Bluebild: A Next-Generation Radio Interferometric Imager

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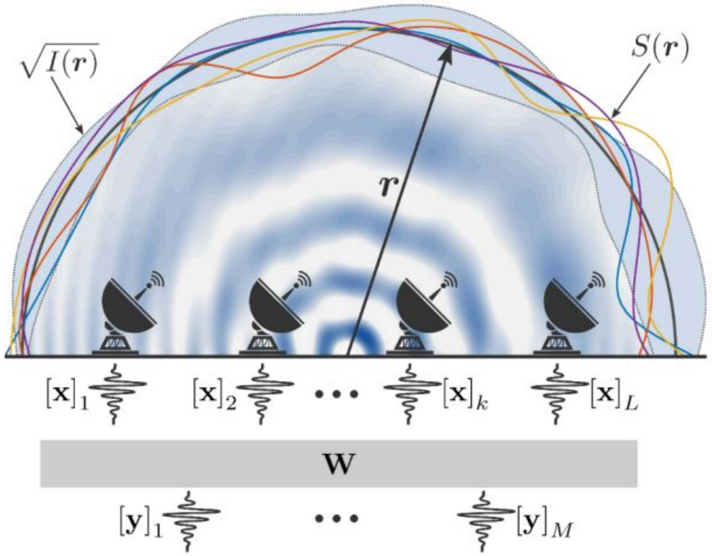
Next-Generation Radio Interferometry

- Leading PASC proposal to optimize, validate, and integrate Bluebild in precursor pipelines
- Team:
  - **Emma Tolley**: Team leader
  - **Etienne Orliac**: HPC expert @ EPFL working on benchmarking, optimization, C & CUDA kernels
  - **Simon Frasch** @ CSCS: GPU nuFFT library
  - **Michele Bianco**: scientific validation & deconvolution
  - **Shreyam Krishna:** scientific use cases (diffuse emission, etc)
  - **Arpan Das**: measurement set interface
  - **Mattheiu Simeoni, Paul Hurley, Sepand Kashani:** Algorithm development/expertise

Radio Interferometric Imaging Process



Single Antenna Signal

Visibilities

$$y = \Psi^* S \xrightarrow{\text{Correlator}} y_i y_j = Y$$

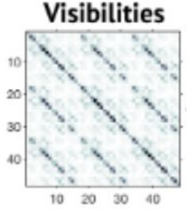
Best reconstructed source emissions

$$\hat{I} = \tilde{D} Y = \tilde{\Psi} E[y_i y_j *] \tilde{\Psi}^*$$

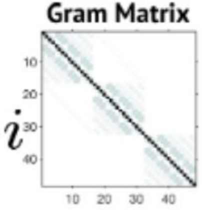
Find a least squares fit for the sky image.

Bluebild Algorithm

- Flexible continuous spherical imager for interferometric applications
- Solves for I(r) in $\int_{\mathbb{S}^{\neq}} I(r)e^{-j<r,p_i-p_j>}dr = V_{ij}$ by framing a generalised eigenvalue problem and decomposing visibilities into different eigenvectors, via fPCA → $\mathbf{E}[yy^*]\alpha = \sum_{a=0}^{N_{Station}} \lambda_a G_\Psi \alpha_a$
- Eigenvector + sampling operator gives eigenfunctions. These give eigenimages - independent and sorted by energy. Can be truncated (automatic denoising) or filtered.
- 3D NuFFT Type-3
- Low computational complexity and affinity for parallel execution



$\alpha_i = \lambda_i$



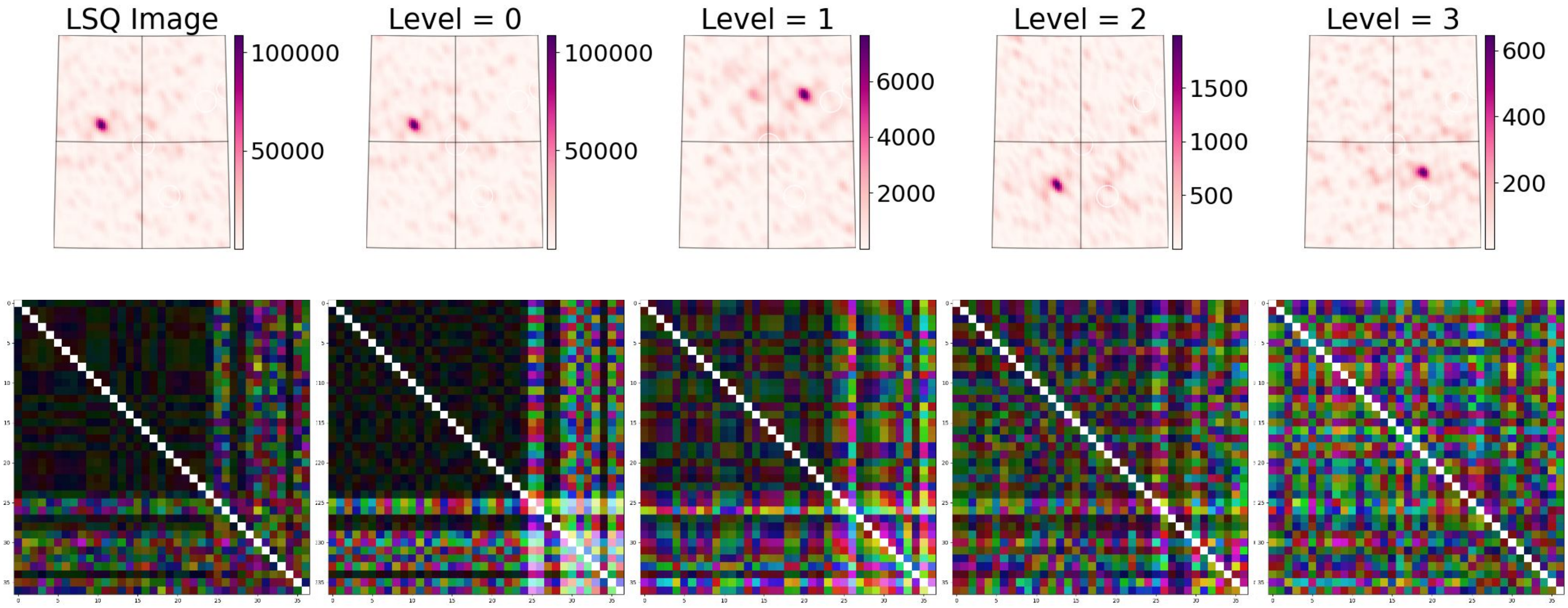
α_i

Normalised Eigenfunctions

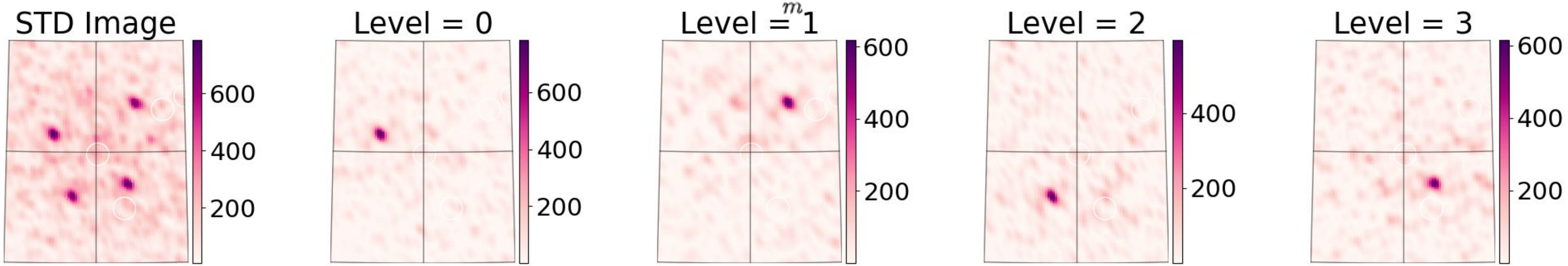
$$\epsilon_m = \frac{\Psi\alpha_m}{||\Psi\alpha_m||} = \frac{\Psi\alpha_m}{\sqrt{\alpha_m^H G_\psi \alpha_m}}$$

$$\hat{I}(r) = \sum_m \lambda_m |\epsilon_m(r)|^2 = \sum \lambda_m \frac{|\Psi\alpha_m|^2}{v_m^H G_\Psi \alpha_m}$$

$$\hat{I}_{lsq} = \sum_m \lambda_m |\epsilon_m|^2$$



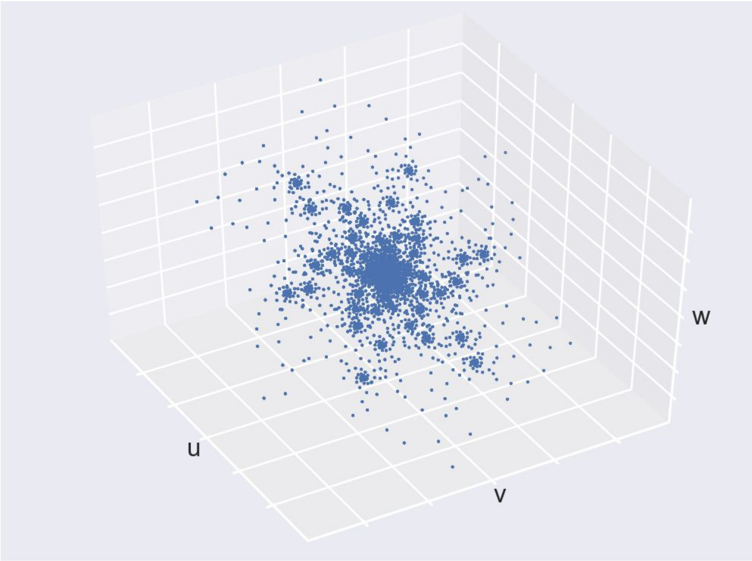
$$\hat{I}_{std} = \sum_m |\epsilon_m|^2$$

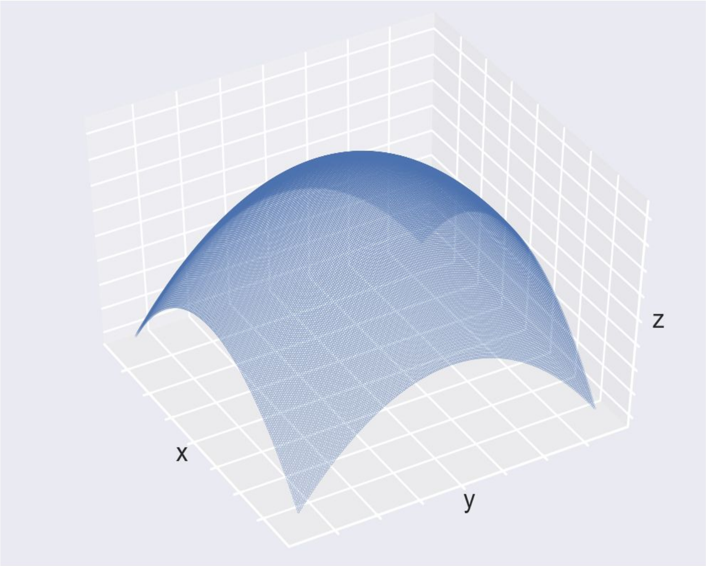


Bluebild Imaging Plus Plus (BIPP)

