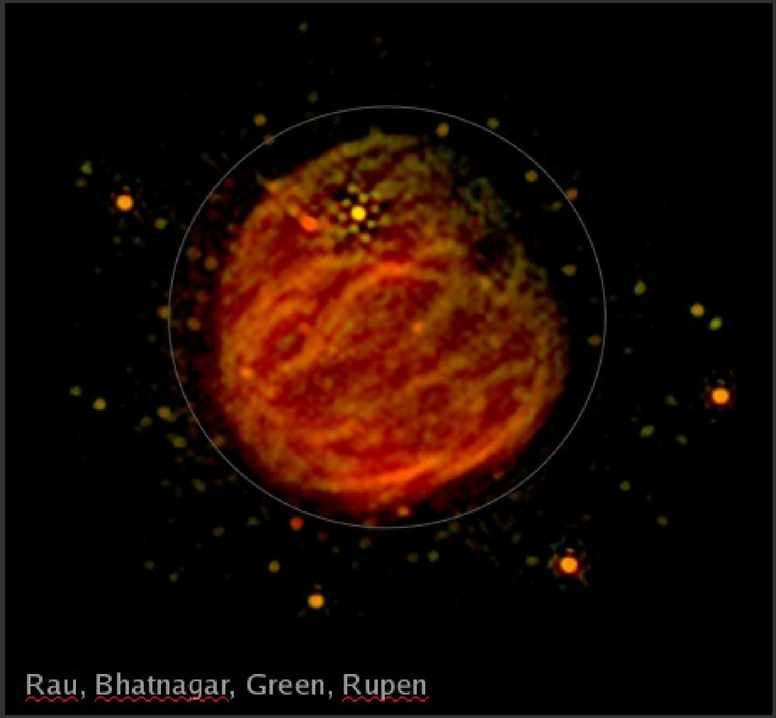
GPU based imager for radio astronomy

GTC2014, San Jose, March 27th 2014



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P. K. Gupta, NVIDIA-India, Pune
M. Clark, NVIDIA-US, CA

NRAO

Introduction

- Sanjay Bhatnagar
  - Algorithms R&D Scientist at the National Radio Astronomy Observatory, Socorro, New Mexico

- Motivation:
  - Deploy all compute-intensive imaging operations on the GPU
  - Why? How? Listen on...

Overview of the talk

- Introduction to NRAO
  - What is it? Why it is?
- Quick intro. to the scientific projects that pose the HPC problem
- Overview of RA imaging
  - What is needed for imaging with current & future telescopes
- Details of the current hot-spots
  - Motivate the three Proof-of-Concept (PoC) projects
  - Progress so far, future plans

National Radio Astronomy Observatory

- A NSF funded national observatory

- To build and operate large radio facilities
  - Operate three of the largest ground-based radio telescopes
    - » EVLA, ALMA, VLBA, GBT

  - Central Development Lab (CDL):
  - Digital Correlators for EVLA, ALMA, VLBA; digital back-end for the GBT

  - Off-line software for calibration, imaging and astronomical computing
    - » Open source
    - » Most widely used RA imaging software world-wide
    - » Runs on laptops, desk-tops, Compute Clusters

    - » Now exploring using GPUs to mitigate compute and memory footprint hotspots

The Very Large Array (NM, USA)

- Very Large Array
- 27 antennas
- Antennas movable on rails
  1 – 27 Km radius
- Spread over
  27 Km radius
- Size of the “lens”
  30 Km
- Frequency range
  300 MHz – 50 GHz

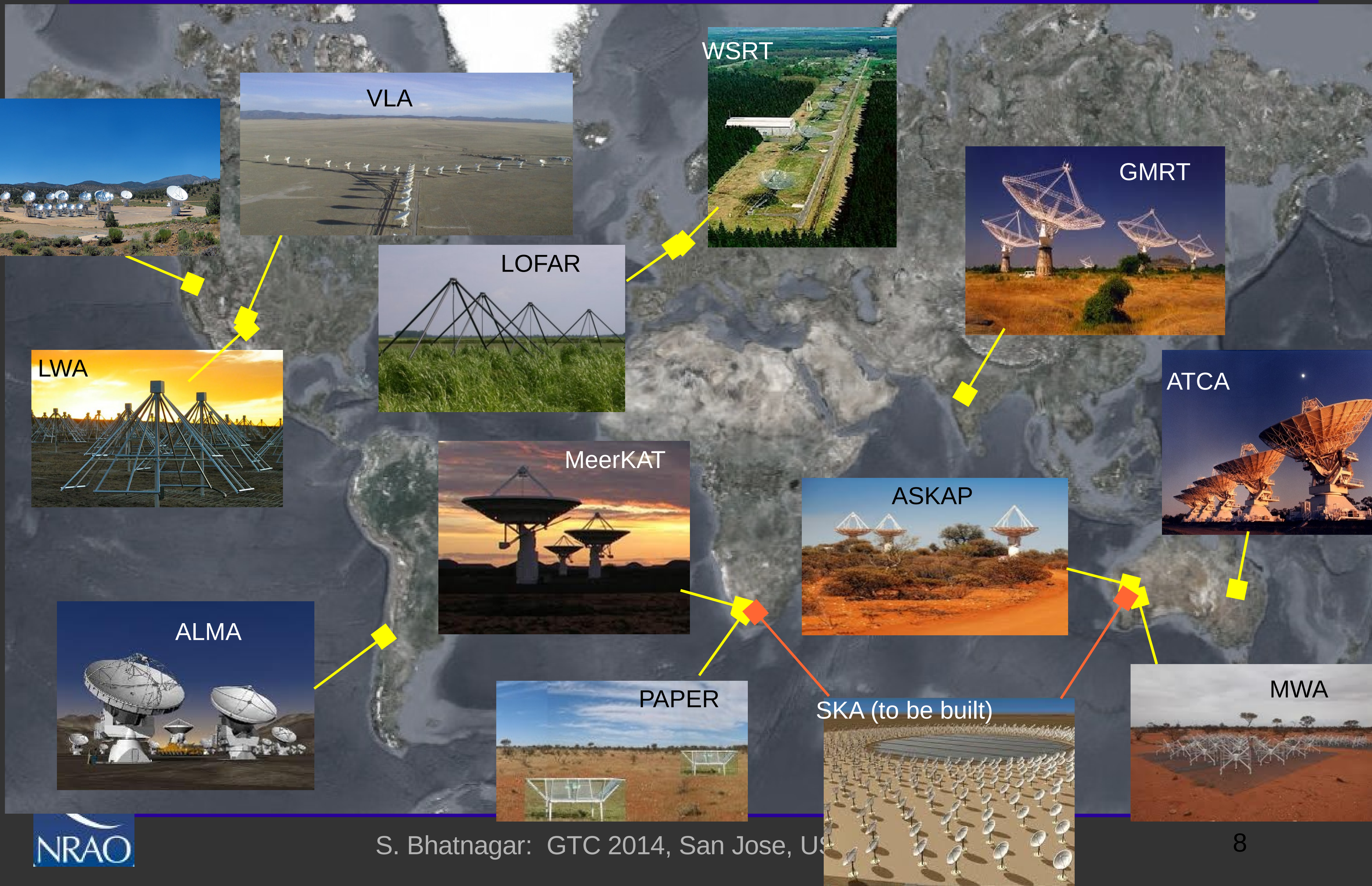
Atacama Large MM Array (ALMA), Chile

- In partnership with EU & Japan
- At an altitude of 16,500 ft
- 50 antennas
- Effective size of the lens: 3 Km
- Frequency range 100 GHz – 950 GHz
- Re-configurable with antennas movable on a special transporter.

Very Long Baseline Array (VLBA), US

- 10 antennas
- Antennas across the US
- Size of the “lens” few 1000 Km
- Frequency range 100 GHz – 950 GHz
- Angular resolution milli arcsec

Other RA Observatories in the world



Other RA Observatories in the world

Interferometric Imaging: Big Data

- Uses the technique of Aperture Synthesis to synthesize a “lens” of size equal to the maximum separation between the antennas

- Not a direct imaging telescope: Data is in the Fourier Domain

- Image reconstruction using iterative algorithms
  - Data volume with existing telescopes : 10 – 200 TB
    with SKA Telescope: Exa Bytes

Effective data i/o for image reconstruction: 10x

Interferometric Imaging: HPC

- Sensitivity improvements of 10x or more in modern telescopes
  - What was an ignorable/too weak an effect earlier, now limits the imaging performance of modern telescopes

- Need more compute-intensive imaging algorithms
  - Tera/Peta Flops now. Exa Flops SKA (soon....ish)

- **Orders of magnitude more expensive algorithms for imaging using many orders of magnitude more data**

Imaging algorithms in CASA for EVLA and ALMA
The "aw-imager" for LOFAR (NL) – a modified version of CASA Imager
ASKAP Imager (AU) optimized for large cluster computing

Interferometric Imaging

- Bottom line for computing
  - Tera – Exa(SKA) scale computing using Tera – Exa(SKA) Bytes of data to make Giga-Pixel images

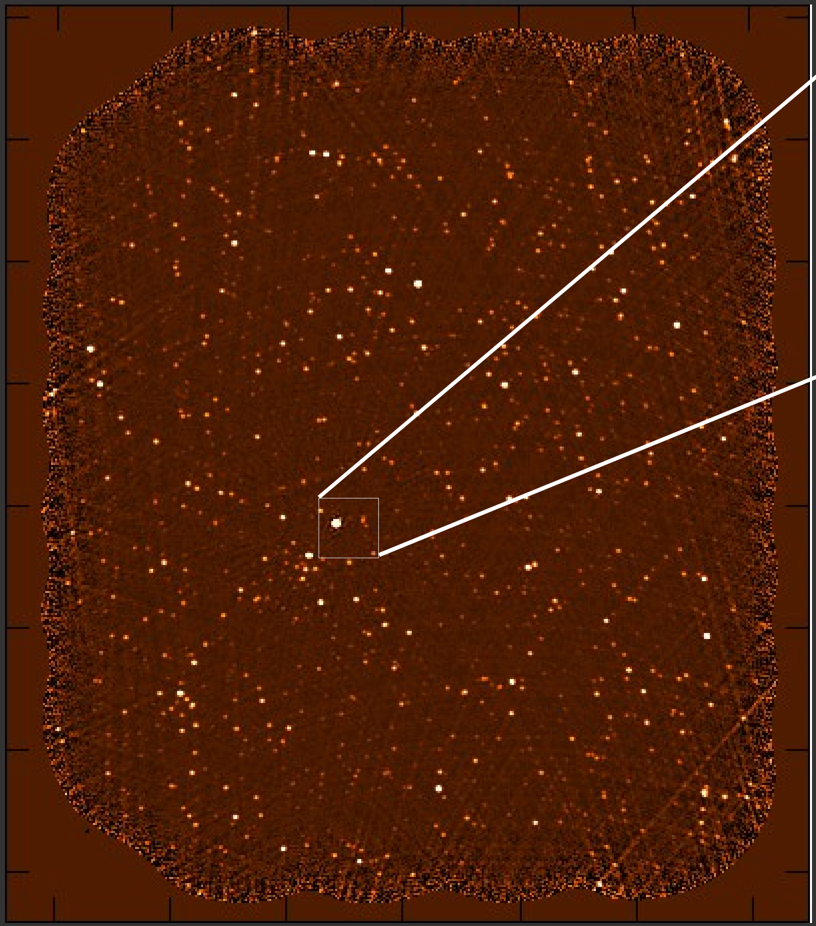
- Full end-to-end processing will require a cluster

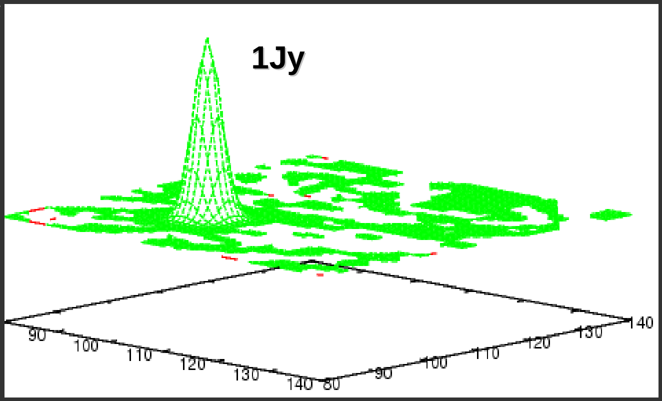
Computing hot spots

- Gridding / de-gridding: PoC - 1
  - Irregularly sampled data to a regular grid for FFT
- Computing Convolution Functions (CF): PoC - 2
  - Computing convolution kernels for Gridding
    - » Pre-compute-n-cache OR On-demand computing
    - » Memory foot print issues
- Wide-band Image Reconstruction: PoC - 3
  - Requires convolutions of many large images
    - » Pre-compute-n-cache OR
    - » On-demand Computing using GPU

Scientific projects: Deep Imaging

- Requires high resolution, high dynamic range imaging
  - i.e. Big Data
  - Compute-intensive algorithms
- Large area surveys of the radio sky





- Dynamic range
  - Ratio of strongest to weakest Source: 10^6
  - Dynamic range of raw images 10^{2-3}
- Need high resolution to reduce background sky-noise ("confusion noise")

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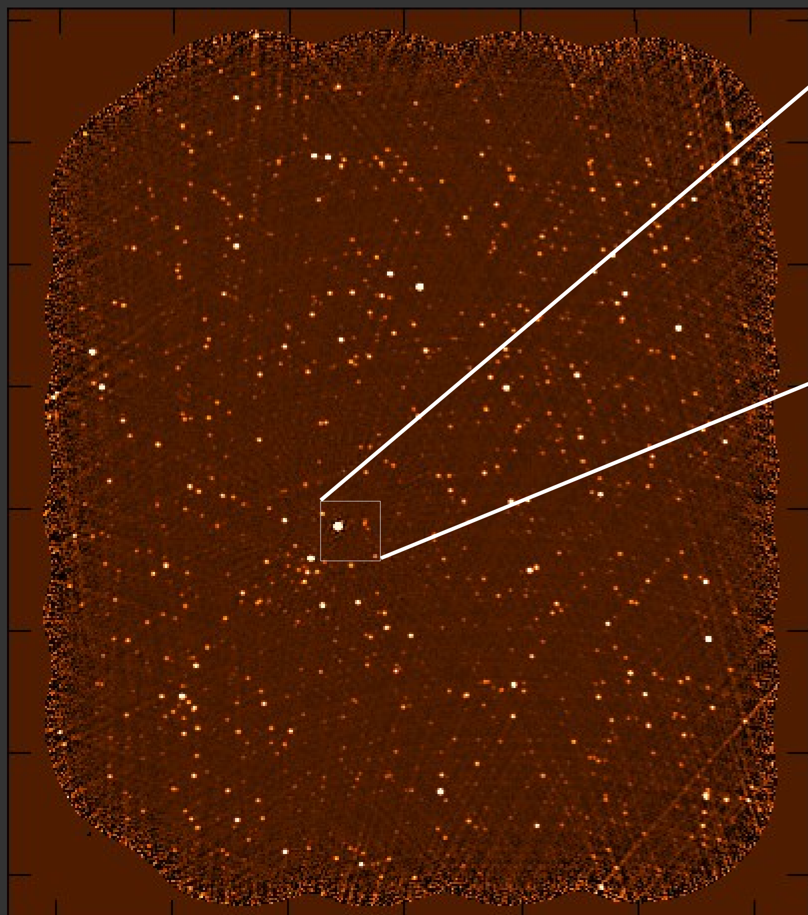

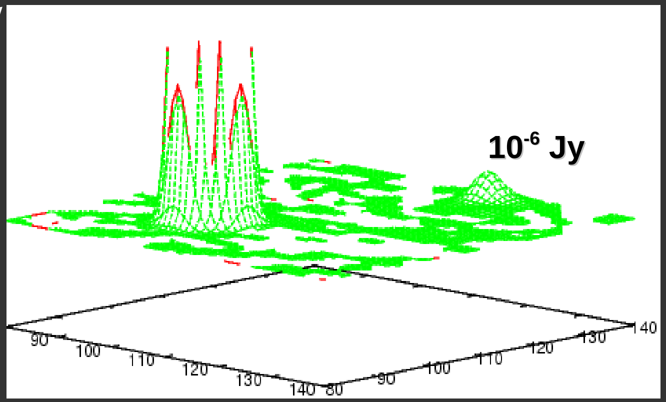

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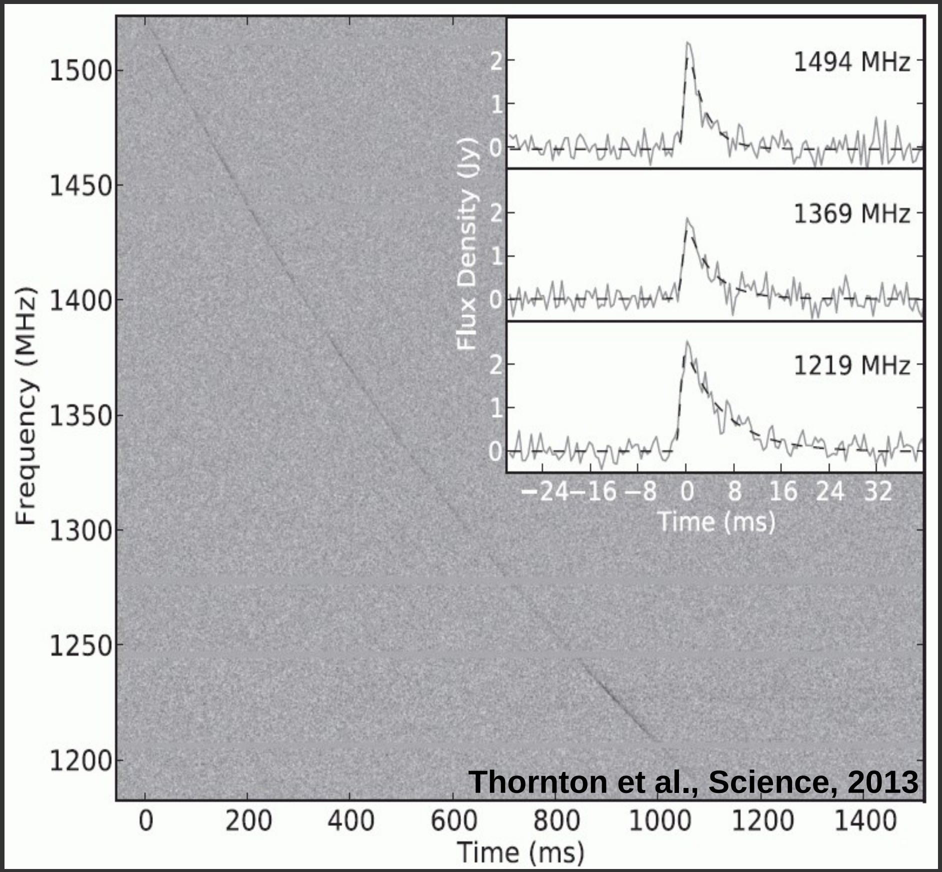
Scientific projects: Fast Imaging

- Transient sky
  - Storing data at high time resolution for later processing is not an option
  - Needs fast (near real-time) imaging → as a trigger to store busts of data



- A short blip in time
  - Spike of ms in 10s of hours of data
- Data rate too high to be recorded at ms resolution
- Need fast imaging as a trigger to record short busts of data
- Need interferometric imaging to localize on the sky

