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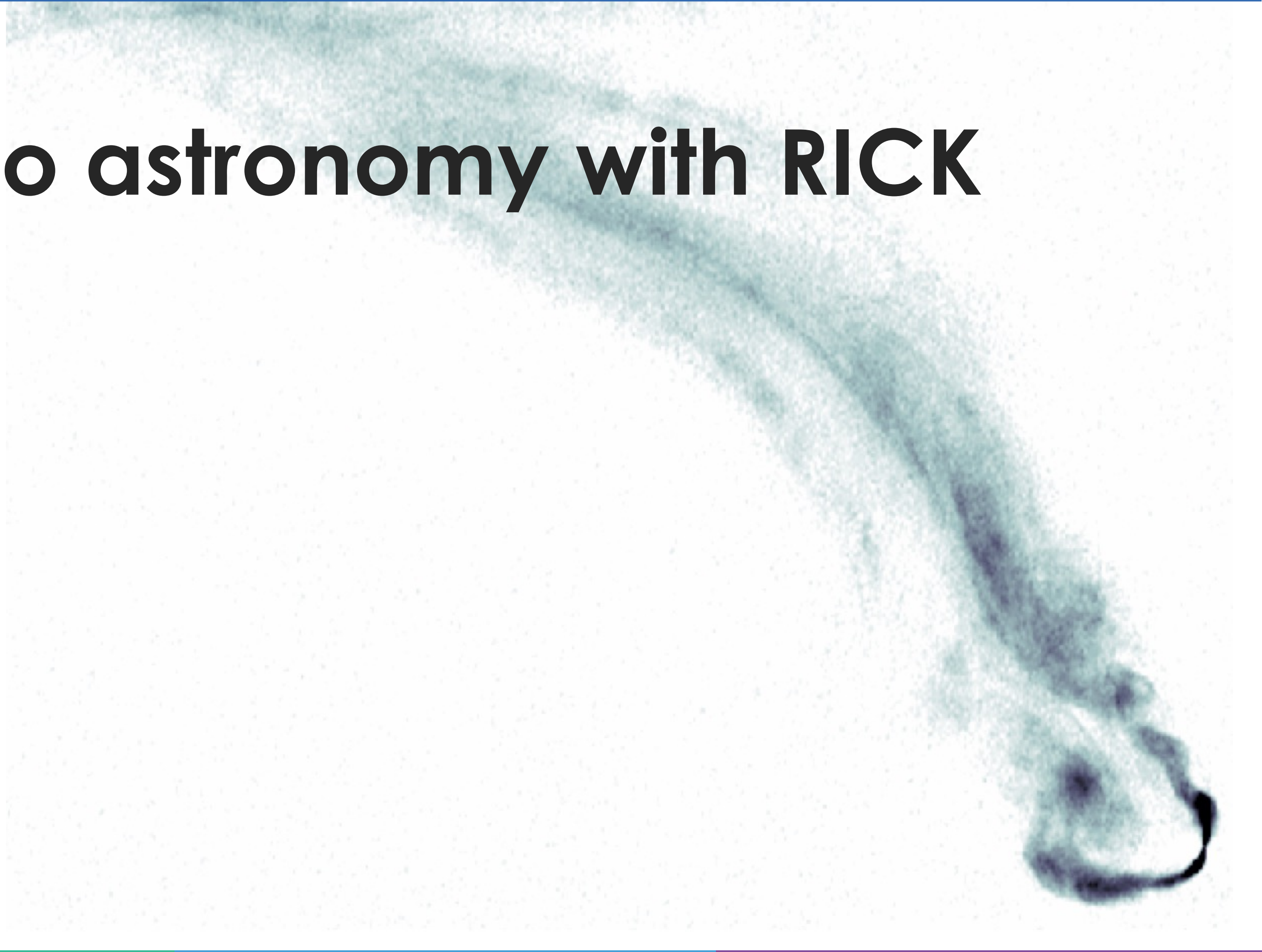
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing



