Separating Point Source Contaminants at the Visibility Level

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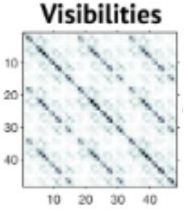
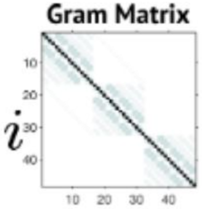
Bluebild Algorithm

- 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.
  Eigenvector + sampling operator gives eigenfunctions. These give eigenimages - independent and sorted by energy. Can be filtered.



$\alpha_i = \lambda_i$



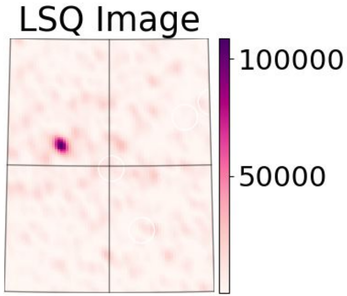
α_i

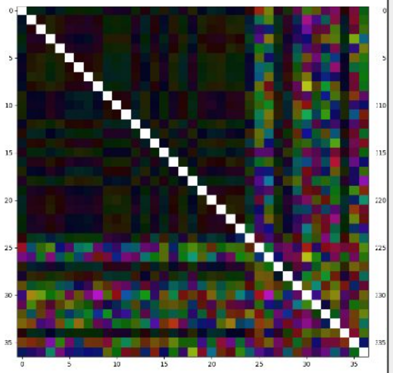
Normalised Eigenfunctions

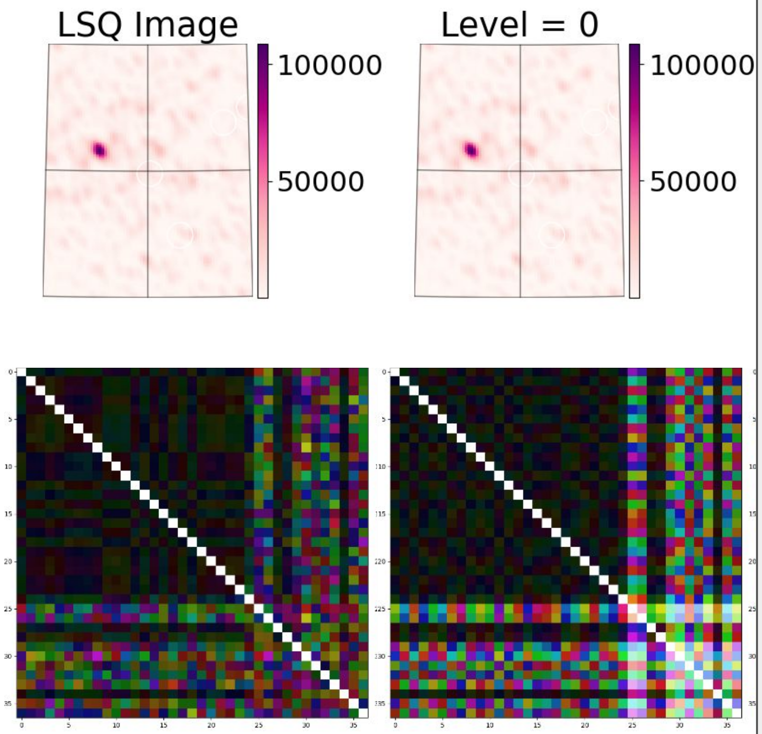
$$\epsilon_m = \Psi \alpha_m$$

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

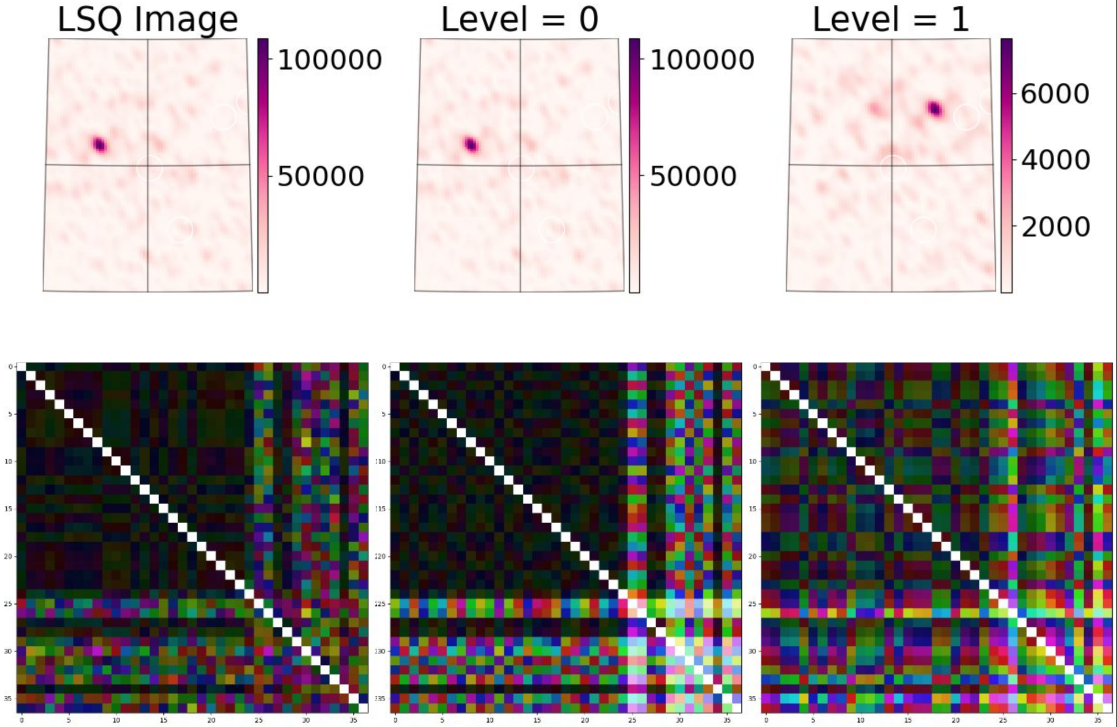
- Flexible continuous spherical imager for interferometric applications; 3D nuFFT Type-3 - no w approximation/stacking