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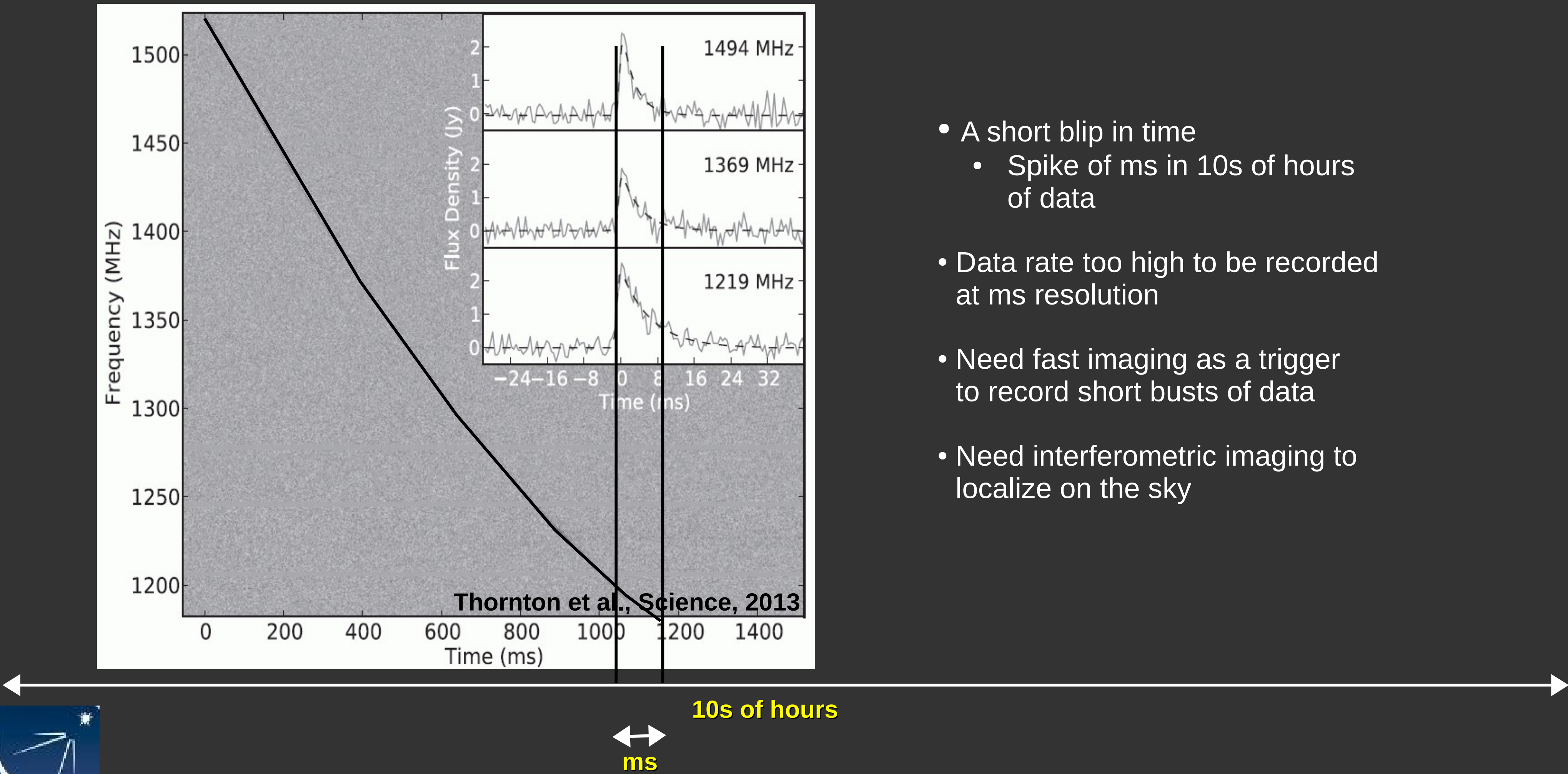

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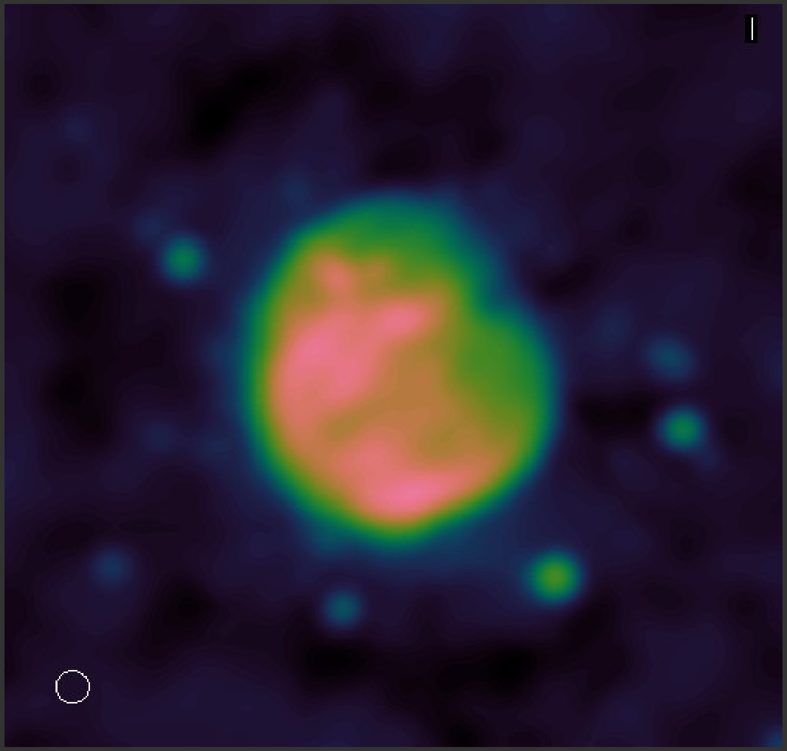
Aperture Synthesis Imaging: Why?

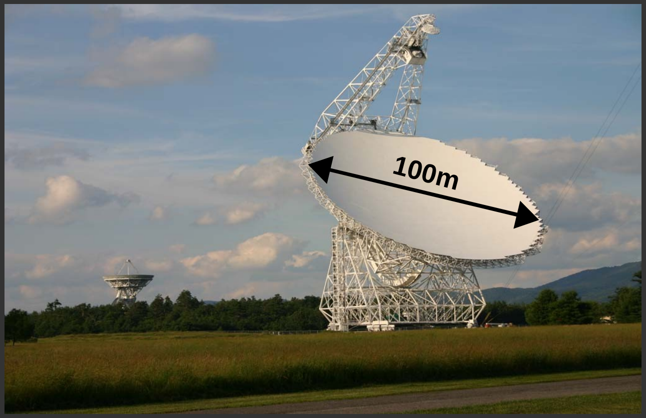
- Single dish Resolution too low for many scientific investigations
  - Limited collecting area + resolution limits sensitivity at low frequencies



Single dish resolving power

$$\frac{\textit{Wavelength}}{\text{Dish Diameter}}$$

Biggest steerable single dish = 100 m



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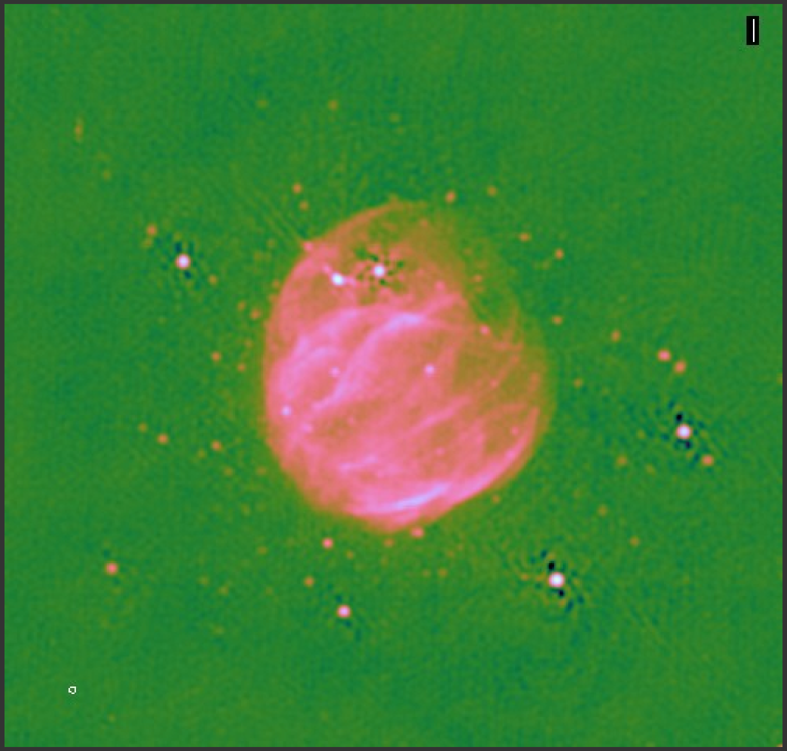
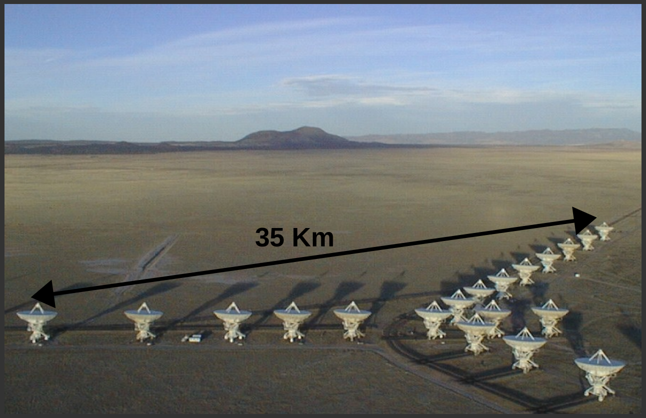


Synthesis Array resolving power

$$\frac{\textit{Wavelength}}{\text{Max. separation between antennas}}$$

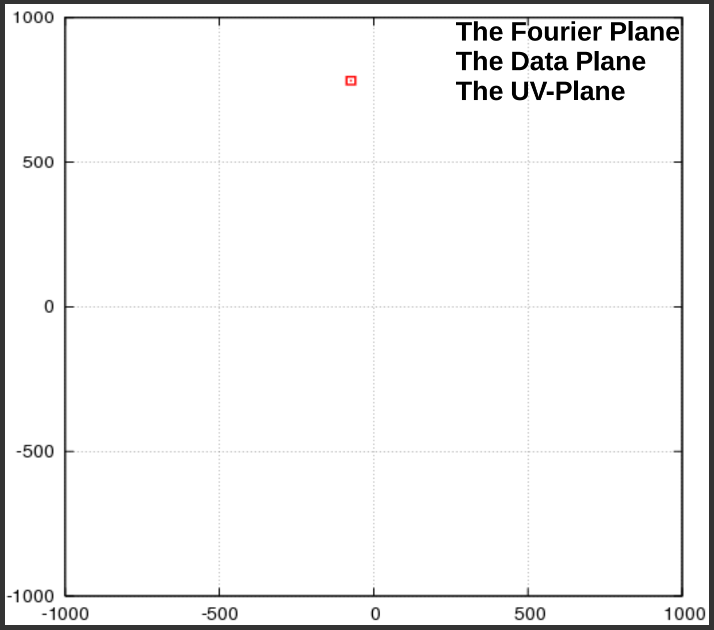
Max. separation in VLA
= 35 km

Resolution: ~ 350x better



Aperture Synthesis Imaging: How?

- Aperture Synthesis or Fourier Synthesis technique
  - An interferometric imaging technique (Nobel Prize in '74)
  - Many antennas separated by 10s – 100s Km
  - Each pair of antennas measure **one** Fourier Component



  - Synthesized aperture equal to the largest separation between antennas

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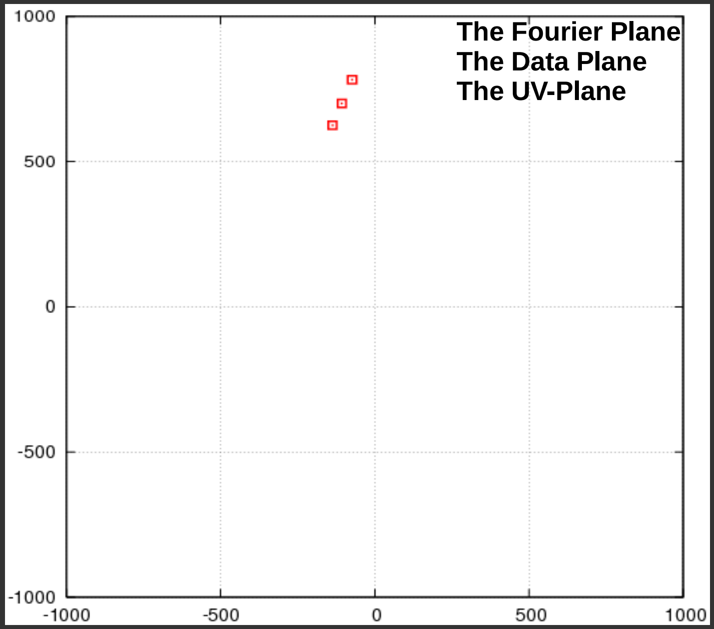

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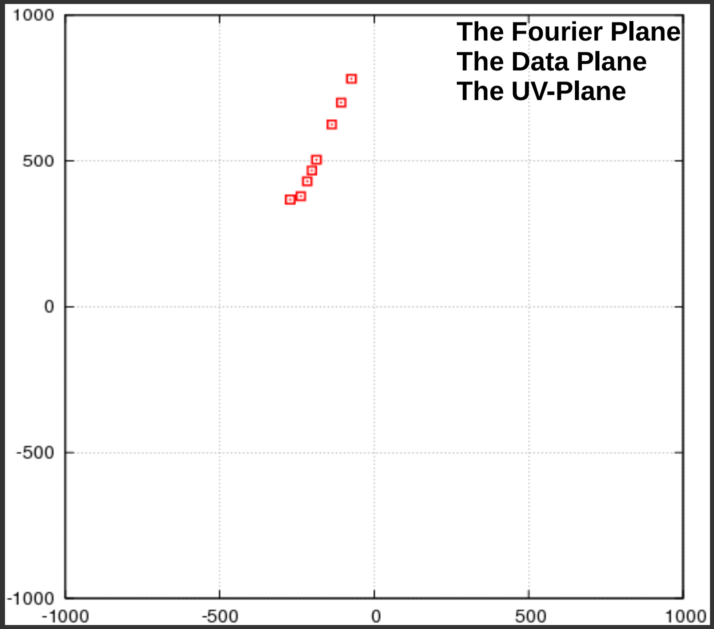

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Aperture Synthesis Imaging: How?

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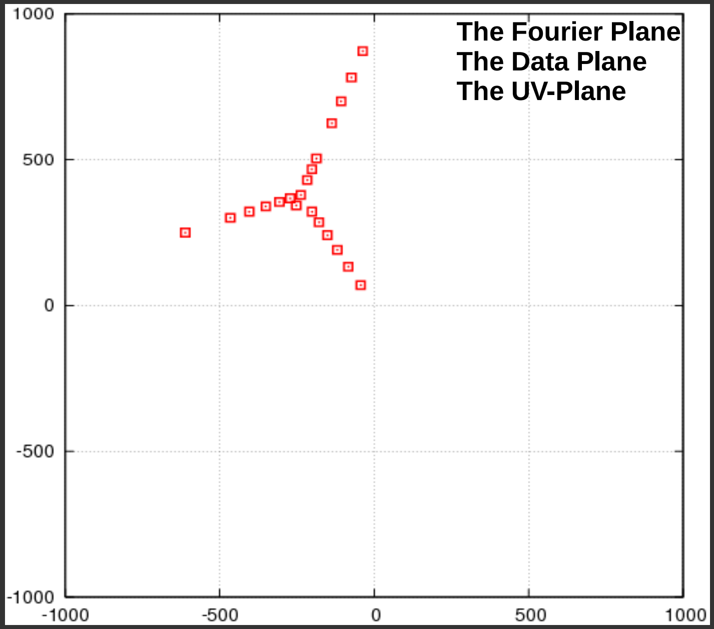
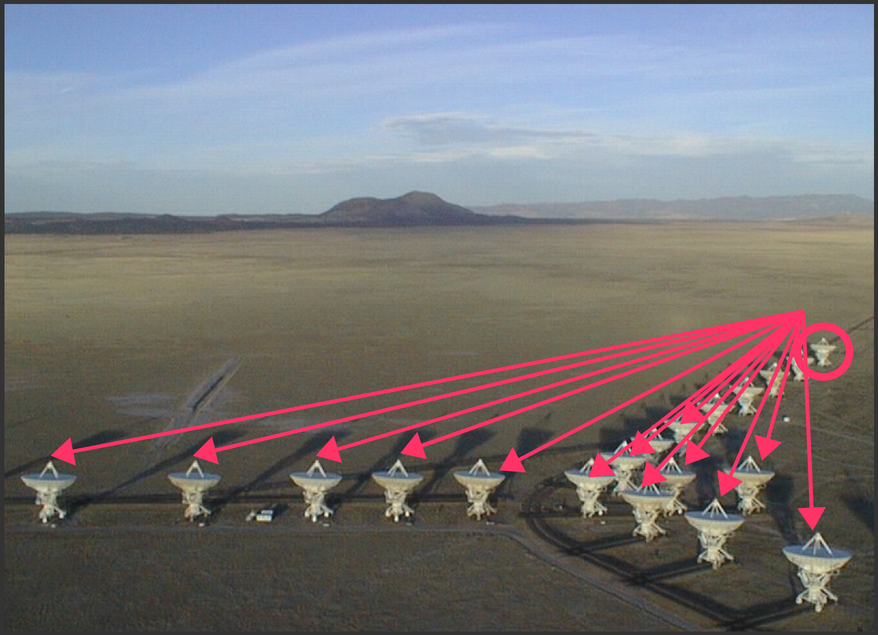
  - Many antennas separated by 10s – 100s Km
  - **All** pairs with **one** antenna measure N-1 Fourier Component = **26**





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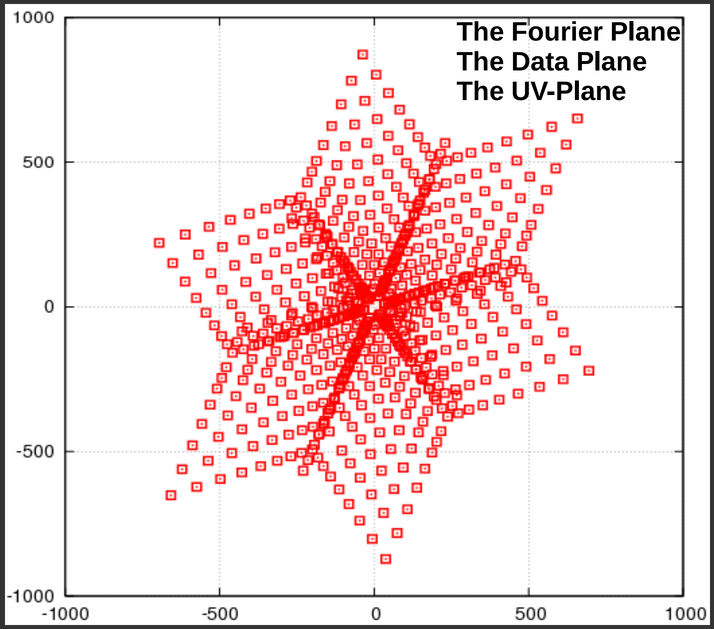
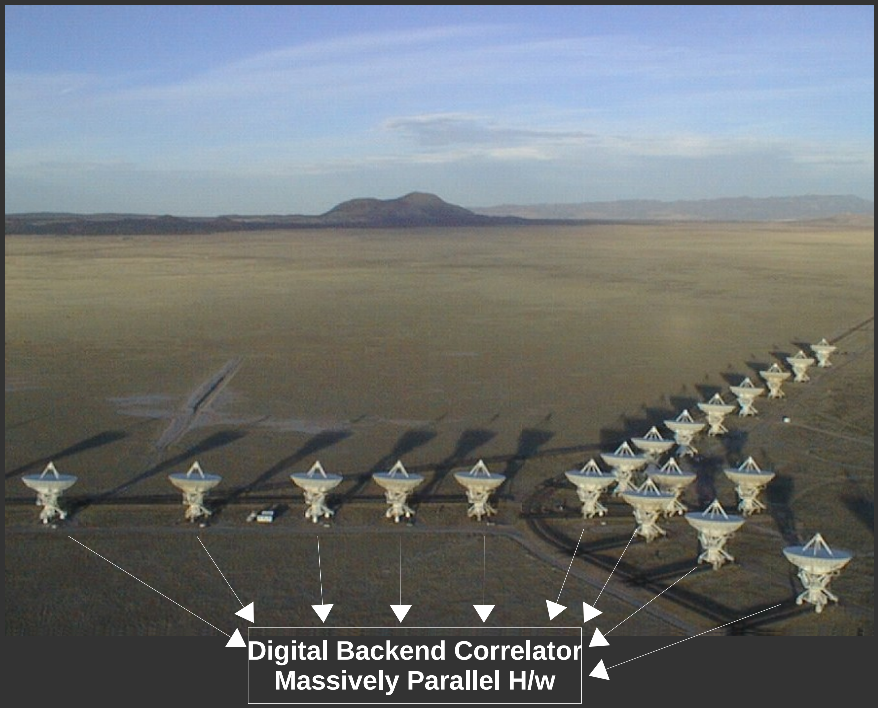
Aperture Synthesis Imaging: How?