Accelerated radio astronomy with RICK

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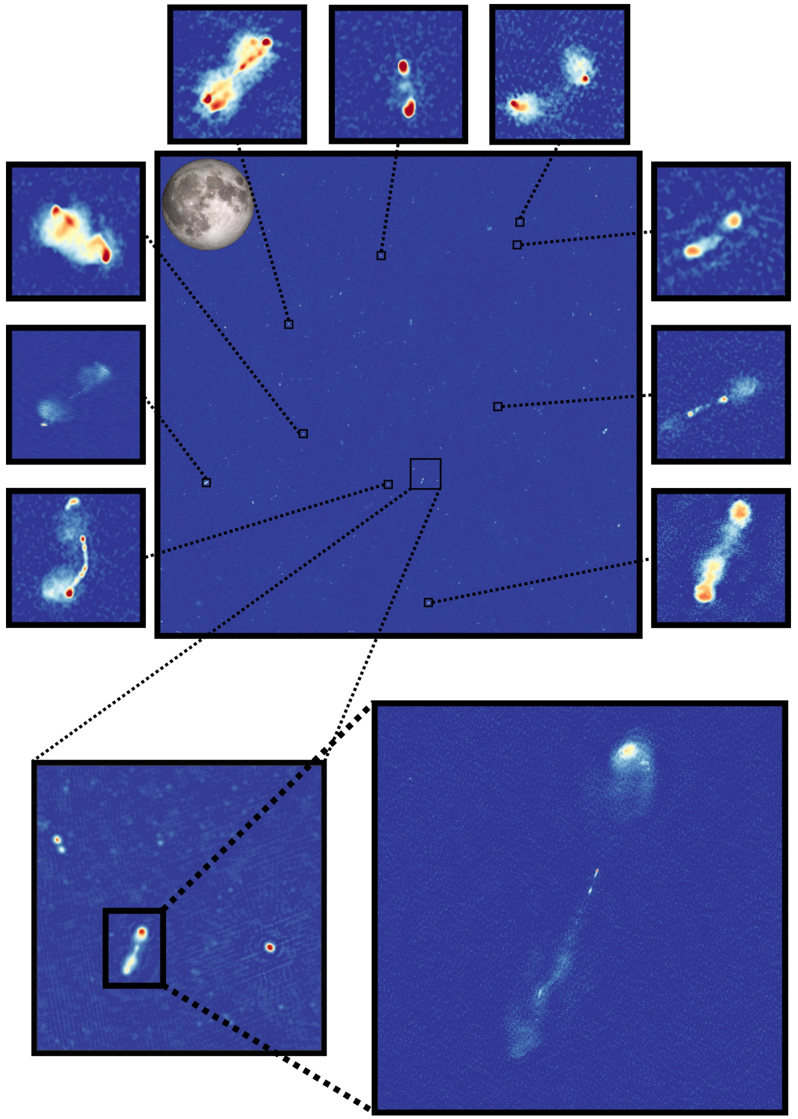
Why HPC in radio astronomy

Current and upcoming radio-interferometers are expected to produce **volumes of data of increasing size** that need to be processed to generate the corresponding sky brightness distributions through imaging.

This represents an **outstanding computational challenge**, especially when **large fields of view** and/or **high-resolution** observations are processed.

Imaging represents one of the most computational demanding steps of the processing pipeline, both in terms of memory request and in terms of computing time.

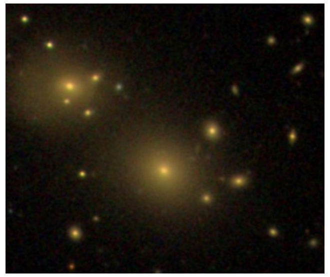


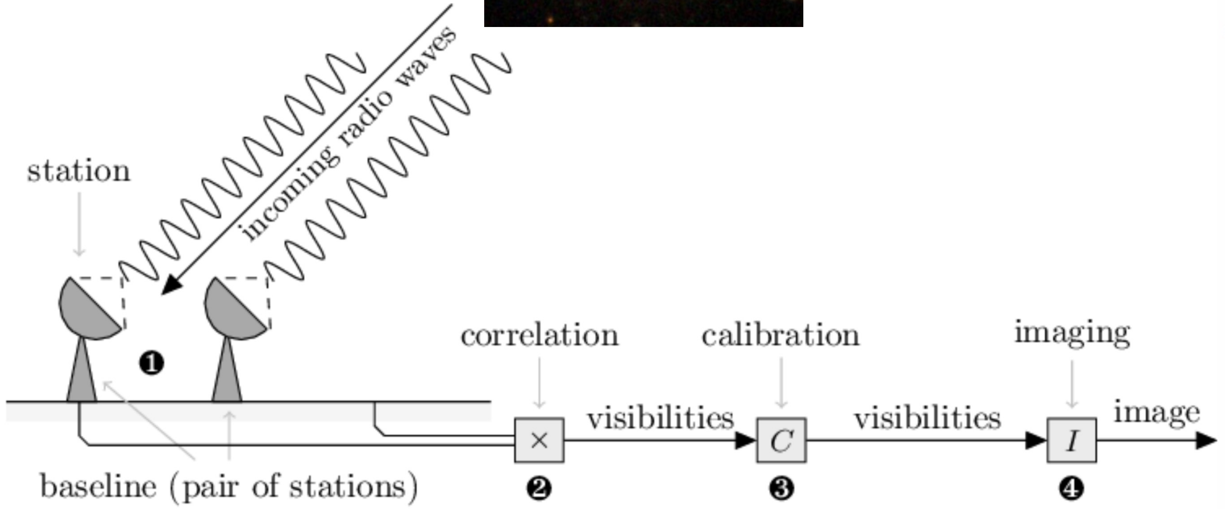
Sweijen et al. (2022)

