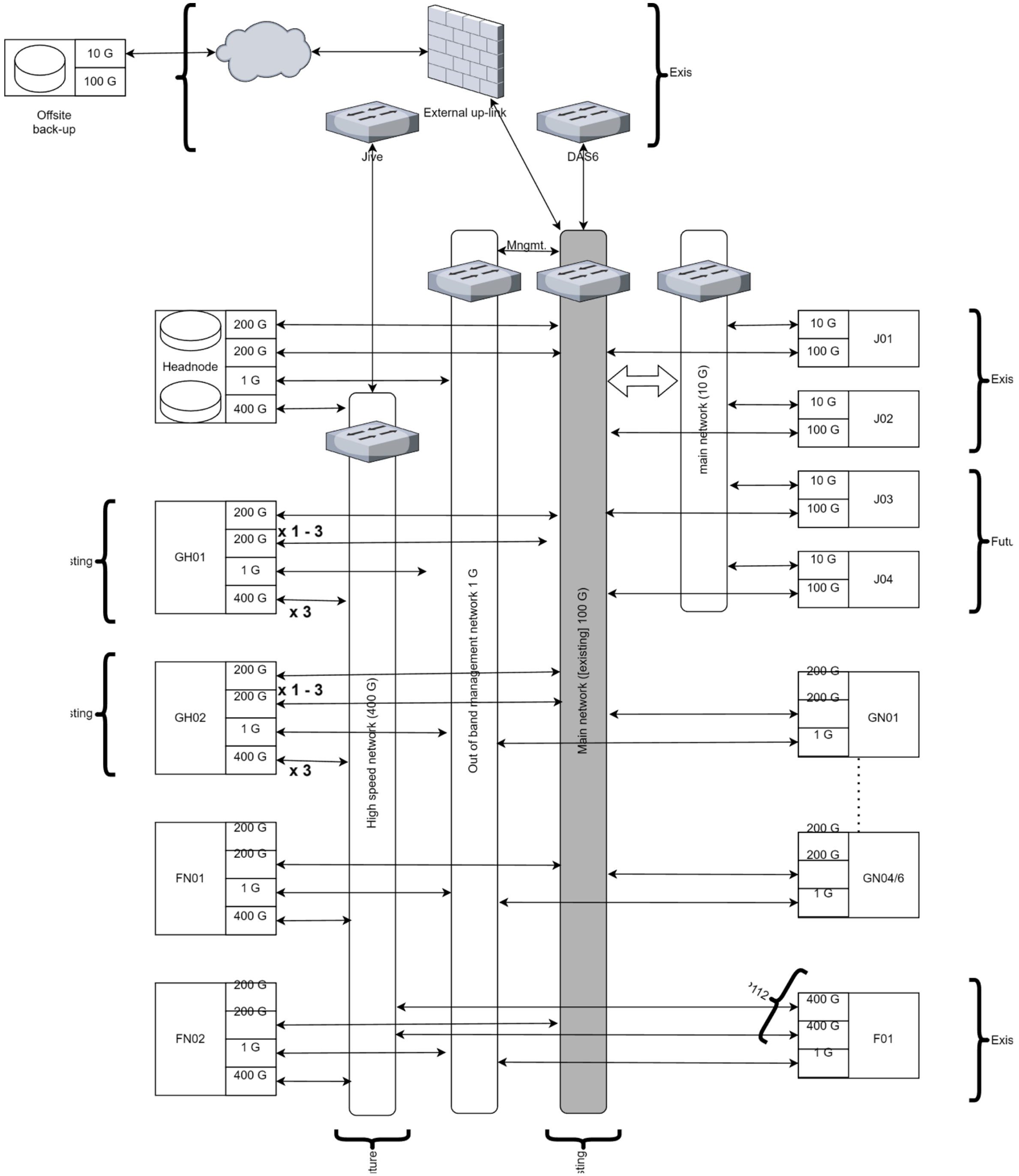
- Hardware based (RDMA)
- Software based (DPDK)




> 1 Tbps GPU mem ⇒ GPU mem

# Longer term plans

- Explore TC correlator for LOFAR2
- GPU correlator for the EVN
- ALMA new correlator