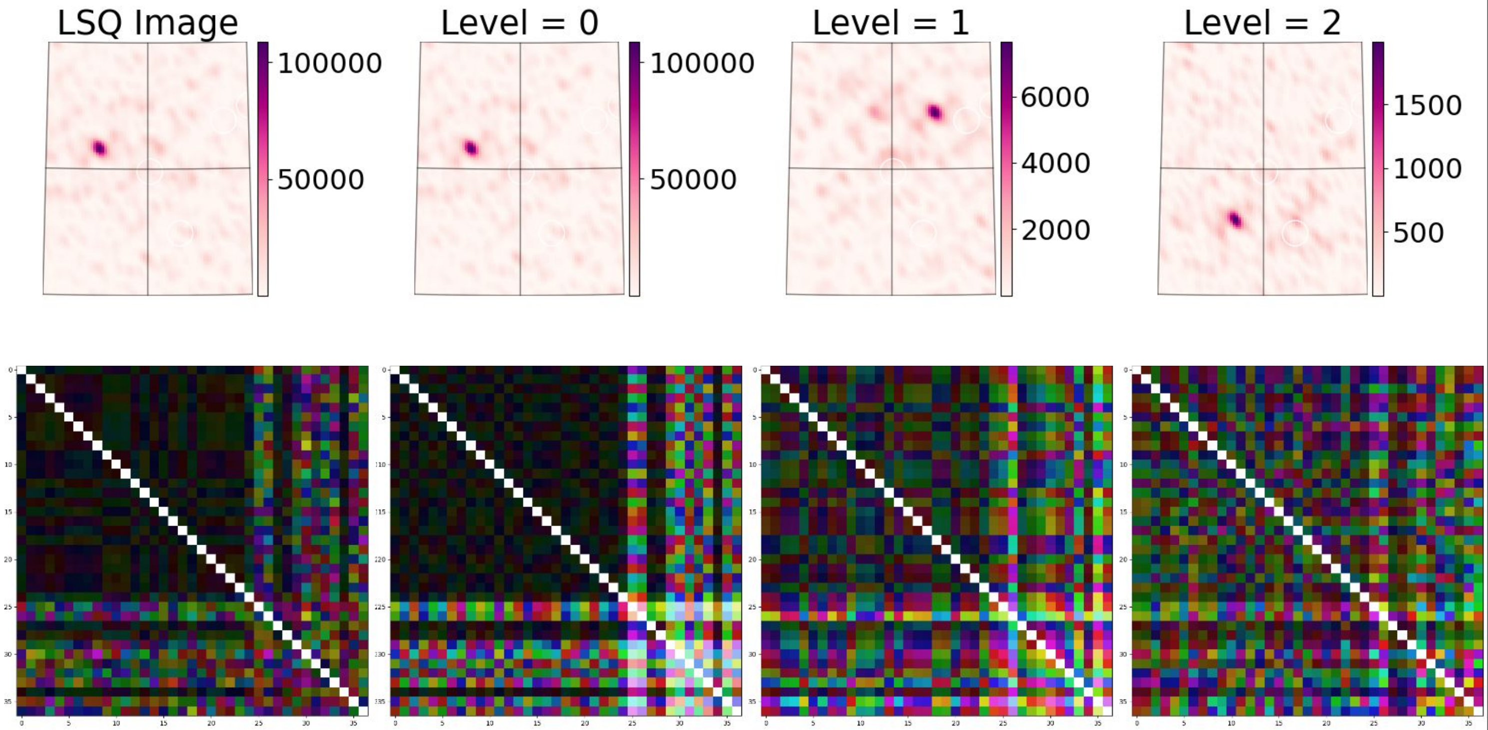

LSQ Image
100000
50000


0
5
10
15
20
25
30
35

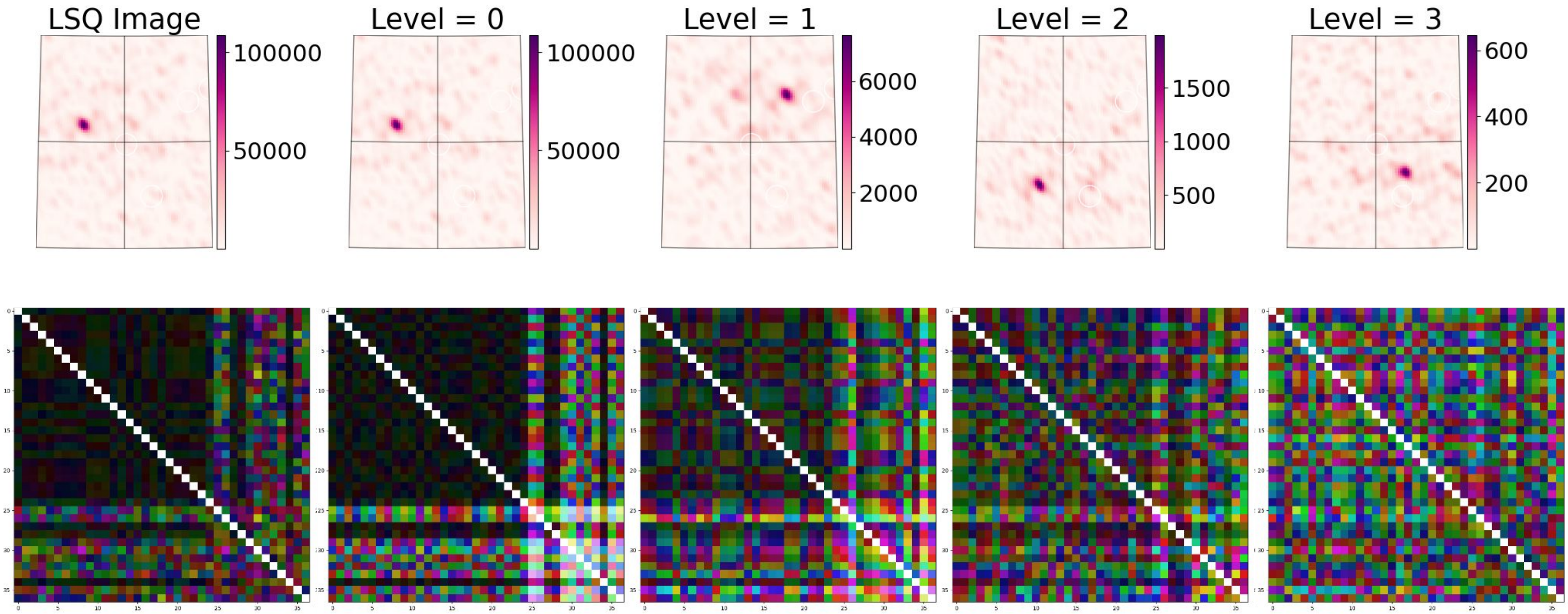


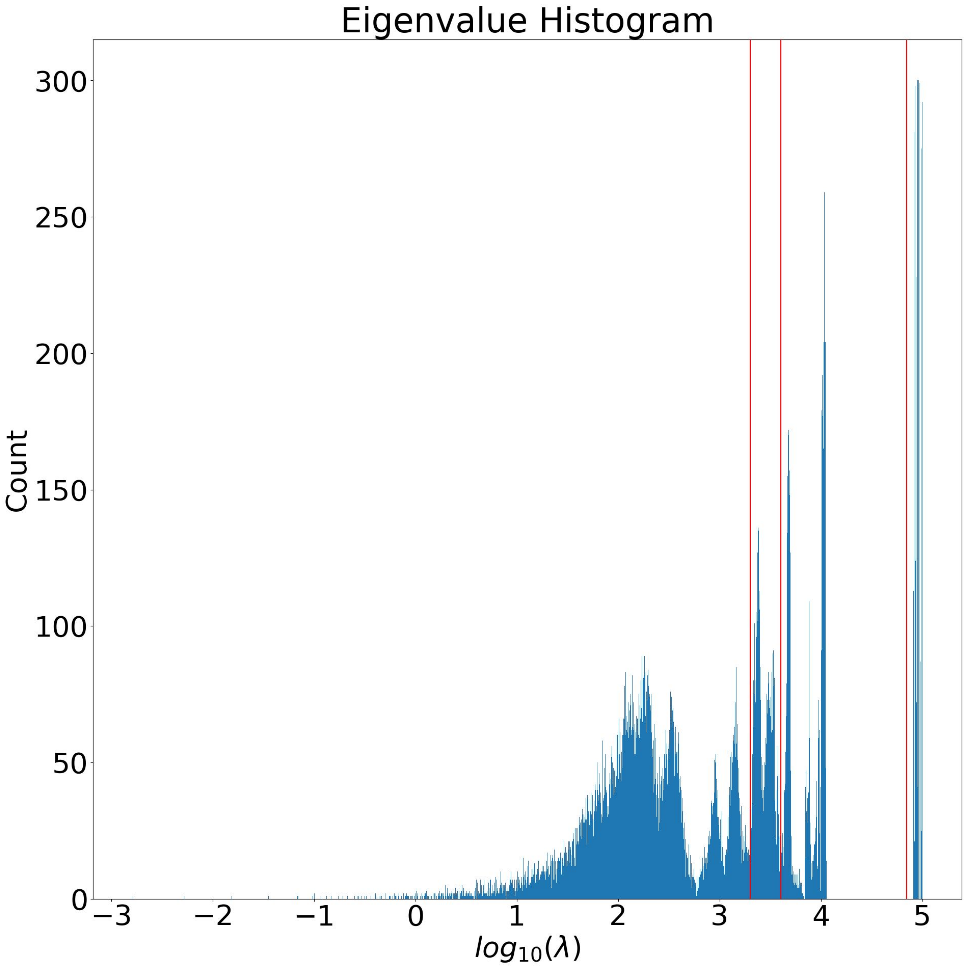
LSQ Image
100000
50000
Level = 0
100000
50000


LSQ Image
100000
50000
Level = 0
100000
50000
Level = 1
6000
4000
2000



LSQ Image
100000
50000
Level = 0
100000
50000
Level = 1
6000
4000
2000
Level = 2
1500
1000
500


LSQ Image
100000
50000
Level = 0
100000
50000
Level = 1
6000
4000
2000
Level = 2
1500
1000
500
Level = 3
600
400
200



Eigenvalue Histogram
Count
300
250
200
150
100
50
0
−3
−2
−1
0
1
2
3
4
5
$log_{10}(\lambda)$

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)
- **MPI Parallelism** and **Domain partitioning** inbuilt
- No deconvolution - only dirty images
- **Github**: https://github.com/epfl-radio-astro/bipp
- **Arxiv**: https://arxiv.org/pdf/2310.09200