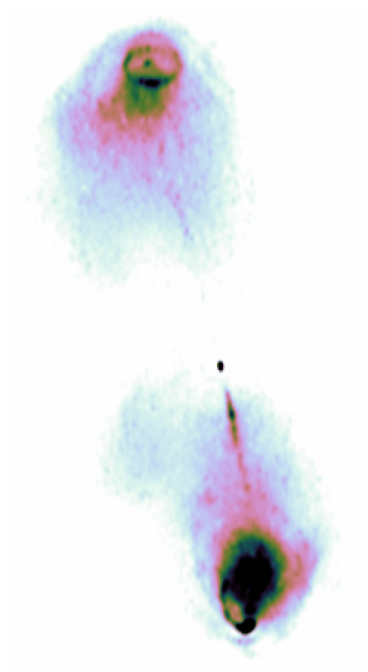
For example, this 83,900x83,500 pixels image can take ~250,000 core-hours!

Radio astronomy imaging

In radio astronomy, imaging is the process through which the brightness distribution $I(l,m)$ is determined by the complex visibility $V(u,v,w)$ observed by a radio telescope.







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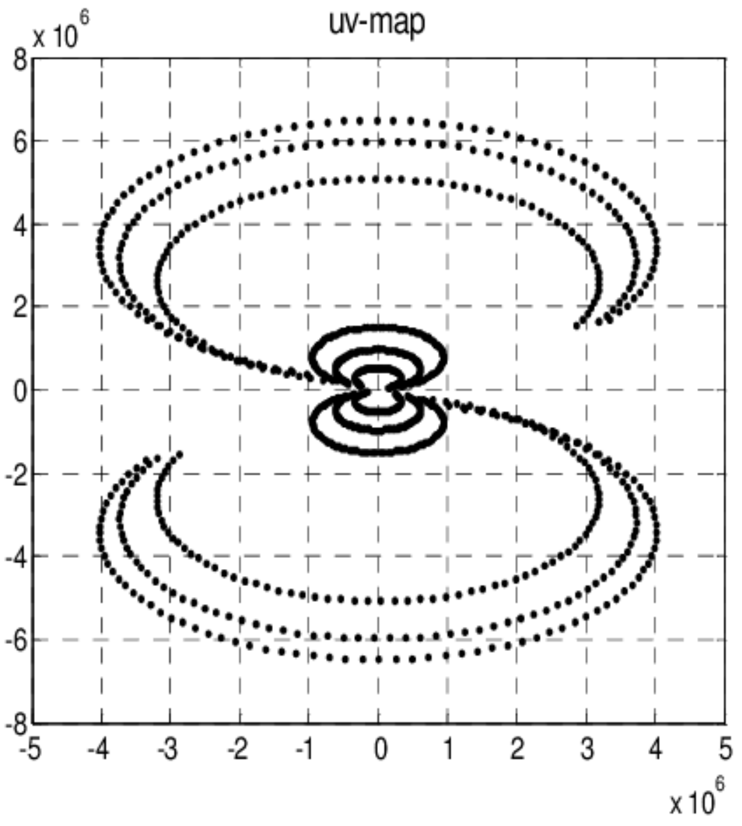

Visibility points are displaced into a regular mesh (so-called **gridding**).

$$\mathcal{N} \propto 0.5 \times N_b(N_b - 1) \times \tau_{time} \times \tau_{freq}$$

