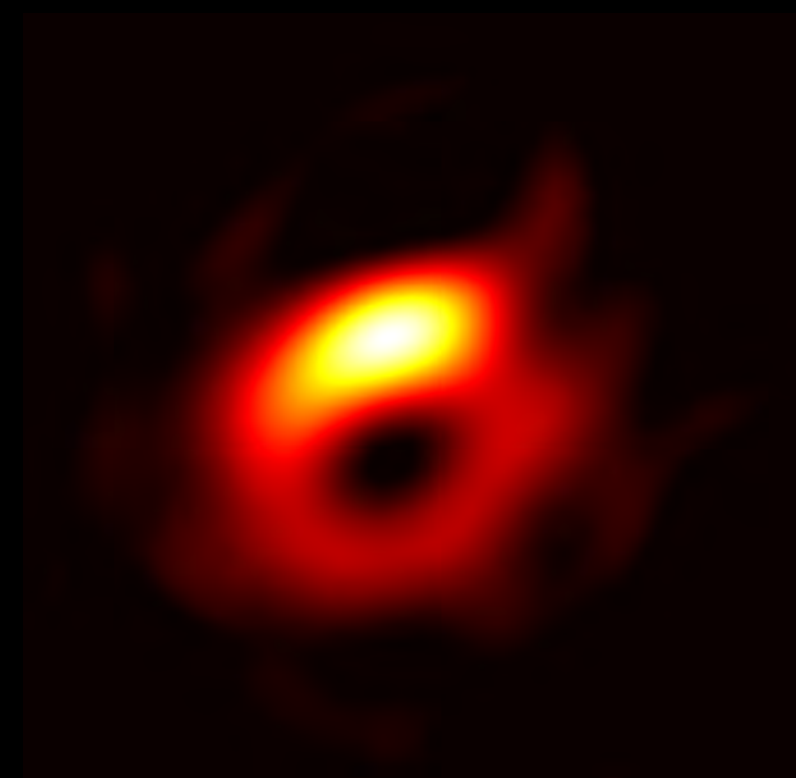
Imaging (and filming) the Black Holes with the Event Horizon Telescope



Kazu Akiyama

(NRAO Jansky Fellow / MIT Haystack Observatory)

On behalf of the EHT Imaging Working Group

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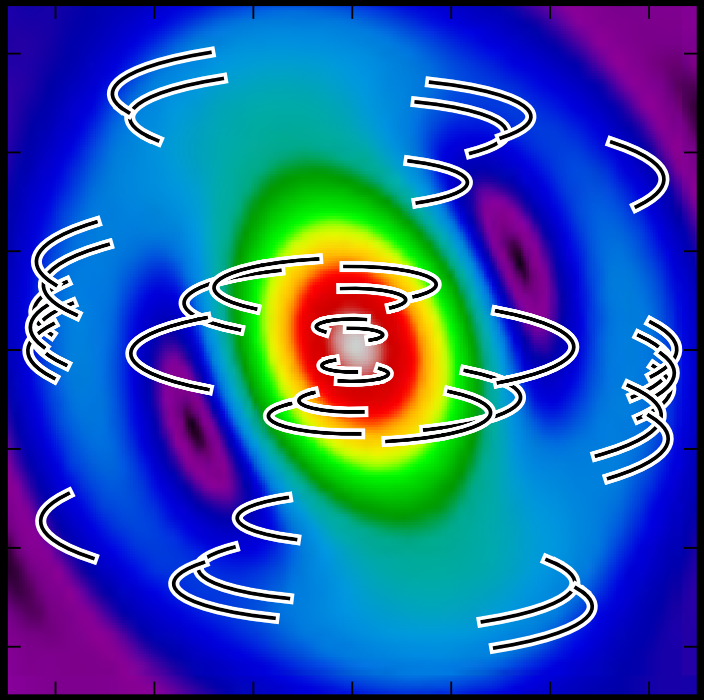
NSF