- Aperture Synthesis
  - An interferometric imaging technique (Nobel Prize in '74)
  - Many antennas separated by 10s – 100s Km

  - **All** pairs with **all** antenna measure N(N-1)/2 Fourier Component = **351**

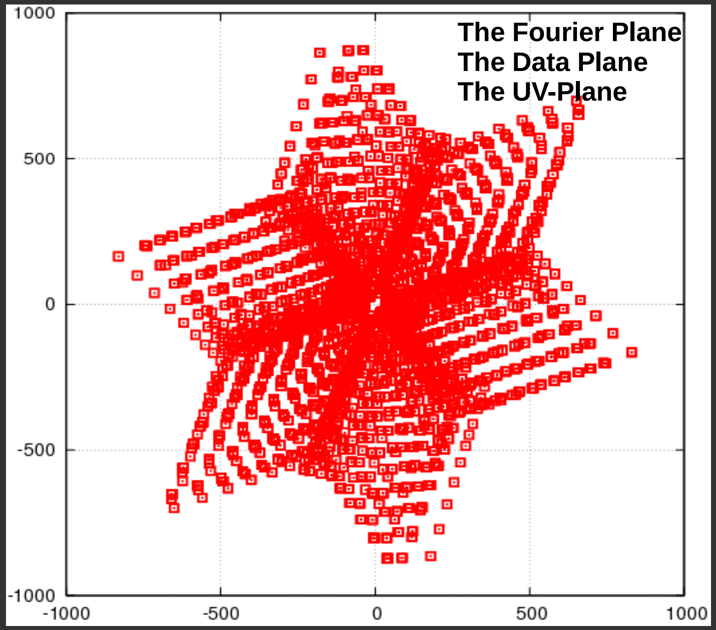


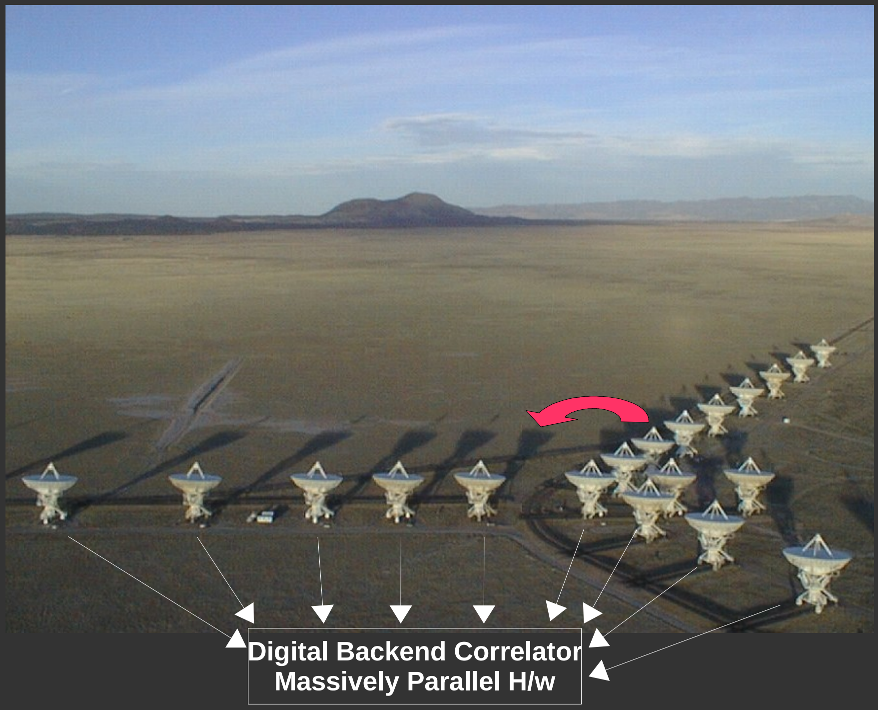


  - Synthesized aperture equal to the largest separation between antennas

Aperture Synthesis Imaging: How?

- Aperture Synthesis
  - Use **Earth Rotation Synthesis** to fill the Fourier plane
  - **All** pairs with **all** antenna measures N(N-1)/2 Fourier Component
  - Measure N(N-1)/2 x 2 Fourier components over 2 integration time = **702**





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Aperture Synthesis Imaging: How?

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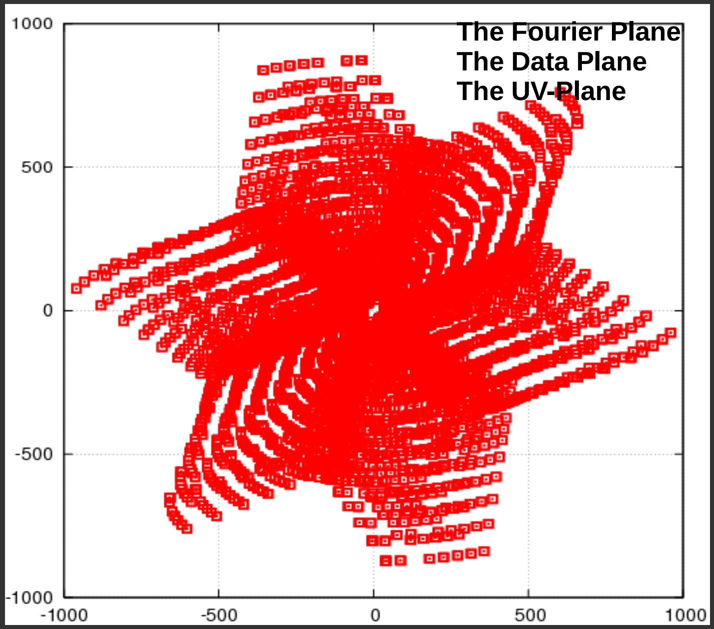
  - Use **Earth Rotation Synthesis** to fill the Fourier plane
  - **All** pairs with **all** antenna measures N(N-1)/2 Fourier Component
  - Measure N(N-1)/2 x 10 Fourier components over 10 integrations = **7020**

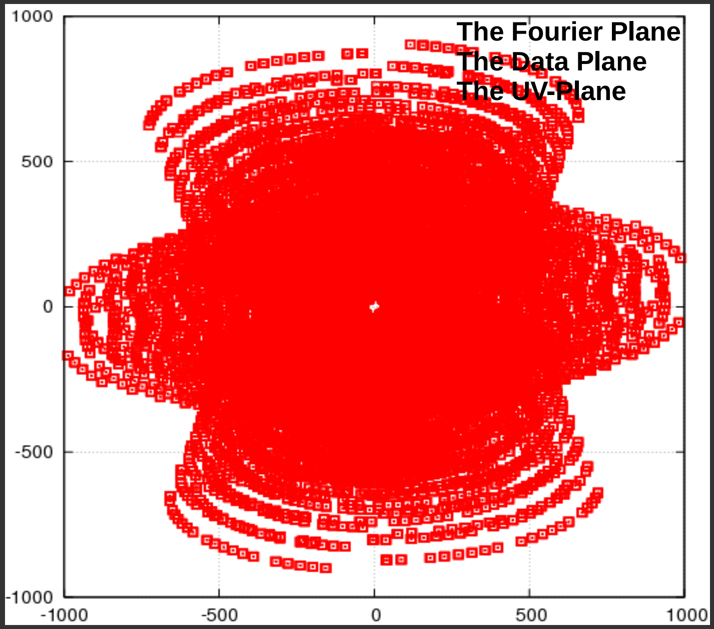


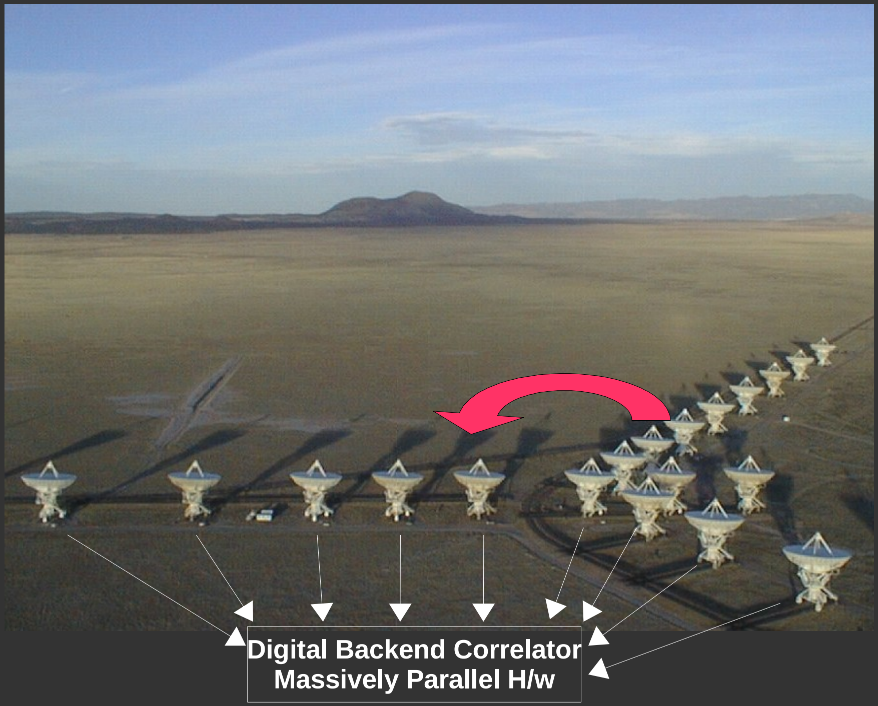
Digital Backend Correlator
Massively Parallel H/w

  - Synthesized aperture equal to the largest separation between antennas

Aperture Synthesis Imaging: How?

- Aperture Synthesis
  - Use **Earth Rotation Synthesis** to fill the Fourier plane
  - **All** pairs with **all** antenna measures N(N-1)/2 Fourier Component
  - Fourier Components measured over 10 hr: **$O(10^{11-12})$**

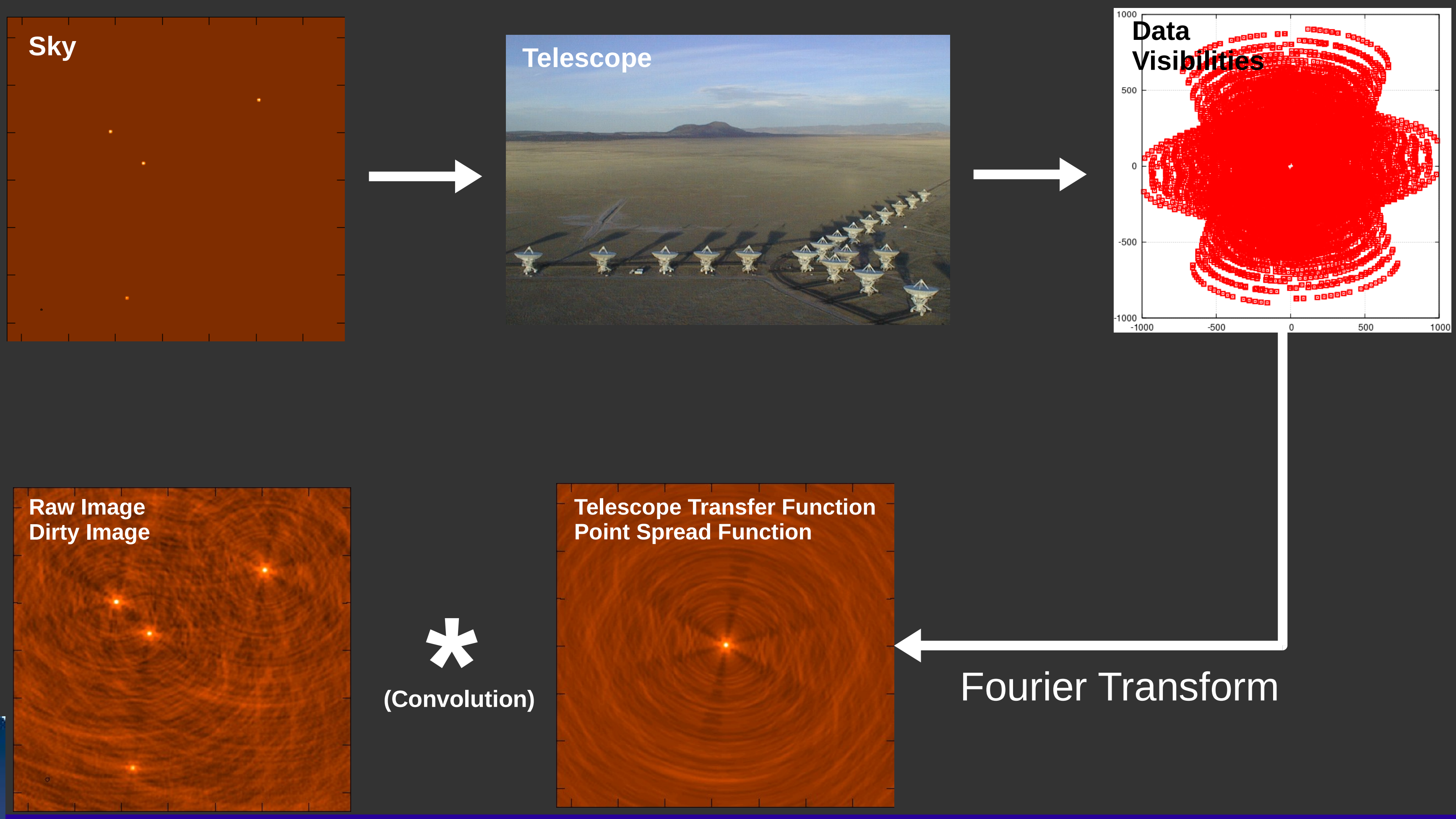




- Data Size: 10s – 100s TB now Up to Exa Bytes for SKA-class telescopes
- Data not on a regular grid.

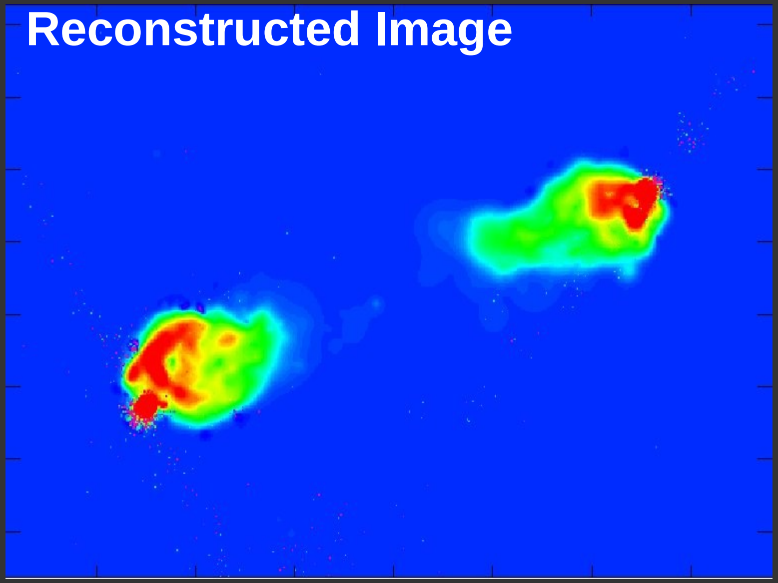
Interferometric Imaging

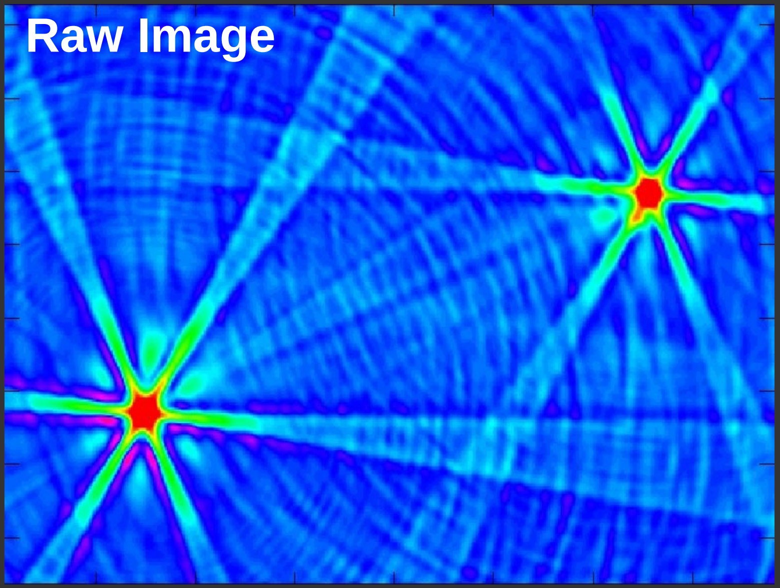
- Aperture Synthesis Imaging
  - Indirect imaging: data in the Fourier domain
  - Incomplete sampling → artifacts in the image



Interferometric Imaging

- Raw image (FT of the raw data) is dynamic range limited





Dynamic range: > 1 : 1000, 000

Dynamic range: 1 : 1000

- Processing: Remove telescope artifacts to reconstruct the sky brightness
- Image reconstruction is a High-Performance-Computing-using-Big-Data problem

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Interferometric Imaging

- Image reconstruction is an ill-posed Inverse Problem

$$D = A \, I^{true}$$

D: The Raw Data
A: The Measurement Matrix
I^{true}: The True Sky Brightness distribution

- Recover I^{true} given D

$$A^{-1} D = I^{True}$$

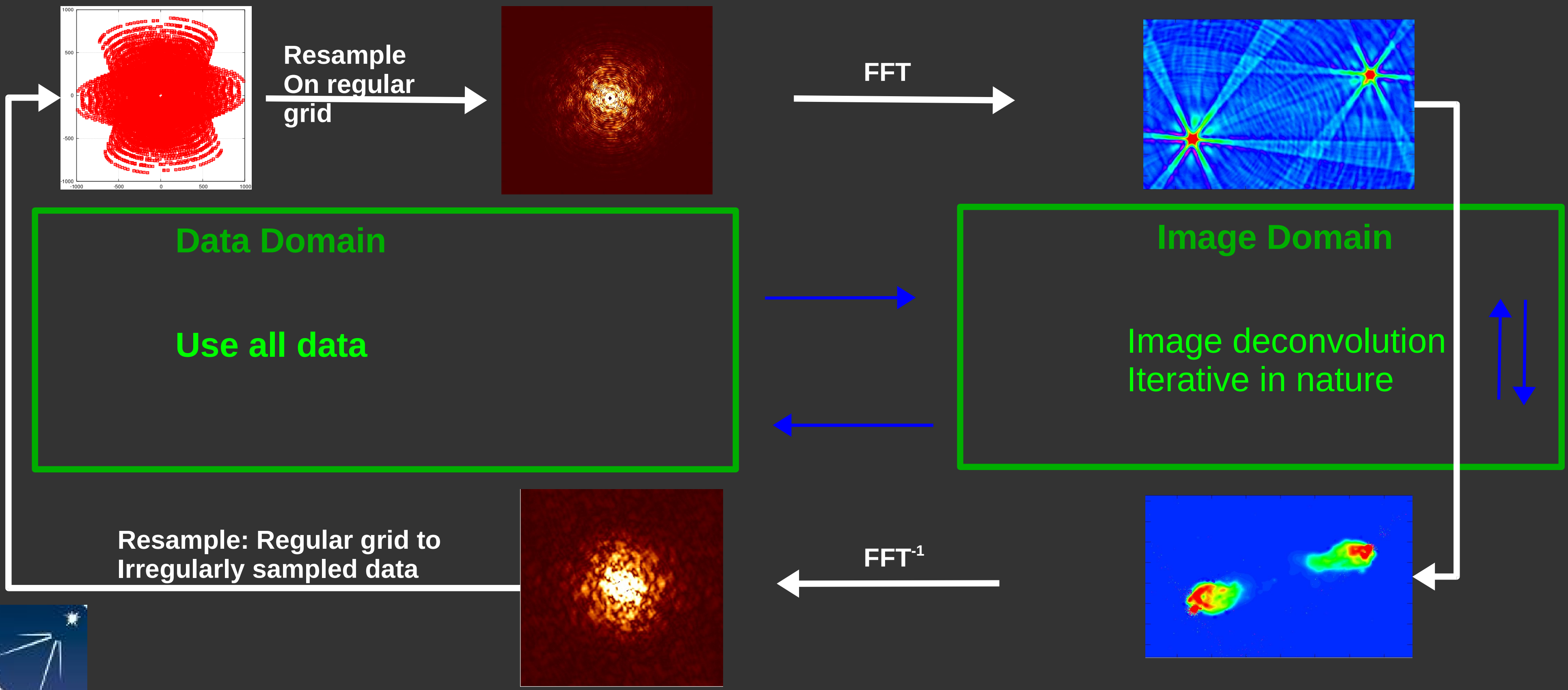
- **A** is singular ==> Non-linear (iterative) algorithms required to reconstruct the Sky Brightness distribution