The SKA will produce **hundreds of billions of visibility points!**

Radio astronomy imaging

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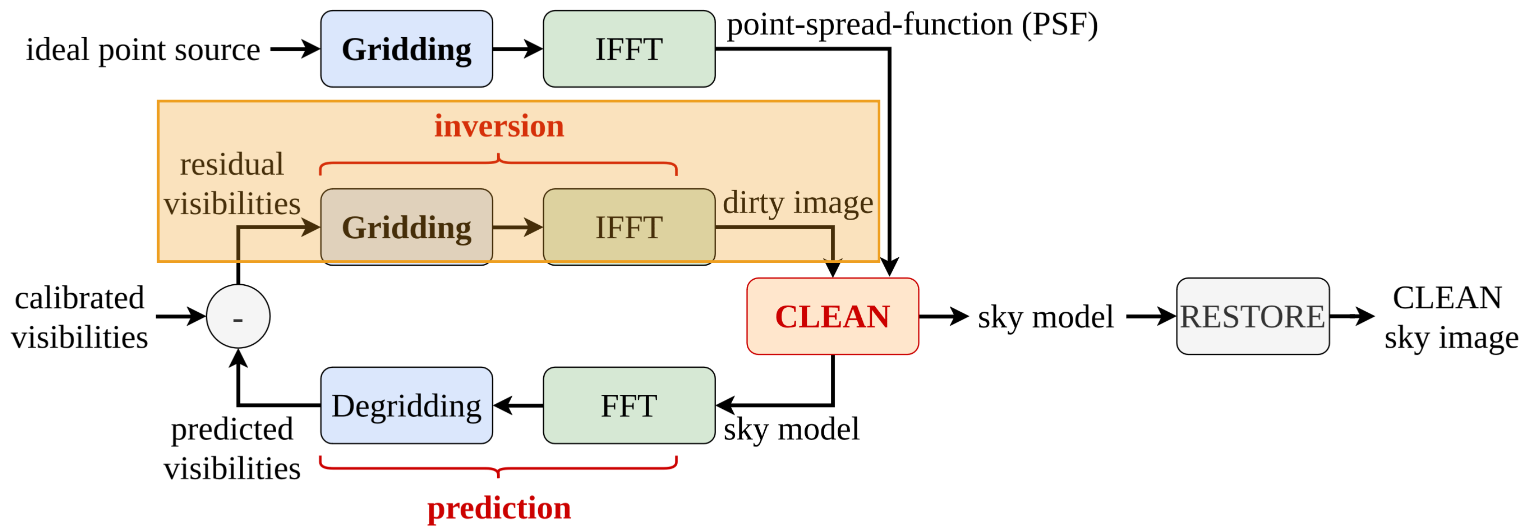
There is a Fourier transform relationship between the observed visibilities V(u,v,w) and the brightness distribution I(l,m):

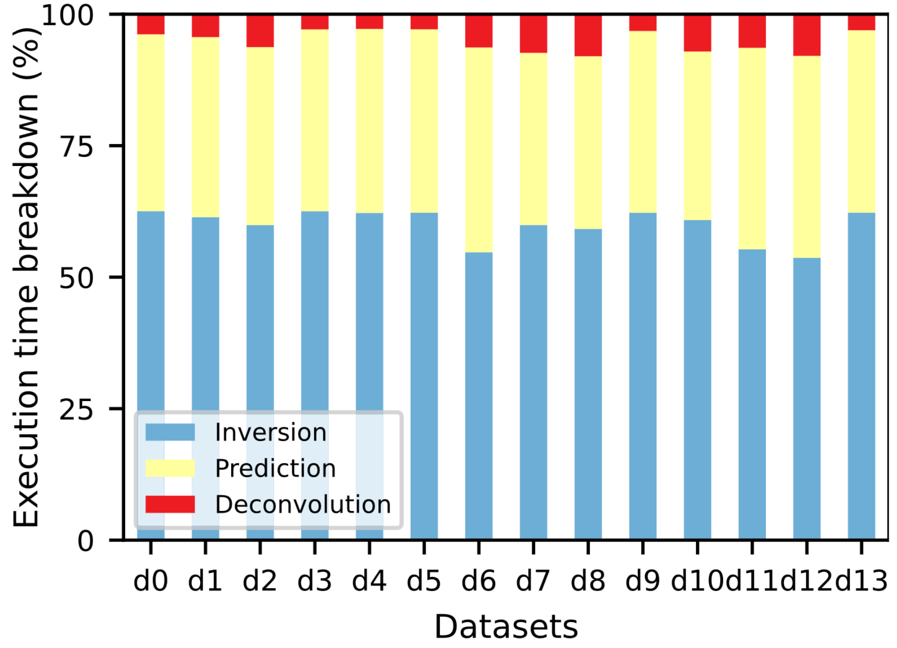
$$V(u,v,w) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(l,m) e^{-2\pi i\left[ul+vm+w\left(\sqrt{1-l^2-m^2}-1\right)\right]} \frac{dl\,dm}{\sqrt{1-l^2-m^2}}$$

After gridding and Fourier transform, we get a so-called **dirty image**, which is the starting point to produce a final, scientific radio image.