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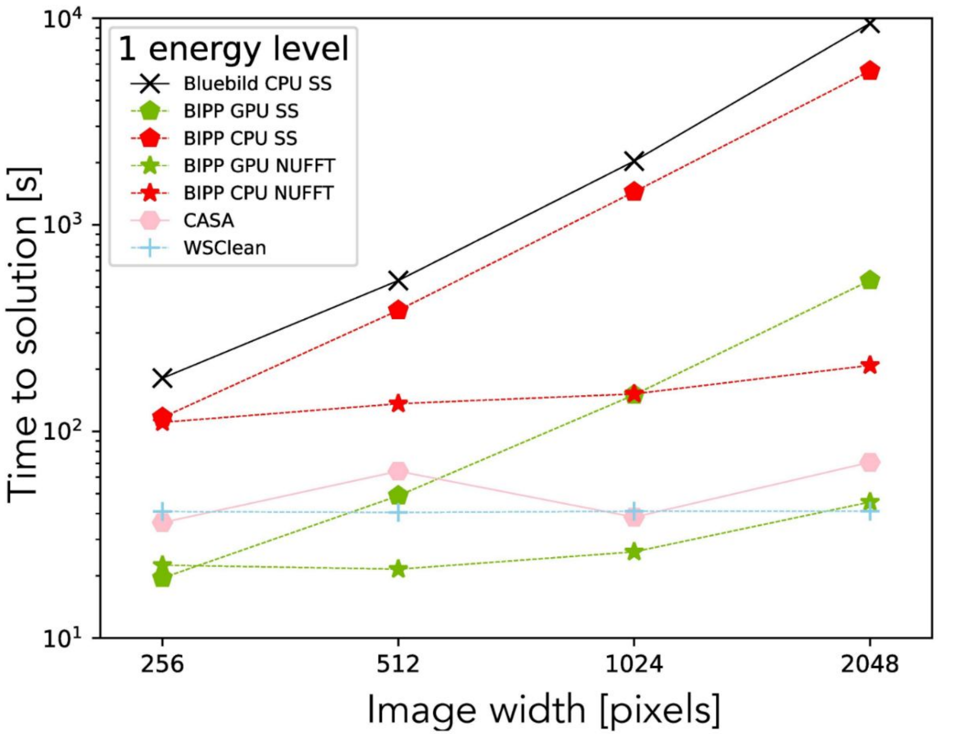
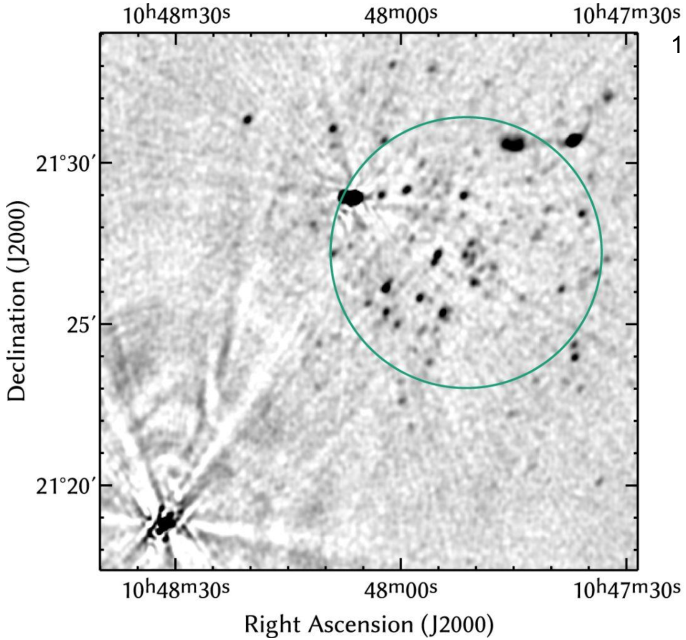


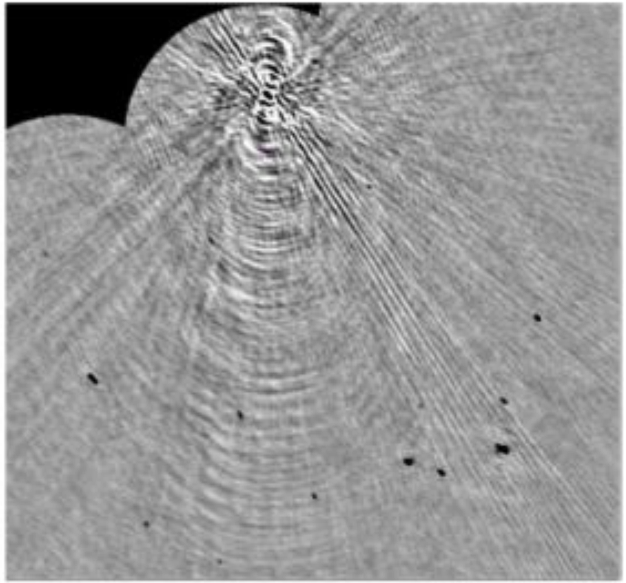
Ongoing Work:

- **Deconvolution** incorporation: Radler (Radio Astronomical Deconvolution Library), ML deconvolution

Bright Point Source Contaminants are Ubiquitous in Radio Astronomy



1

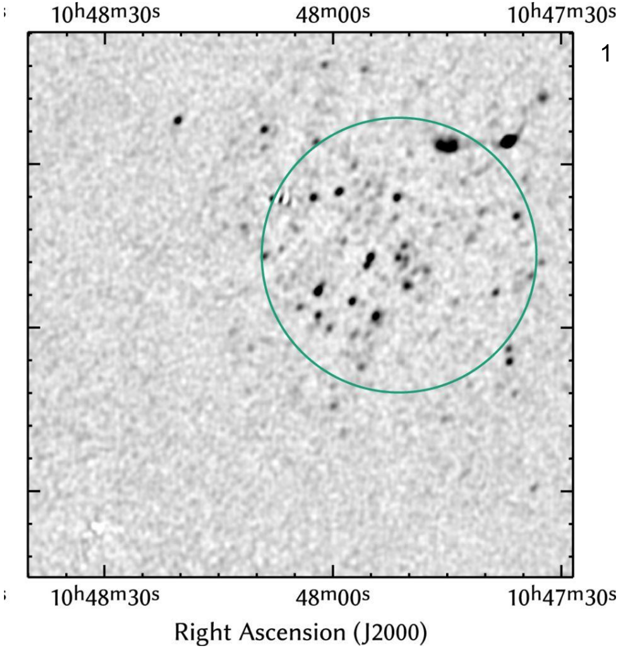


2

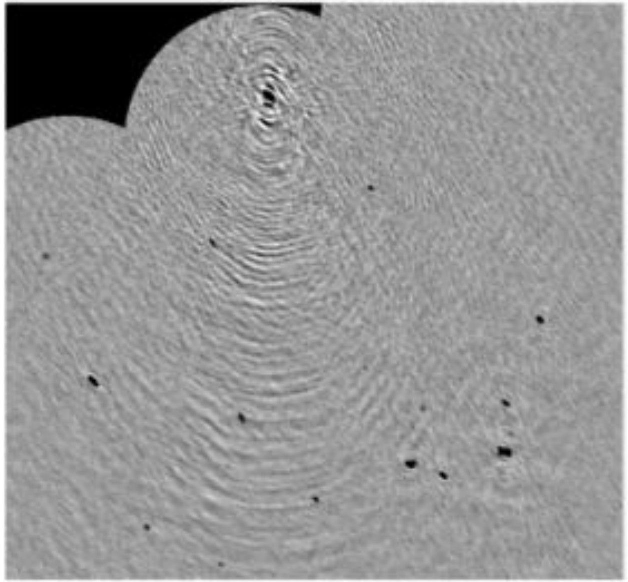
Typically solved by peeling or modelling and subtracting source in visibility space
Eg: Obit[4], Ionpeel[5] etc.

1: Williams et al 2019, 2: Obit Development Memo Series No. 54, Cotton 4: Cotton 2013 5: Offringa et. al. 2016

Bright Point Source Contaminants are Ubiquitous in Radio Astronomy



1



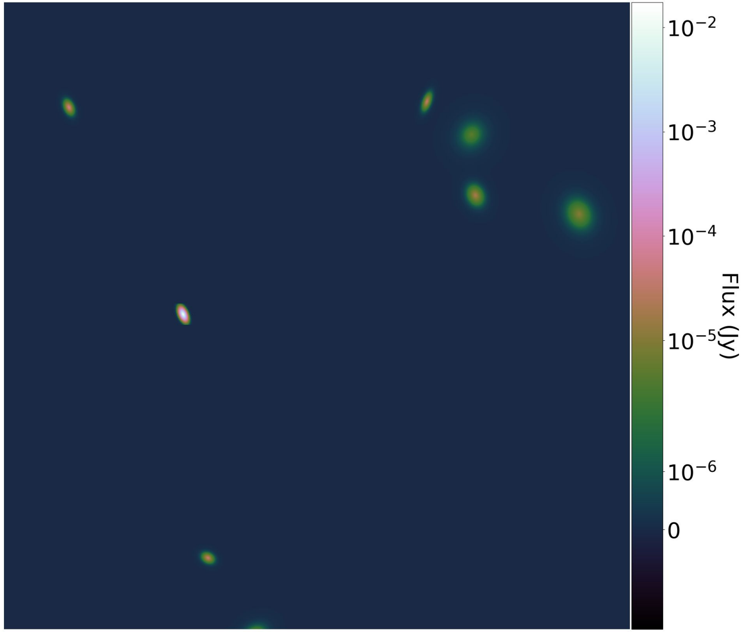
2

But perfect peeling is not always possible.

