Exploring Regularized Maximum Likelihood Reconstruction for the ngVLA: Stellar Imaging as a Case Study

Next Generation Very Large Array

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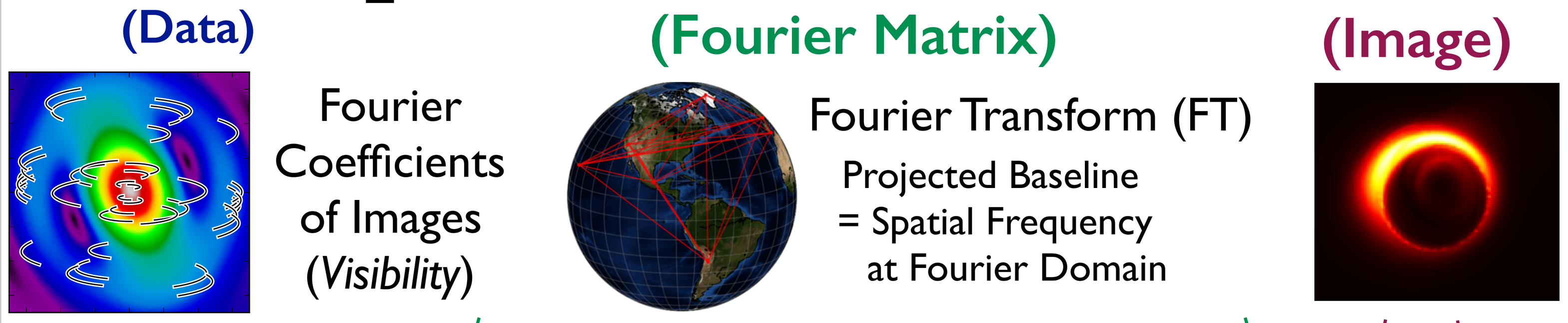
Introduction & Motivation of This Work

The proposed ngVLA will provide an imaging capability with an order of magnitude improvement in sensitivity and angular resolution compared with radio interferometers currently operating at 1.2--116 GHz. However, the current ngVLA array design may limit the imaging fidelity due to a highly non-Gaussian dirty beam that may make it difficult to enable both maximum sensitivity and maximum angular resolution using traditional CLEAN deconvolution methods. This challenge may be overcome with new imaging techniques designed for the Event Horizon Telescope, collectively called regularized maximum-likelihood (RML) methods. RML methods take a forward-modeling approach solving for the images without the direct use of the dirty beam. Consequently, this method has the potential to improve the fidelity and effective angular resolution of images produced by the ngVLA. As an illustrative case, we present ngVLA imaging simulations of stellar radio photospheres performed with both multi-scale (MS-) CLEAN and RML methods implemented in the CASA and SMILI packages, respectively.