- Typically 10 iterations, using **ALL** the data in each iteration

Raw Data: 10 – 100 TB **Effective data volume: 100 – 1000 TB**

The Computing Problem

- Basic computing steps
  1. Use FFT to transform to the image domain: Gridding + FFT
  2. Image-plane deconvolution of the PSF : Search and subtract on images
  3. Inverse transform to the data domain: De-gridding + Inv. FFT



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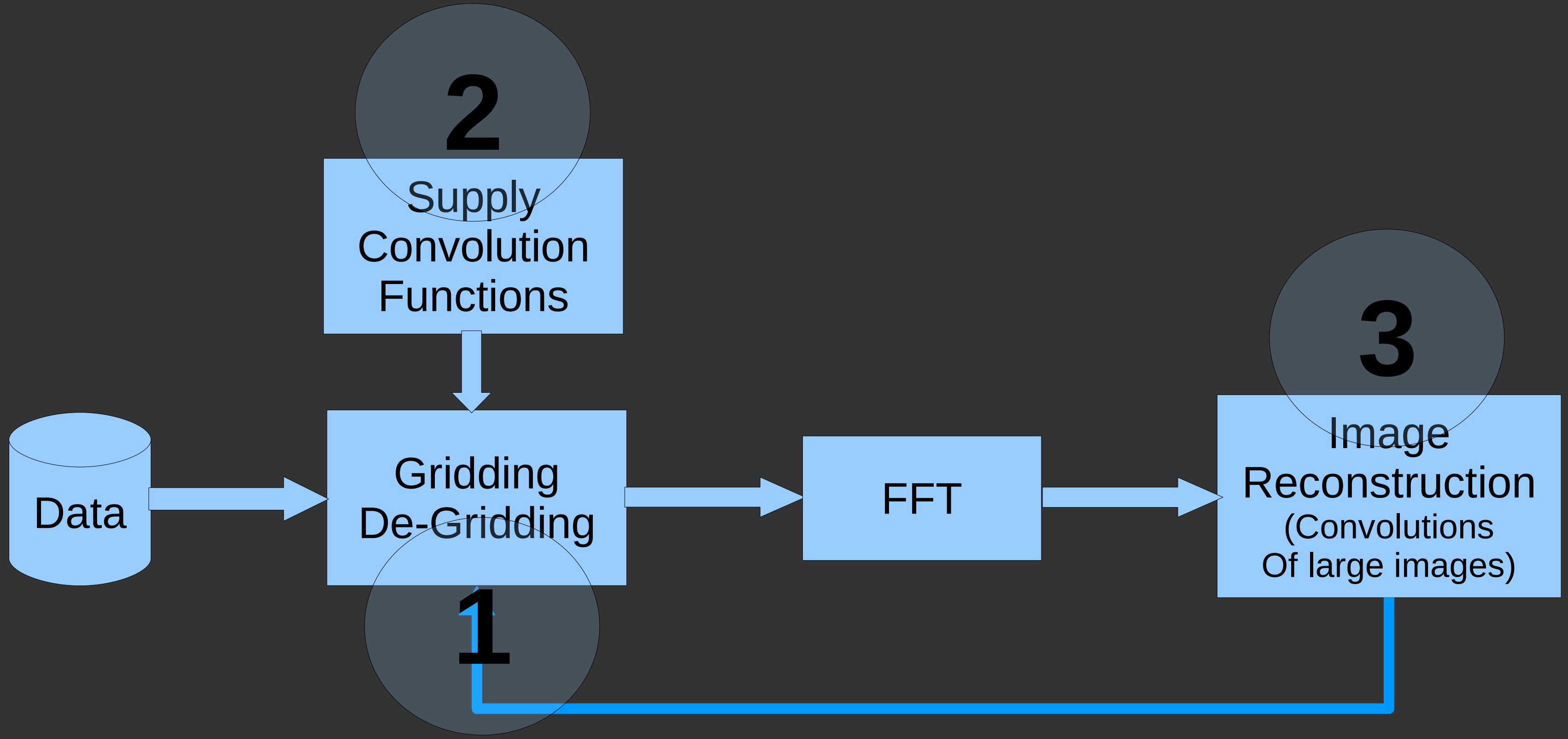
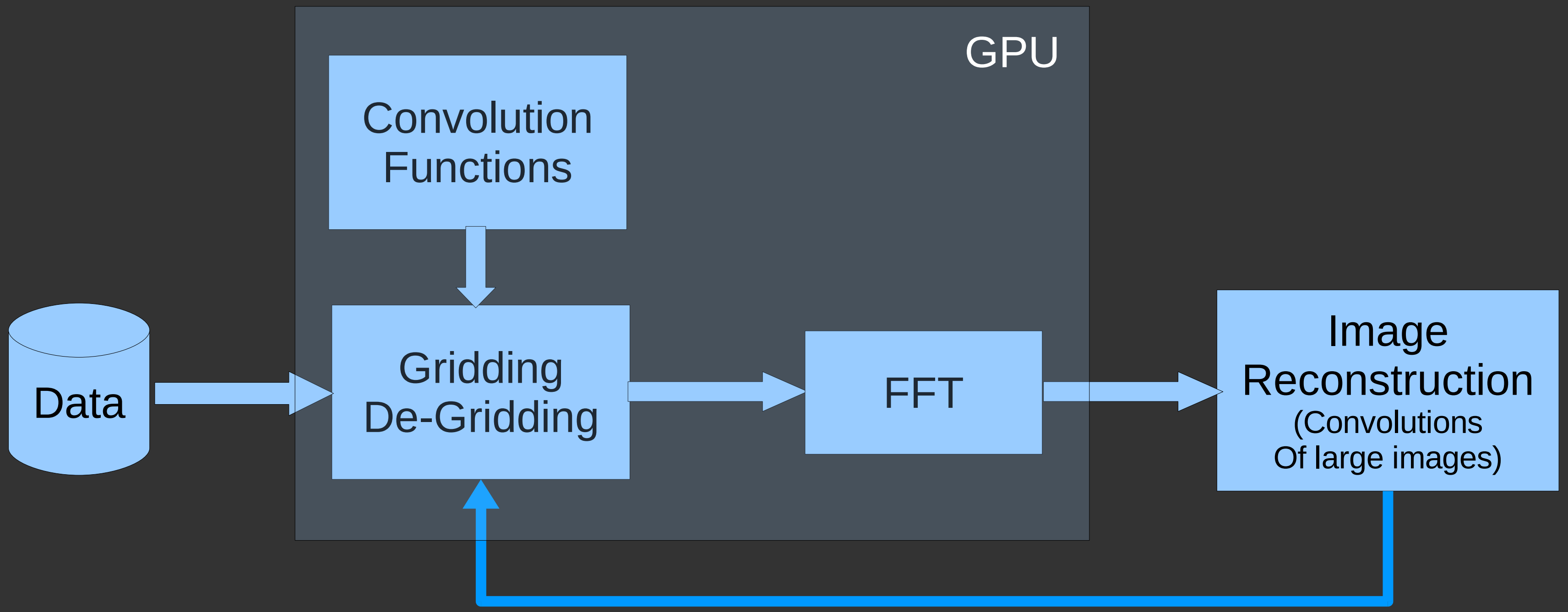


Computing architecture

- Make images on the GPU
  - Use GPU as a Gridding + FFT server
  - CPU host for image reconstruction



Computing architecture

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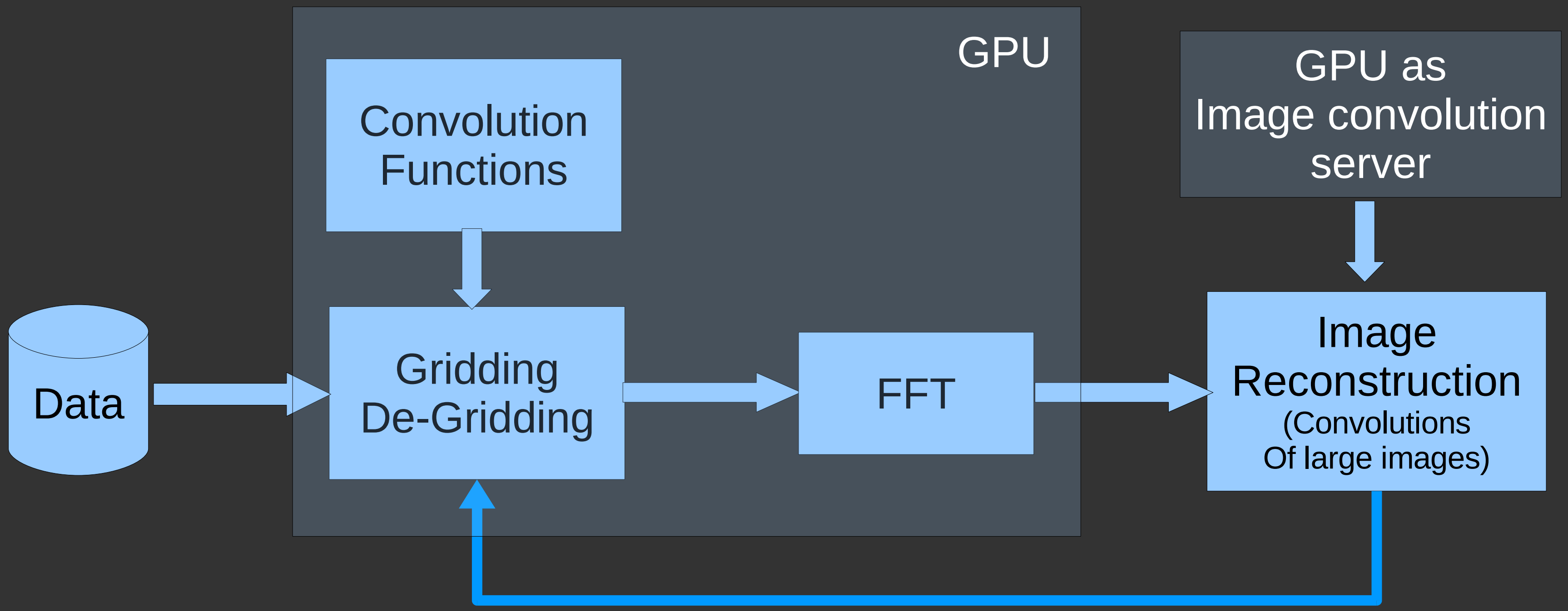
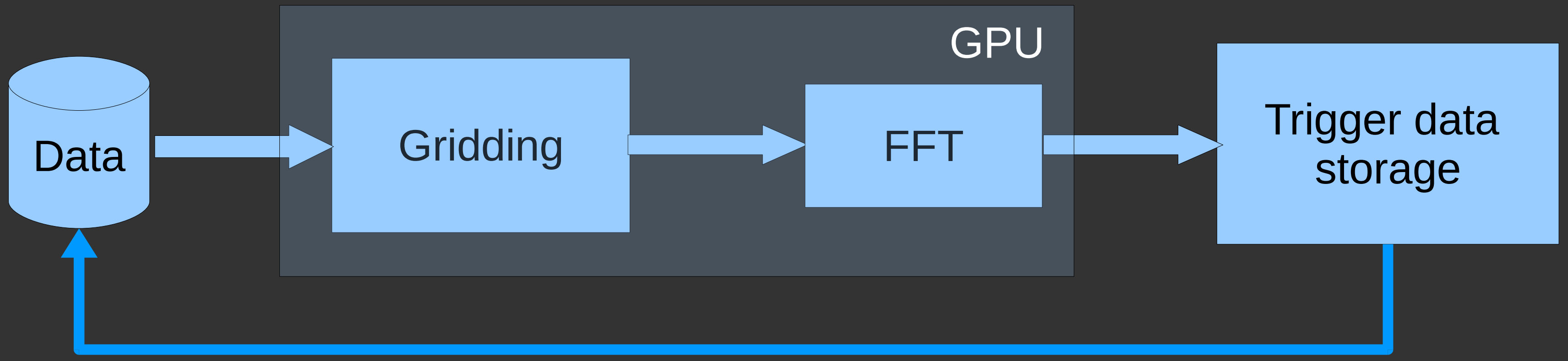
  - CPU host for image reconstruction + GPU as a image convolution server



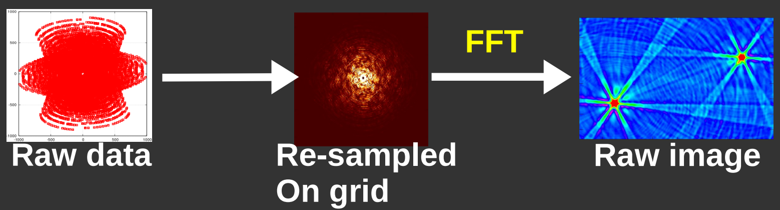
Computing architecture

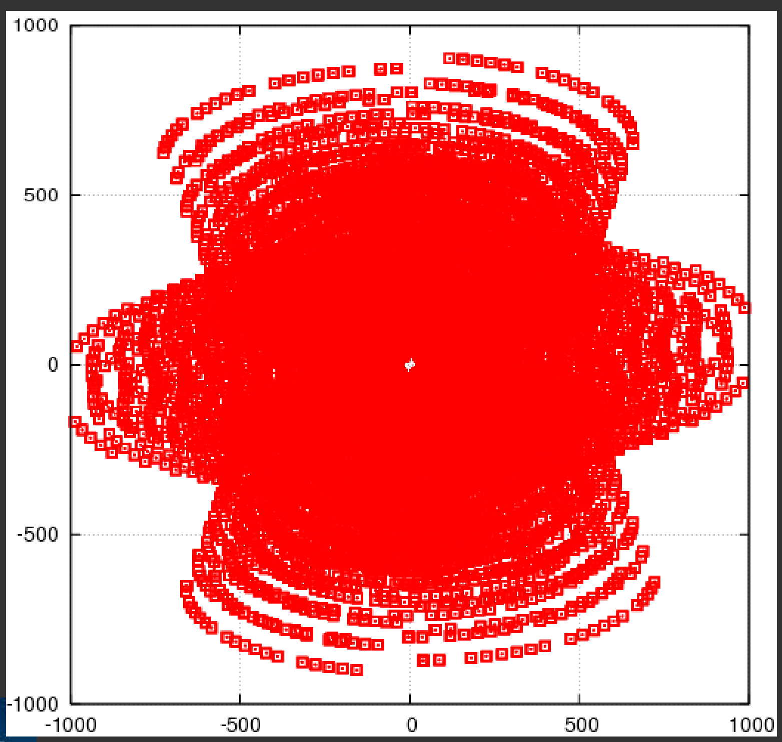
- Fast imaging
  - 100s of image in milli seconds on the GPU
  - Search for peak on the GPU
  - If peak found, send a trigger to the host to save the data buffer on the disk



The Computing Problem: Why Gridding?

- Use FFT to transform to the image domain
  - Raw data is not on a regular grid





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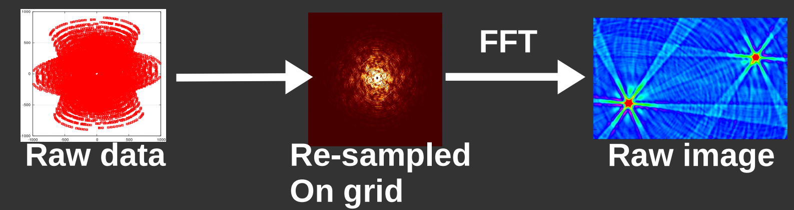

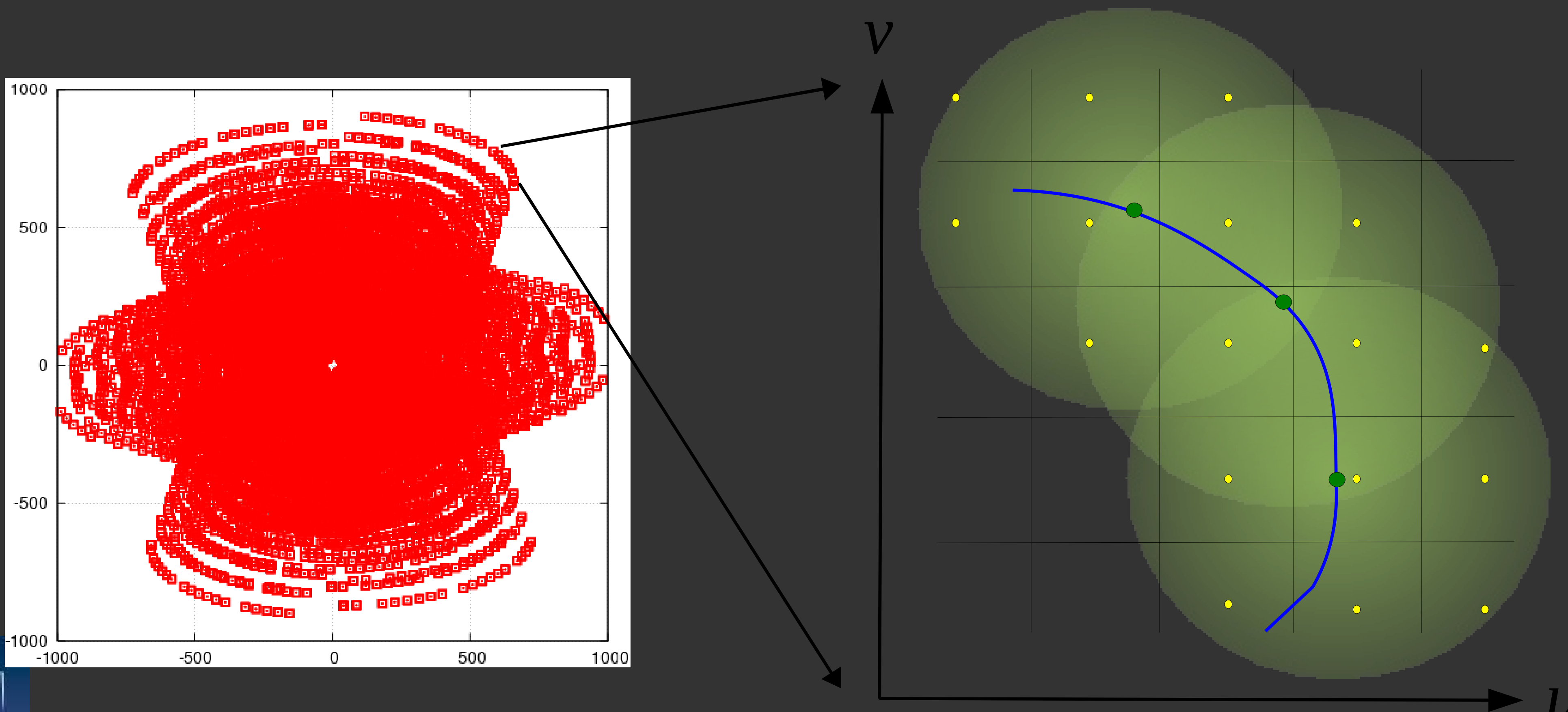

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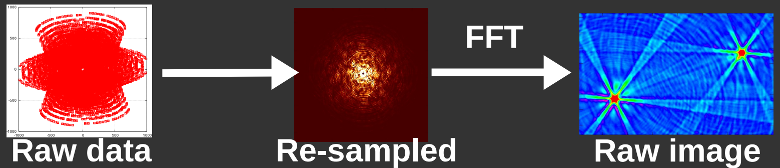