1: Williams et al 2019, 2:Obit Development Memo Series No. 54, Cotton

Separating Contaminating Point Sources at the Visibility Level

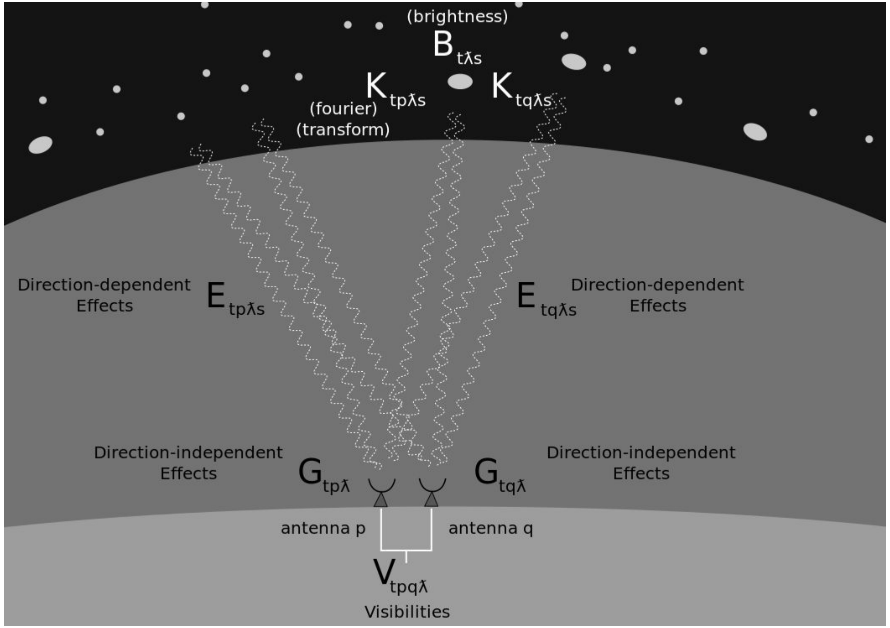
- Model: **T-RECS**[1] x 1000
  100x range in SNR for gaussian sources in small FOV (0.025 deg) image; 1 frequency channel
- Visibilities Generated using **SKA Low Configuration on OSKAR** utilising Karabo Pipeline[2]
  - 200 MHz
  - 1.5 GHz (SKA Mid Frequencies)
- Realistic Simulation - **Observational Effects**
- Since BIPP works on visibilities - **separation of interferometric artifacts?**



1: Bonaldi et. al. 2018 2: https://github.com/i4Ds/Karabo-Pipeline

(Simplified) Radio Interferometric Measurement Equation

$$V_{tpq} = G_{tp} E_{tps} B_{pq} E_{tqs} G_{tq} + N_t$$ [1]



G_{tp} - Direction Independent (DI) gains, antenna p

E_{tps} - Direction Dependent (DD) gains, antenna p, direction s

B_{pq} - Sky brightness, baseline pq

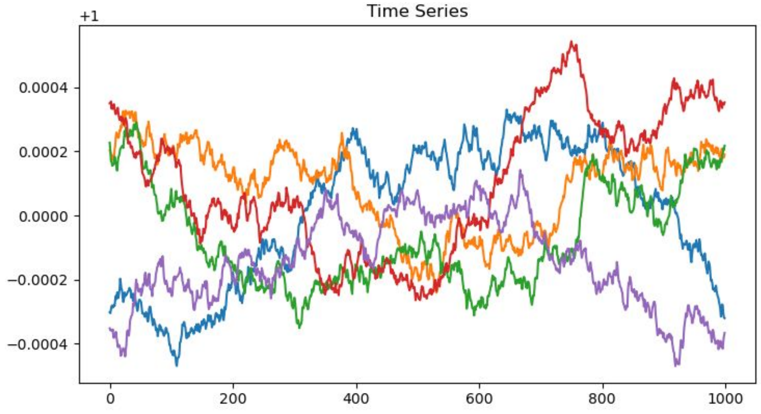
N_t - Receiver Noise

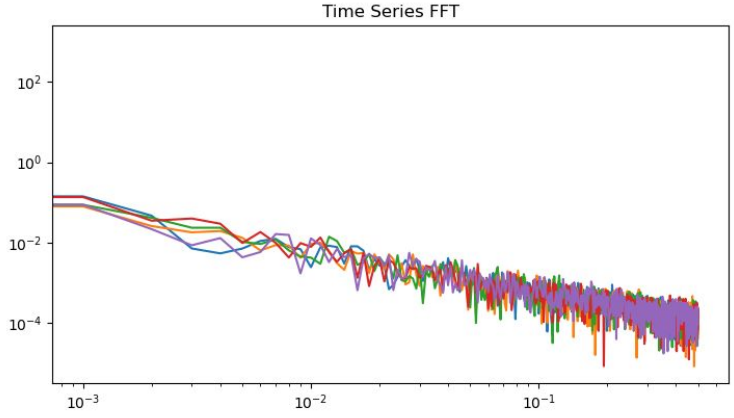
1:[RATT RU Radio Interferometry Course, EPFL Radio Sky II]

Additive (Noise) and Multiplicative (Calibration) Errors

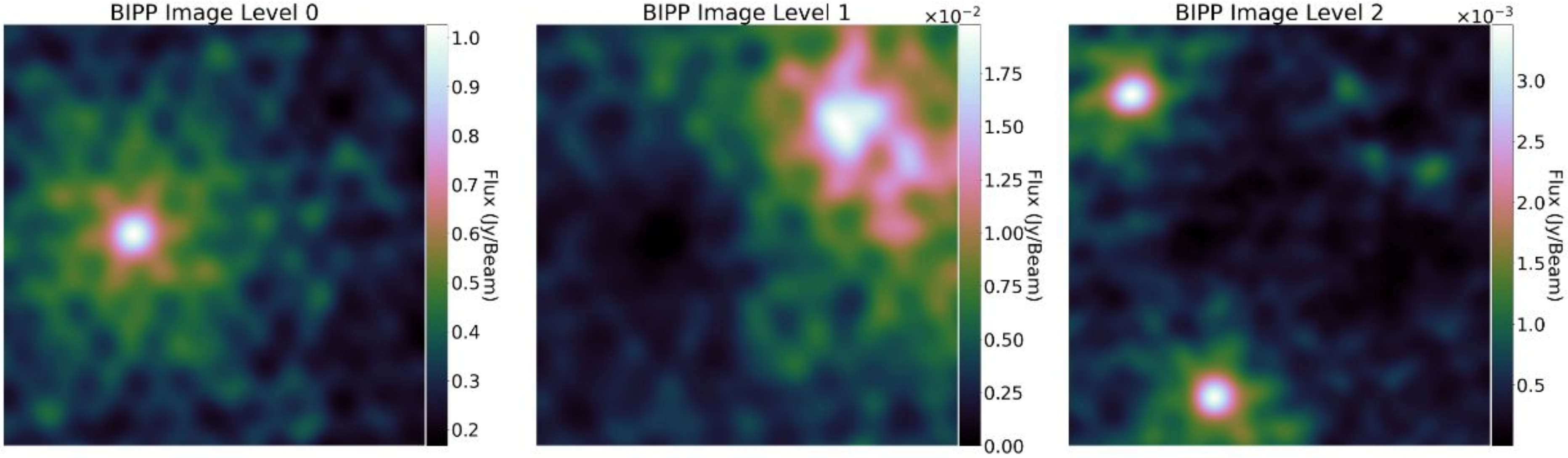
$$\Delta\sigma_N = \frac{2kT_{sys}}{A_e\sqrt{2N_{baselines}N_{pol}\Delta v\Delta t}}$$