- C++ ported version with python wrapper for wider community release
- HPC implementation with support for CUDA (NVIDIA) and HIP (AMD)
- Support for MWA, LOFAR, Oskar SKA-Low measurement sets
- Domain partitioning inbuilt
- No deconvolution - only dirty images
- Github: https://github.com/epfl-radio-astro/bipp
- Validation & benchmarking against WSClean and CASA tclean(ongoing)

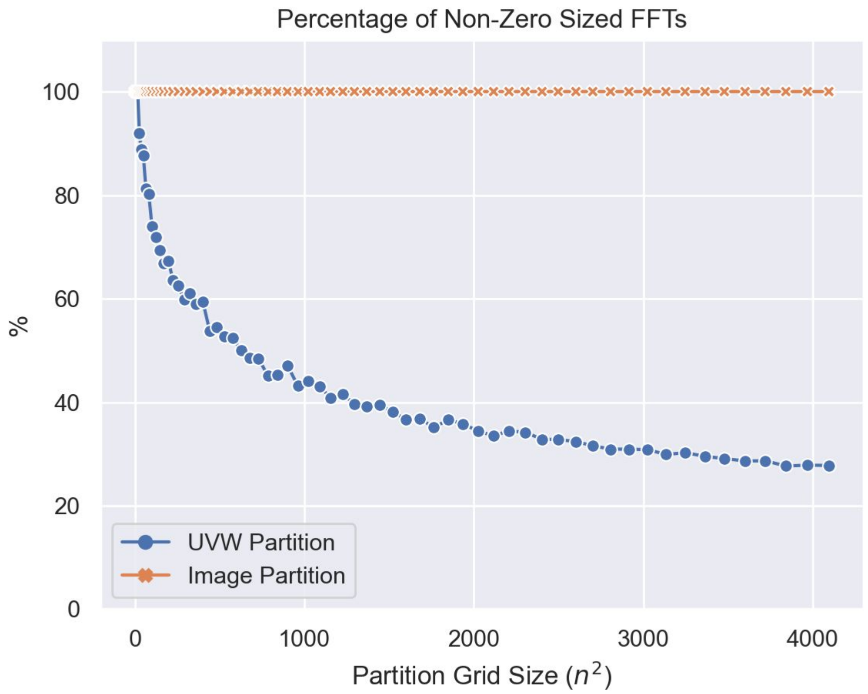
NuFFT Domain Partitioning - Inspired by HVOX[1]
Plots courtesy Simon Frasch

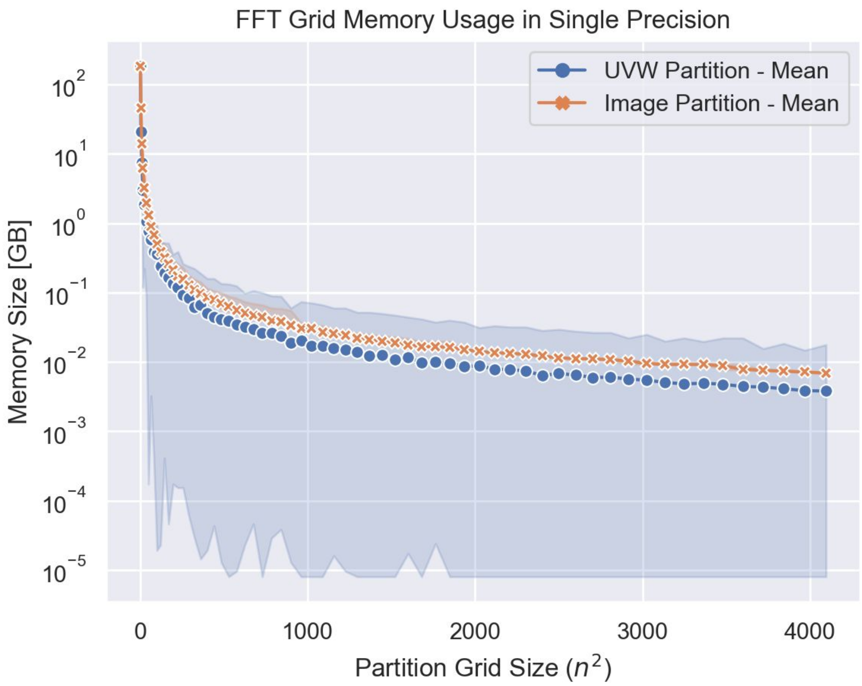




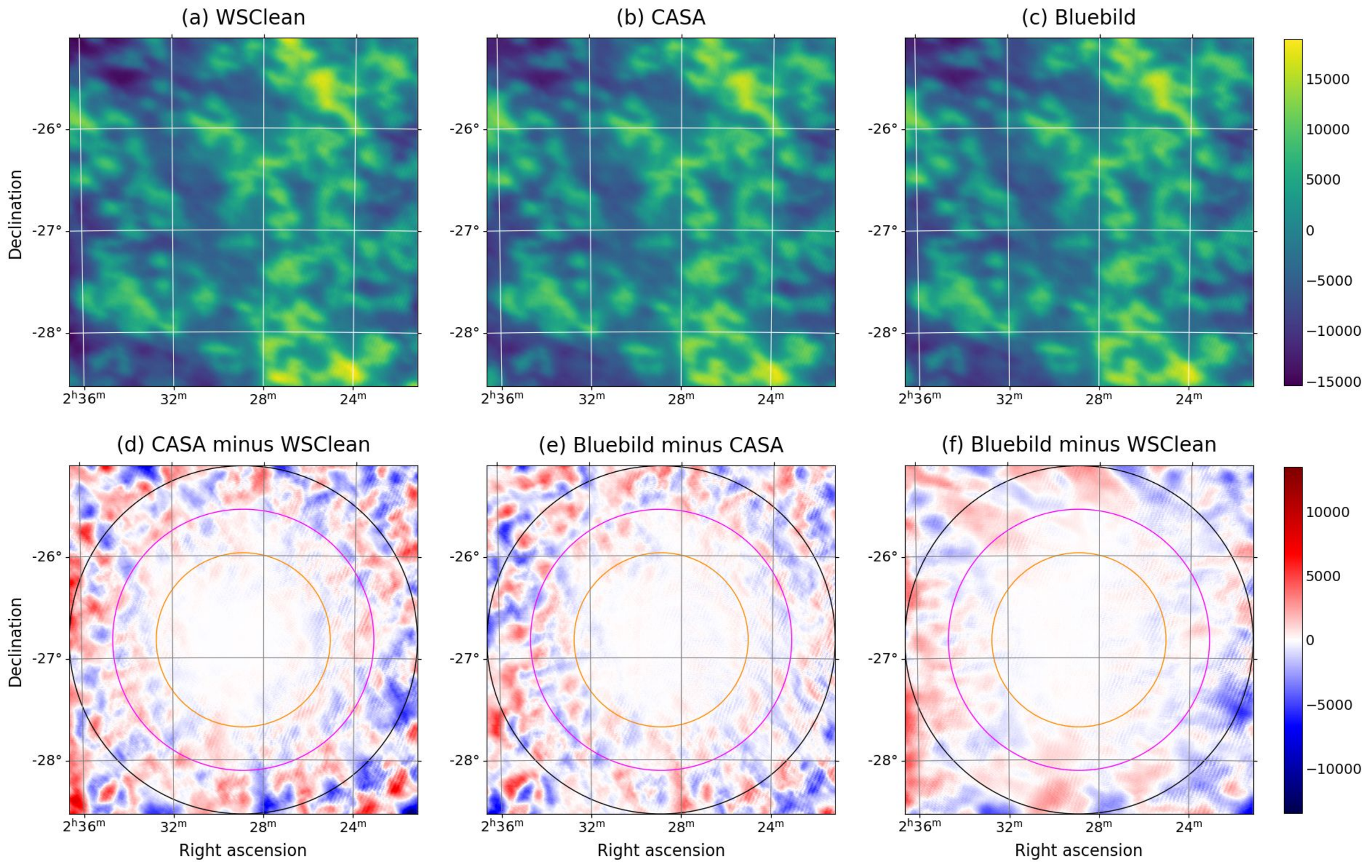
1: [Kashani, Queralt, Jarret and Simeoni 2023]

$$\tilde{B}_{pix} = \sum_{n=1}^{N_1} V'_n e^{i x'_{pix} \dot{b}'_n} + \ldots + \sum_{n=N_{I-1}+1}^{N_I} V'_n e^{i x'_{pix} \dot{b}'_n}$$