# New cluster:

- Systems:
  - Grace Hopper
  - Jetson Orin
- Architectures:
  - Various GPUs
  - AMD Epyc + ThreadRipper Pro CPU
    - *many* cores
- Network:
  - 100-, 200-, 400 GbE
  - DMA from Storage or Networking into GPU

# WP5 Data processing tool kit

*"Provide modular, open-source and flexible analysis toolkit components for associated workflows to enable rapid, reproducible and scalable analysis of the large-volume and complex data products"*

Rob Beswick (UMAN) & Marjolein Verkouter (JIV-ERIC)

15 institutes:

JIV-ERIC, ASTRON, CSIC, MPG, ULEI, VENTSPILS, ~~SDU~~UHEI,

INAF, RU, EPFL, SKAO, CNIG, ICRAR, RATT, UP?

# WP5 Tasks

1. Post processing pipelines: explore DASK
2. DASKy fringe fitter
3. Calibration and dynamic imaging
4. Bayesian imaging
5. Modular PAF back-end processing

*“Modular open-source flexible components to process interferometry data”*

Grant number: 101093934

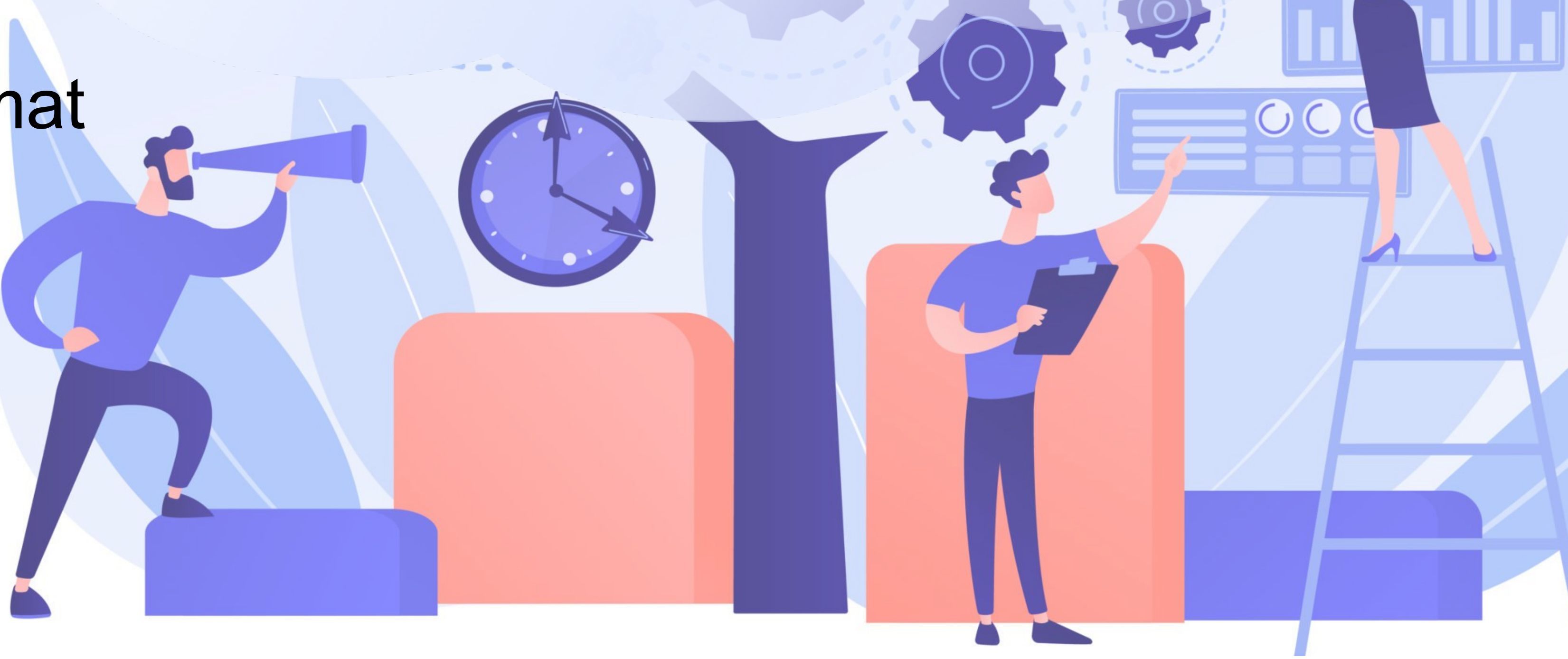
# Impact on VLBI

- Larger bandwidth: FPT calibration
- High frequency VLBI
- Wide field VLBI data processing
- LOFAR2 with international stations
- Relevance for SKA-VLBI