Radio Interferometry: Equation



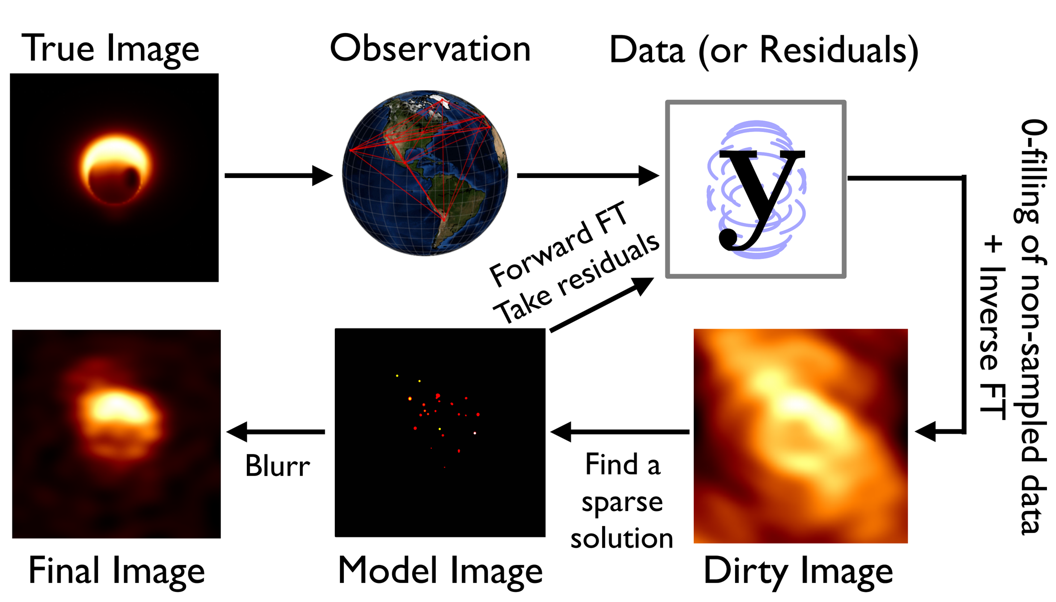
$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_M \end{pmatrix} = \begin{pmatrix} \exp(i2\pi u_1 x_1) & \exp(i2\pi u_1 x_2) & \dots & \exp(i2\pi u_1 x_N) \\ \exp(i2\pi u_2 x_1) & \exp(i2\pi u_2 x_2) & \dots & \exp(i2\pi u_2 x_N) \\ \exp(i2\pi u_3 x_1) & \exp(i2\pi u_3 x_2) & \dots & \exp(i2\pi u_3 x_N) \\ \vdots & \vdots & & \vdots \\ \exp(i2\pi u_M x_1) & \exp(i2\pi u_M x_2) & \dots & \exp(i2\pi u_M x_N) \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ \vdots \\ x_N \end{pmatrix}$$

M, N

- Sampling Fourier components (visibilities) of images at spatial frequencies corresponding to baseline vectors seen from the observing source.
- Sampling is NOT perfect
  Number of data **M** < Number of image pixels **N**
- Equation is *ill-posed*: infinite numbers of solutions
- Interferometric Imaging: derive a reasonable solution based on a prior assumption

CLEAN and Regularized Maximum Likelihood (RML) Methods

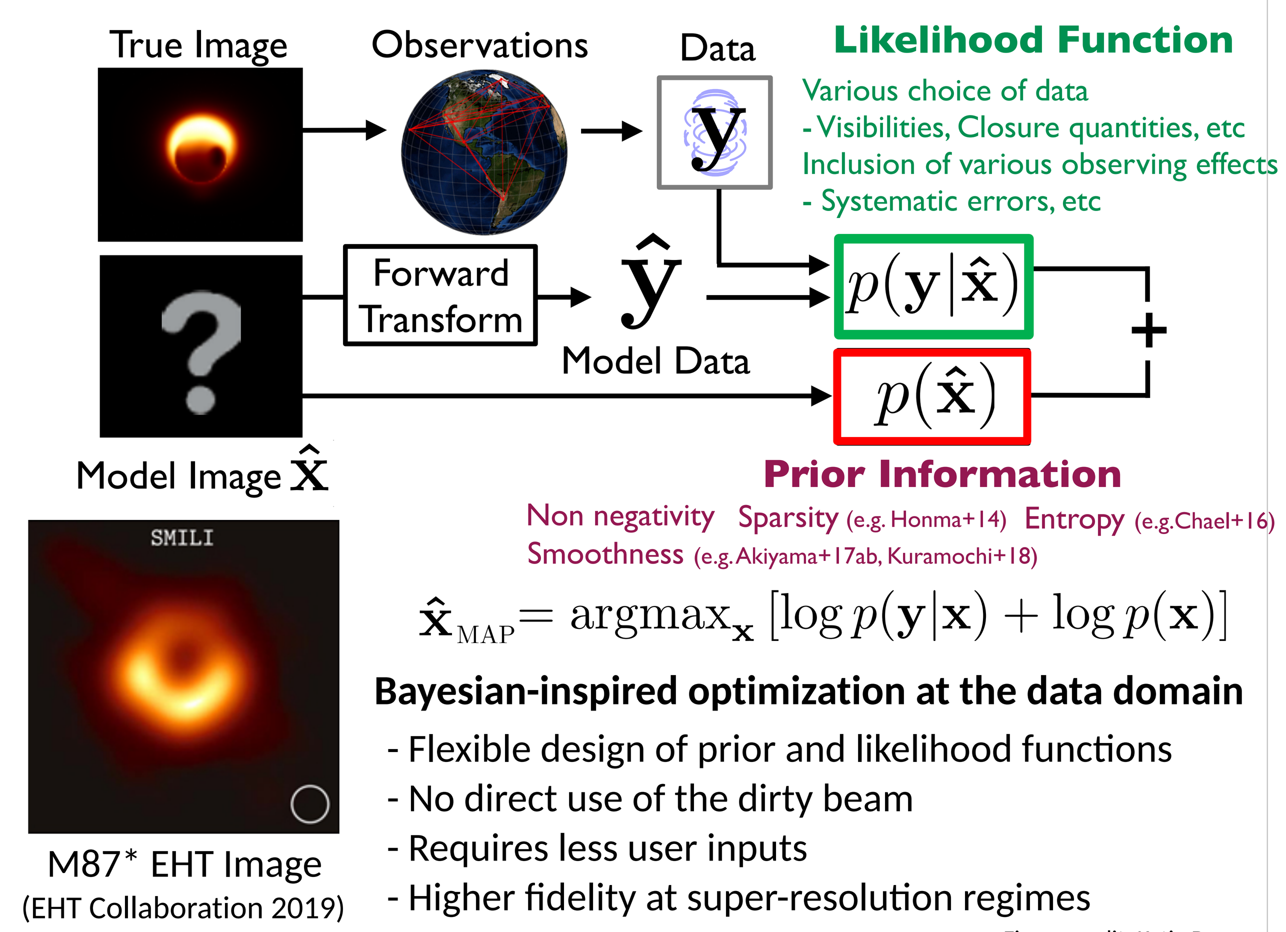
CLEAN: Traditional Techniques
Inverse Modeling with a Sparsity Prior