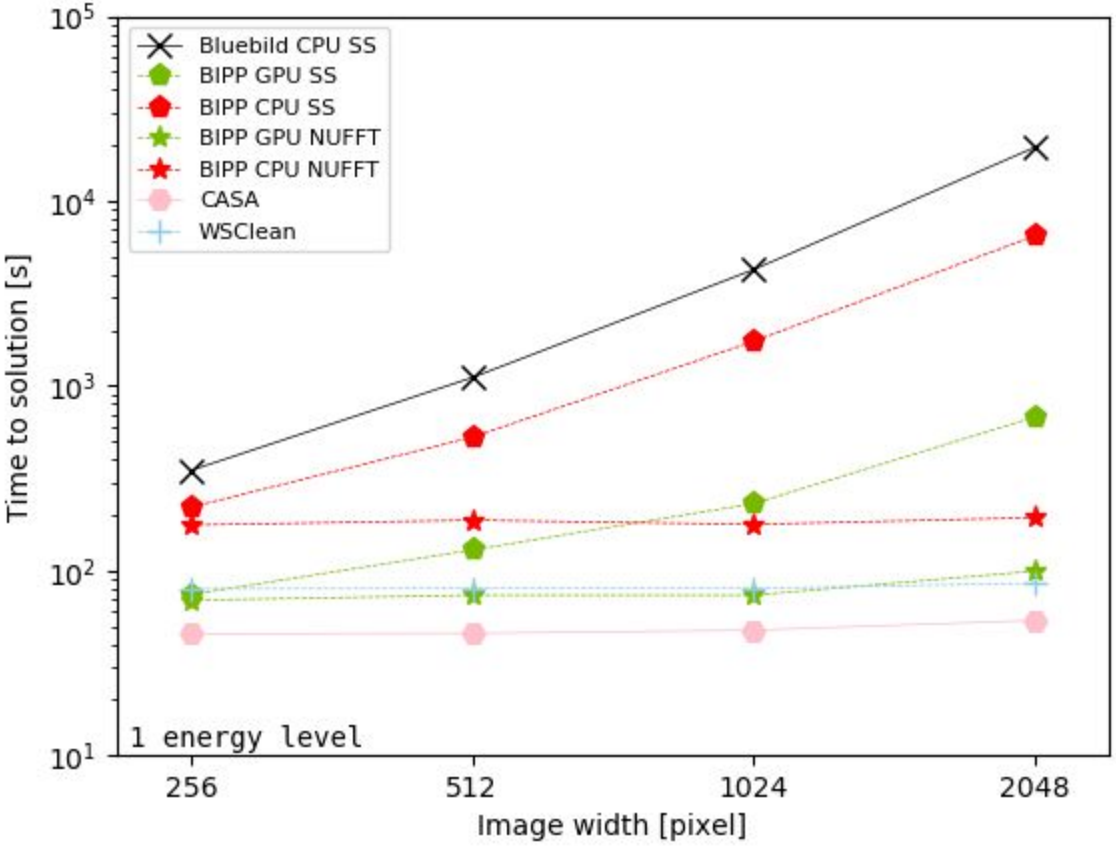




Validation - Plots courtesy of Etienne Orliac

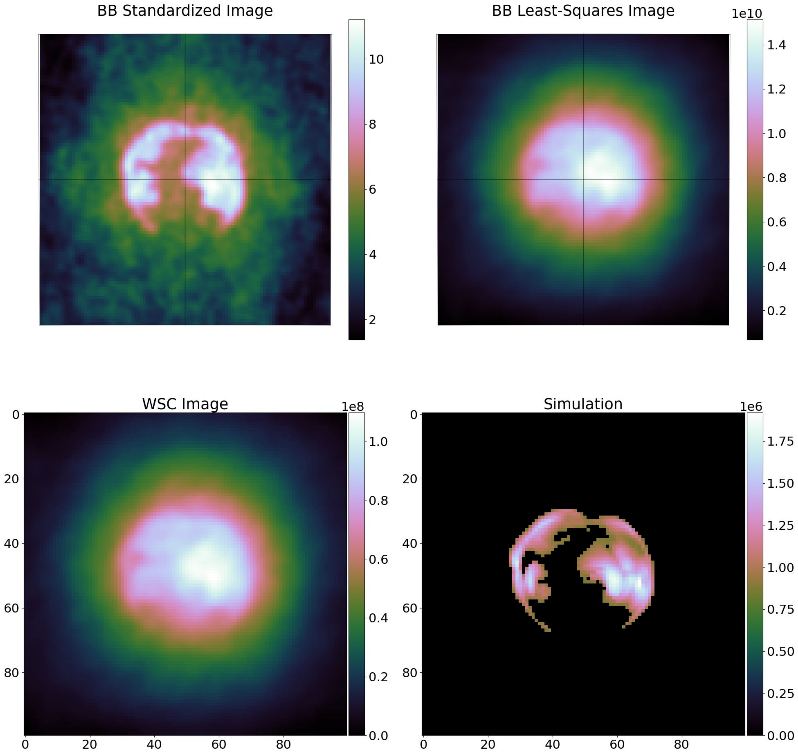


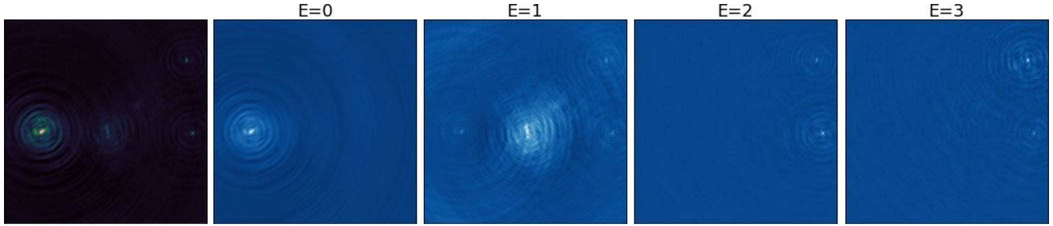
Benchmarking - Plots courtesy of Etienne Orliac



Some science-use cases: Plots courtesy Michele Bianco

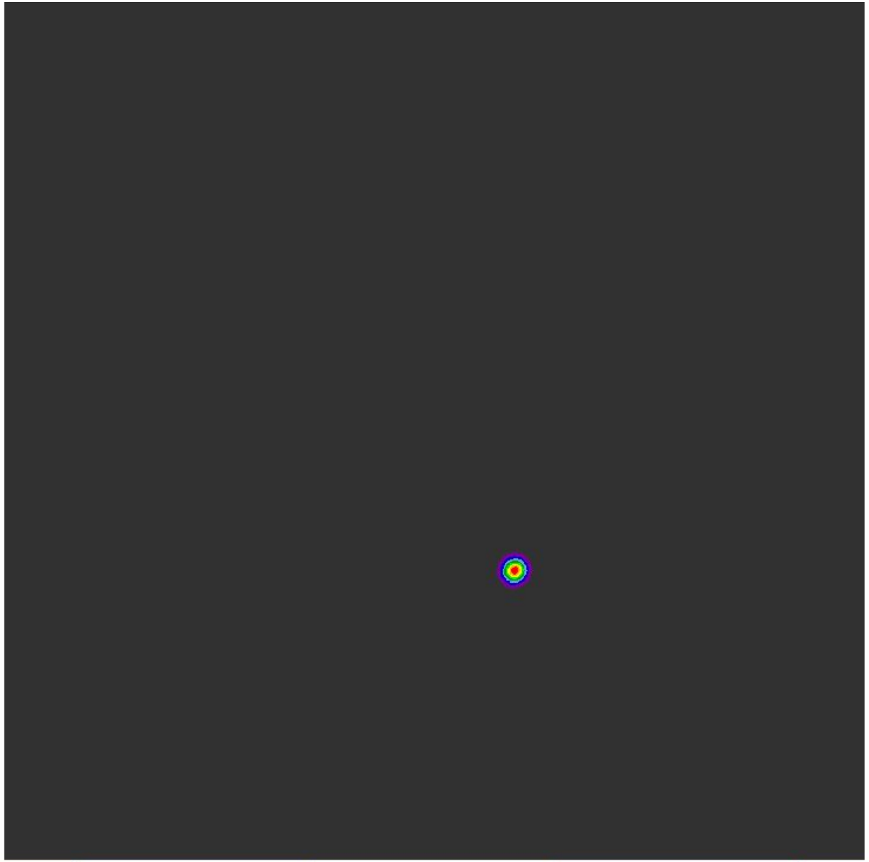
- Solar limb brightening
- Bright Source PSF separation
- EoR Point Source removal?
- Galaxy Cluster Emission?
- Transient Detection?