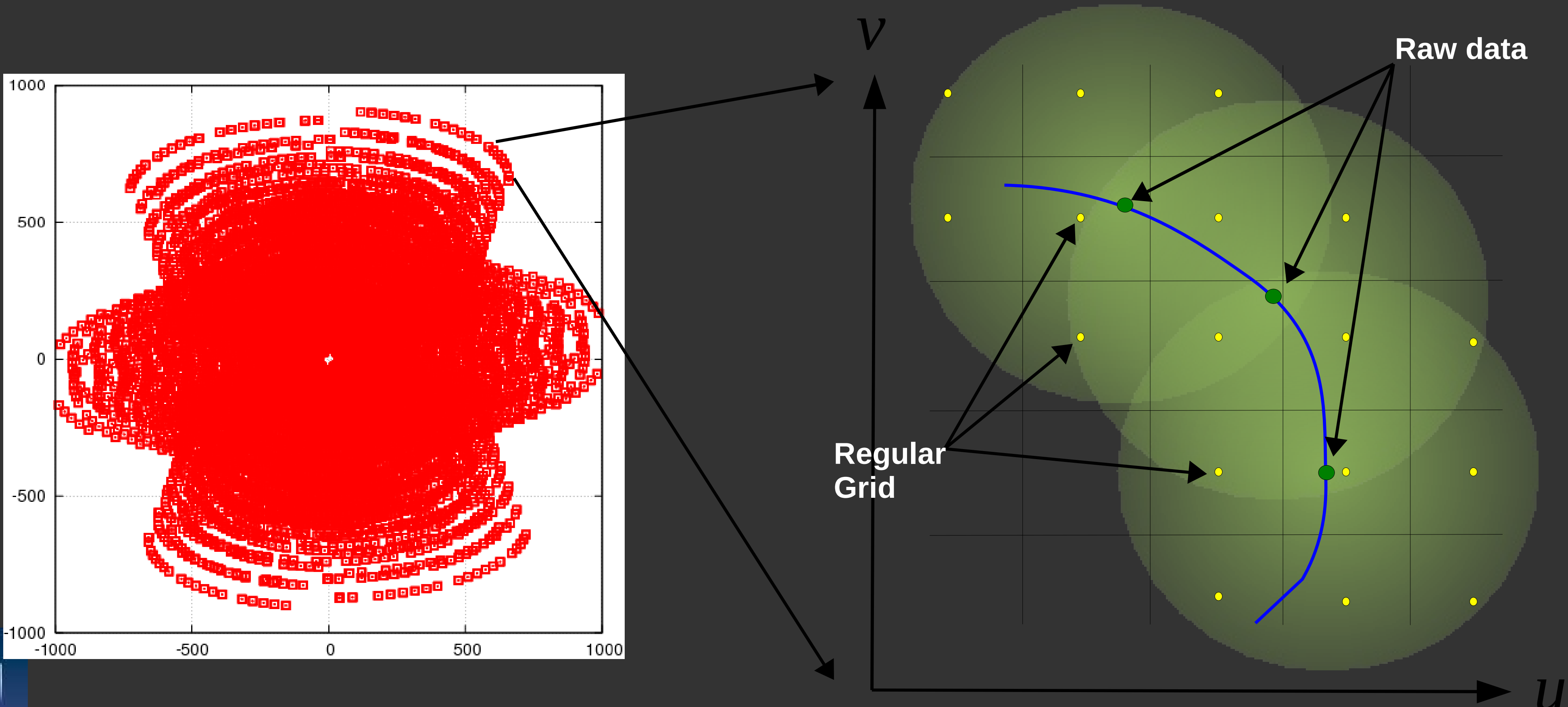

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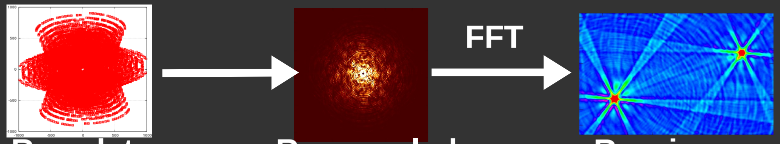
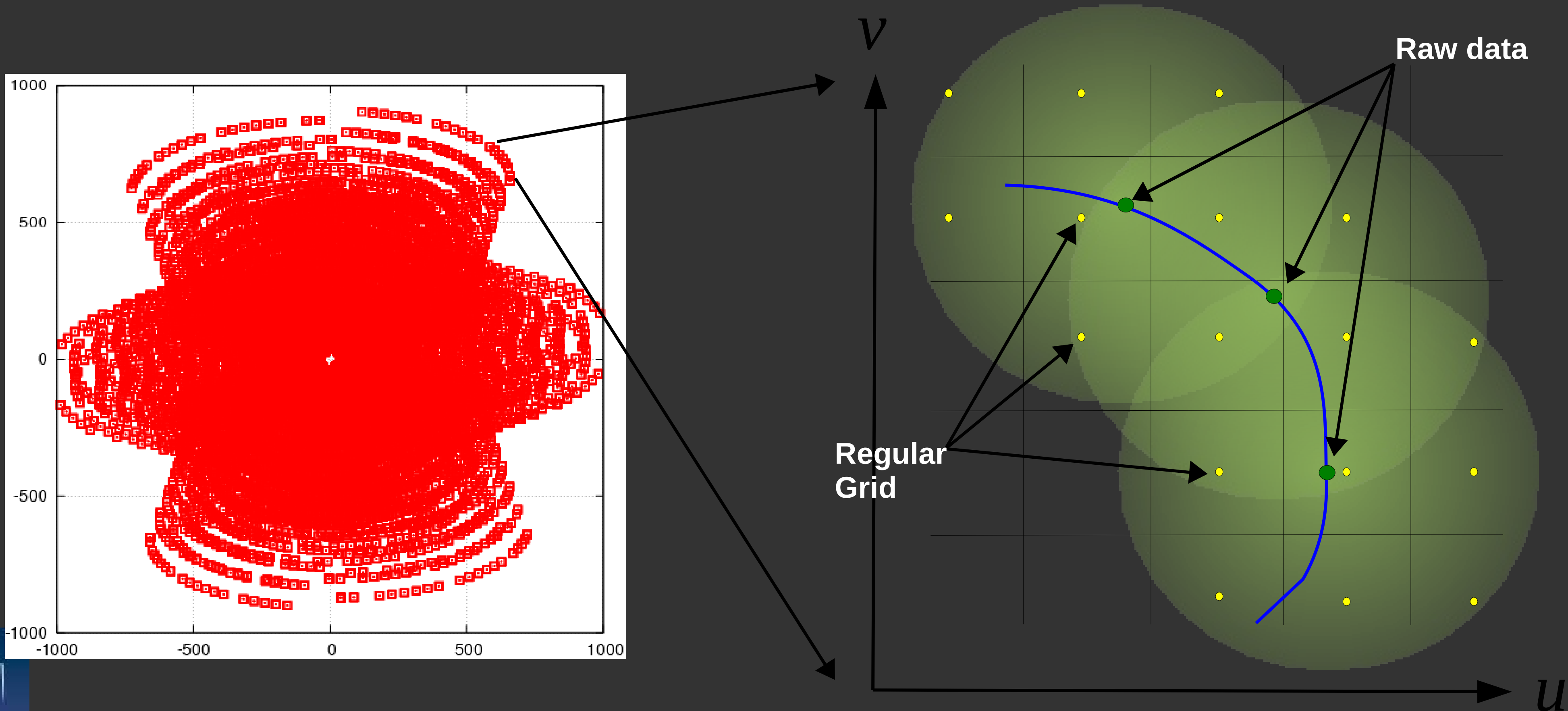
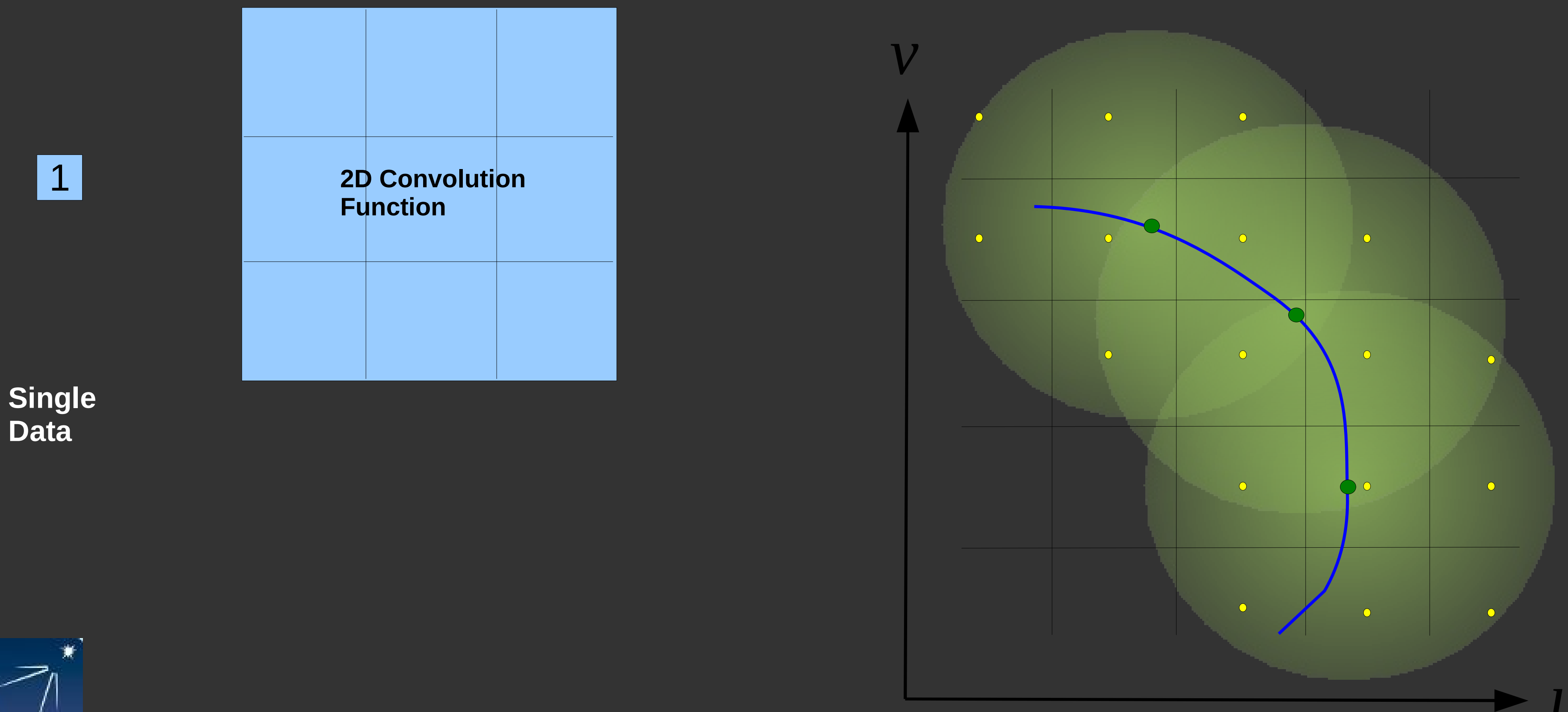


Requires re-sampling ALL the data on a regular grid
Using 2D Convolutional resampling → 2D Interpolation



Gridding – How?

- Gridding/De-gridding ← → 2D Interpolation via convolutional re-sampling
- Convolution Function ← → 2D Weighting Function



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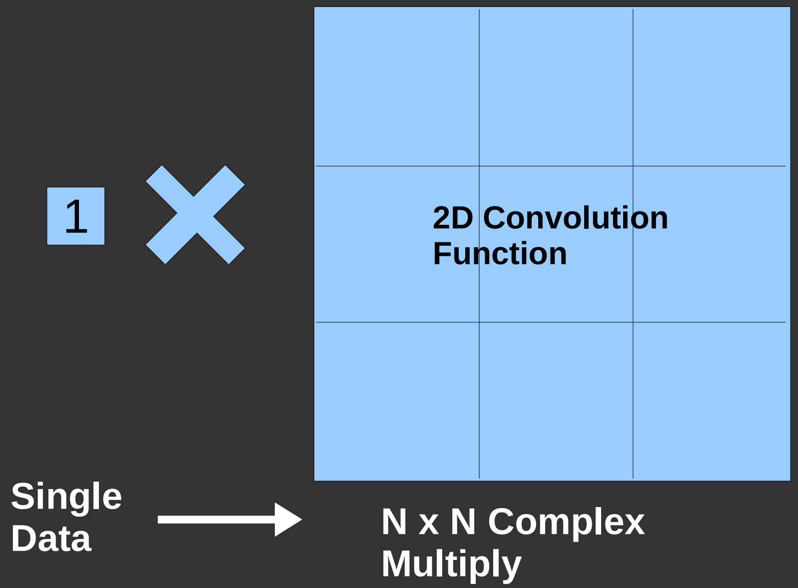

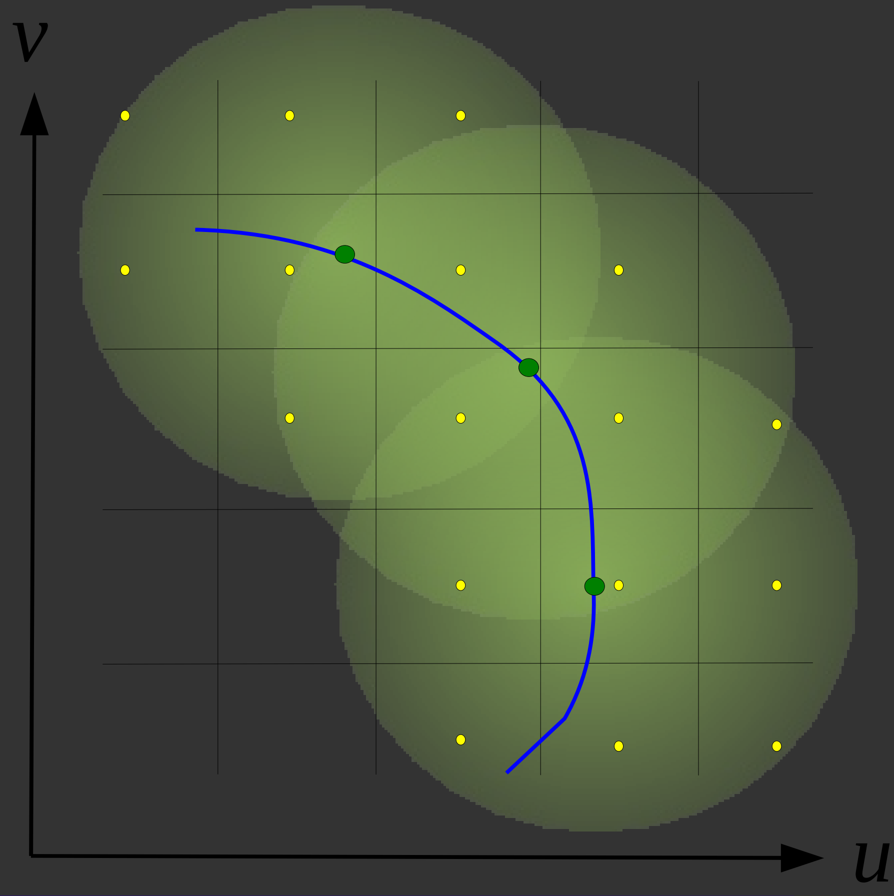

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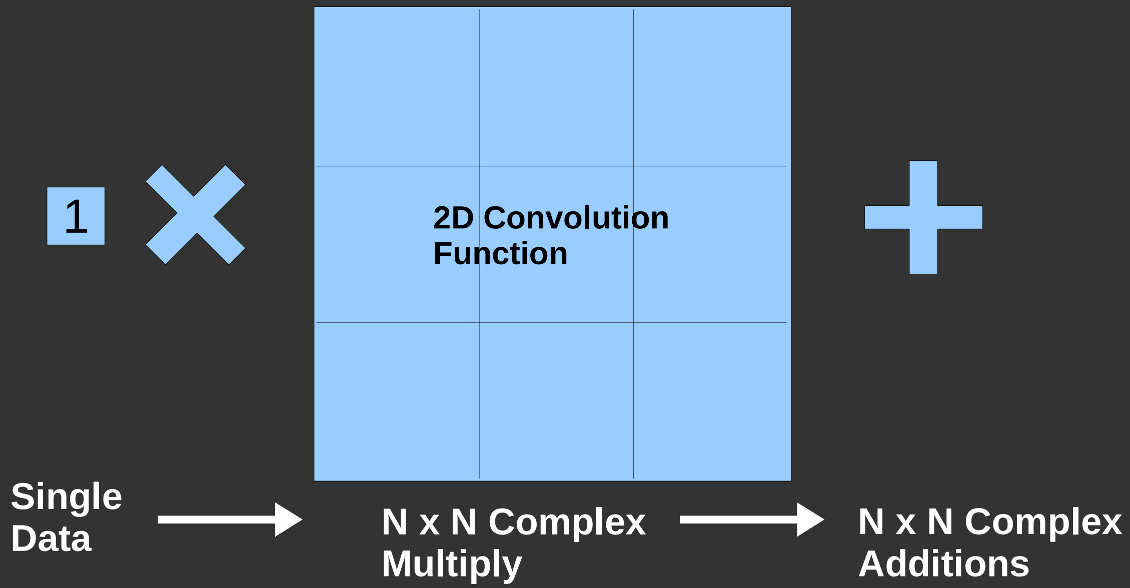

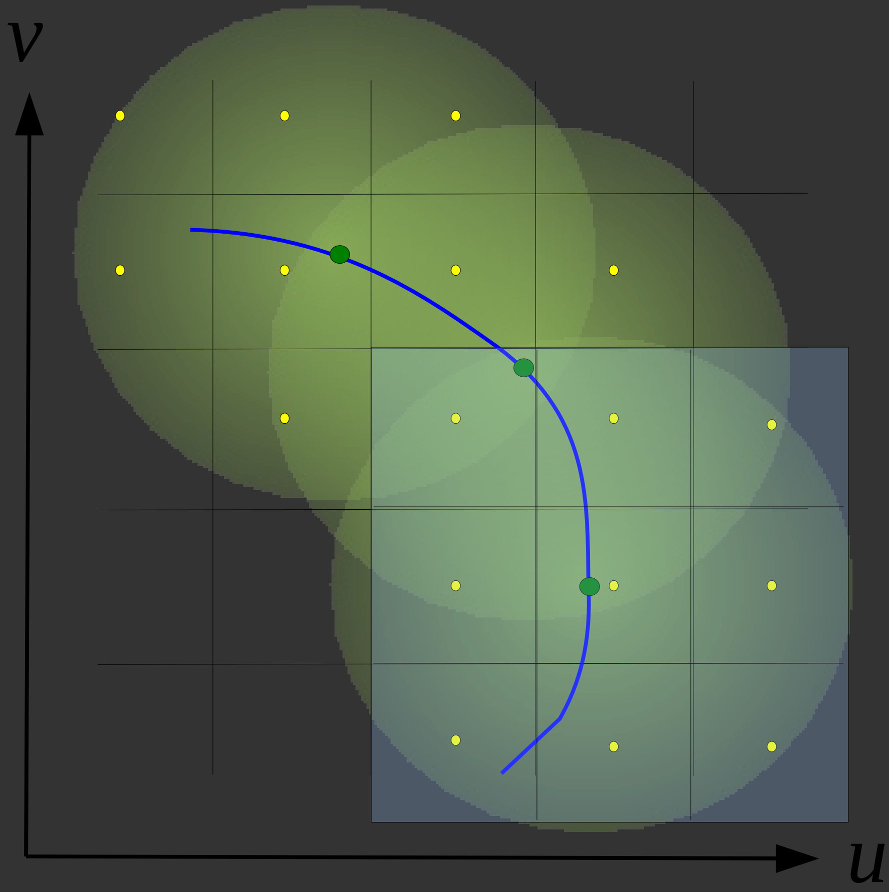

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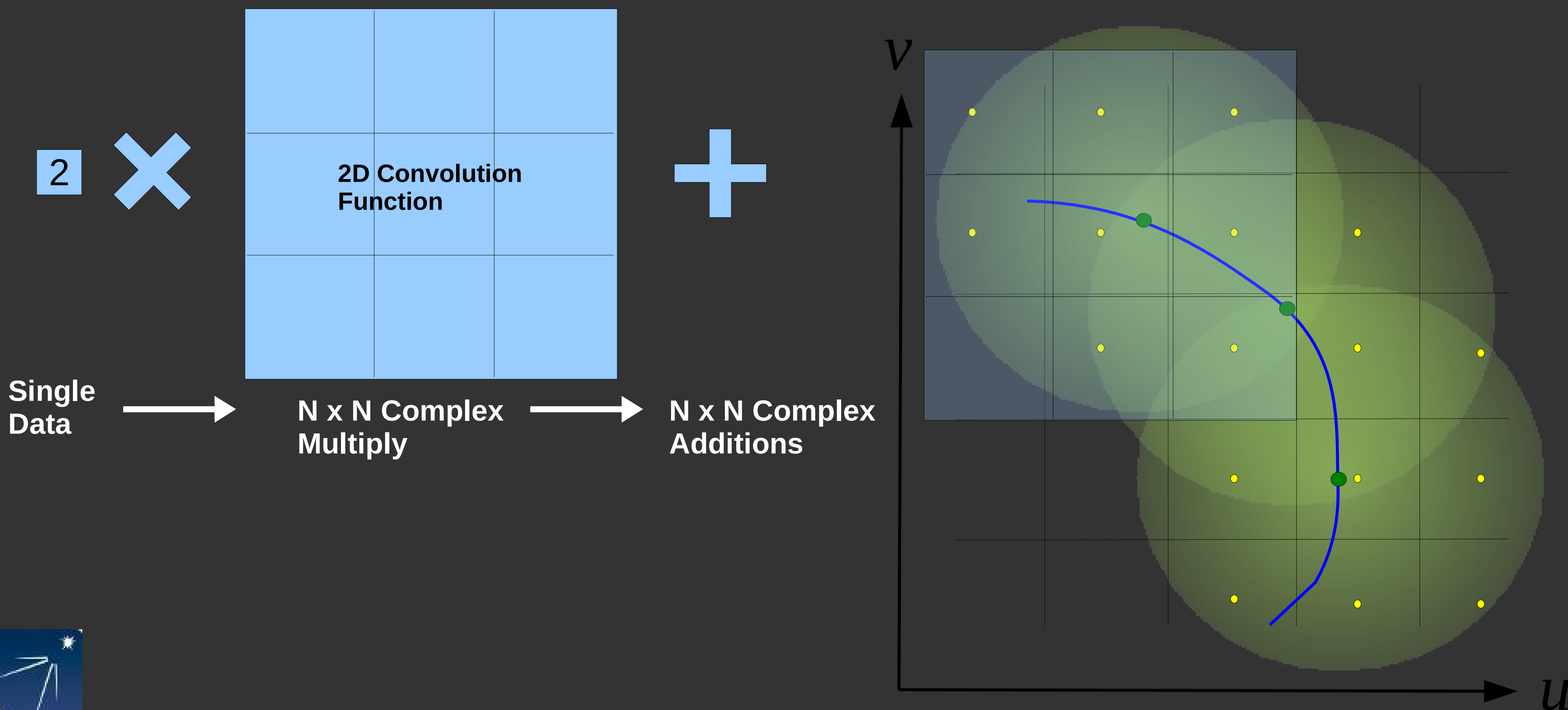