Sparse reconstruction mainly at the image domain

- Well vetted & computationally cheaper
- Resolution and fidelity are affected by the synthesized beam
- Only use complex visibilities: difficult to handle systematic errors
- Needs more user inputs (e.g. CLEAN box settings)

RML Methods: New EHT imaging Techniques
Forward Modeling with Various Priors



M87* EHT Image
(EHT Collaboration 2019)

$$\hat{\mathbf{x}}_{\rm MAP} = \mathrm{argmax}_{\mathbf{x}} \left[\log p(\mathbf{y}|\mathbf{x}) + \log p(\mathbf{x})\right]$$

Bayesian-inspired optimization at the data domain

- Flexible design of prior and likelihood functions
- No direct use of the dirty beam
- Requires less user inputs
- Higher fidelity at super-resolution regimes

Figure credit: Katie Bouman

ngVLA Simulations of Stellar Imaging with MS-CLEAN (CASA) and RML methods (SMILI; Akiyama+17ab)

Simulated Observations

- ngVLA main array (244 x 18 m antennas)
- Frequency: 43 GHz = 7 mm (Q band)

Four Model Images

Freytag Asymptotic Giant Branch (AGB) star (Freytag+08)
1 M_{Sun}, R ~ 800 R_{Sun}, T_{eff} ~ 2700 K
@150 pc, RA = 2.3h, Dec = -3°

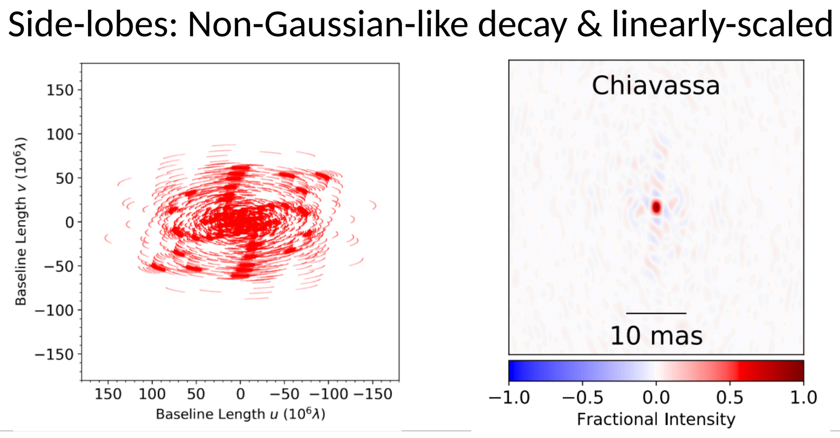
Chiavassa Red Super Giant (RSG) star (Chiavassa+09)
12 M_{Sun}, R ~ 830 R_{Sun}, T_{eff} ~ 3500 K
@222 pc, RA = 6h, Dec = +7.5° (Betelgeuse)