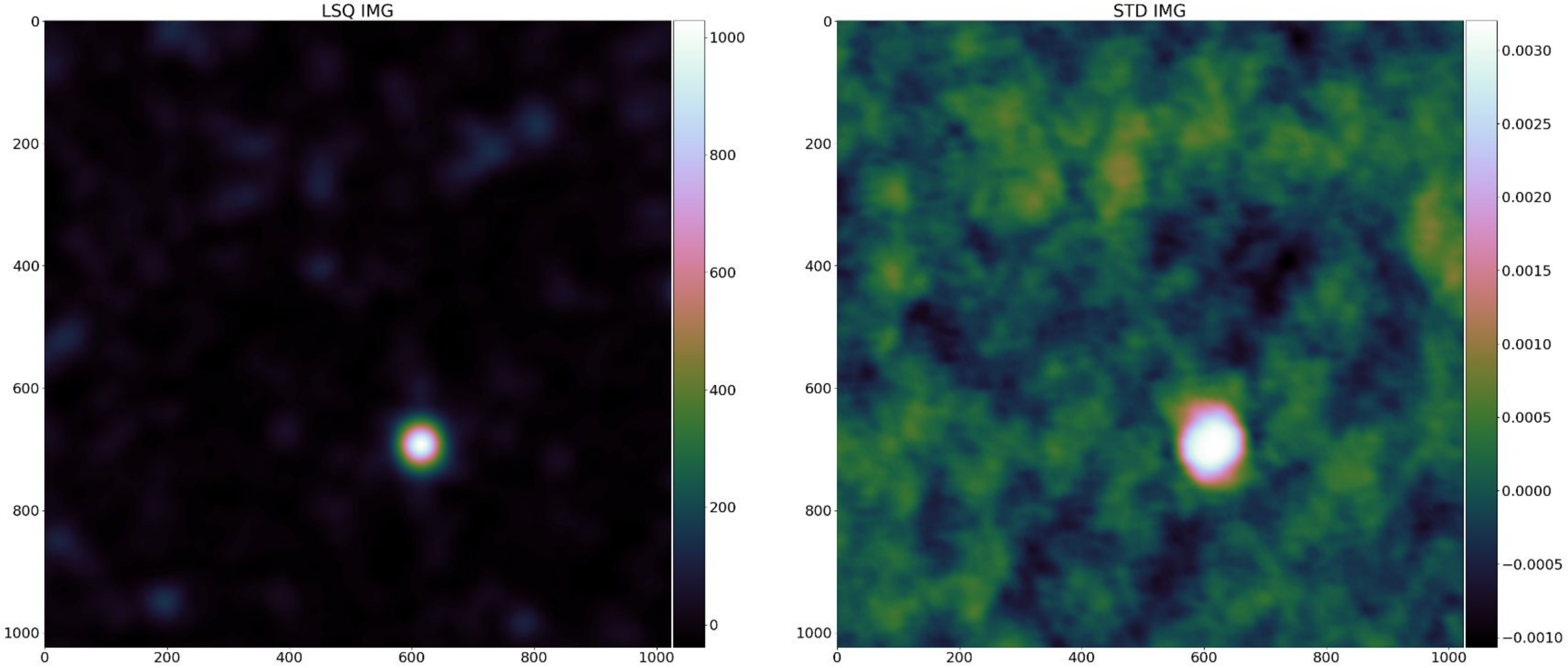




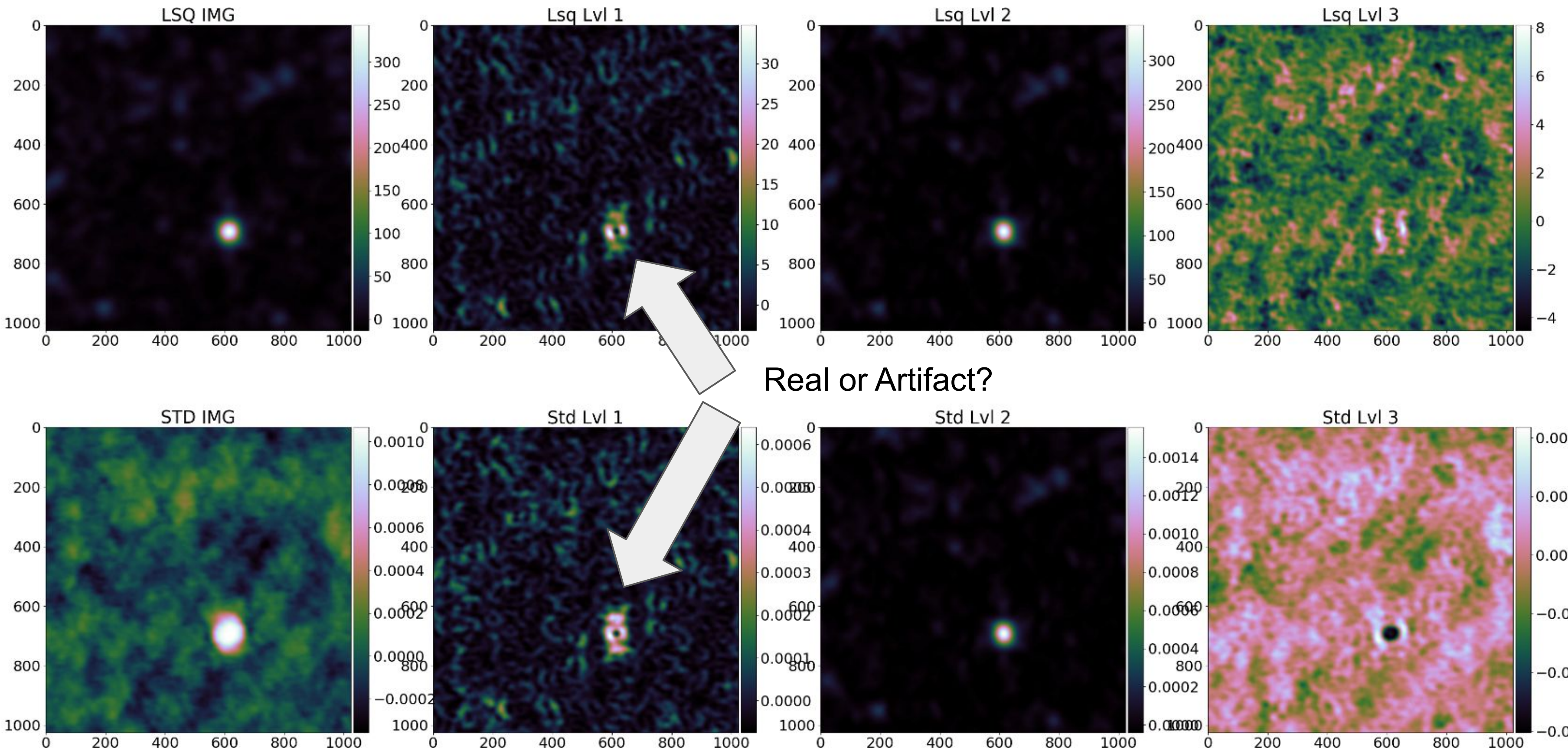
Solar Observations Using Bluebild

- Image of free-free emission from the solar corona, affected by anisotropic scattering and refraction due to coronal medium
- ~14.3° FOV
- 10s integration time, 0.5 second time steps
- MWA Phase I observation (128 phased arrays)
- 3’ in resolution, so diffuse features > PSF
- ν ~ 239-241 MHz, 64 Channels, Bandwidth 40 kHz
- Power scaled

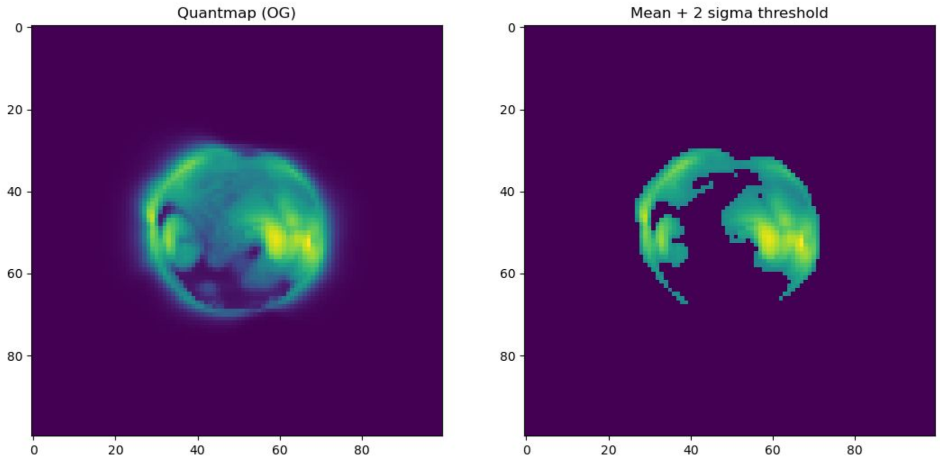




LSQ IMG
STD IMG
0
200
400
600
800
1000
0
200
400
600
800
1000
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
−0.0010


LSQ IMG
Lsq Lvl 1
Lsq Lvl 2
Lsq Lvl 3
STD IMG
Std Lvl 1
Std Lvl 2
Std Lvl 3
Real or Artifact?

Solar MWA Simulation

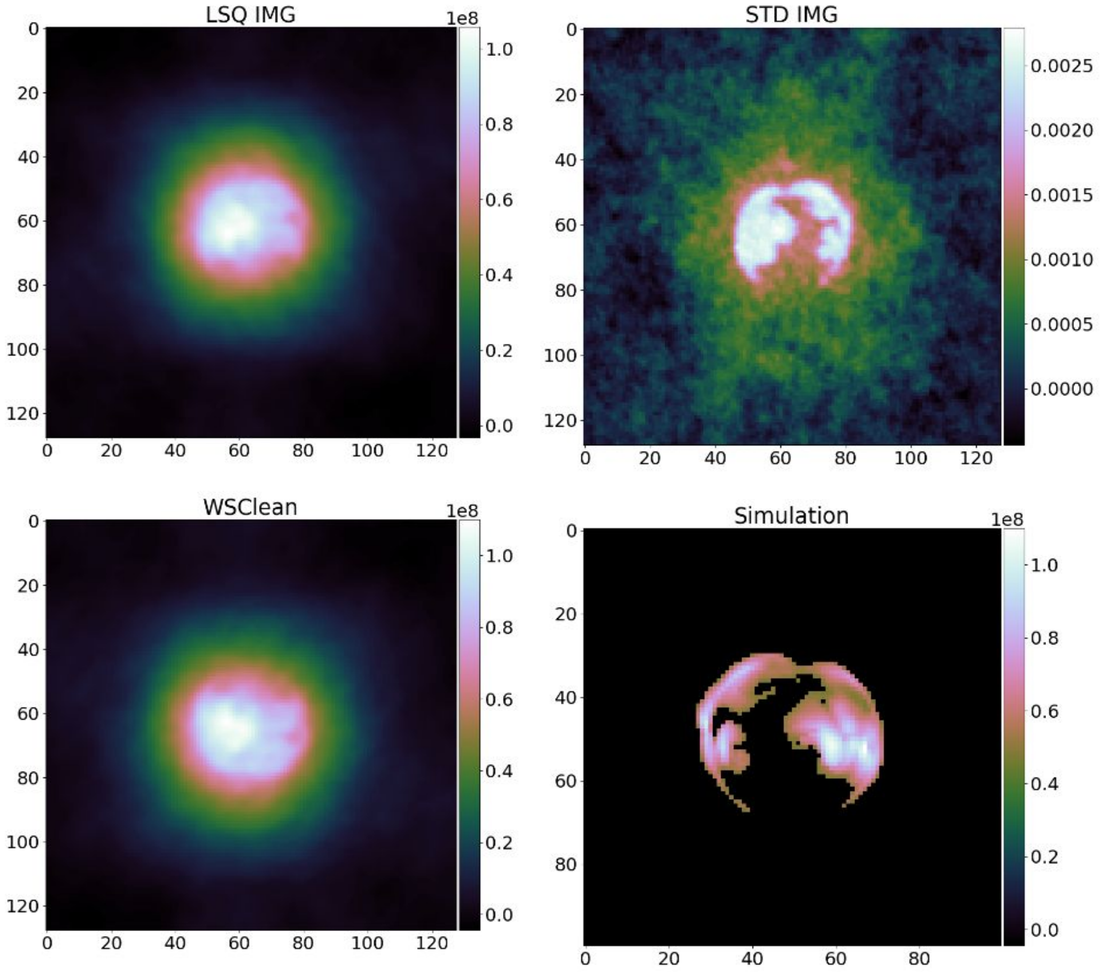


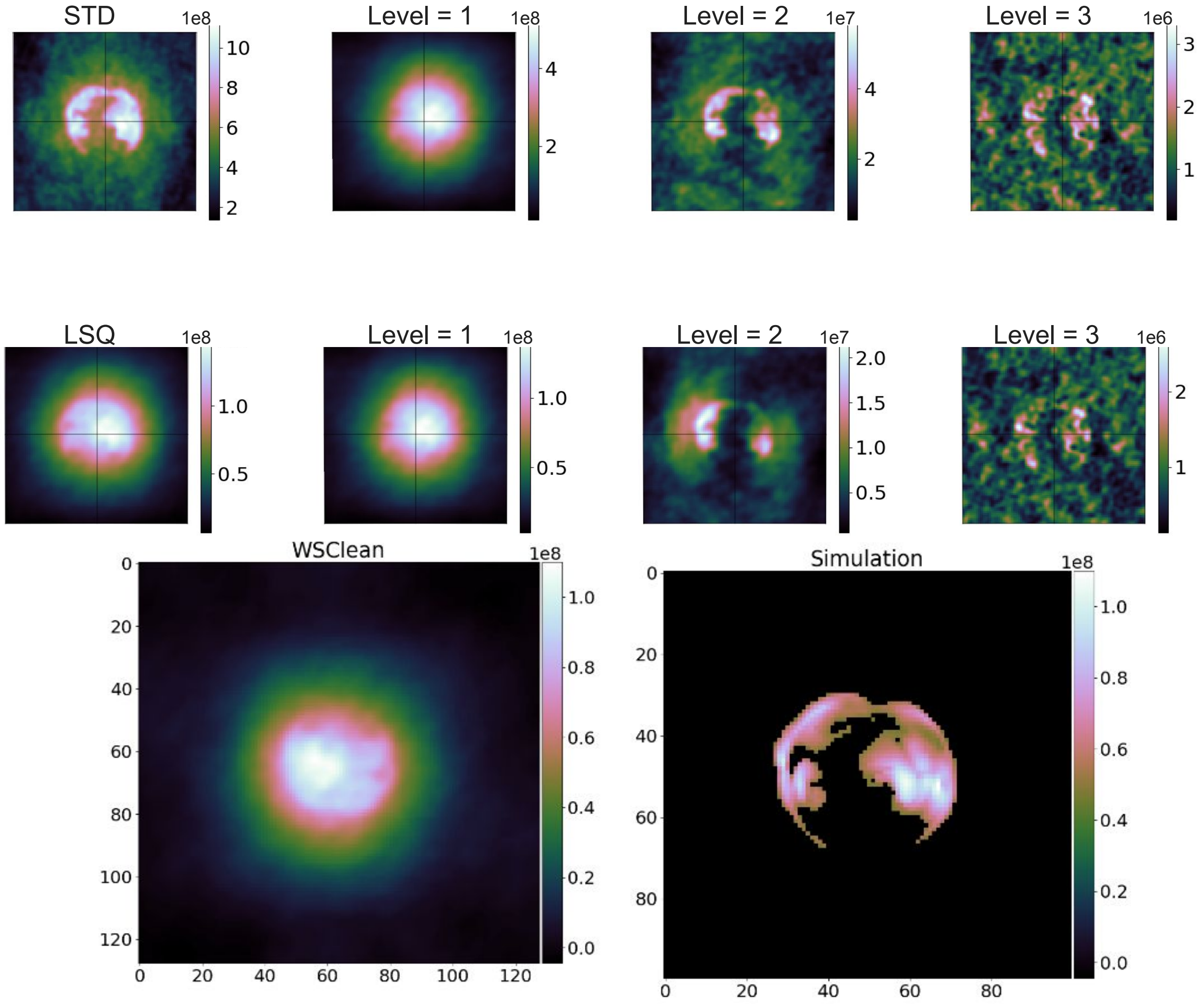
No objective truth with celestial observations

Mock observations of Solar simulation using OSKAR[2]:

- Simulated 1.4° FOV free-free maps using FORWARD[1] software.
- Forward uses a self-consistent Magnetohydrodynamic Algorithm outside a Sphere (MAS) coronal model.
- N_e, T_e and B evolved from input HMI magnetogram and normalised against photospheric values. Also calculated brightness temperature, T_B, in various Stokes parameters
- Propagation effects (scattering, refraction) not included.
- Stokes I parameter imaged using MWA Phase I configuration on OSKAR.
- Simulation thresholded **(μ + 2*σ)**, then imaged.