This procedure, known as **inversion**, is particularly time consuming, reaching several tens of hours for large images and/or datasets.

Radio astronomy imaging





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Corda et al. (2022)

Where are we now?

The state-of-the-art for radio astronomy imaging is WSClean* (Offringa+ 2014; 2017), a C++ software which implements the *w*-stacking algorithm for imaging exploiting multi-threading, multi-processing, and CUDA (but only for gridding and single-GPU).

✓ Most used tools for current radio interferometers (such as LOFAR or MeerKAT), great behaviour in several scientific cases (e.g., multiple scales of emission, faceting, etc.).

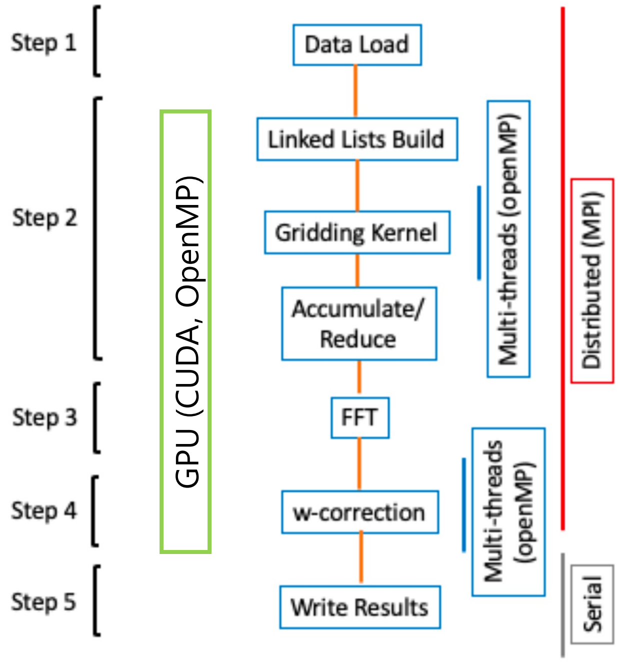
❖ Its parallel and GPU enabling is trivial and not yet fully “digested” by the users.

*https://wsclean.readthedocs.io/en/latest/

What is RICK?

RICK (Radio Imaging Code Kernels) is a code that addresses the *w*-stacking algorithm (Offringa+14) for imaging, combining parallel and accelerated solutions.

- **C**, **C++**, **CUDA, HIP**
- **MPI** & **OpenMP** for CPU parallelization
- The code is now capable of **running full on multiple GPUs**, using CUDA, HIP or OpenMP for offloading
- An optimized version of the **reduce** has been developed on both CPU (combining MPI+OpenMP) and GPU (using **NCCL** or **RCCL**, for Nvidia and AMD respectively); the **FFT** is done through the **cuFFTMp** library for Nvidia
- Publicly released*; a paper has been submitted to Astronomy and Computing (waiting for peer review)



De Rubeis et al. (2024)

*https://github.com/ICSC-Spoke3/RICK

Why do we need multiple GPUs?

Modern and future radio telescopes will produce a **huge amount of data**, that hardly fit the memory of a single GPU (not even a single node)

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↓

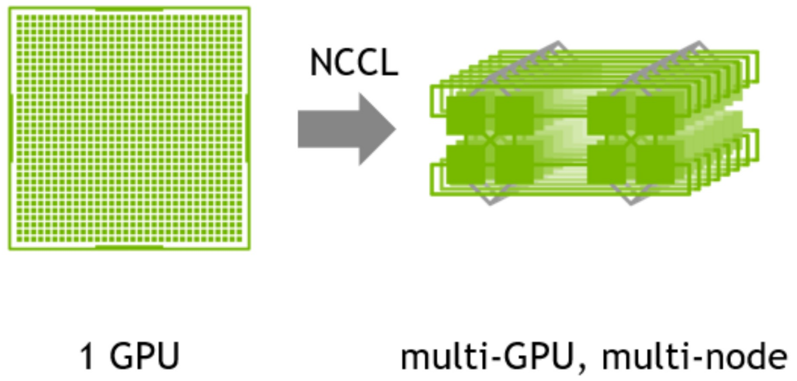
The answer is then **to distribute the problem** among multiple GPUs and multiple nodes