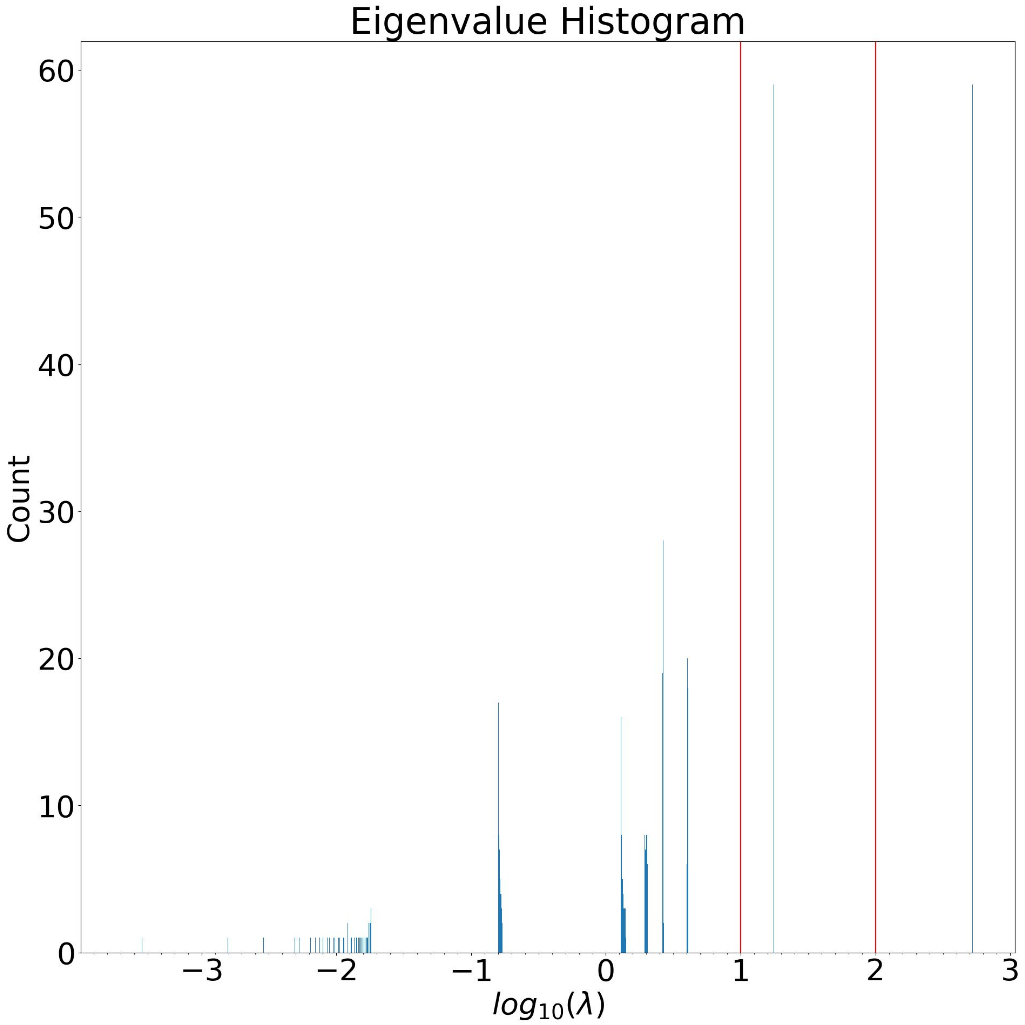
$$G_{tp} = A_{tp}e^{i\theta_{tp}}$$





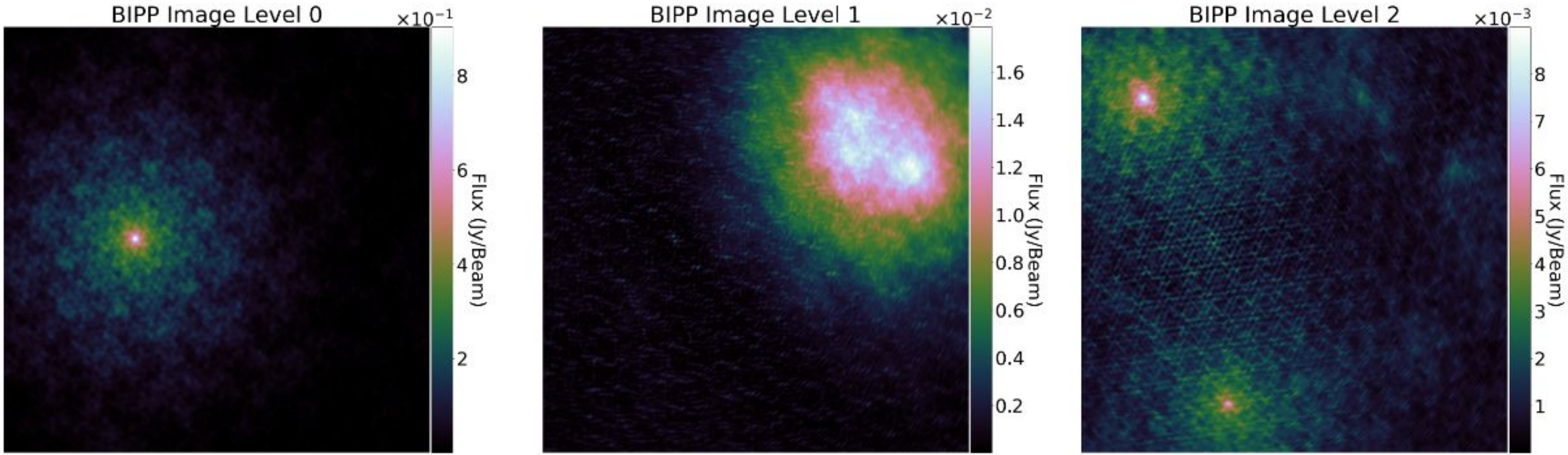
200 MHz; 10 min observation; No noise; No cal. Errors

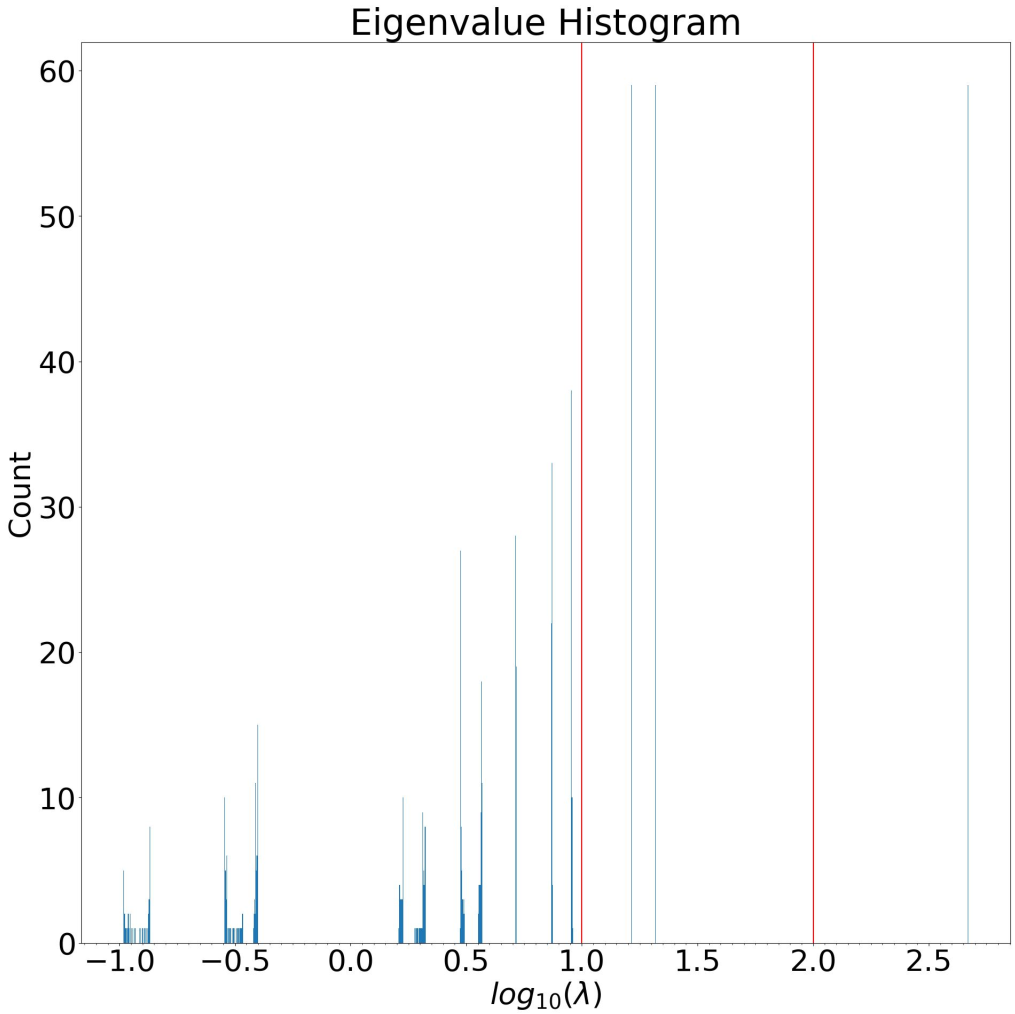




Eigenvalue Histogram
Count
60
50
40
30
20
10
0
−3
−2
−1
0
1
2
3
$log_{10}(\lambda)$