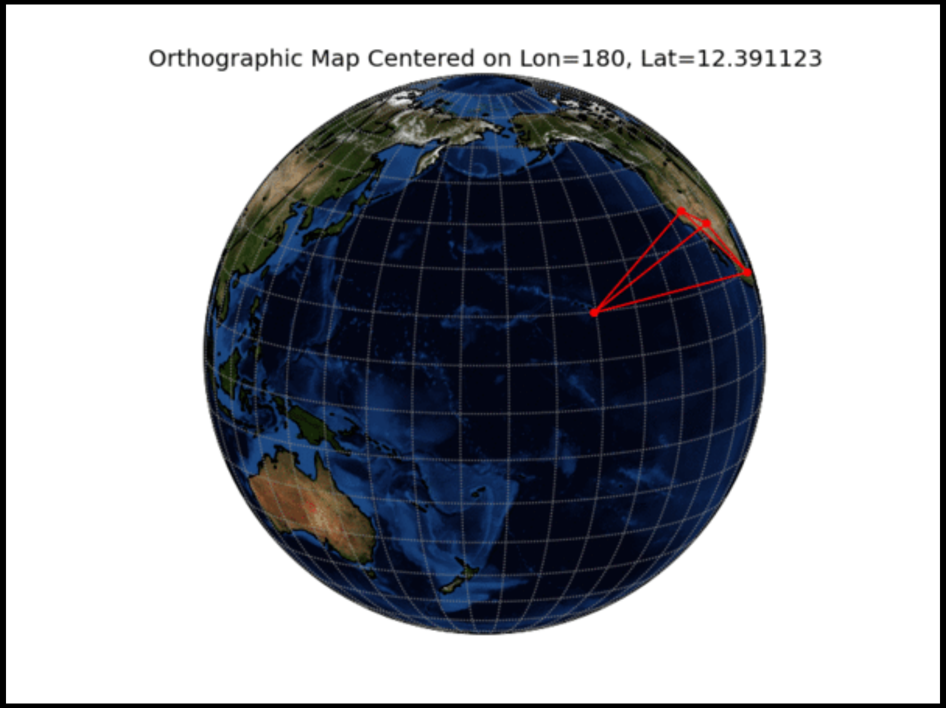
Radio Interferometry:
Sampling Fourier Components of the Images

Image

Fourier Domain
(*Visibility*)



Sampling Process
(Projected Baseline = Spatial Frequency)



(Images: adapted from *Akiyama* et al. 2015, ApJ ; Movie: Laura Vertatschitsch)

Sampling is NOT perfect

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Interferometry Imaging: Observational equation is *ill-posed*

$$\underset{\text{(Data)}}{Y} = \underset{\text{(Fourier Matrix)}}{A} \; \underset{\text{(Image)}}{X}$$

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

- Sampling is NOT perfect
  Number of data $\boldsymbol{M}$ < Number of image pixels $\boldsymbol{N}$
- Equation is *ill-posed*: infinite numbers of solutions
- Interferometric Imaging:
  Picking a reasonable solution based on a prior assumption

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Sparse Reconstruction: CLEAN (greedy approach)

CLEAN (Hobgom 1974) = Matching Pursuit (Mallet & Zhang 1993)

Philosophy: **Reconstructing images with the smallest number of point sources within a given residual error**

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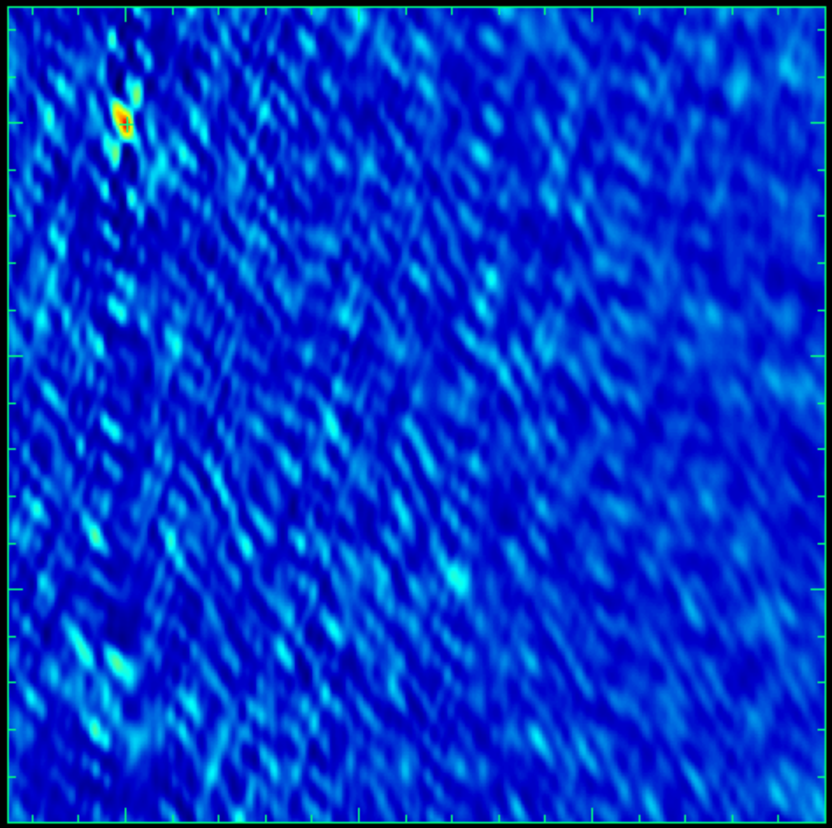