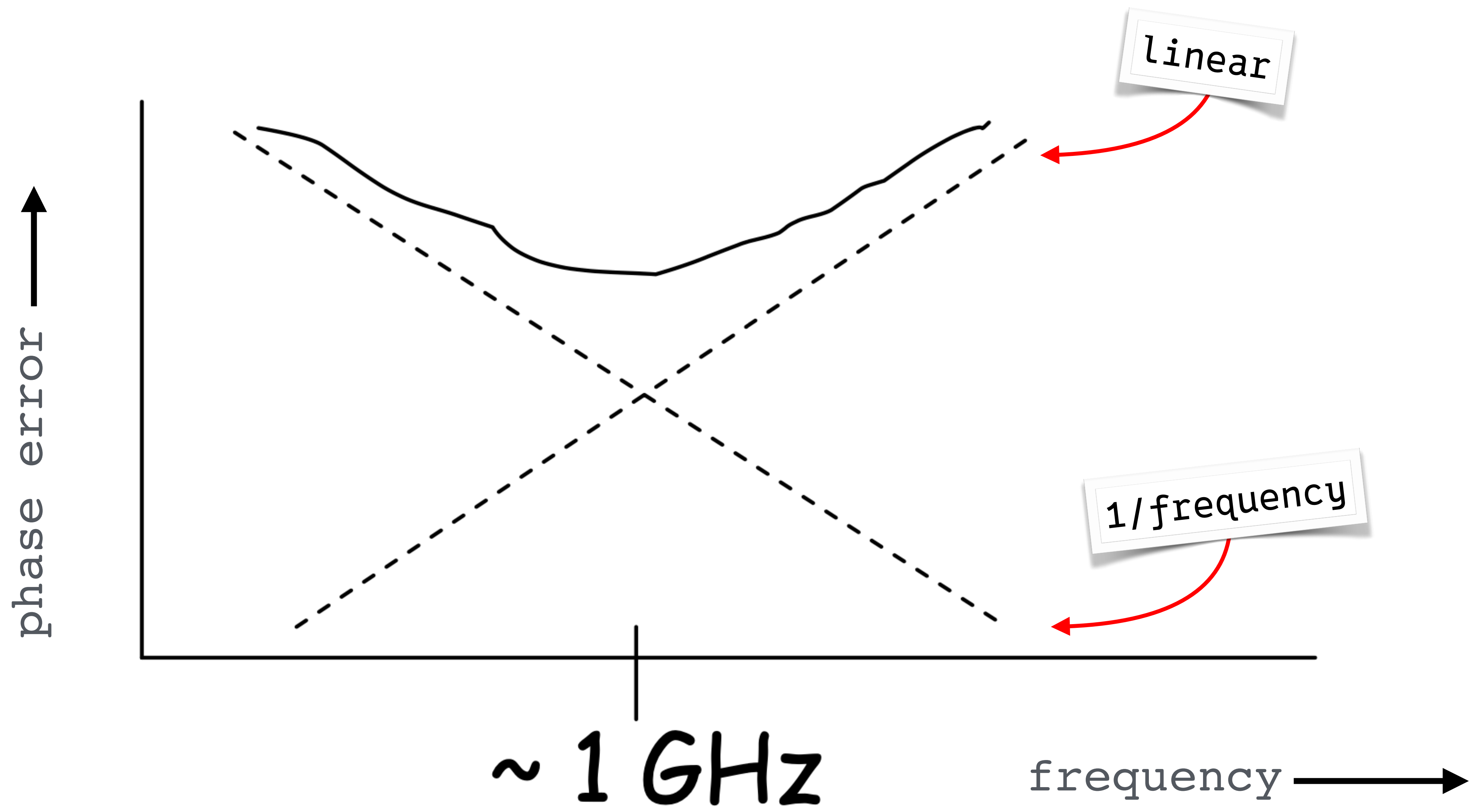
Grant number: 101093934

# 5.1 & 5.2 DASK for automated workflows

- FAIR and scalable solutions for data processing
- Uniform approach for multiple facilities
- DASKy fringe fitter
- Discussion on data format