Easy to say, more difficult to do…

Nvidia Collective Communication Library (NCCL)

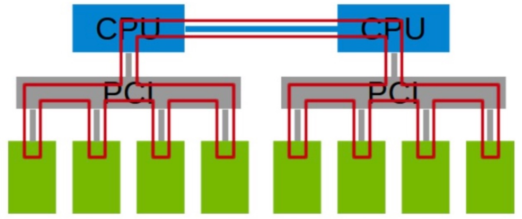
NCCL is a library of multi-GPU collective communication used to support the *Reduce* operation.

- Provides **fast collectives** over **multiple GPU both within and across nodes**.
- Supports a variety of **interconnect** technologies (e.g. NVLink, PCIe).
- NCCL closely follows the popular **collectives** API defined by **MPI**, so can be very “natural” to use.

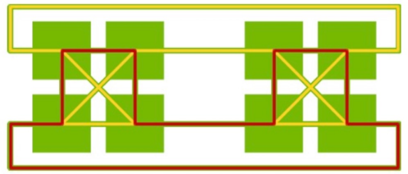


Nvidia Collective Communication Library (NCCL)

NCCL implements the *Reduce* operation as an intra-node ring, and an inter-node ring, when GPUs assigned to the main tasks communicate with RDMA with GPUs in different nodes without passing through the CPUs.



PCIe / QPI : 1 unidirectional ring



DGX-1 : 4 unidirectional rings

```
ncclUniqueId id;
ncclComm_t comm;

ncclCommInitRank(&comm, size, id, rank);

ncclReduce(send_g, recv_g, size_g, ncclDouble, ncclSum, taget_rank, comm, stream)
```

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```

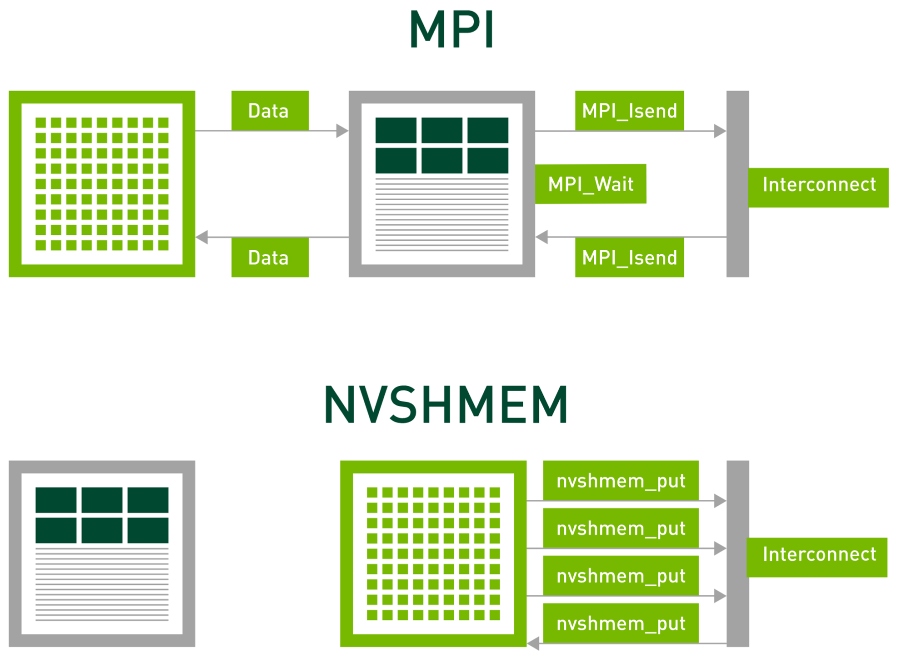
The requirement of a dedicated stream for the *Reduce* comes from the presence of asynchronous memory copies that collided with the ones within a previous function call

cuFFTMp

Fast Fourier Transform is a critical operation in radio astronomy, because it determines the relationship between the “observed” and the “desired” data (the final image).