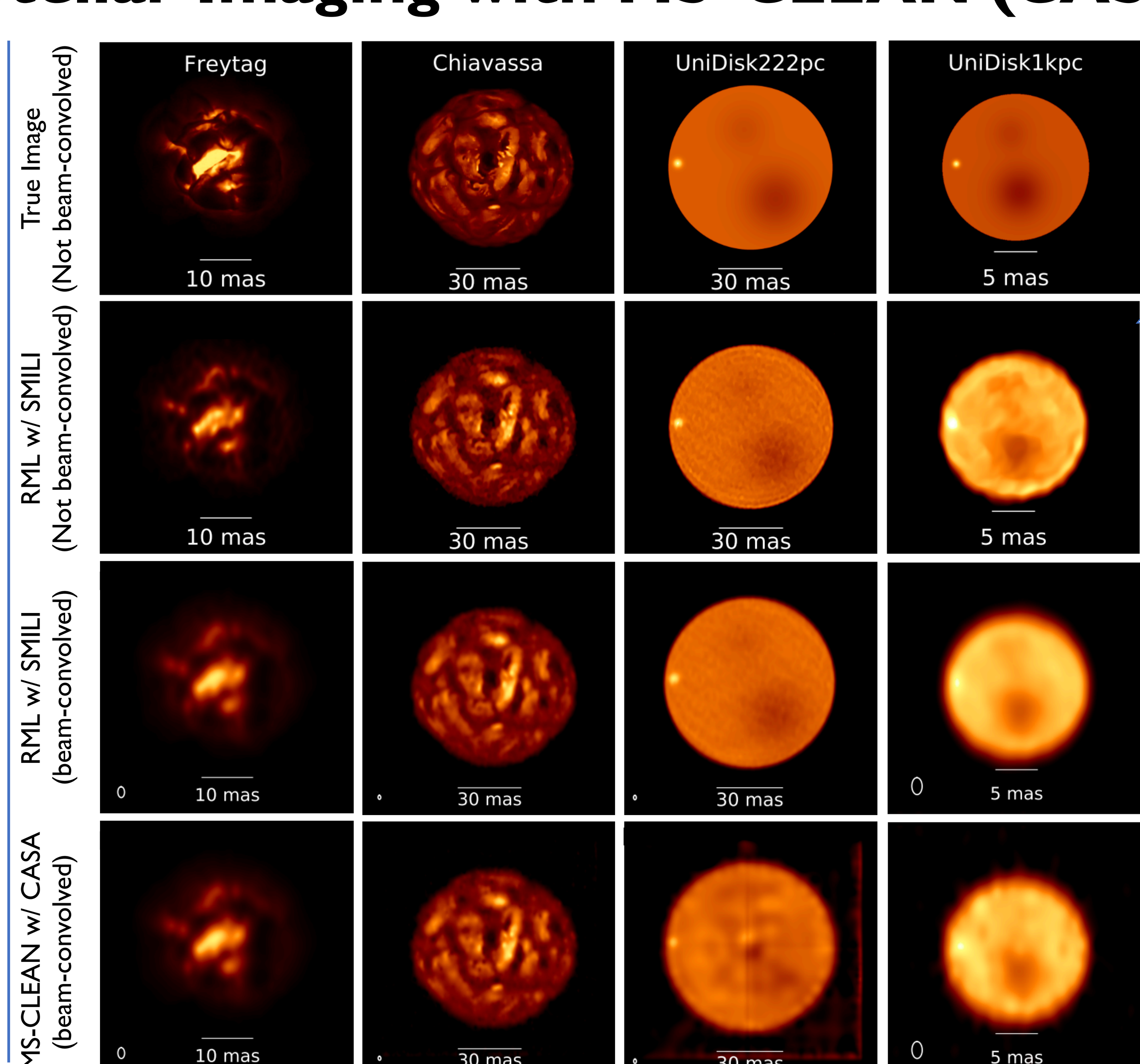
UniDisk Uniform Disk Model, R ~ 950 R_{Sun}, T_{eff} ~ 3600 K
@222 pc/1 kpc, RA = 2h, Dec = -2°