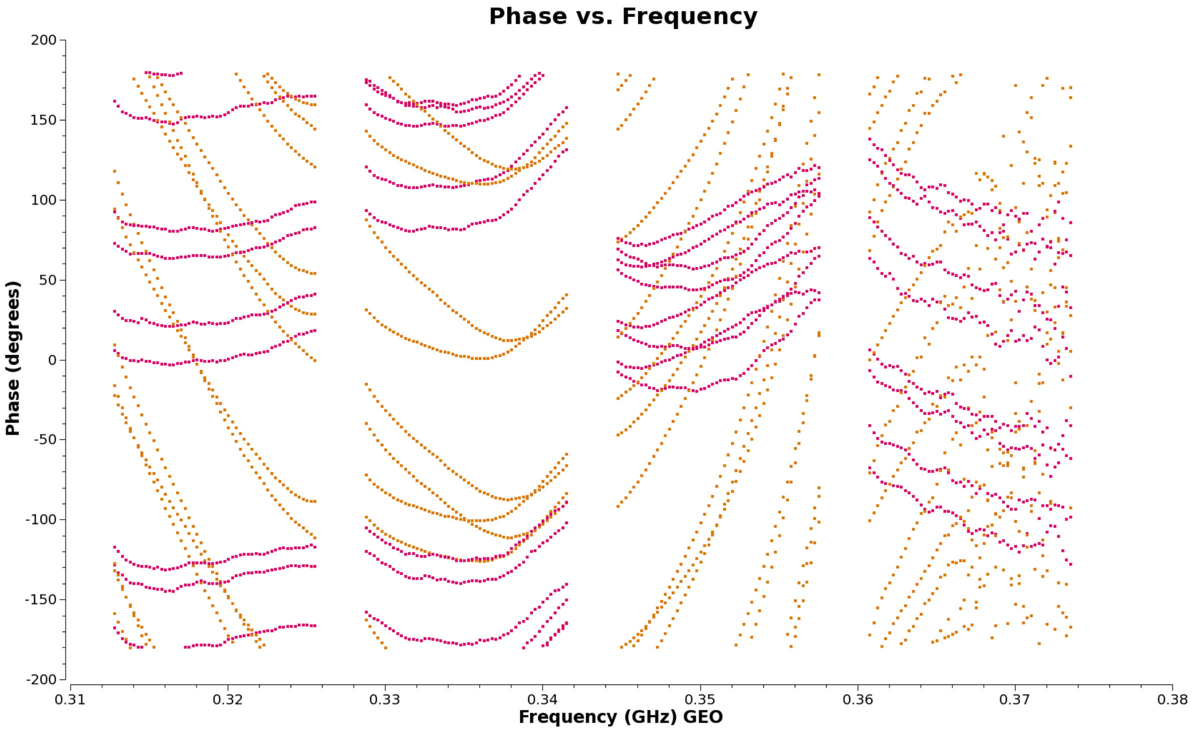


# Ionospheric phase error

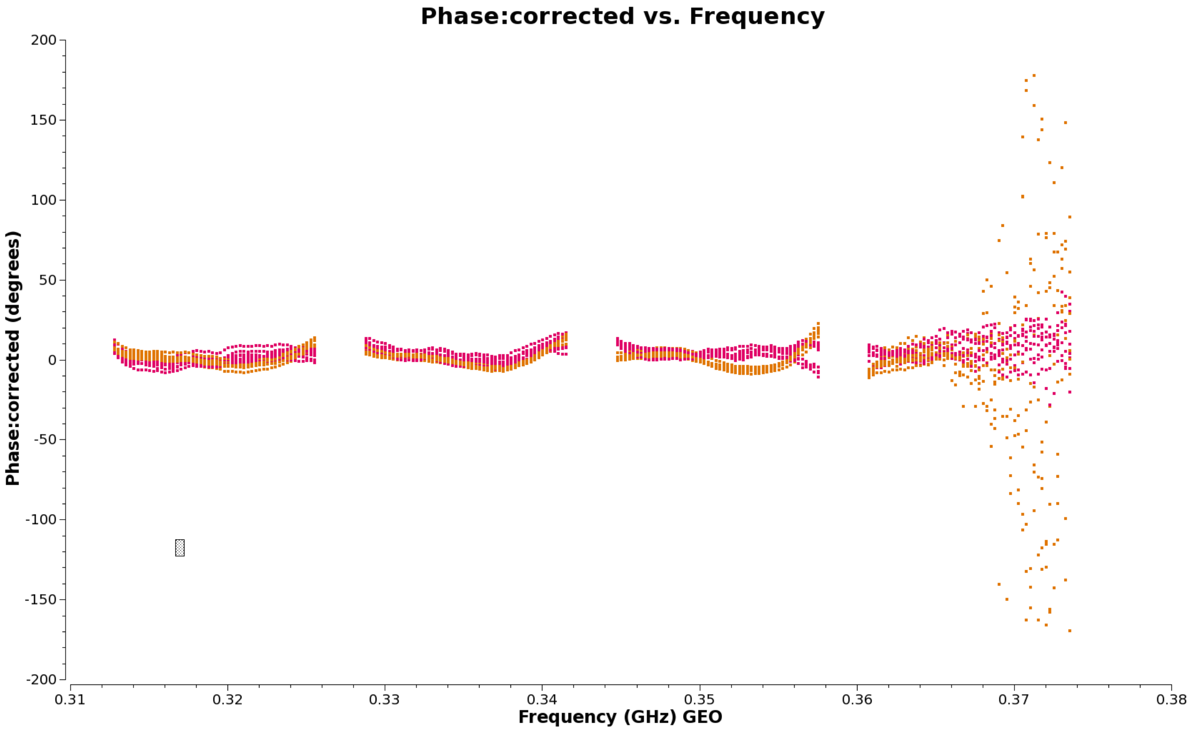


# fringefit

## BEFORE

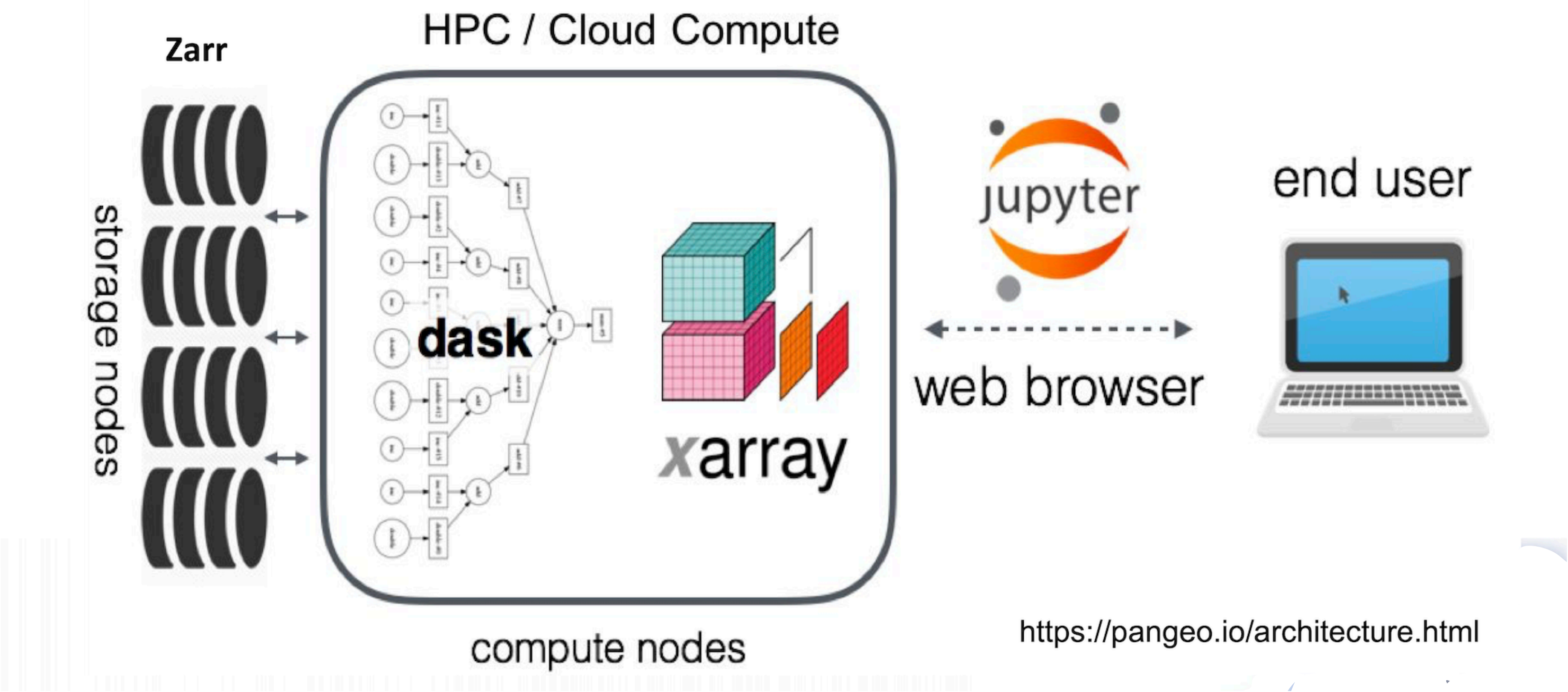



## AFTER




*fits linear + dispersive corrections in one go!*