1500 MHz; 10 min observation; No noise; No cal. errors

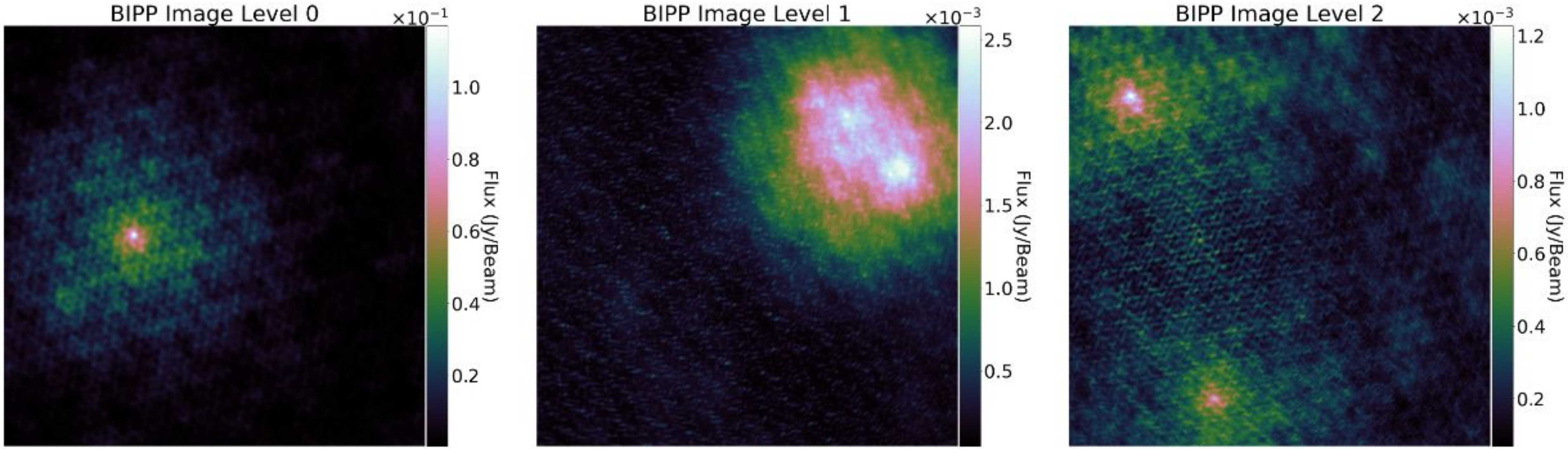




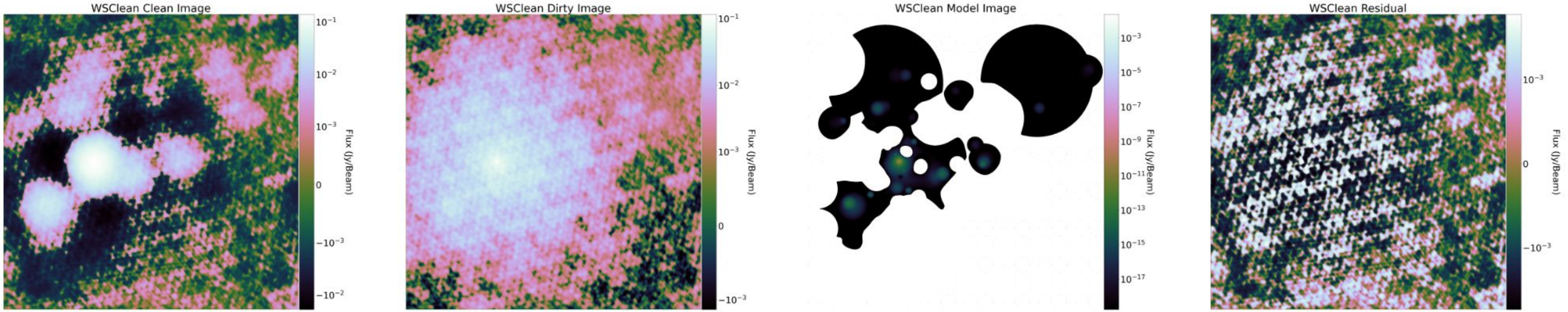
Eigenvalue Histogram
Count
60
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
$log_{10}(\lambda)$

1500MHz; 10 min obs.; No noise; Low calibration errors

$$g_p = A_p e^{i\theta_p} \qquad \mu_A = 1, \sigma_A = 0.07, \mu_\theta = 0, \sigma_\theta = 0.1667$$

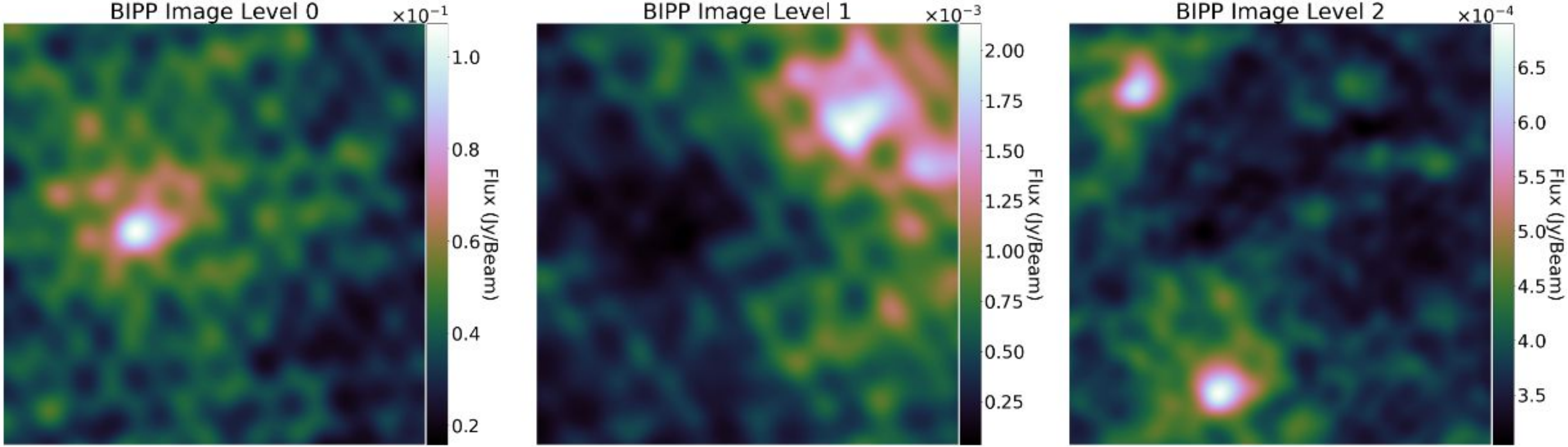


1500MHz; 10 min obs.; No noise; Low calibration errors



200MHz; 10 min obs.; 8 h noise; Low calibration errors

$$g_p = A_p e^{i\theta_p} \qquad \mu_A = 1, \sigma_A = 0.07, \mu_\theta = 0, \sigma_\theta = 0.1667$$



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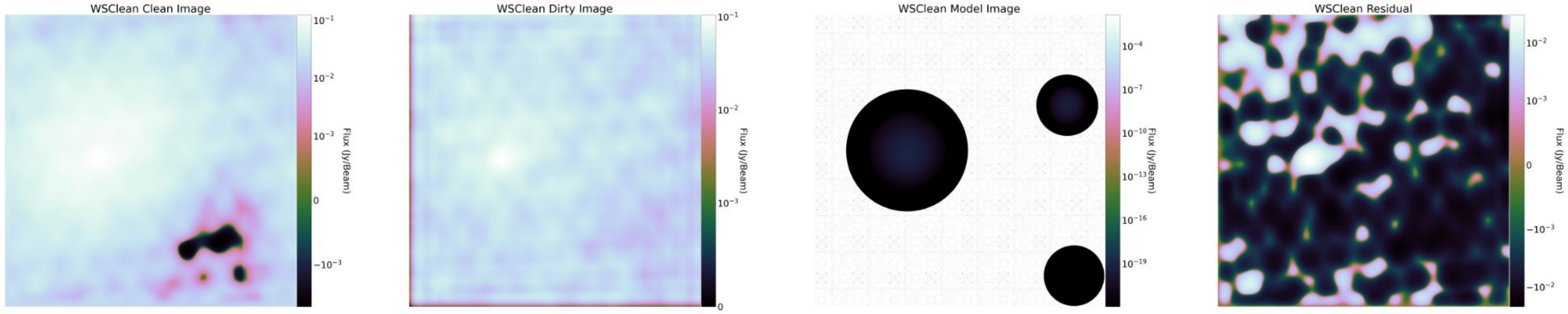
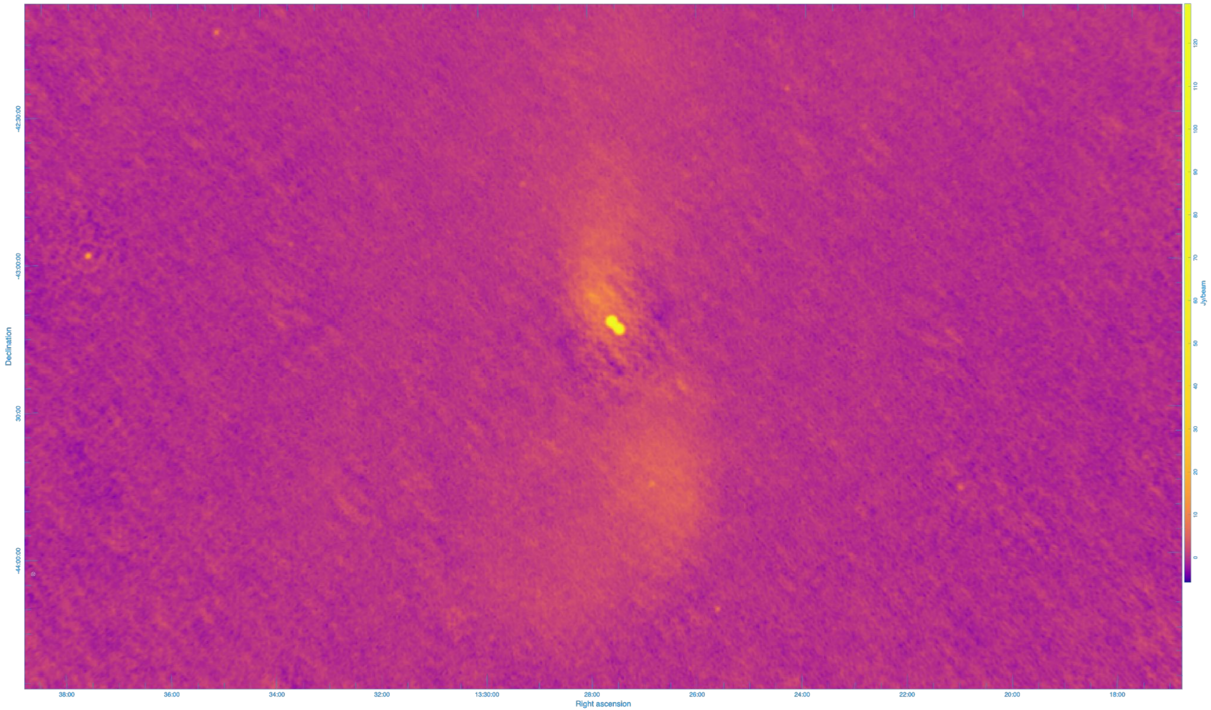
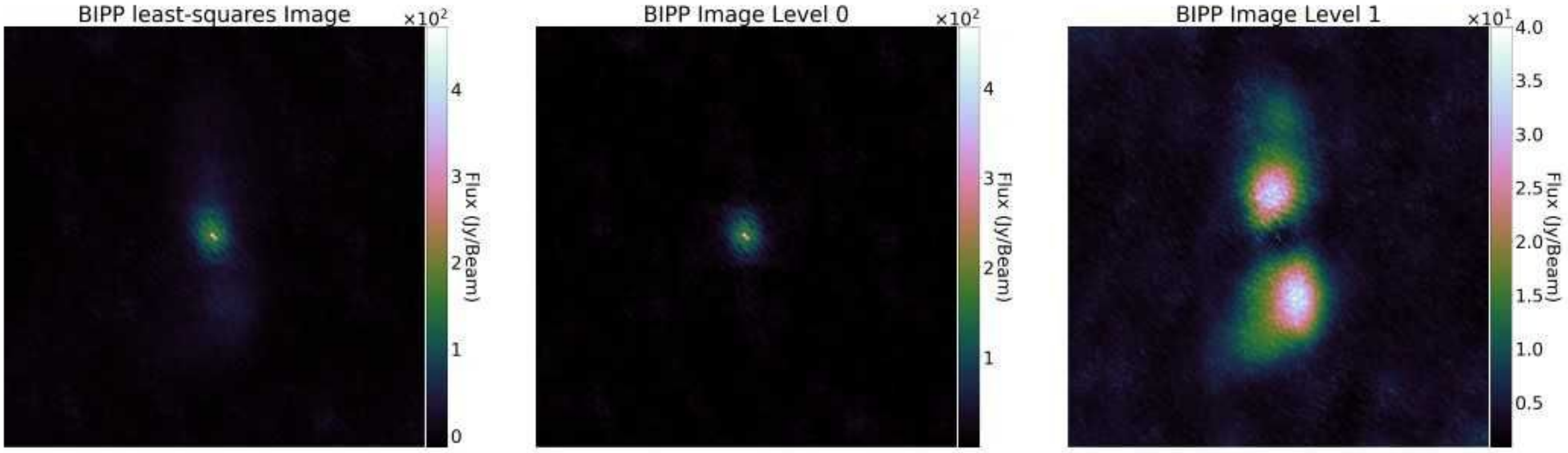