Note: Both Freytag and Chiavassa models are for near-infrared photospheres, and adopted as illustrative models in this work.

uv-coverage and Synthesized Beam

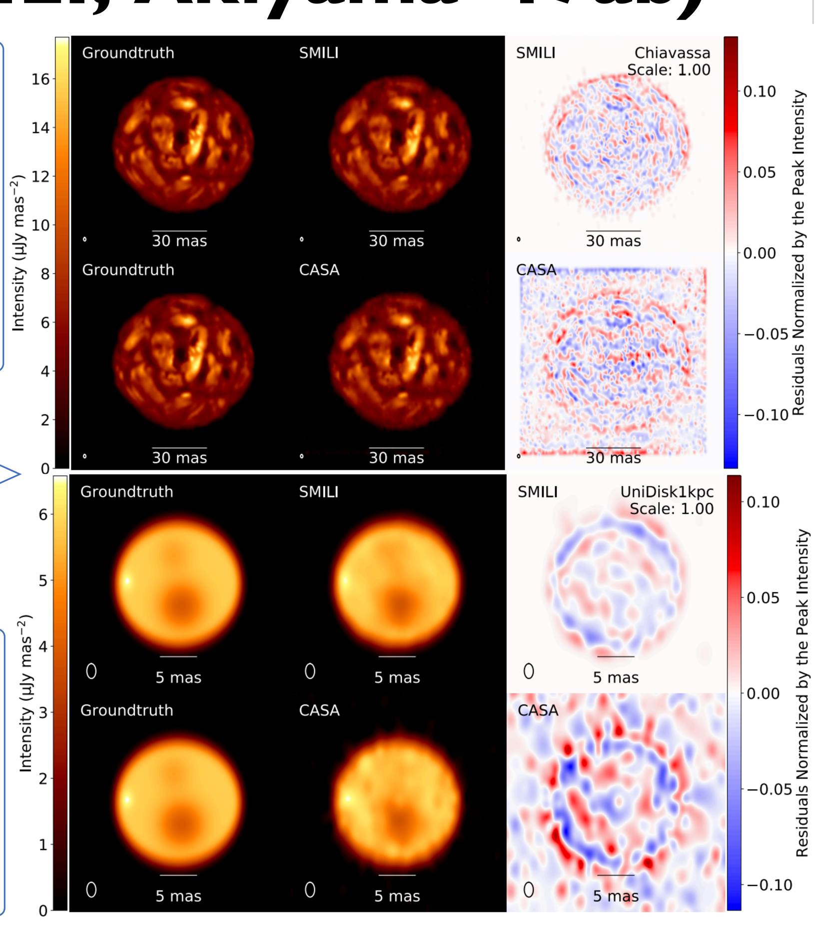
- Shape: 2 mas x 1.3 mas at PA~0° at uniform weighting
- Side-lobes: Non-Gaussian-like decay & linearly-scaled tails





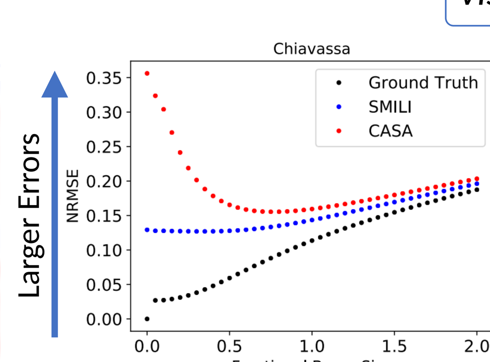
Groundtruth (1st row), SMILI (2nd/3rd rows) and CASA (4th rows) images of all four stellar models. Images in 1st and 2nd rows are not beam-convolved, while 3rd and 4th rows are convolved with the restoring beam for uniform-weighting. *Regardless of techniques, most of representative structures are well recovered.*

SMILI and CASA reconstructions and their residuals for *Chiavassa* and UniDisk 1kpc models, illustrating the fidelity at the nominal CLEAN resolution. *SMILI outperforms CASA for all four models.*



Model	SMILI	CASA
Freytag	1.00	1.05
Chiavassa	1.00	1.05
UniDisk222pc	1.00	32.70
UniDisk1kpc	1.00	1.01