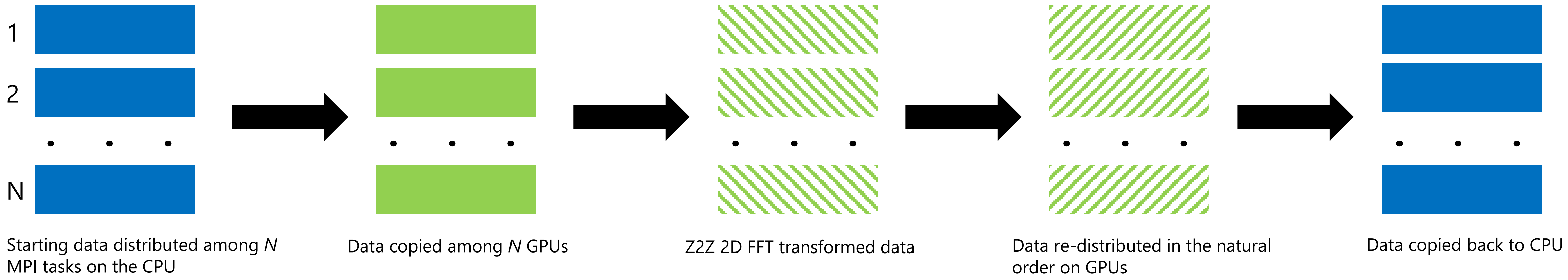
For the FFT step, RICK implements the **cuFFTMp** library, that allows to **distribute the FFT** problem using **NVSHMEM**

NVSHMEM uses asynchronous, **GPU-initiated data transfers**, eliminating synchronization overheads between the CPU and the GPU



cuFFTMp

Data are distributed among multiple GPUs and inverse-transformed.


1
2
N
Starting data distributed among *N* MPI tasks on the CPU
Data copied among *N* GPUs
Z2Z 2D FFT transformed data
Data re-distributed in the natural order on GPUs
Data copied back to CPU

However, **now we have data already on the GPU!**

cuFFTMp

- ❖ We may need to do this FFT process even 100-1000s times, and at each time we need to create and destroy the *descriptor*, which is the data structure used by the library for the FFT.
- ✓ This was critical for the performance, but we overcame this problem using CUDA kernels to write the *to-be-transformed* data each loop, and then putting them directly inside the descriptor.

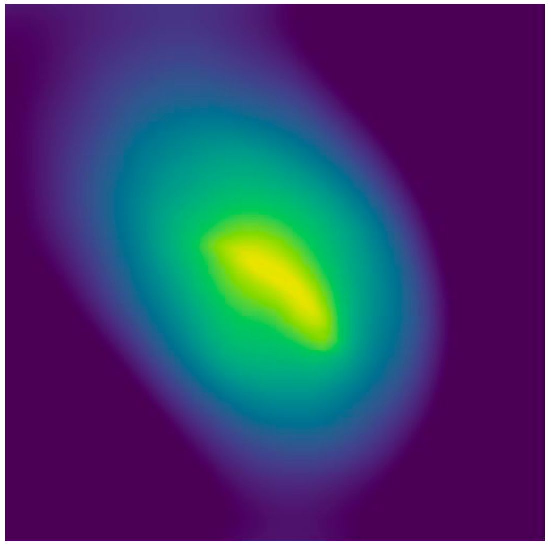
- ❖ The joint usage of NCCL and NVSHMEM, which can bring to severe errors during the FFT.
- ✓ There is the possibility to switch off NCCL support for NVSHMEM at runtime by setting *NVSHMEM_DISABLE_NCCL=1*.

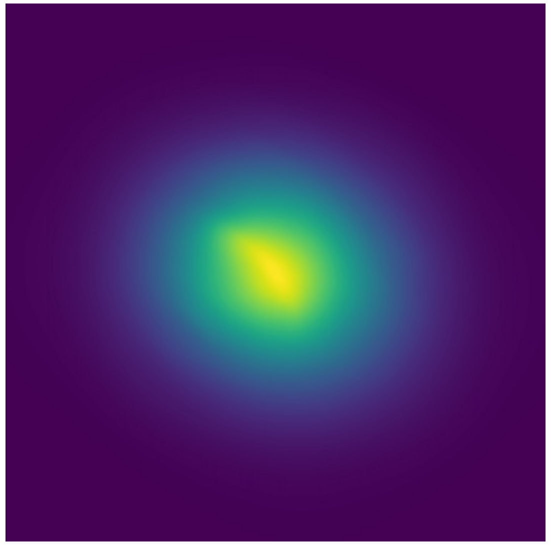
Was it worth it?