Porting `fringefit` algorithm to this framework already ongoing




https://pangeo.io/architecture.html

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# 5.3 Optimizing calibration

- VLBI data processing is perceived as DIFFICULT
- Relies on human experience: it is also biased

  ⇒ automate calibration choices where possible

- Synthetic data generation
- Dynamic imaging of sparse datasets (EHT)

Use cases: EVN, SKA-VLBI

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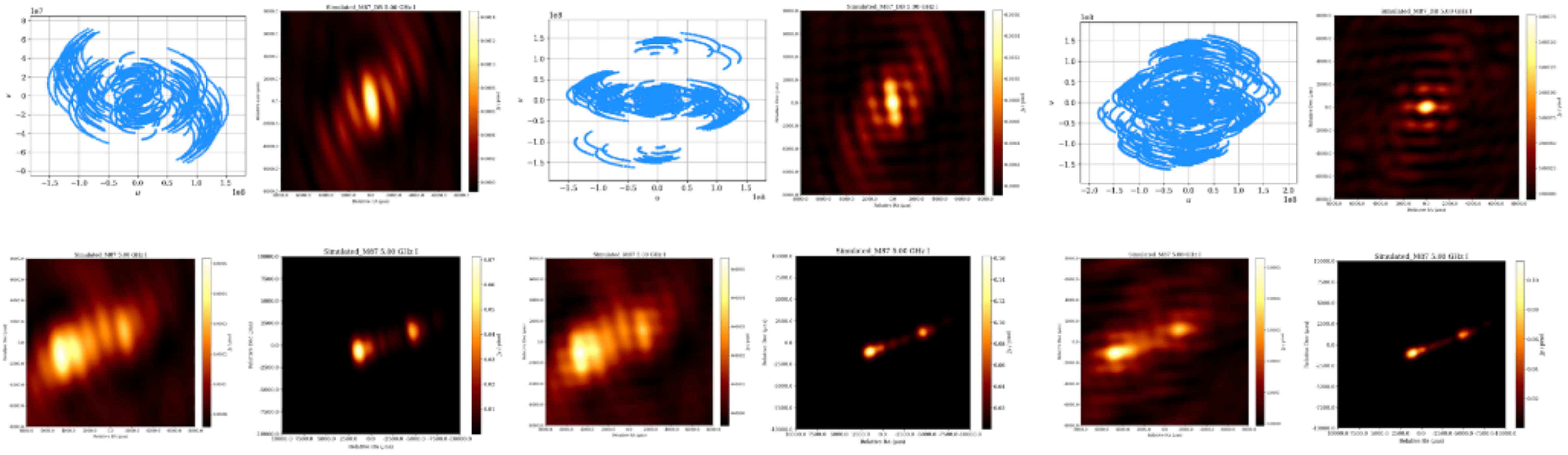
# Synthetic data generation