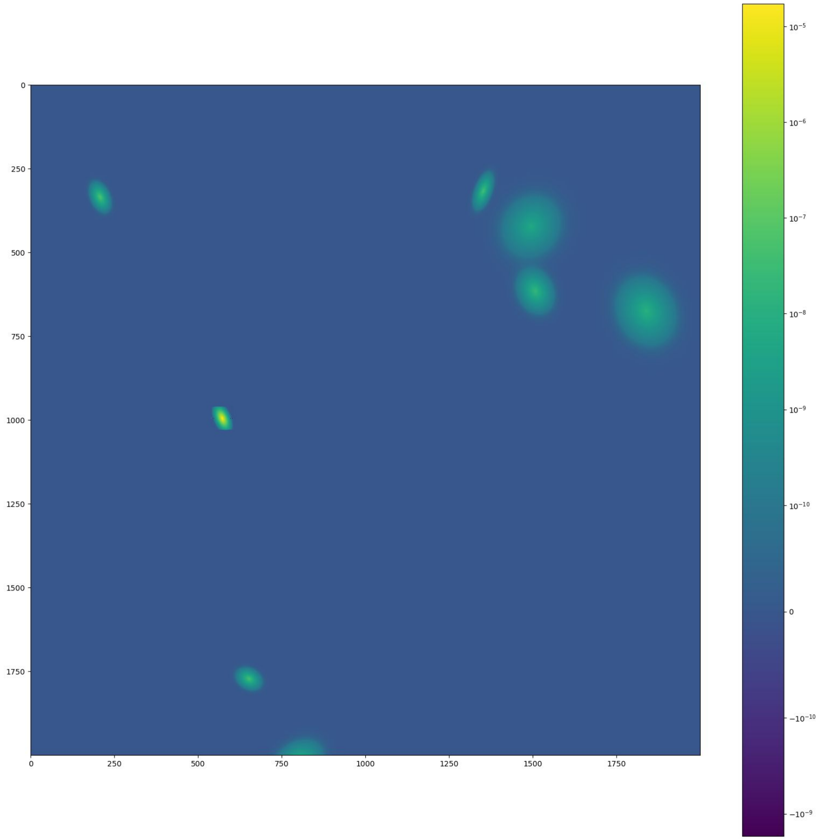
1: [Gibson et al. 2016] 2: [Mort 2010]


LSQ IMG
STD IMG
WSClean
Simulation
1e8

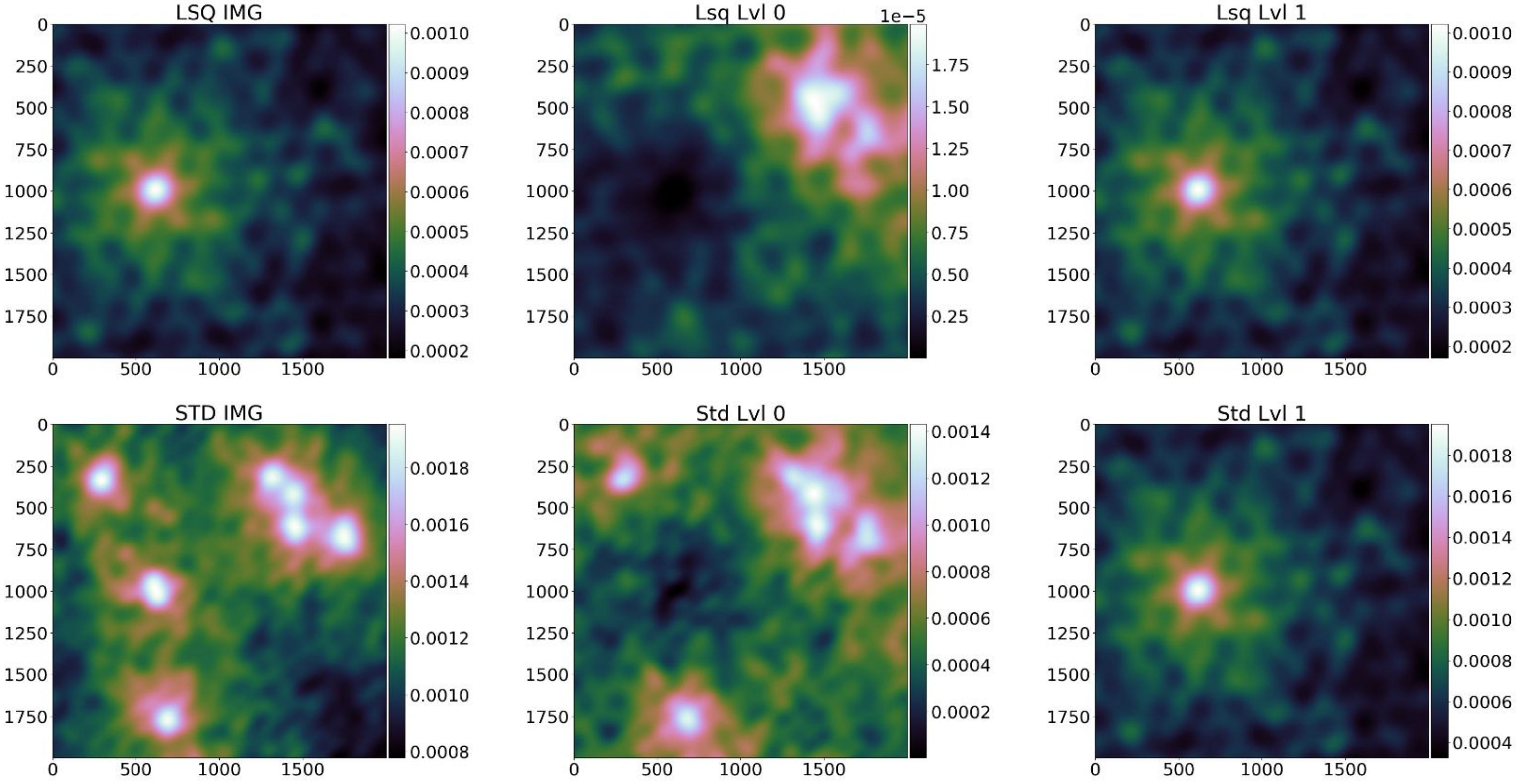

STD
1e8
Level = 1
1e8
Level = 2
1e7
Level = 3
1e6
LSQ
1e8
Level = 1
1e8
Level = 2
1e7
Level = 3
1e6
WSClean
1e8
Simulation
1e8

Bright Source PSF separation - model courtesy Ian Harrison!

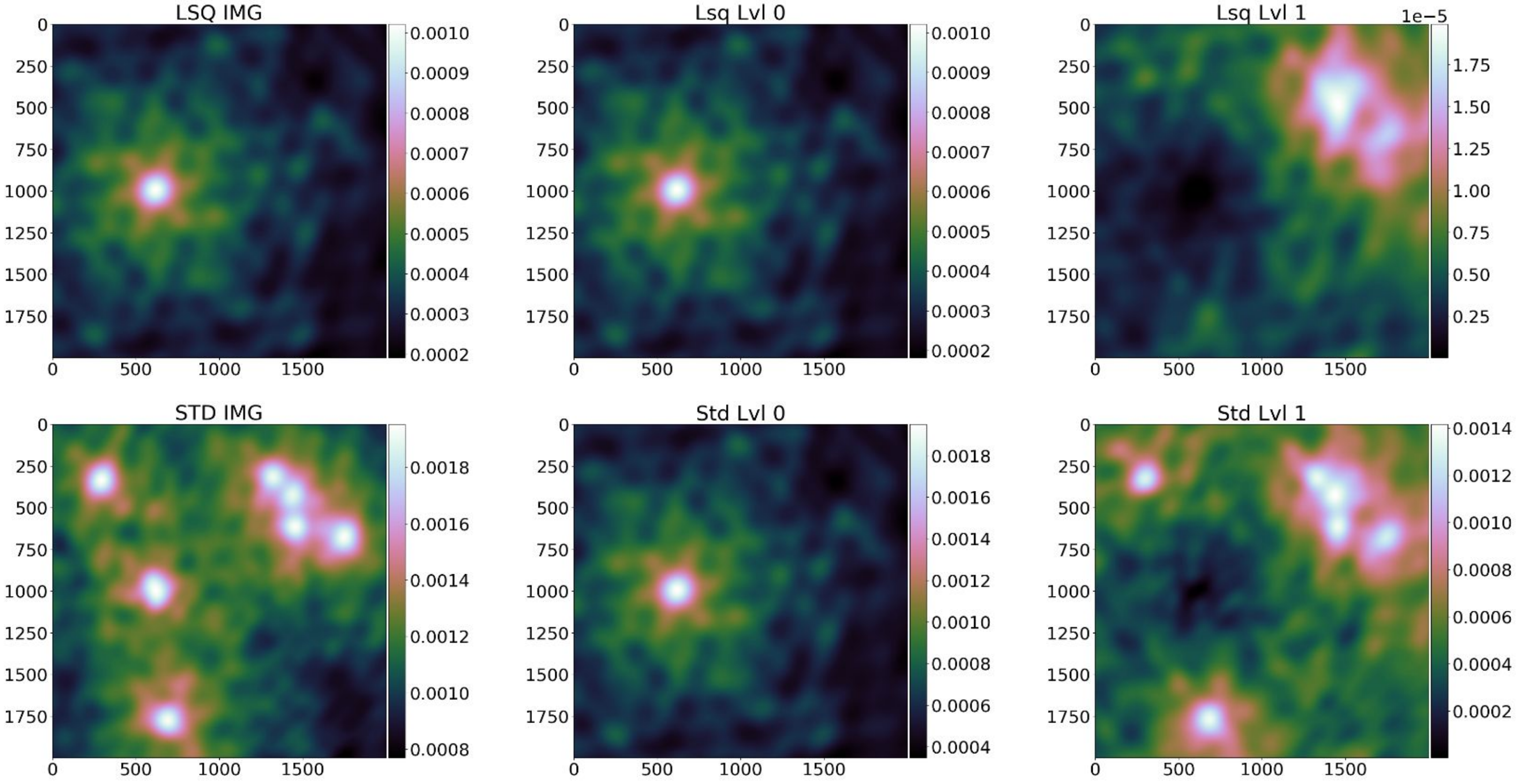
- Model: 1000x range in SNR for gaussian sources in small FOV (0.025 deg) image; 1 frequency channel
- Imaged using SKA Low Config on OSKAR using Karabo
  - 200 MHz
  - 1.5 GHz (SKA Mid Frequencies)
- Different integration times
  - 1 hour
  - 10 minutes
- Since BB works on visibilities - separation of interferometric artifacts?