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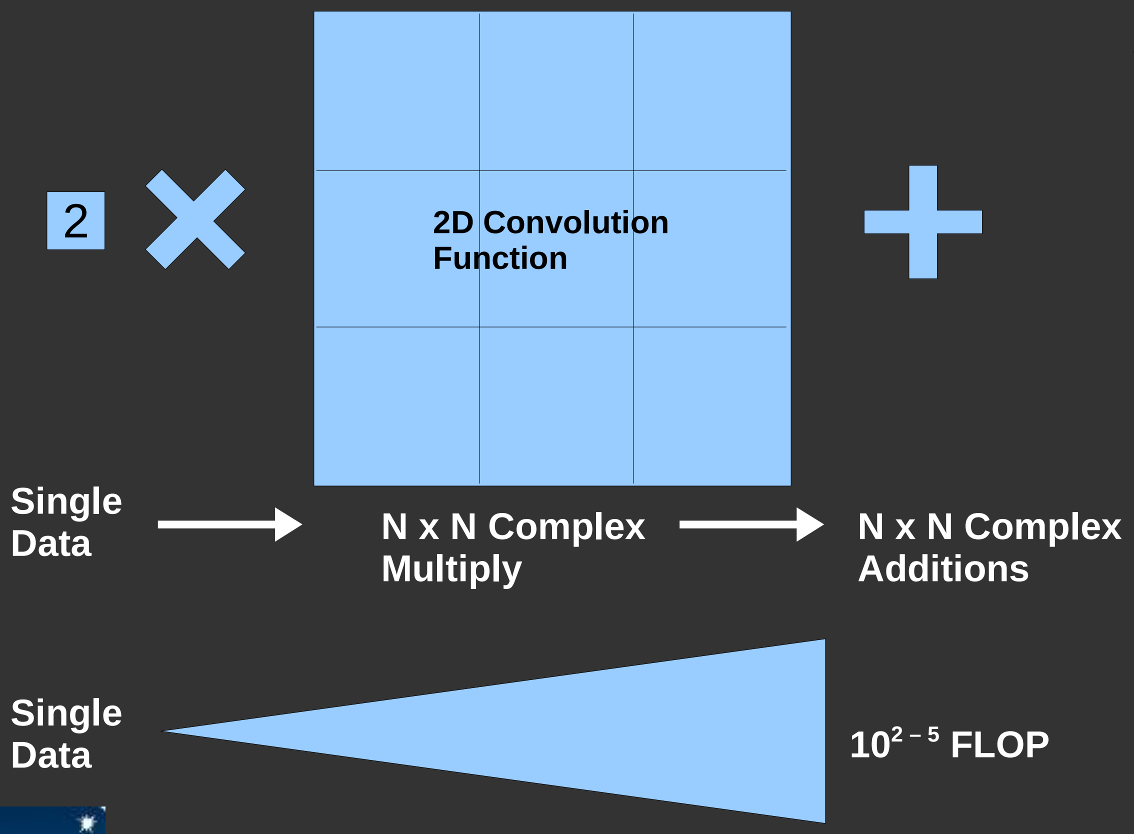
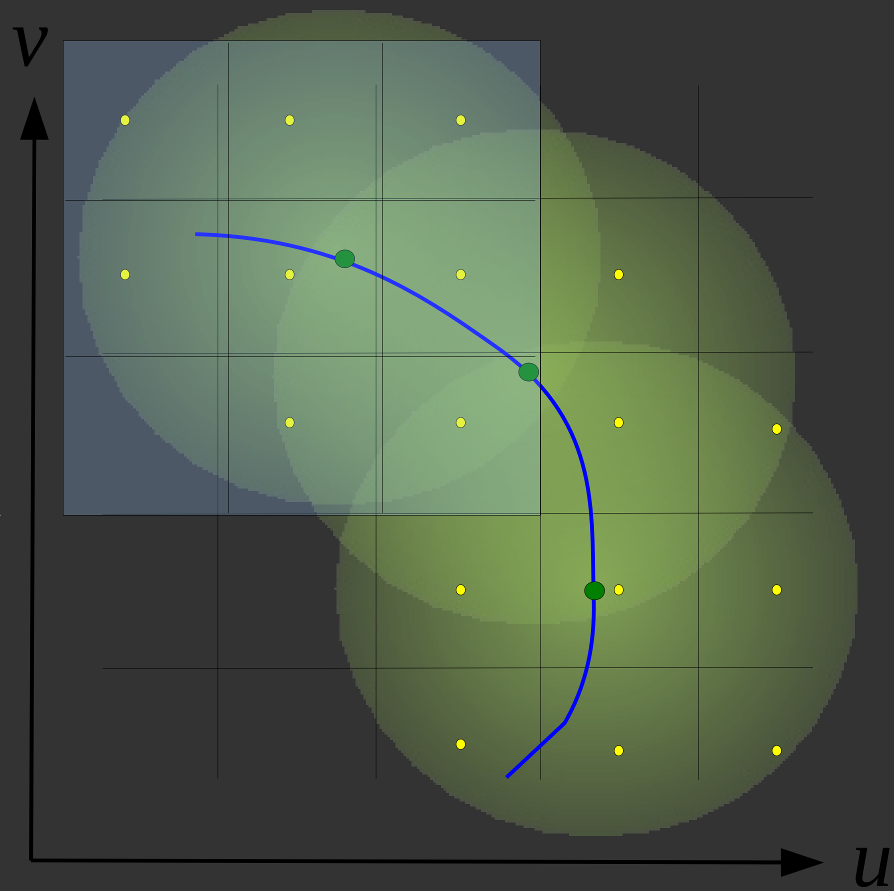
- Gridding/De-gridding ← → 2D Interpolation via convolutional re-sampling
- Convolution Function ← → 2D Weighting Function





Massively Parallel H/W should help: PoC 1

Status-3: Gridding – PoC-1 (on-going)

- Divide the grid into sub-grids, each with multiple pixels
- Map each sub-grid to a CUDA Block of threads
  - One thread per sub-grid pixel
- For each data D_i

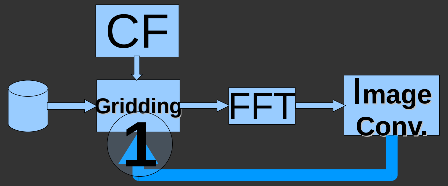
  Calculate the range of the CF centered on D_i

  If this block in range

  For all threads in range

  $local\_Grid_j \mathrel{+}= D_i * Cf_{i-j}$

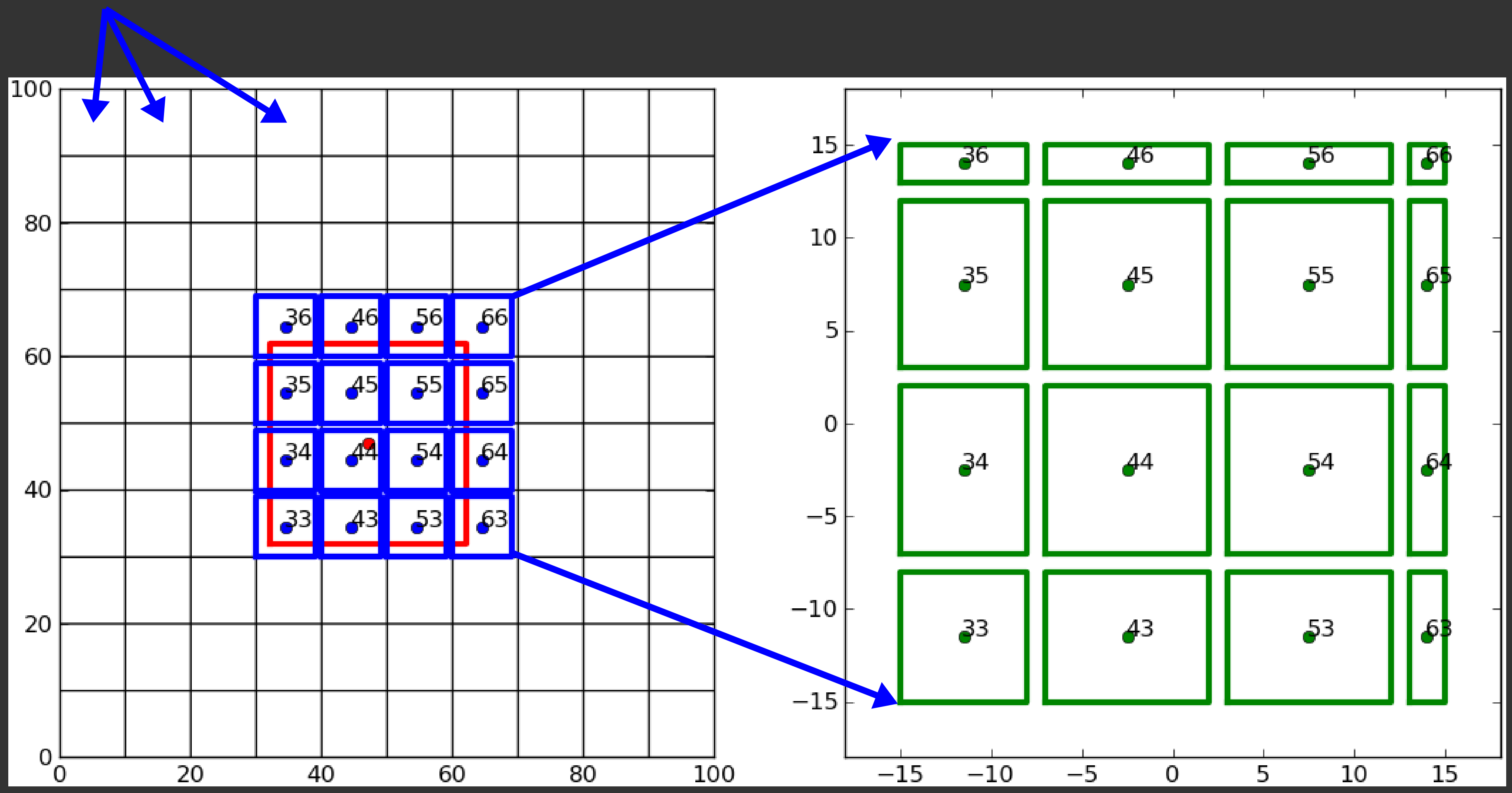
  Write local_Grid to GMEM Grid



Status-3: Gridding – PoC-1 (on-going)

For Data 1
    Calculate the range of the CF centered on D_i
    If this block in range
        For all threads in range
            $\text{local\_Grid}_j \mathrel{+}= D_i * Cf_{i\text{-}j}$
Write local_Grid to GMEM Grid

Sub-grids/Blocks of 10x10 threads



Status-3: Gridding – PoC-1 (on-going)

For Data 2

Calculate the range of the CF centered on D_i

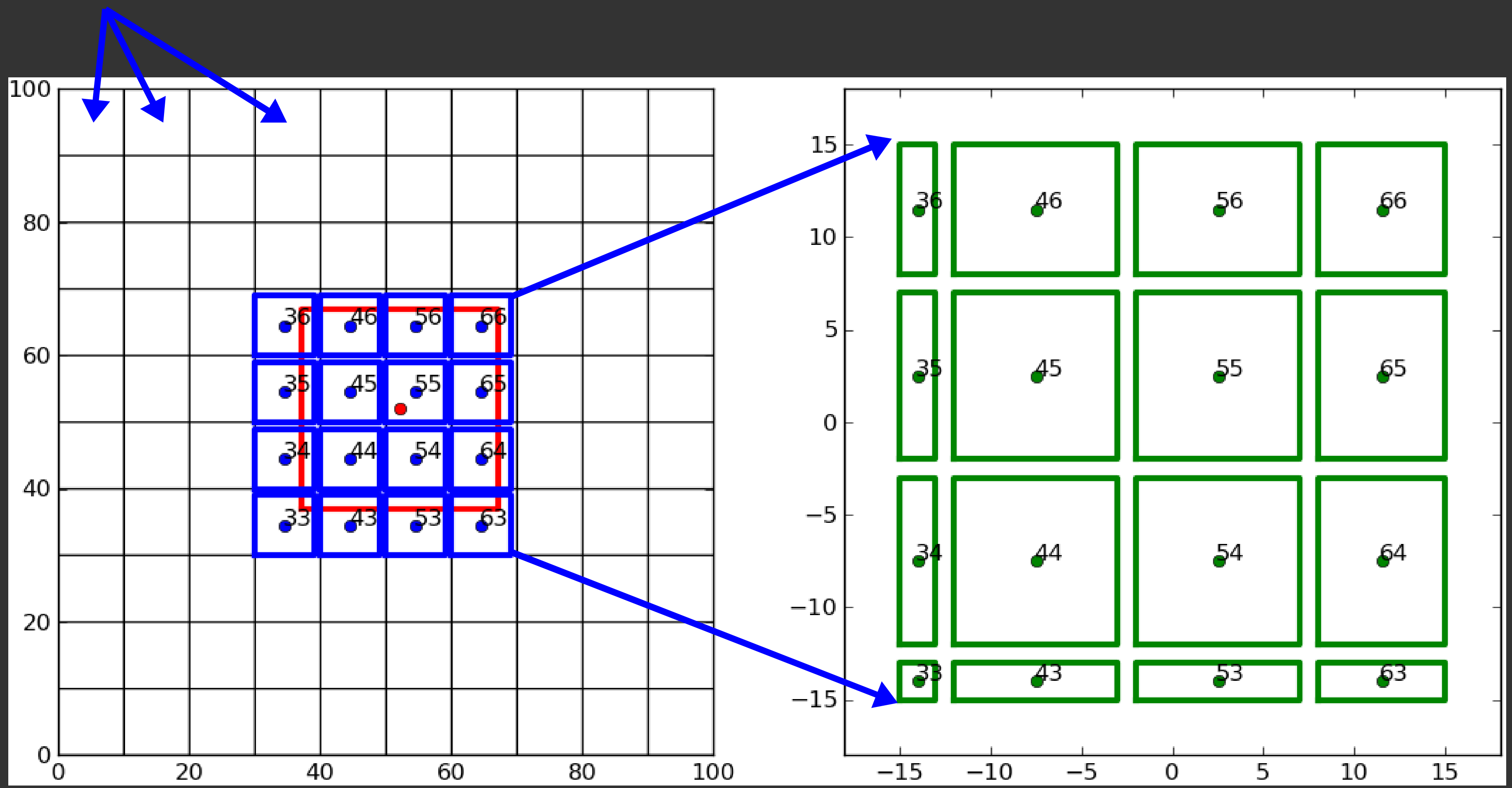
If this block in range

For all threads in range

$local\_Grid_j \mathrel{+}= D_i * Cf_{i-j}$

Write local_Grid to GMEM Grid

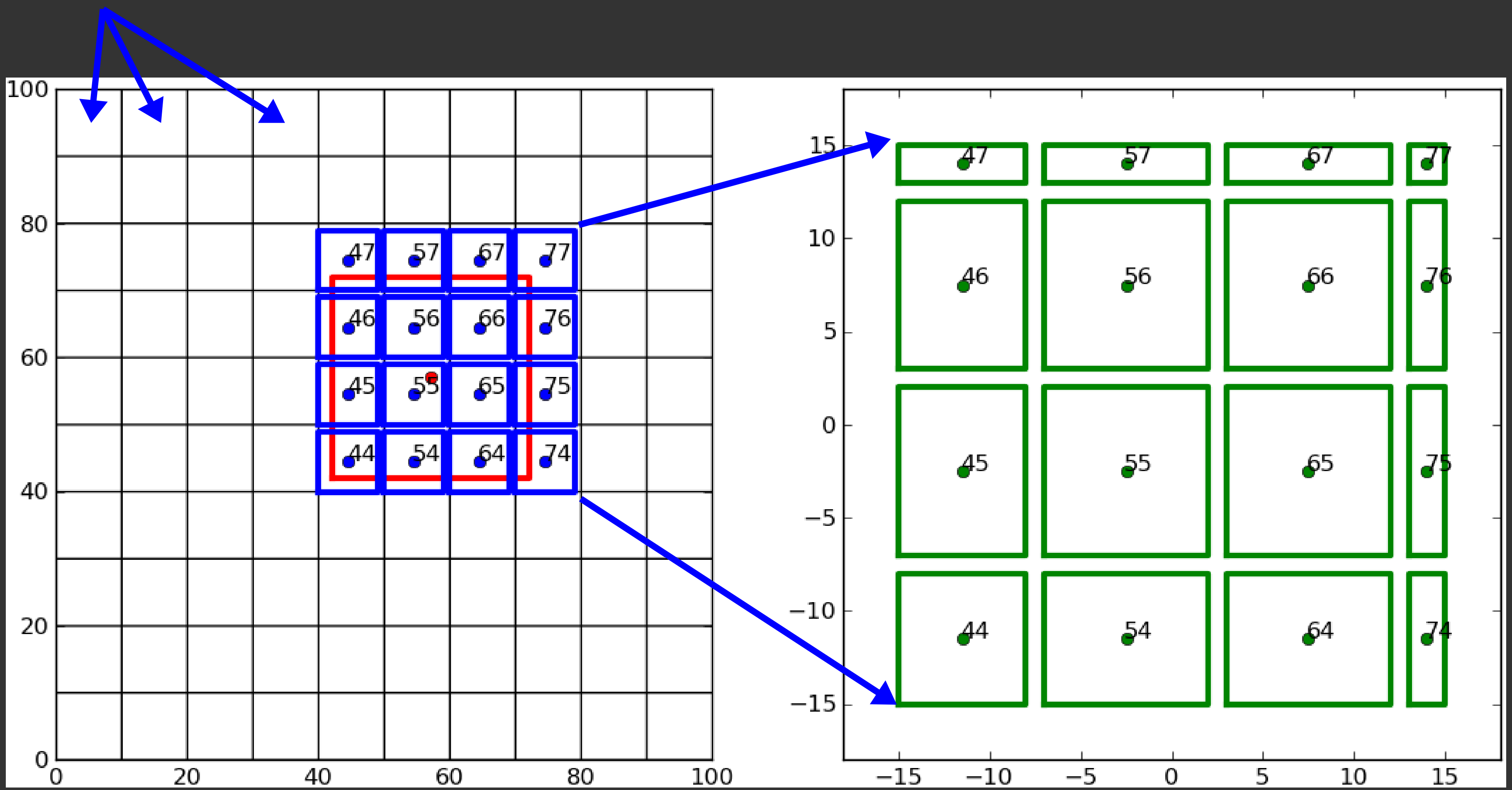
Sub-grids/Blocks of 10x10 threads



Status-3: Gridding – PoC-1 (on-going)