**CASE 1:**
**EVN (only NE antennas)**

**CASE 2:**
**EVN + SKA core (4 km)**

**CASE 3:**
**EVN + SKA + AVN**



science in Radio Astronomy: applying cutting-edge technology to enhance the entire data chain, from receiver to final output
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# Synthetic data generation

- Software selection
- Benchmark datasets
- Astronomical datasets with realistic errors
- Vary calibration settings
- Compare results

# WP 5.4 Bayesian inference imaging

- Exploit EHT experience for imaging sparse arrays
- Apply to centimeter wavelengths
- Links to synthetic data generation and calibration in WP5.3

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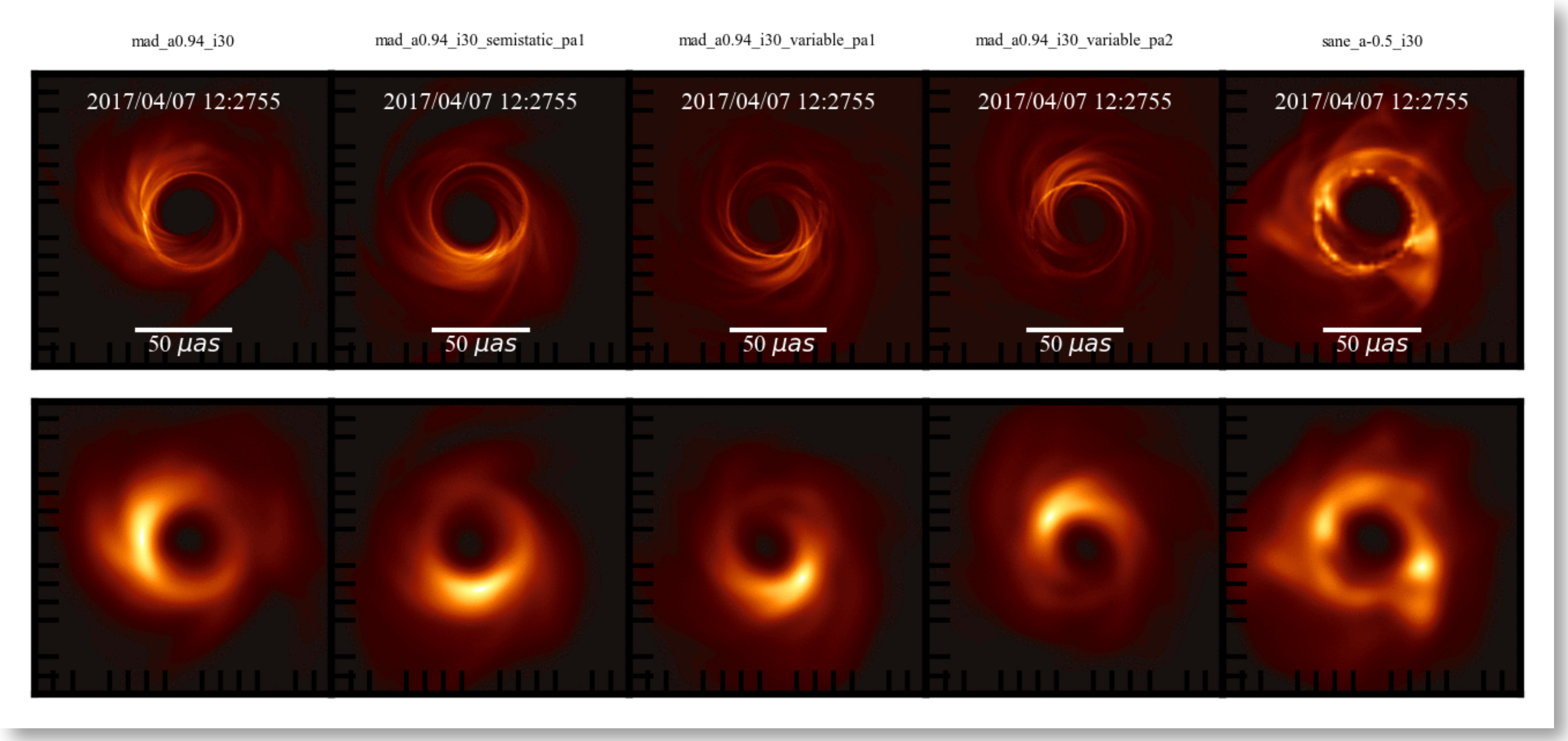
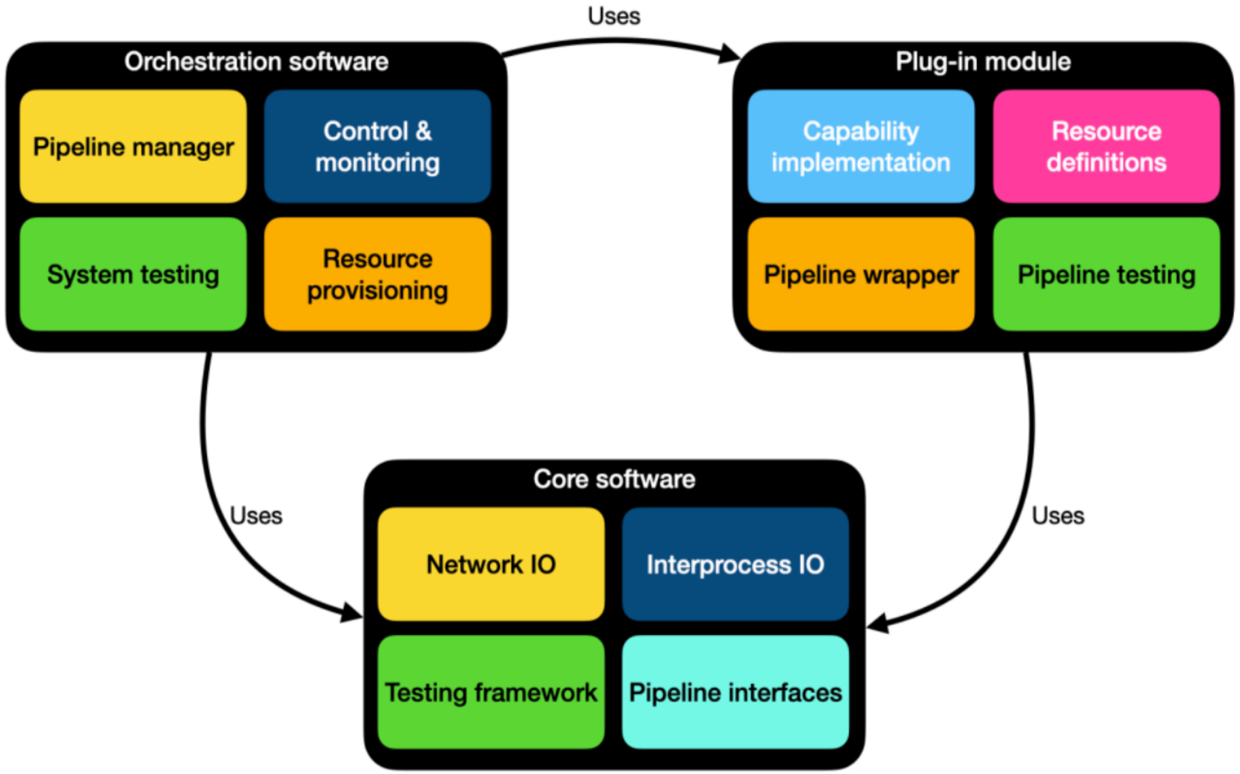
# Dynamic imaging




José L. Gomez (IAA)

# WP 5.5 PAF backend software

- Links to WP3
- Plug-in architecture based on Effelsberg Direct Digitization software package
- PAF beamformer & correlator
- VLBI tests Ef, Mc, Yb & SKA-MPG




Building radio telescopes for the future: brick by brick