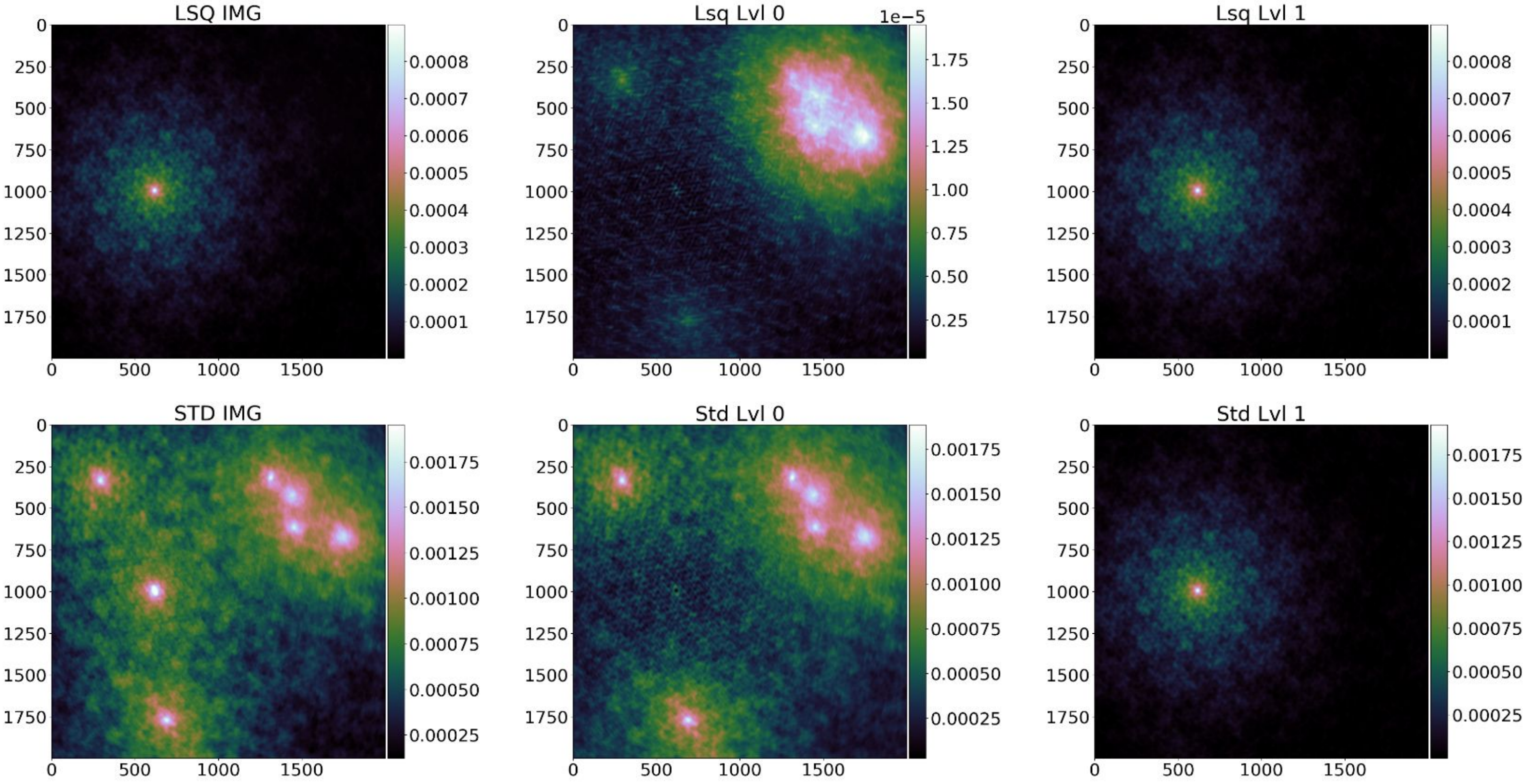
200 MHz 10 min



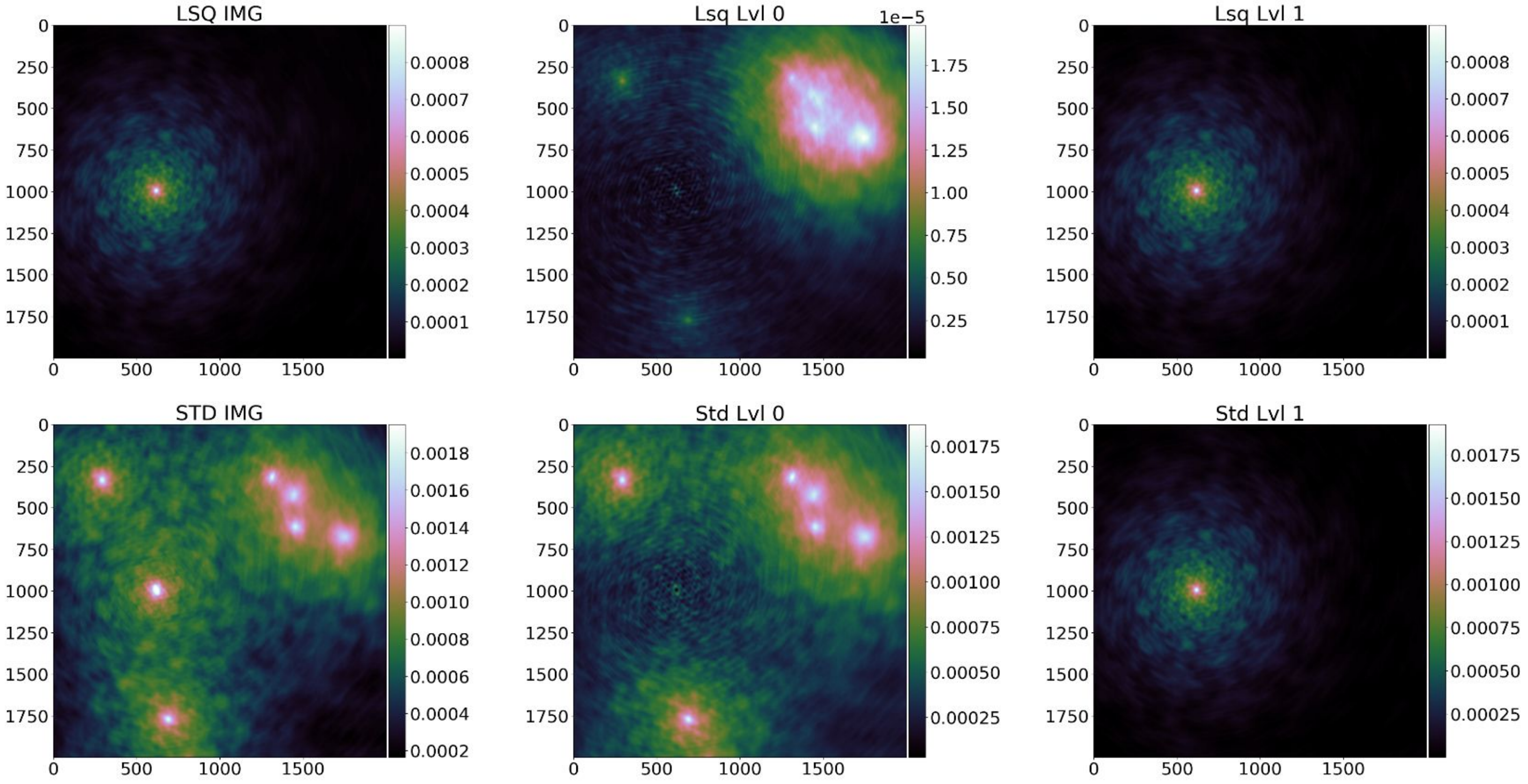
200 MHz 1 hr


LSQ IMG
Lsq Lvl 0
Lsq Lvl 1
1e−5
STD IMG
Std Lvl 0
Std Lvl 1
0
250
500
750
1000
1250
1500
1750
0.0010
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002

1500 MHz 10 min

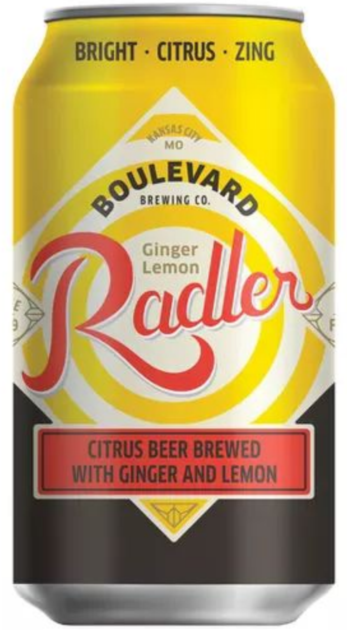


1500 MHz 1 hr



Bright Source PSF Separation

- Effective when bright source is seen as a point source (resolution!!!)
- Deconvolution (probably) important when it isn’t!



Ongoing and Future Work:

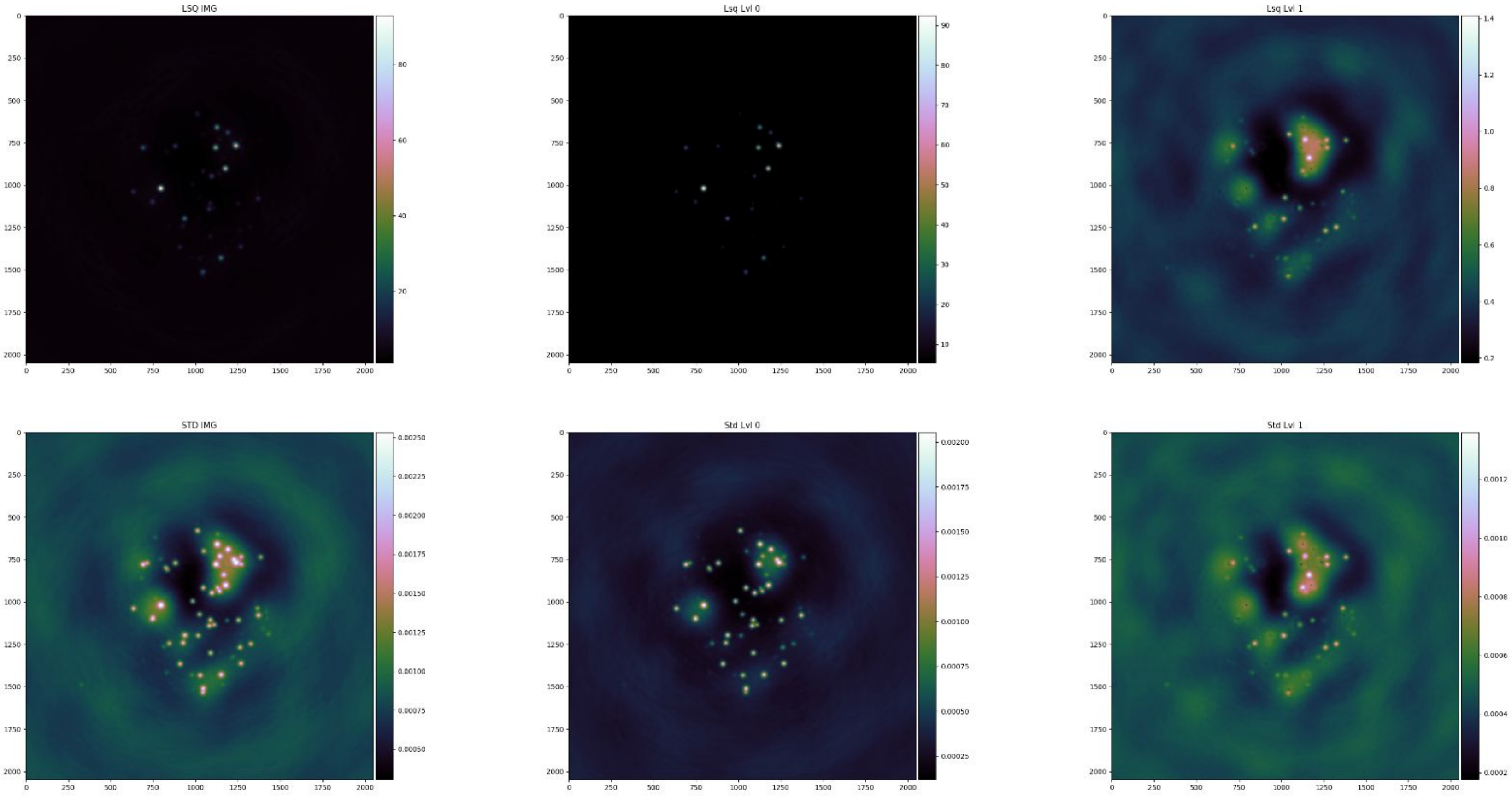
- Dish Array Support!
- Eigen-image recombination
- Radler (Radio Astronomical Deconvolution Library) incorporation
- BIPP data release paper (Tolley et al) for MNRAS RASTI inaugural issue
- Bluebild algorithm paper (Simeoni et al)

Contact me at shreyam.krishna@epfl.ch for any questions!