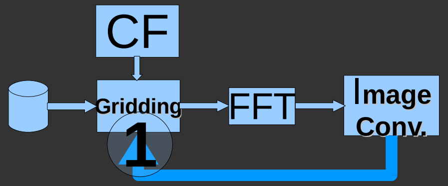
For Data 3
    Calculate the range of the CF centered on D_i
    If this block in range
        For all threads in range
            $local\_Grid_j$ += $D_i * Cf_{i\text{-}j}$
Write local_Grid to GMEM Grid

Sub-grids/Blocks of 10x10 threads



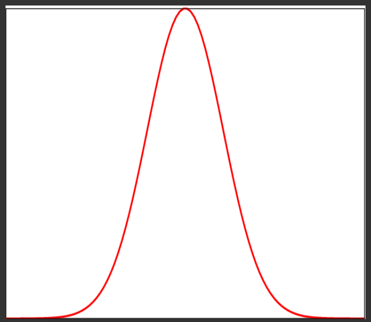
Status-3: Gridding – PoC-1 (on-going)

- No thread contentions
  - No atomic-operations required
- But current implementation is limited by global memory accesses
- Solution: reduce GMEM access
  - Coarse-grid the raw data / sort the raw data
  - Copy data required for each block to SMEM
- Cache-coherent access
  - Re-arrange GMEM buffers



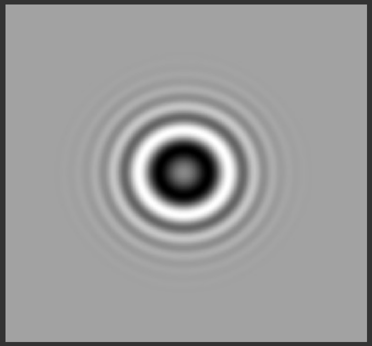
Convolution Functions (CFs)

- Convolution Functions encode the physics of the measurement process



- Prolate Spheroidal: As anti-aliasing operator
- W-Term: Account for Frensel Propagation term

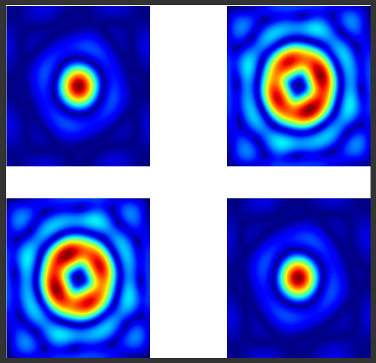
Cornwell et al. (2008)



- A-Term: Account for antenna optics

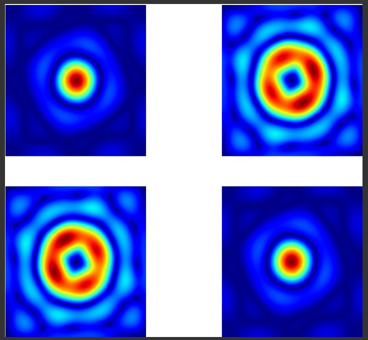
Bhatnagar et al. (2008)

- Final function: Convolution of all three
  - PS * W-Term * A-Term
  - NxN = 10x10 – few x 100x100

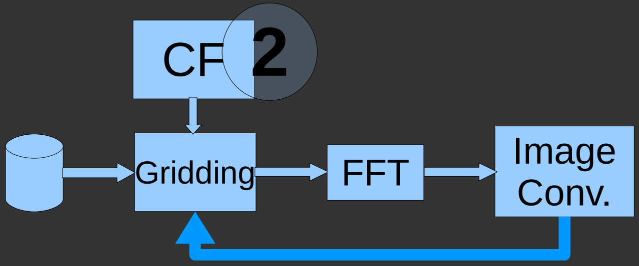


In use in
CASA (NRAO),
“aw-imager” for LOFAR (NL),
ASKAP Imager (AU)

Compute CFs on the GPU: PoC - 2



- CFs as tabulated functions in the computer RAM
- Minimize the quantization errors, by over-sampling
  - Typical over-sampling 10x – 100x
- Memory footprint gets prohibitive
  - Total Memory = 10^{3-8} x 1000s of CF = 10s – 100s GB
- **PoC-2: Can we compute the CF s on-the-fly (as against compute-n-cache)?**
  - **Compute + Multiply + FFT**

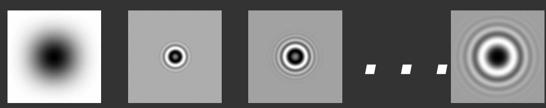


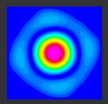
Status-1: CF Computations – PoC-2

- Negligible I/O – mostly computing

W-Terms × **A-Term**

T0





FFT

CF set used for 100s of gridding cycles

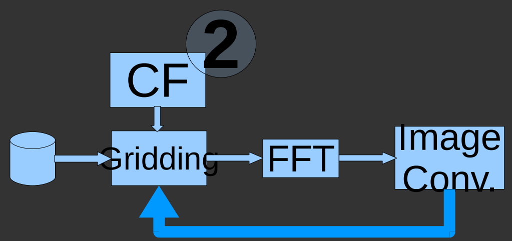
100s – 1000s

Compute per pixel

Analytically computed

Cached

No analytical expr.

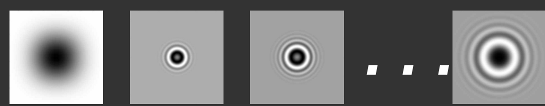


Status-1: CF Computations – PoC-2

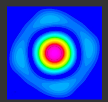
- Negligible I/O – mostly computing

W-Terms ✖ **A-Term**

T0

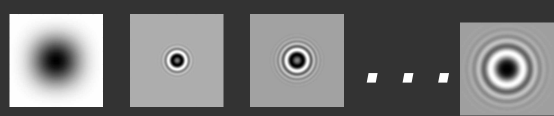


✖

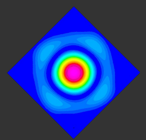


FFT → **CF set used for 100s of gridding cycles**

T1



✖



FFT → **CF set used for 100s of gridding cycles**

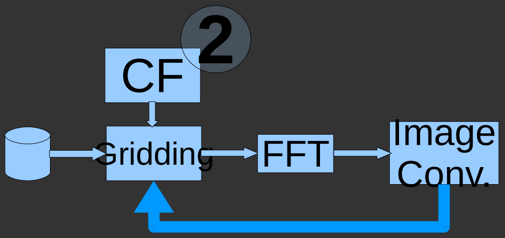
100s – 1000s

Compute per pixel

Analytically computed

Cached

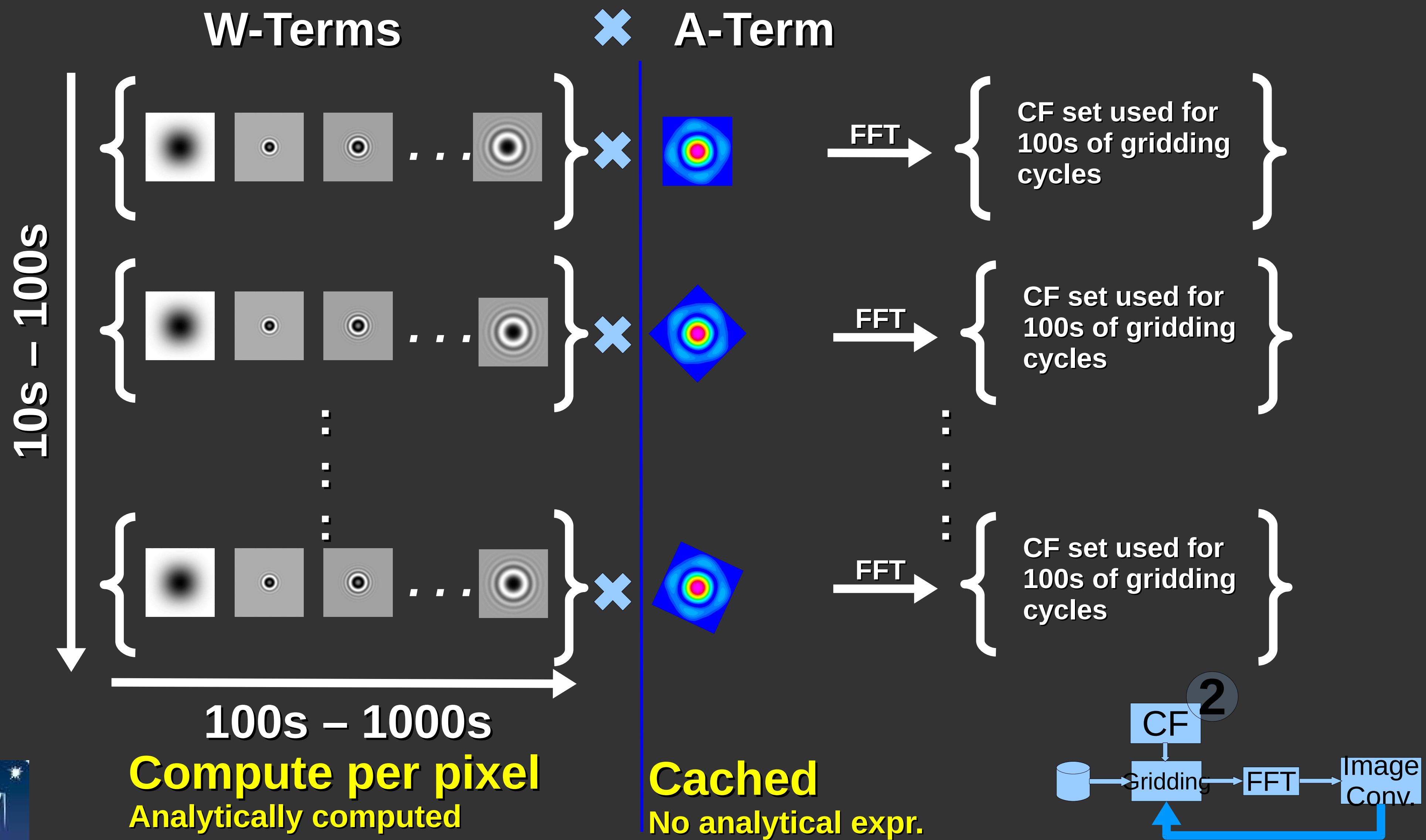
No analytical expr.



NRAO

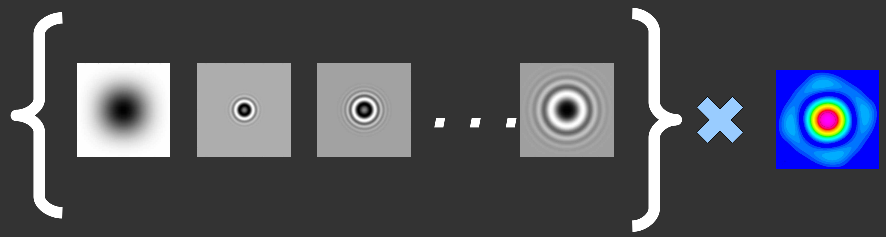
Status-1: CF Computations – PoC-2

- Negligible I/O – mostly computing



Status-1: Compute CFs on GPU – PoC-2

- Negligible I/O – mostly computing



- GPU: Pre-compute A-Term and cache it in GPU GMEM
  - Compute W-term OTF – one thread per pixel
  - Multiple A x W
  - FFT

- Sizes involves: 2K x 2K Complex images
- GPU: 1024 CFs made in ~1 ms.
  - ~20x faster than CPU
  - Room for improvement by another 2 – 3x

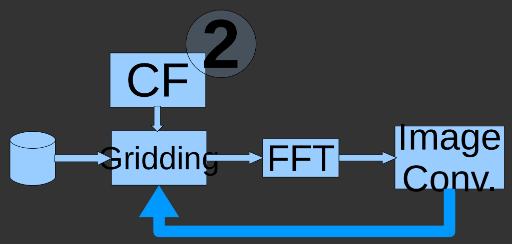
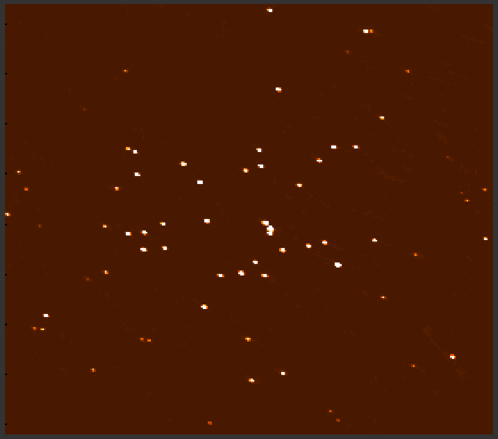
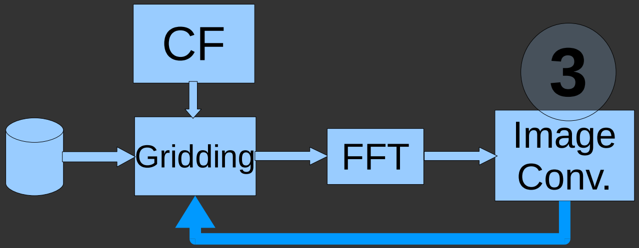


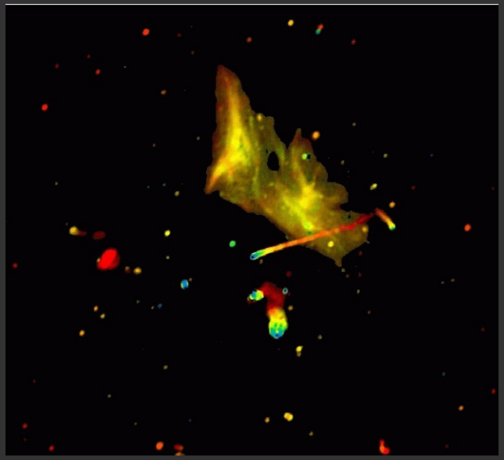
Image reconstruction: PoC - 3

- Simplest algorithm: CLEAN
  - Iteratively search for the peak in the Raw image and subtract the PSF image at the location of the peak





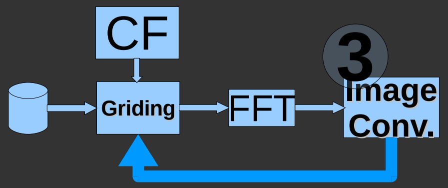
- Most complex algorithms: Multi-scale Multi-freq. Synthesis (MS-MFS)
  - Requires convolutions of large images +
  - Requires CLEAN



- **Use GPU as a convolution-server PoC – 3**
- Do deconvolution on the GPU (future)

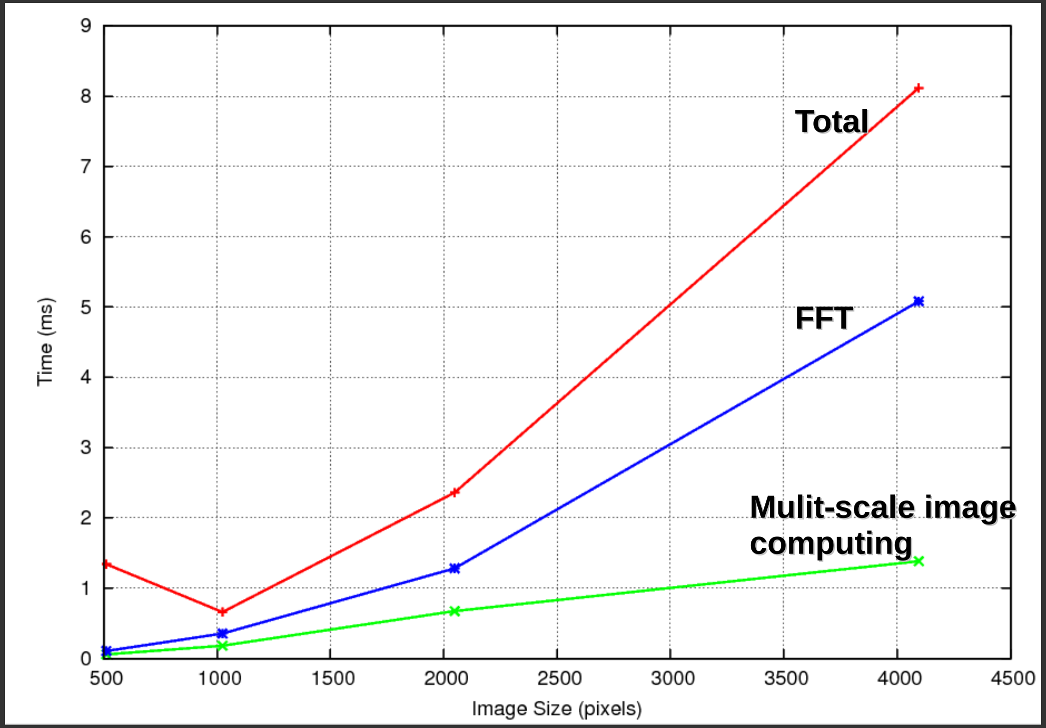
Status-2: Image deconvolution – PoC-3

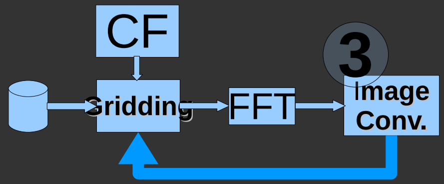
- Wide-band image reconstruction
  - Multi-Term Multi-Scale
  - $N_{terms} = 2 – 3$ $N_{scales} = 3 – 10$
- Computing cost
  - N_{terms} gridding cycles
  - Convolutions of N^2_{Terms} x N^2_{scales} images
  - Search in N_{terms} images



Status-2: Image deconvolution – PoC-3

- High memory footprint: High resolution wide-band imaging currently not possible
- Solution being pursued
  - Use GPU as an enabler technology (high resolution wide-band imaging)
  - Compute the multi-scale images OTF
  - Use GPU as a convolution-server





Low DR, fast imaging needs

- Transient source localization on the sky
  - Data rates too high for store-n-process approach
  - Need fast, low-DR imaging to trigger storage of short busts of data
- EVLA: Data dumps every 5 ms
- Computing
  - Make 119 images (DM search): 1K x 1K size
  - Trigger storage if peak > threshold
- Current CPU based processing (14 nodes x 16 cores)
  - ~ 10x slower than real-time

Fast-imaging GPU pipeline

- Simplify the gridder

- On-GPU FFT
- On-GPU peak detection
  - If (peak > threshold) trigger data storage

- Compute to I/O ratio ~ $O(10^{5-6})$
  - Data (@900MB per sec) goes into the GPU
  - Only trigger info. Comes out

Fast-imaging GPU pipeline estimates

- Imaging is FFT-limited
- GPU: Gridding + FFT + Peak search
  - Once per ~1 ms
  - 50 (100x?) faster than single CPU core
- Initial estimates for fast-imaging (work-in-progress):
  - 5 (2?) K20Xs become comparable to 14x16 CPU cores
    - » 10x slower than real-time
  - 50 (25?) K20X GPU cluster can enable real-time processing

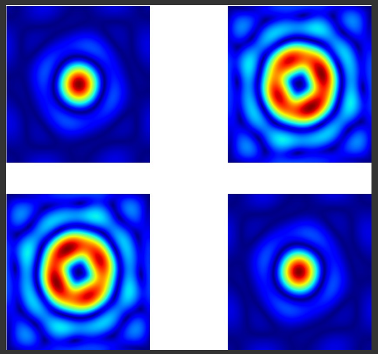
Conclusions, future work

- The algorithms for the three hot-spots ported on GPU (the three PoCs)
- Work in progress on the gridding algorithm
  - Minimize Global Memory transactions, other optimizations
  - Take decision about which algorithm to use
- Optimize the CF severe code and image convolution code
- Integrate to make a imaging pipeline
- Scientifically test the results
  - Measure actual run-time performance with real data
- Prototype and check Fast Imaging pipeline
  - If the estimates of run-time improvements hold up, deploy for real-time fast-imaging

Back up slides

Number of CFs required

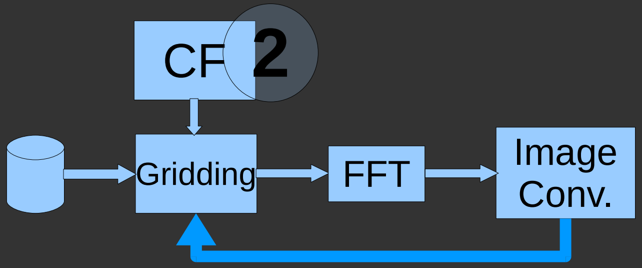
- Not all CF terms can be computed analytically
  - Final convolution function can't be computed analytically