Real~~(istic)~~ Data

- MWA Phase I Observation of Centaurus A
- 11.37 deg FoV
- 175.35 MHz Observation
- MWA Phase I - sensitivity to extended structure



Real~~(istic)~~ Data BIPP Output



Summary:

- Separation of contaminating bright point sources possible with BIPP.
- But if contaminating source is **extended** in size, separation is **incomplete**.
- BIPP point source separation is **resilient to realistic observational errors**.
- BIPP bright source separation works on **real MWA Data**.

Future Work:

- **Deconvolved** Images comparison

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

Next-Generation Radio Interferometry Team

- PASC proposal to optimize, validate, and integrate Bluebild in precursor pipelines
- Team:
    - **Emma Tolley**: Team leader
    - **Etienne Orliac**: HPC, benchmarking, optimization, C & CUDA kernels
    - **Simon Frasch**: GPU nuFFT library, parallelism
    - **Remi Poitevineau:** Baseline reweighting, deconvolution
    - **Shreyam Krishna:** scientific use cases
    - **Paul Hurley, Sepand Kashani:** Algorithm development/expertise
    - Ex Members: Michele Bianco, Arpan Das, Matthieu Simeoni, M. Roshan

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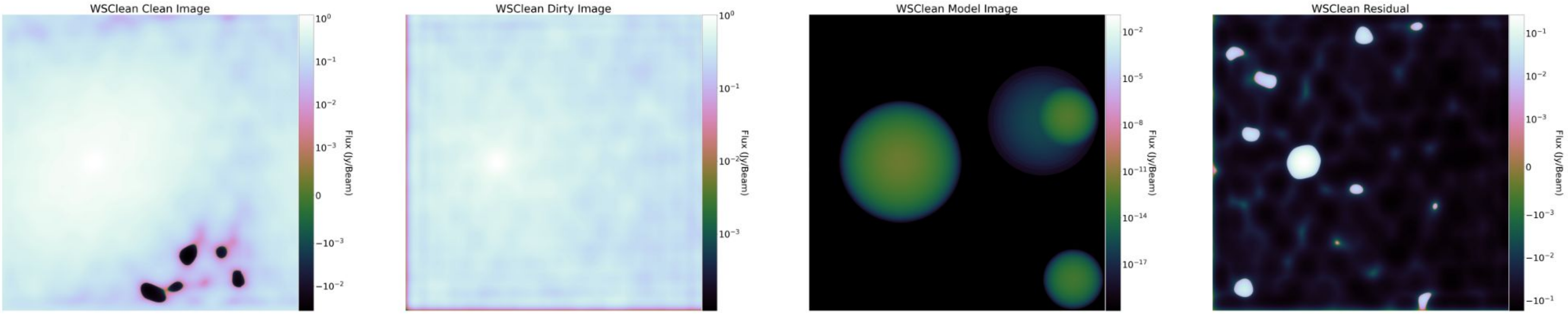
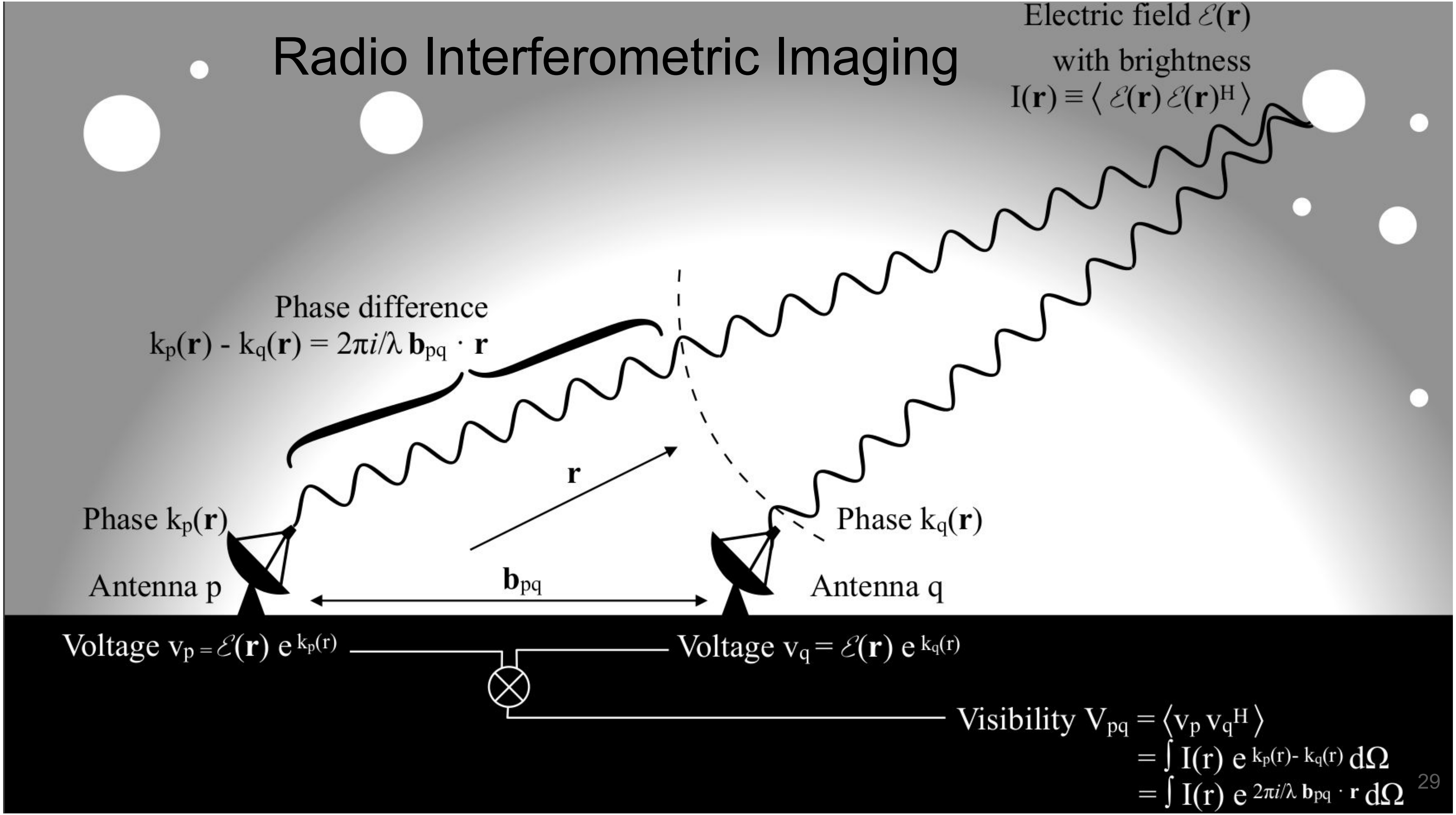
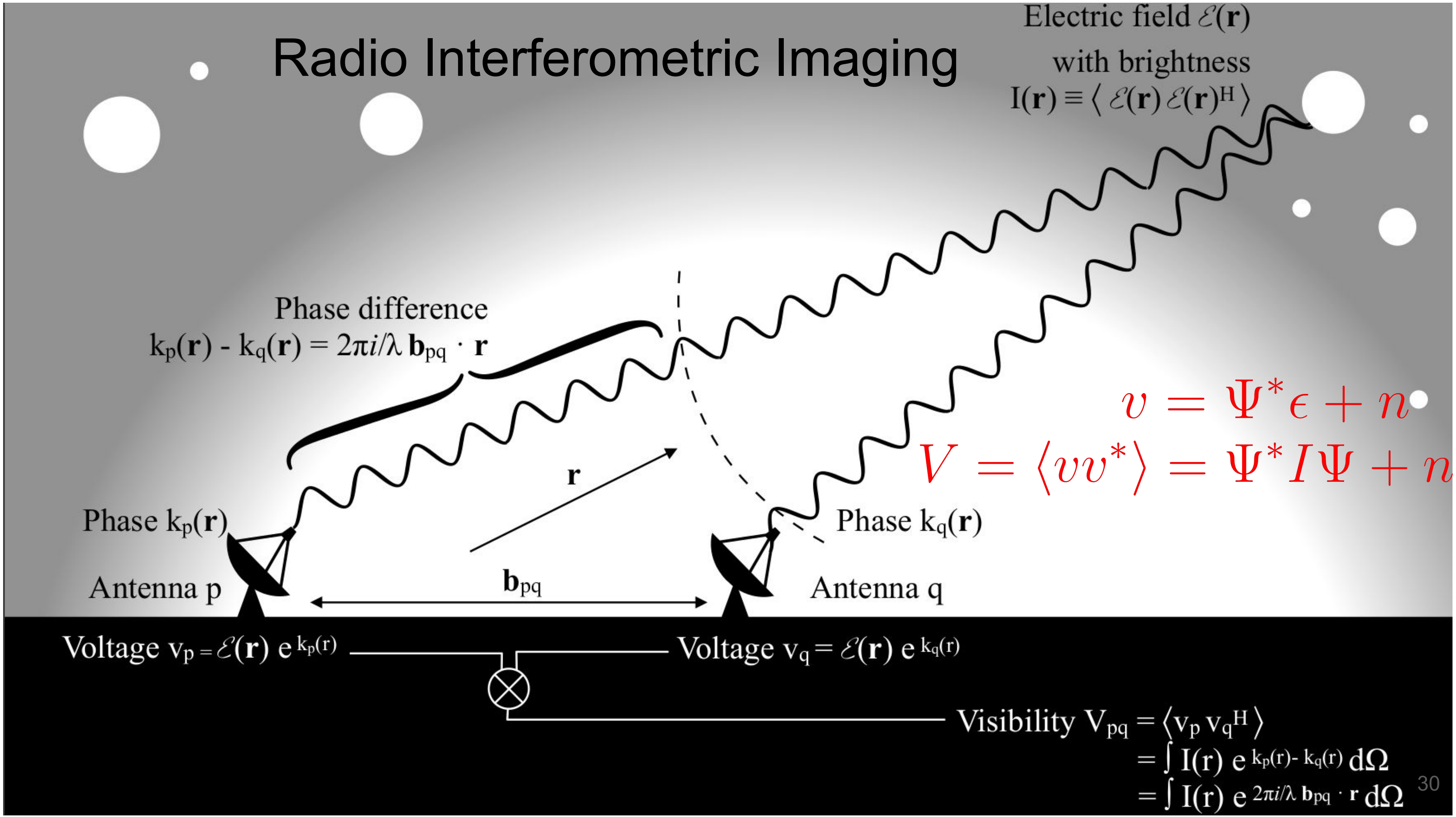
200 MHz; 10 min observation; No noise; No cal. Errors