χ2 of the visibilities from SMILI and CASA images normalized by that of ground truth images. *SMILI shows better goodness-of-the-fit to visibilities.*



The normalized root-mean-square errors (NRMSE) of reconstructions as a function of the restoring beam size. Each NRMSE curve was calculated between the corresponding beam-convolved image and the non-convolved ground truth image adopted as the reference. The beam size on the horizontal axis is normalized to that of the CLEAN beam. *SMILI images have fewer errors and are not degraded in superresolution regimes.*

Summary

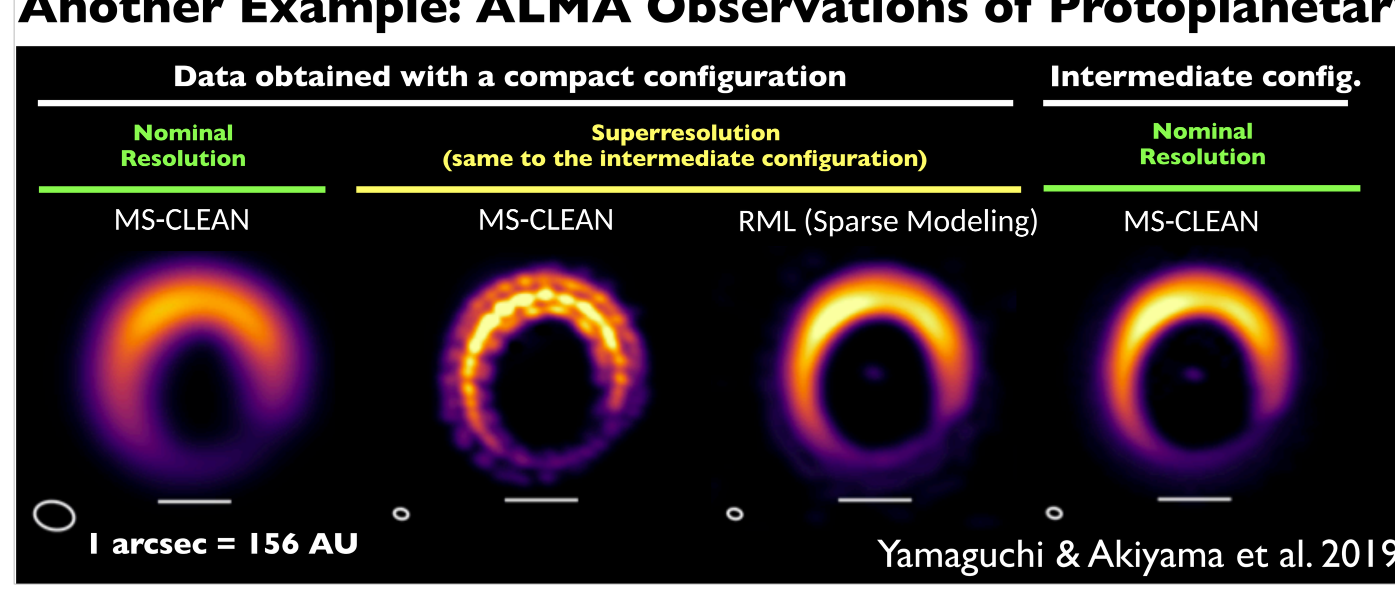
We present ngVLA imaging simulations of stellar radio photospheres with MS-CLEAN and RML implemented in CASA and SMILI, respectively.

Main Results and Conclusions:

- Transformative stellar imaging science is feasible with the ngVLA. Both methods can provide high-fidelity images recovering most of the representative structures for different stellar photosphere models.
- RML methods are an attractive choice for ngVLA imaging. They perform better than MS-CLEAN in many respects.

Movies of AGB and RSG stars from simulated multi-epoch observations

Another Example: ALMA Observations of Protoplanetary Disk HD 142527 at 345 GHz



RML can produce a high-quality image of HD142527 (2nd panel from the right) consistent with an image (the rightmost) obtained with 3-4 times longer baselines.

The image residual normalized with the peak intensity between the RML image and higher-angular-resolution CLEAN image is within few percent.

SMILI (github) ngVLA Memo 66

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