- No. of CF s required for wide-band, full-polarization high-dynamic range imaging is large

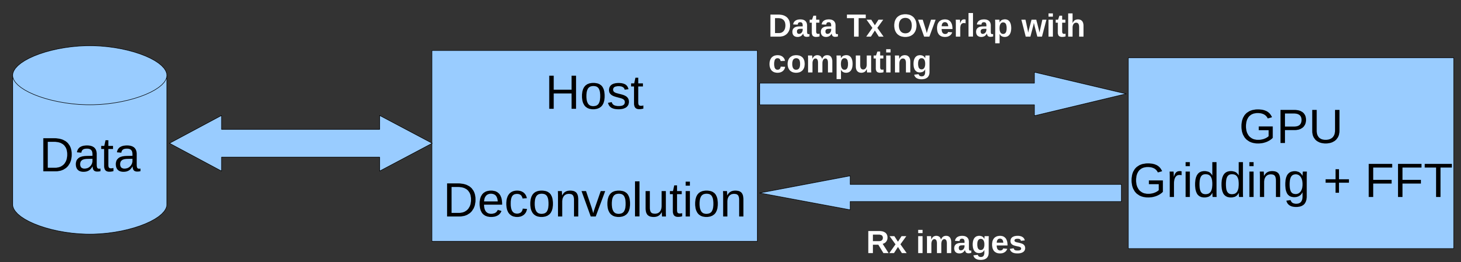
Total number of CF s : 10s – 1000s

- Expensive to compute
  - Current solution: Pre-compute and cache
  - Memory Footprint issues

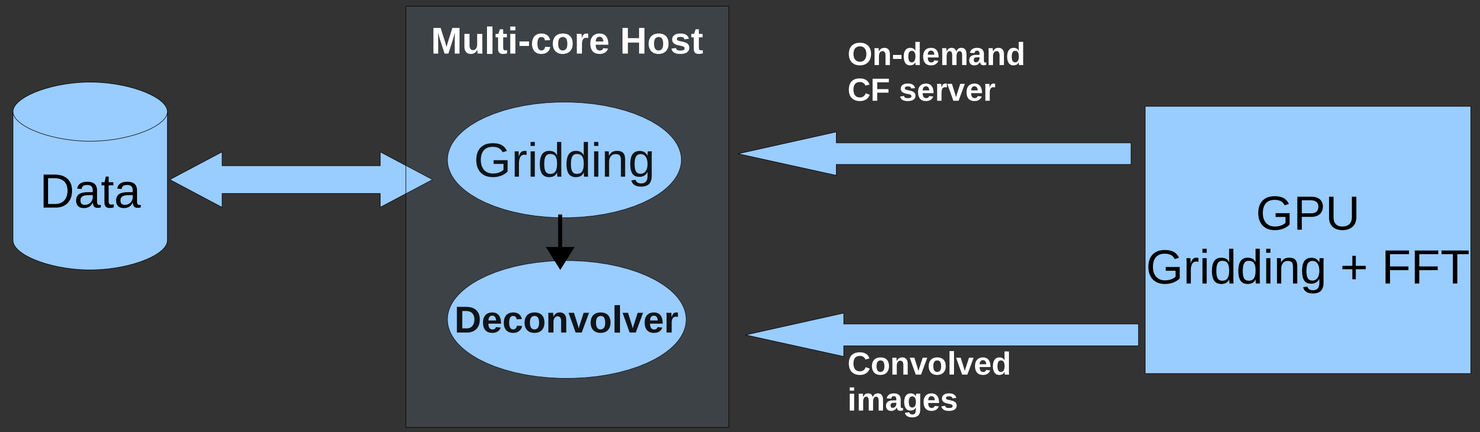


Computing architecture

- Make images on the GPU
  - Use GPU as a Gridding + FFT server
  - CPU host for deconvolution



- GPU as a Image Convolution + on-demand CF server



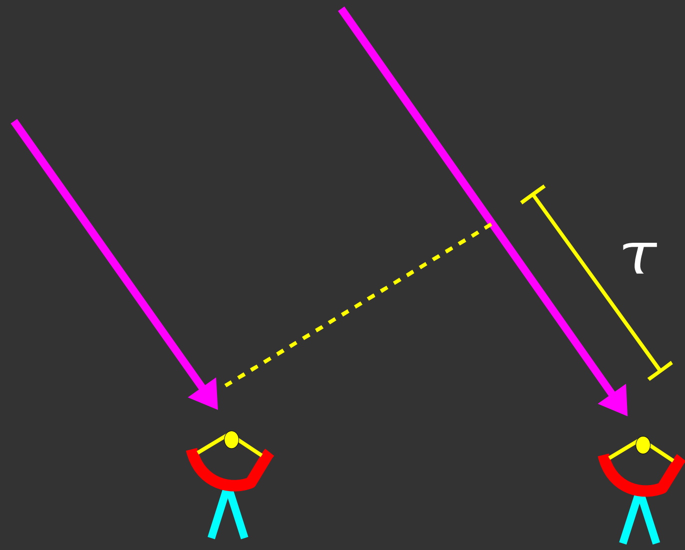
Computing architecture

- Make images on the GPU
  - Use GPU as a Gridding + FFT server
  - CPU host for deconvolution

- GPU as an Enabling Technology
  - GPU as a Convolution and Convolution Functions server
  - Where GPU RAM is not sufficient to hold all CF and buffers for MS-MFS
  - Imaging + Deconvolution loops on the Host

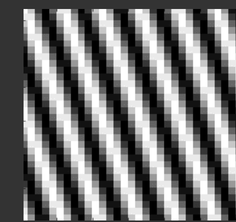
- GPU as a trigger for fast-transients
  - 100s of images from a given set of data
  - Image + search for transients on the GPU

Aperture Synthesis Imaging: How?

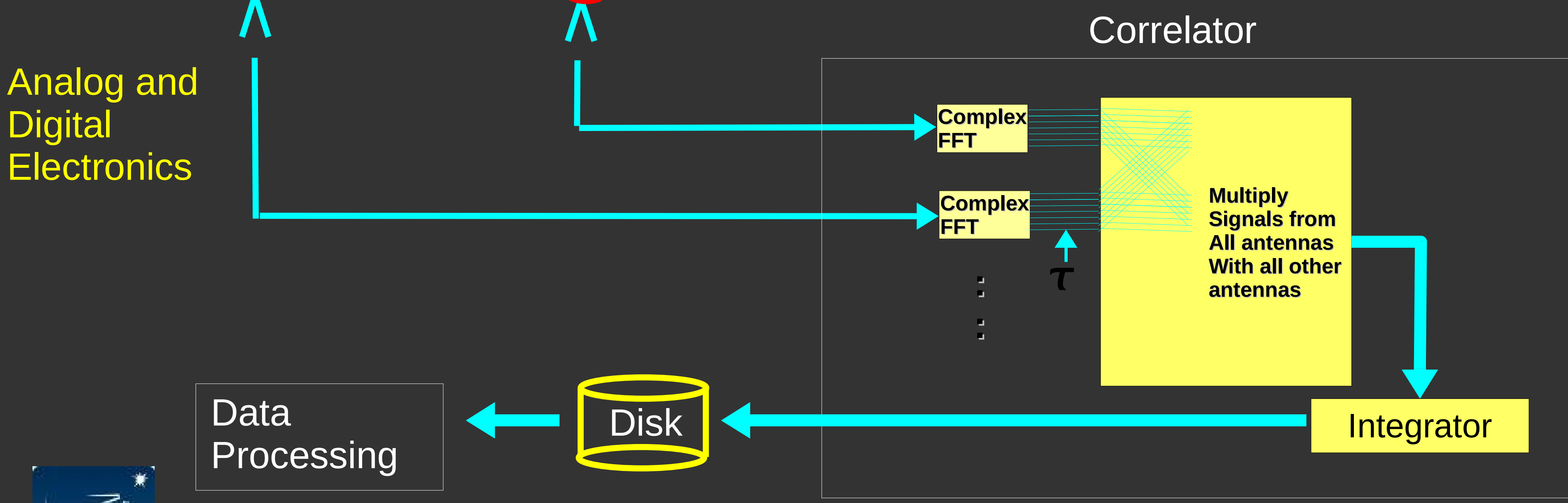


Each Pair of Antennas :

=> Measures one 2D "fringe"



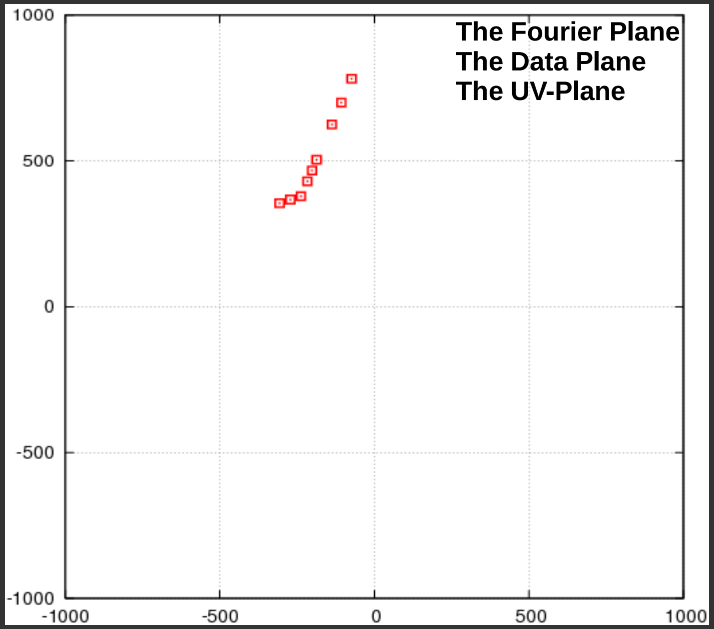
"fringe spacing", "orientation", "amplitude", "phase"

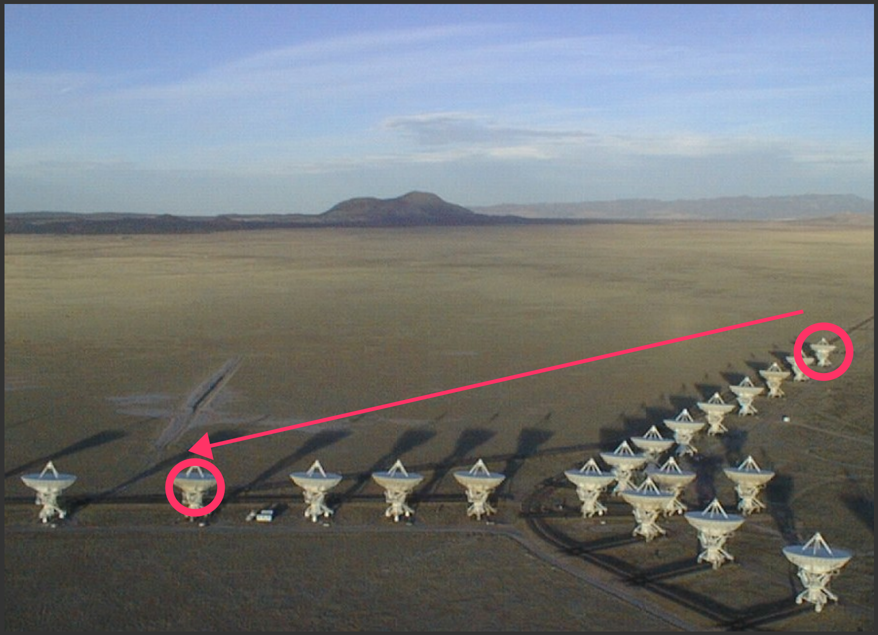


Aperture Synthesis Imaging: How?

- Aperture Synthesis
  - An interferometric imaging technique (Nobel Prize in '74)
  - Many antennas separated by 10s – 100s Km

  - Each pair of antennas measure **another (one)** Fourier Component





  - Synthesized aperture equal to the largest separation between antennas

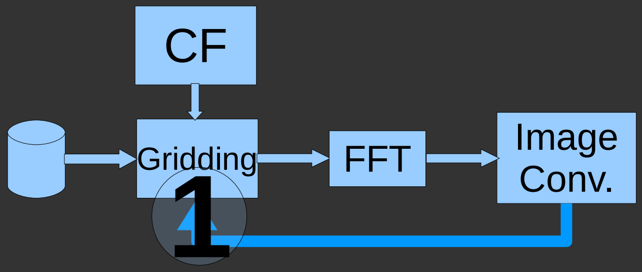
Gridding on the GPU: PoC - 1

- Each data point is multipled by a NxN complex Convolution Function followed by NxN additions to the Global Grid

- N_{data} x N^2_{CF} x 8 FLOP + overheads

  = $O(10^{10-12})$ x (10x10) x 8.2 = 100s TFLOP

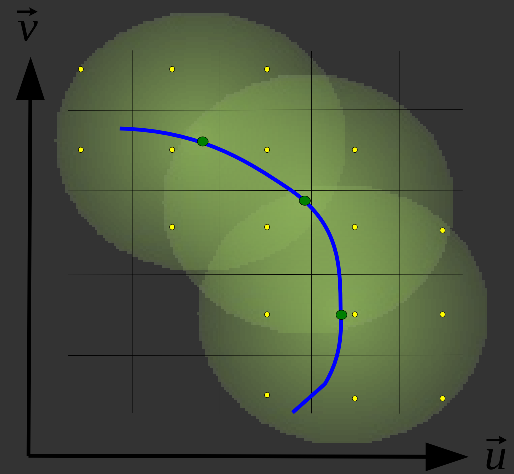
  x (100x100) x 8.2 = ~PFLOP



- SKA

  $O(10^{15})$ x .... x 8.2 = ~ExaFLOP

- Gridding cost dominates computing load for all imaging

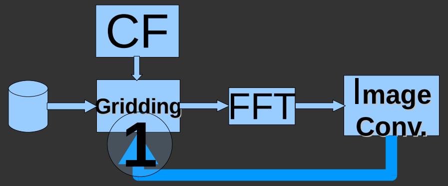


- **Compute to I/O ratio: 10^{2-5}**

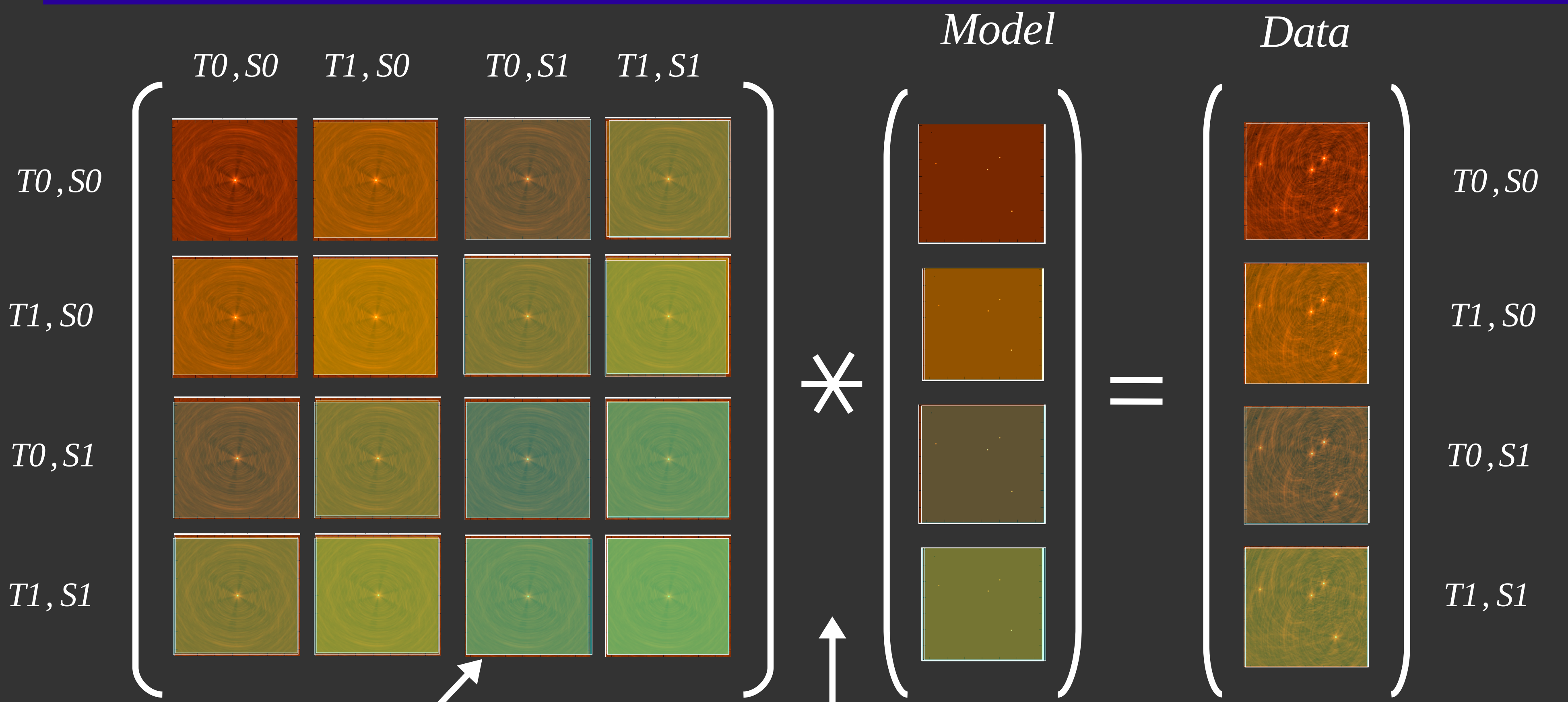
  Massively Parallel H/W should help: PoC 1

Status-3: Gridding – PoC-1 (on-going)

- Gridding / de-gridding:
  - Dominates to cost of High Dynamic Range imaging
- Compute to i/o ratio: 10^{2-5}
  - Dominant cost for most imaging
  - Wide-band imaging: comparable to the cost of the deconvolution step
- Scaling:
  - Run-time cost: (data volume) x (CF size)
  - W-, AW-Projection: 10^{12} x 10^{2-5} FLOP
  - A-Projection: 10^{12} x 10^{2-3} FLOP
- Existing literature
  - GPU: Cornwell et al. (2010), Romien (2012), Daniel Mascot (2014)
    Non-imaging: Margo et al. (2013),
    FPGA: Clarke et al. (2014)

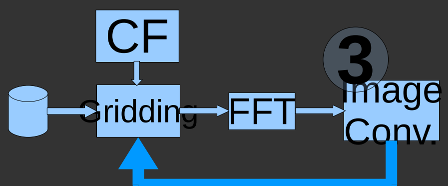


Status-2: Image deconvolution – PoC-3



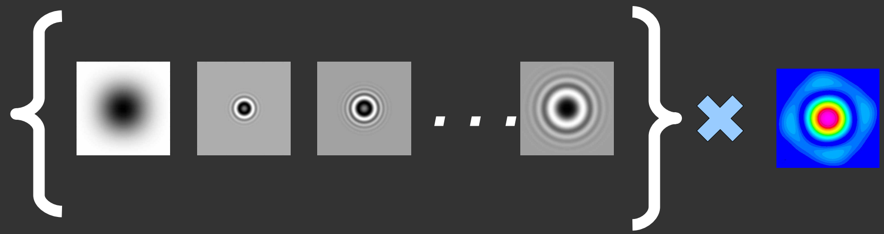
Each element is a
Convolution of 4 functions
(precomputed once)

Every iteration evaluates this matrix
multiply/convolution.



Status-1: CF Memory footprint – PoC-2

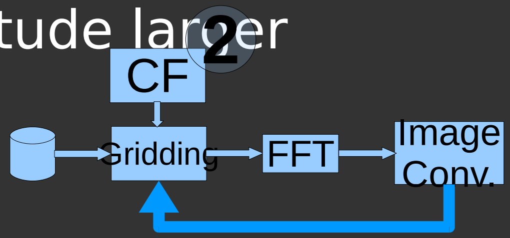
- Negligible I/O – mostly computing



- Tabulated CF requires oversampling to minimize quantization errors

- Memory per CF for high DR imaging with the EVLA:
  - Oversampling: 100; Pixels: 2K x 2K = 8 Mbytes
  - No. of CF s : 100 W-Terms x 100-ATerms = 10^4
  - Total memory footprint : 80 GB

- Memory footprint for SKA several orders of magnitude larger



Status-3: Gridding – PoC-1 (on-going)

- Solutions: Load balancing
  - Non-regular sub-grids