BIPP Github:

Contact me at shreyam.krishna@epfl.ch for any questions!

EoR Point Source Removal - PRELIMINARY RESULTS!



Diffuse Cluster Emission

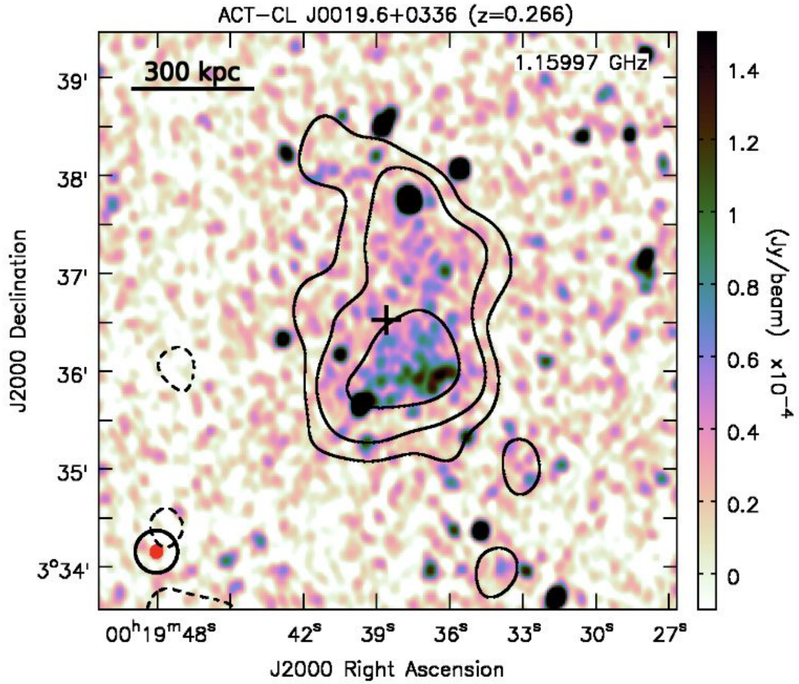
In collaboration with Kenda Knowles (RadioClusters proposal)

Want to look for **Faint, diffuse, cluster-scale radio emission** in the form of radio halos, radio relics, and smaller mini-halos

- Created by synchrotron emission, thus a good probe of cluster magnetic fields
- Cluster dynamics: Form of diffuse emission connected to merger shocks and turbulence

Interesting image synthesis problem: want to remove the dense, compact sources and keep the diffuse emission (Bluebild, deblending)

Need to detect these objects in surveys: anomaly detection



arXiv:2012.15088

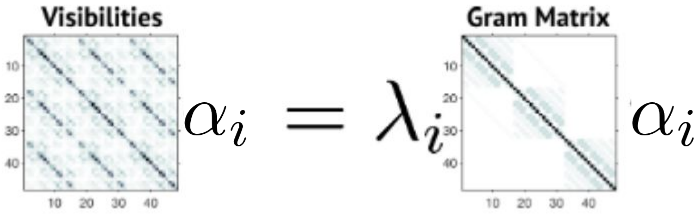
Transient Detection (Without Imaging)

BB/BIPP has 2 steps after initial setup:

1) Parameter Estimator: Eigenvalues calculated and clustered (custom or K-Means)

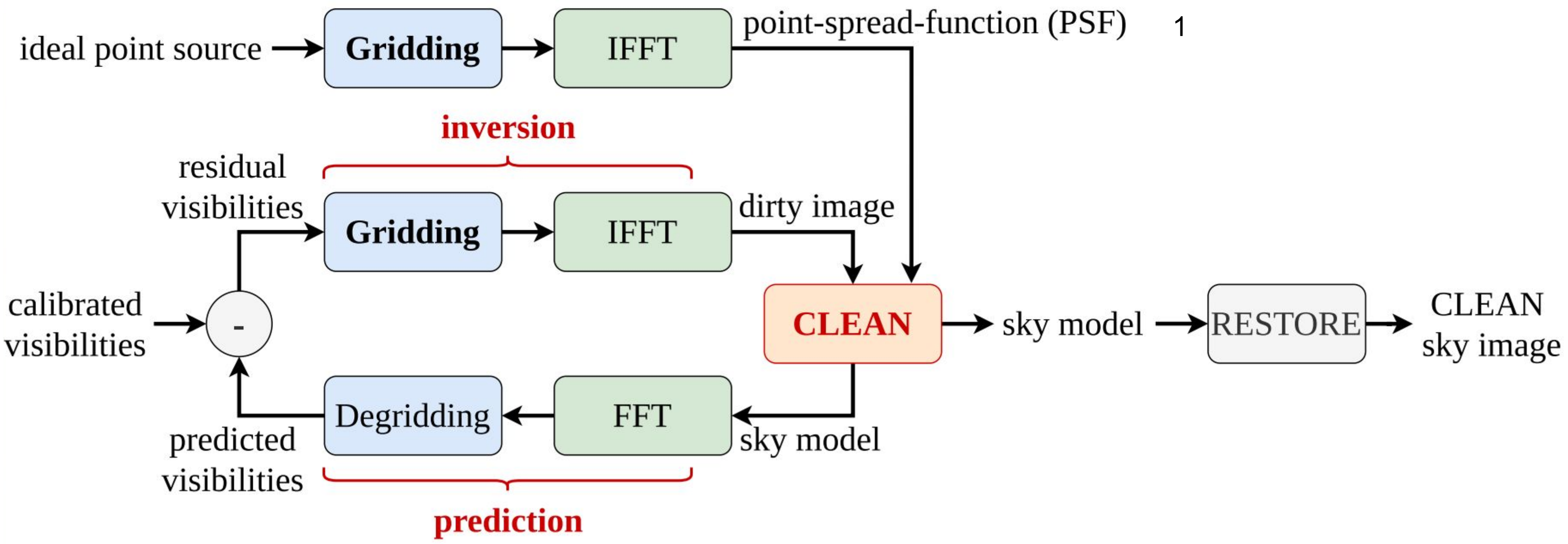
2) Imaging: Eigen visibilities + Eigen images created

Use eigenvalues after step 1 for detection of transients?