We tested our code on Leonardo (CINECA) using Nvidia HPC-SDK 24.3, using real LOFAR-VLBI data, that is the closest facility to SKA in terms of size of end-products.

Comparing the code with GPUs, with respect to the one on CPUs:

- for a small test (~4 GB), we got a speed-up up to a factor ~ **x27** for both *Reduce* and FFT
- for a big test (~530 GB), we got a speed-up up to a factor ~ **x175** for the *Reduce* and ~ **x32** for the FFT


WSClean

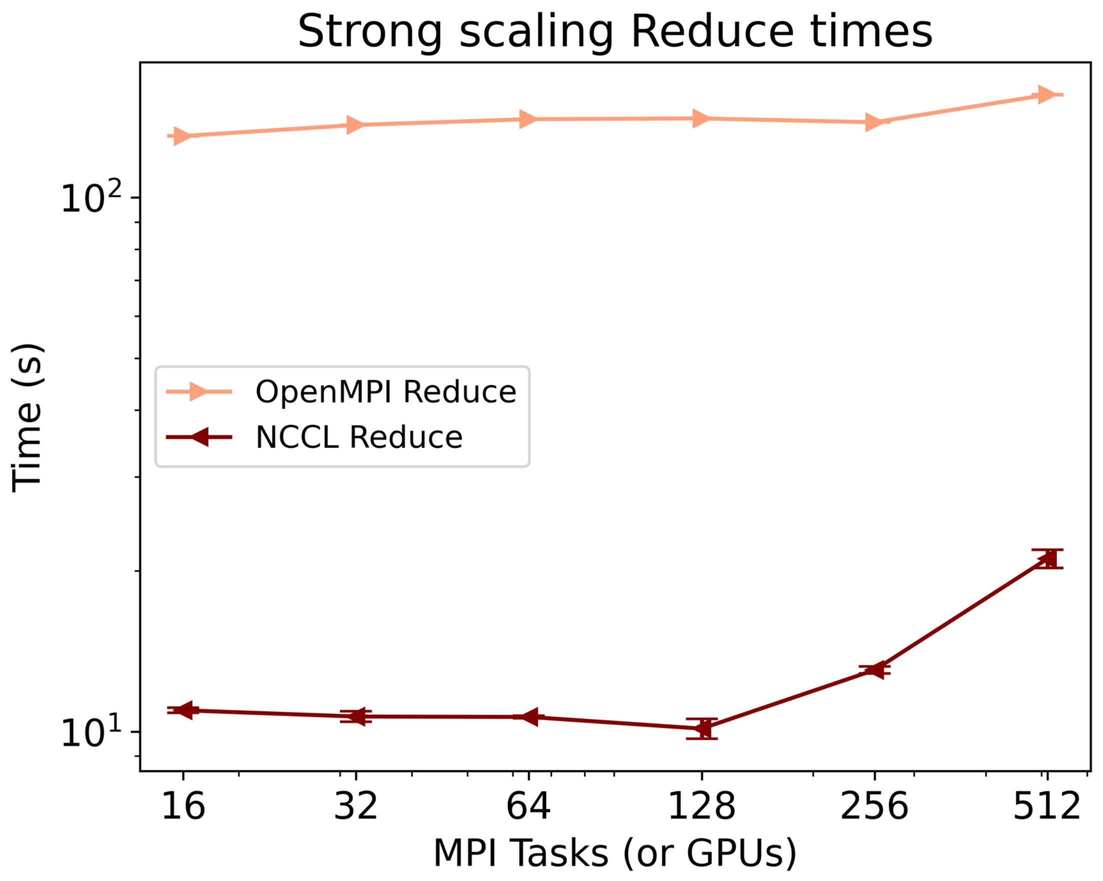

RICK

Was it worth it?

On the other side, RICK is now **limited by the communication costs**, with the reduce operation that becomes the true bottleneck of the code.

This means that it is important to choose the right number of computational resources based on the problem size.

Increasing power does not necessarily return an increasing performance!



De Rubeis et al. (2024)

Conclusions

- Radio astronomy is facing a huge computational challenge with current and upcoming interferometers, that will require the exploitation of HPC techniques.

- With RICK we aim at porting the most computationally expensive steps of radio imaging on multiple GPUs: it is now capable of fully running on Nvidia GPUs thanks to the NCCL *Reduce* and the cuFFTMp.

- We described the new updates on an upcoming paper (submitted in August).

- Next step: introduce RICK into WSClean workflow, to produce scientifically valid images.