Radio Interferometric Imaging



Radio Interferometric Imaging



$$v = \Psi^* \epsilon + n$$

$$V = \langle v v^* \rangle = \Psi^* I \Psi + n$$

Radio Interferometric Imaging

Backprojection for the sky image: $\tilde{I} = \Psi V \Psi^*$

Bluebild uses the Moore-Penrose Inverse:

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

$$\tilde{I} = \Psi^*(G_\Psi)^{-1} V (G_\Psi)^{-1} \Psi$$

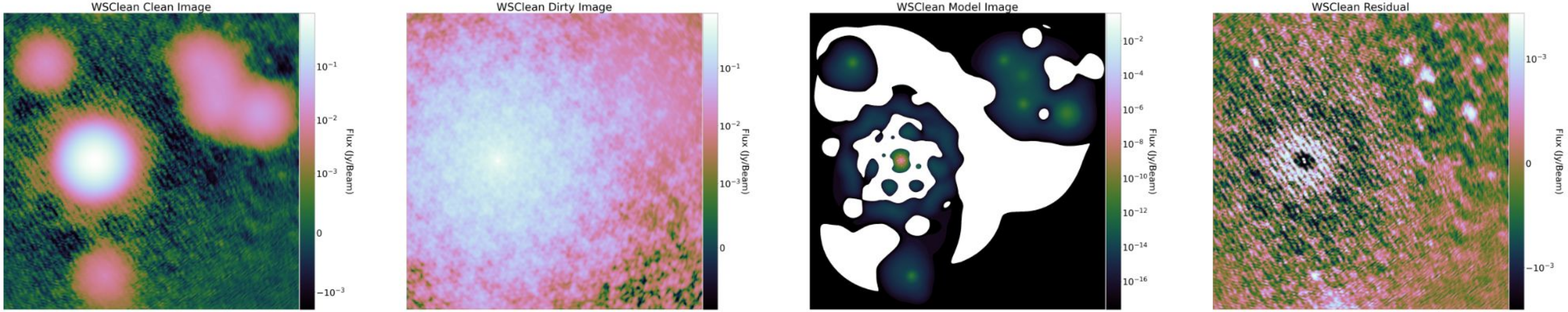
G often ill-conditioned and difficult to invert

$$\tilde{I} = \sum_a \lambda_a |\epsilon_a|^2 = \sum_a \lambda_a |\Psi \alpha_a|^2$$

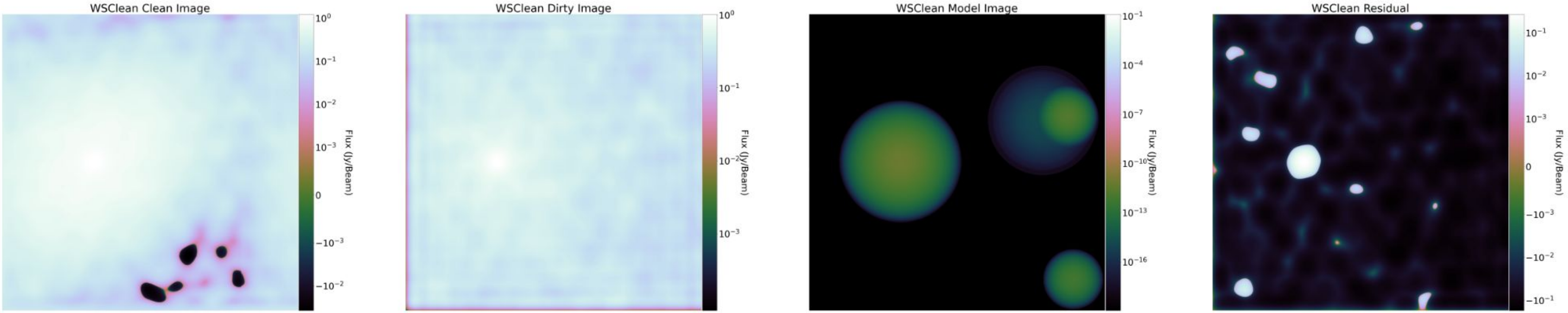
This is achieved by a generalised eigenvalue decomposition:

$$V\alpha_a = \lambda_a G_\Psi \alpha_a$$

1500 MHz; 10 min observation; No noise; No cal. errors



200MHz; 10 min obs.; 8 h additive noise; No cal. errors



Bluebild Algorithm[1]
Psuedo-Inverse Least Squares Solution

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

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

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

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

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

1:[Simeoni, Hurley and Kashani, 2023]