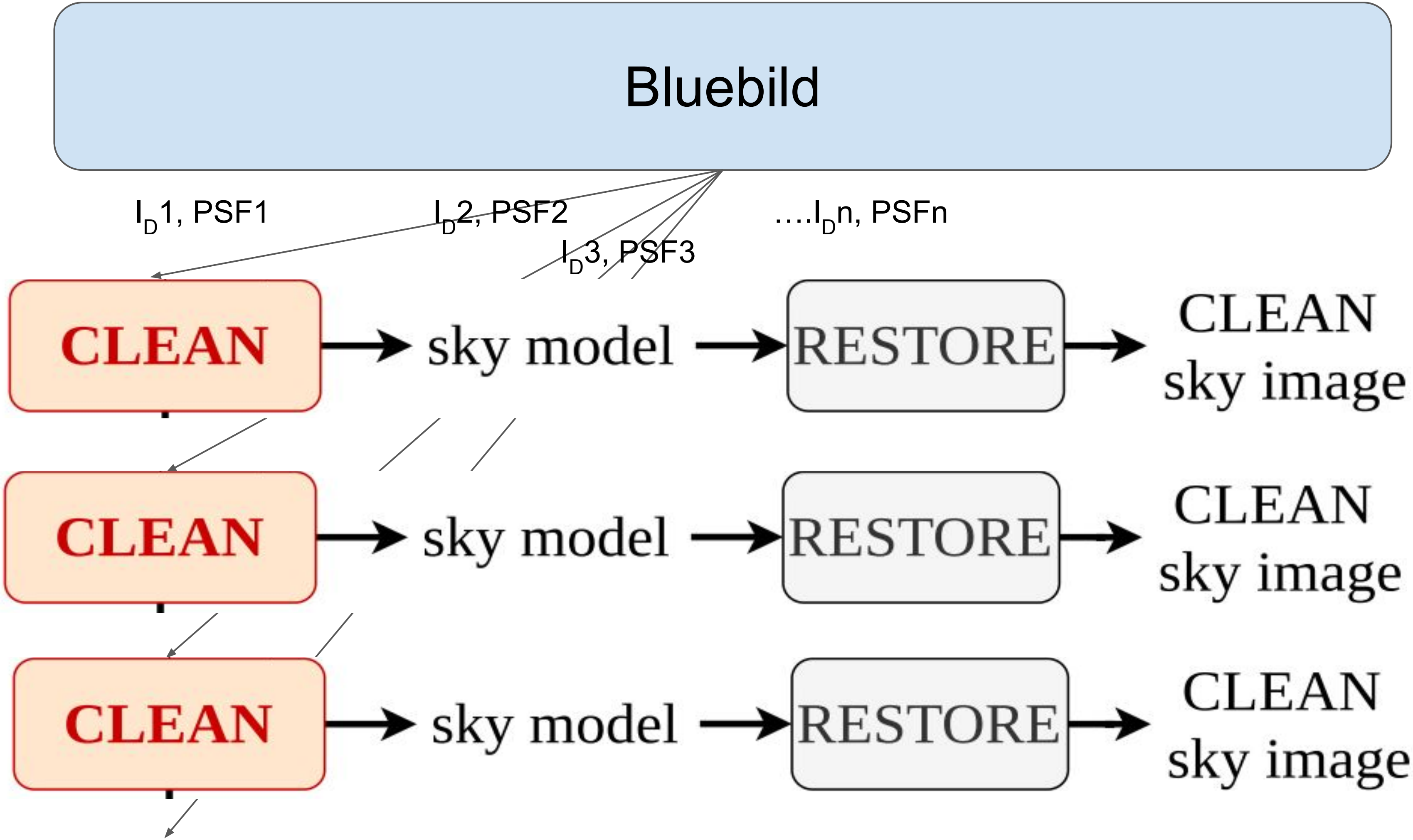


Backup Slides Start Here

CLEAN family of algorithms

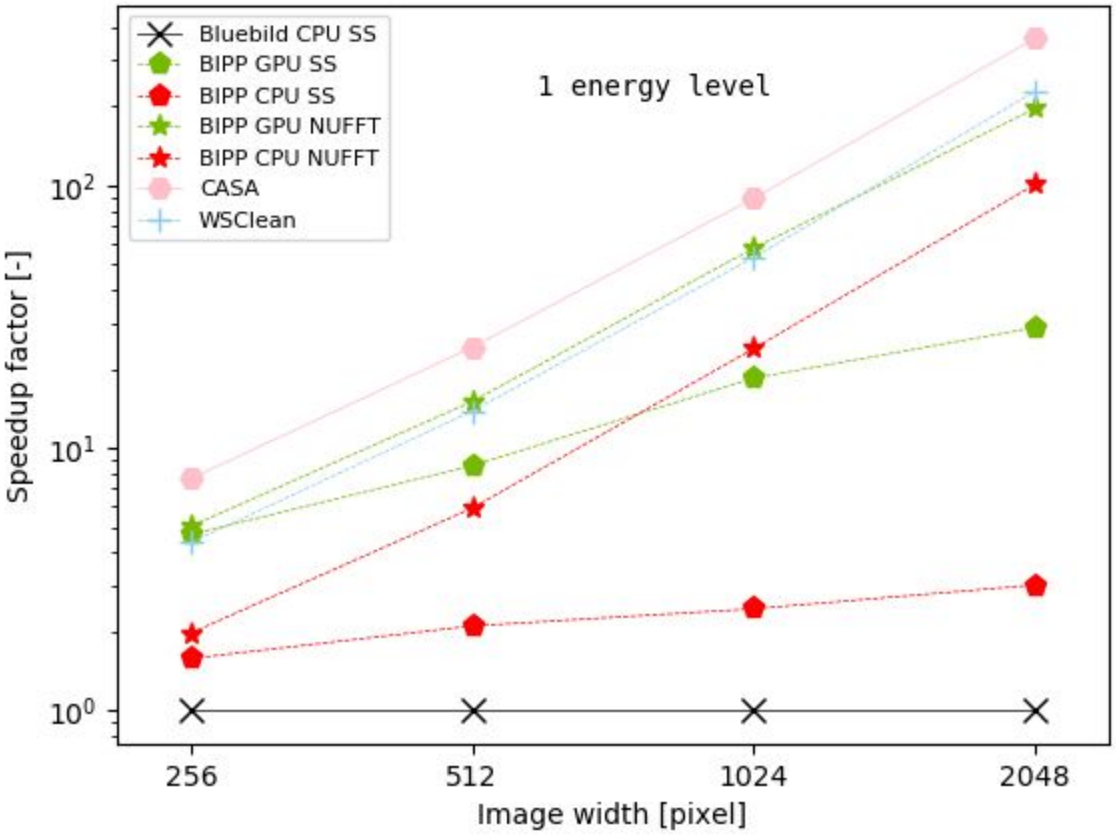


1: [Corda 2022]

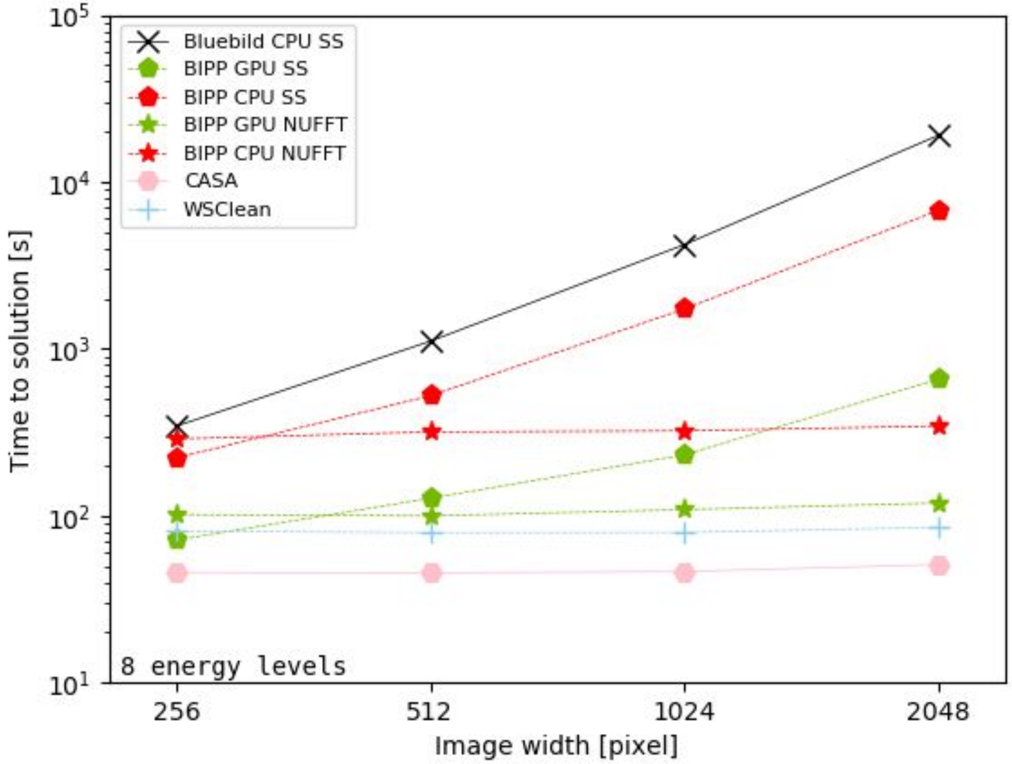


Bluebild
I_D1, PSF1
I_D2, PSF2
I_D3, PSF3
....I_Dn, PSFn
CLEAN
sky model
RESTORE
CLEAN sky image
CLEAN
sky model
RESTORE
CLEAN sky image
CLEAN
sky model
RESTORE
CLEAN sky image

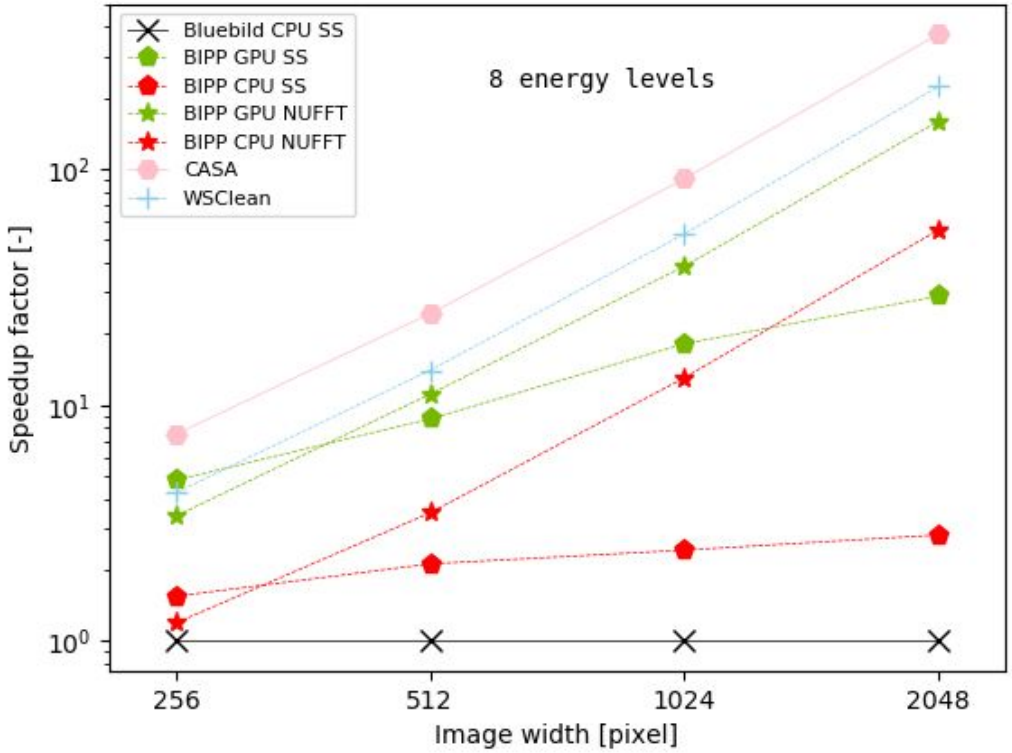
Benchmarking - Plots courtesy of Etienne Orliac



Benchmarking - Plots courtesy of Etienne Orliac



Benchmarking - Plots courtesy of Etienne Orliac



CLEAN[1] family of algorithms

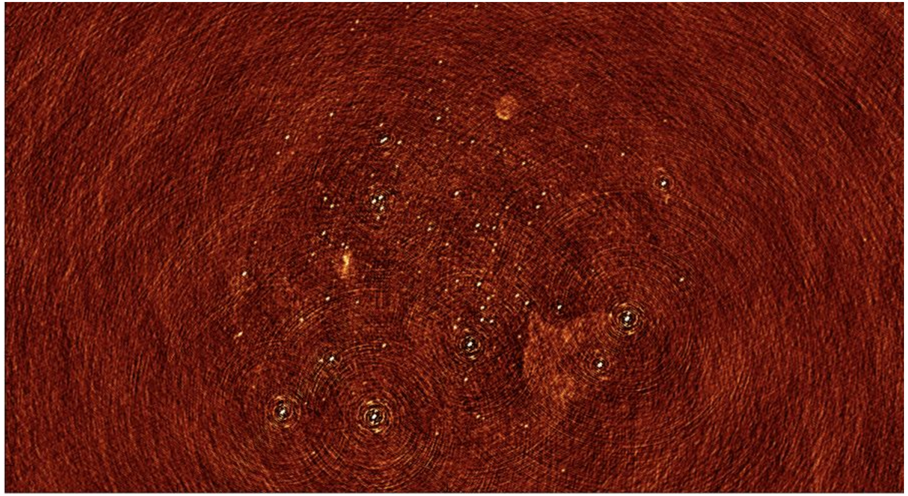
$$\tilde{D} = (D\Sigma D^*)^{-1} D\Sigma$$

$$Y = \mathbf{E}[\Psi^* S(\Psi^* S)^*]$$
$$= \Psi^* \mathbf{E}[SS^*]\Psi = D^* I$$

Generalized Least-Squares Solution

$$\hat{I} = \tilde{D}Y = (D\Sigma D^*)^{-1} D\Sigma Y$$

$$\hat{I} = \underset{x}{argmin} ||\Sigma^{-1/2}(\hat{Y} - Y)||$$


[2]

1: [Högbom 1974]
2:[LOFAR School 2016, Offringa]

Bluebild Algorithm[1]
Psuedo-Inverse Least Squares Solution

$$\tilde{\Psi} = \Psi G_{\Psi}^{-1} = \Psi\left(\Psi^*\Psi\right)^{-1}$$

$$\hat{I}(r) = \tilde{\Psi}\mathbf{E}[yy^*]\tilde{\Psi}^* = \Psi G_{\Psi}^{-1}\mathbf{E}[yy^*]G_{\Psi}^{-1}\Psi^*$$

$$\hat{I}(r) = \sum_m \lambda_m |\epsilon_m(r)|^2$$

$$\epsilon_m = \Psi\alpha_m \qquad \hat{I}(r)\Psi\alpha_m = \lambda_m\Psi\alpha_m$$

$$\mathbf{E}[yy^*]\alpha_m = \lambda_m G_{\Psi}\alpha_m$$

1:[Simeoni, Hurley and Kashani, 2023]