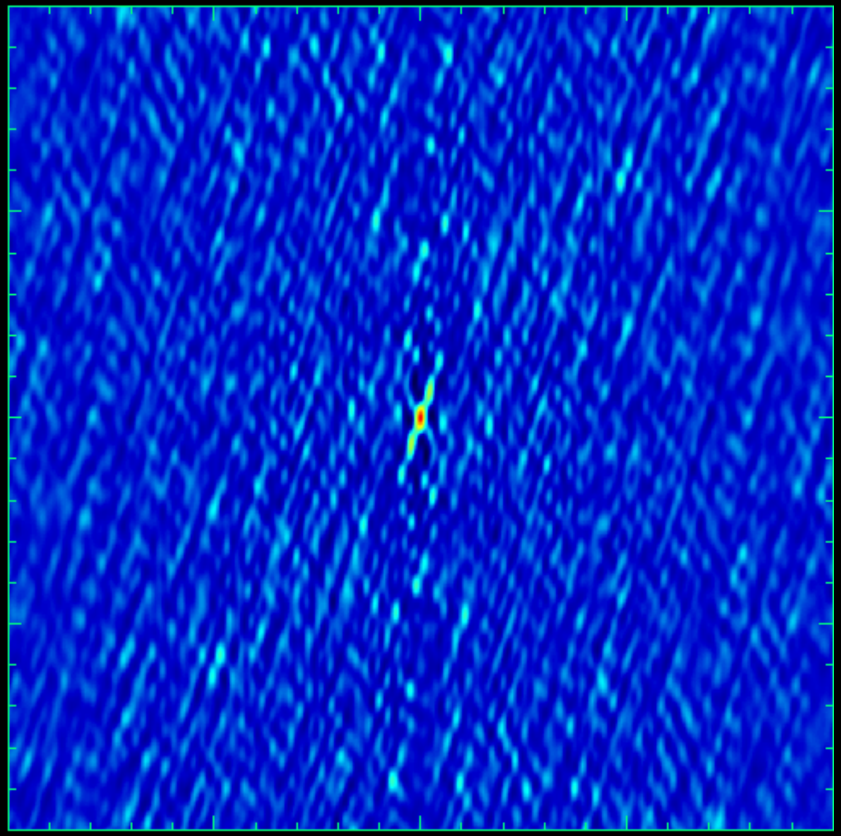

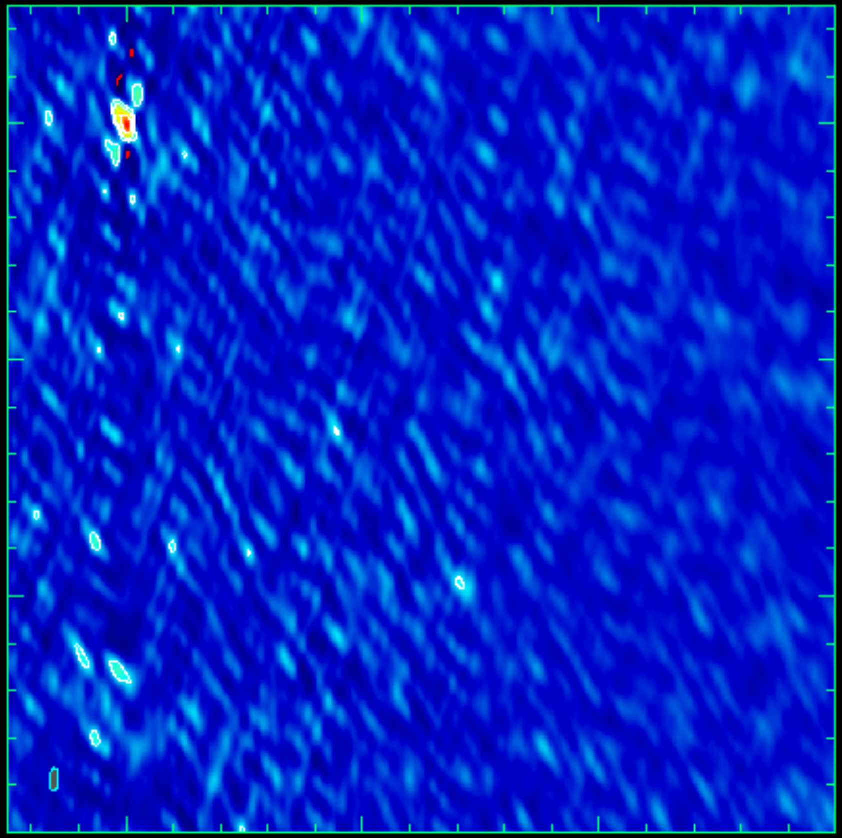

Dirty map:	Point Spread Function:	Solution:
FT of *zero-filled* Visibility	Dirty map for the point source	Point sources + Residual Map

(3C 273, VLBA-MOJAVE data at 15 GHz)

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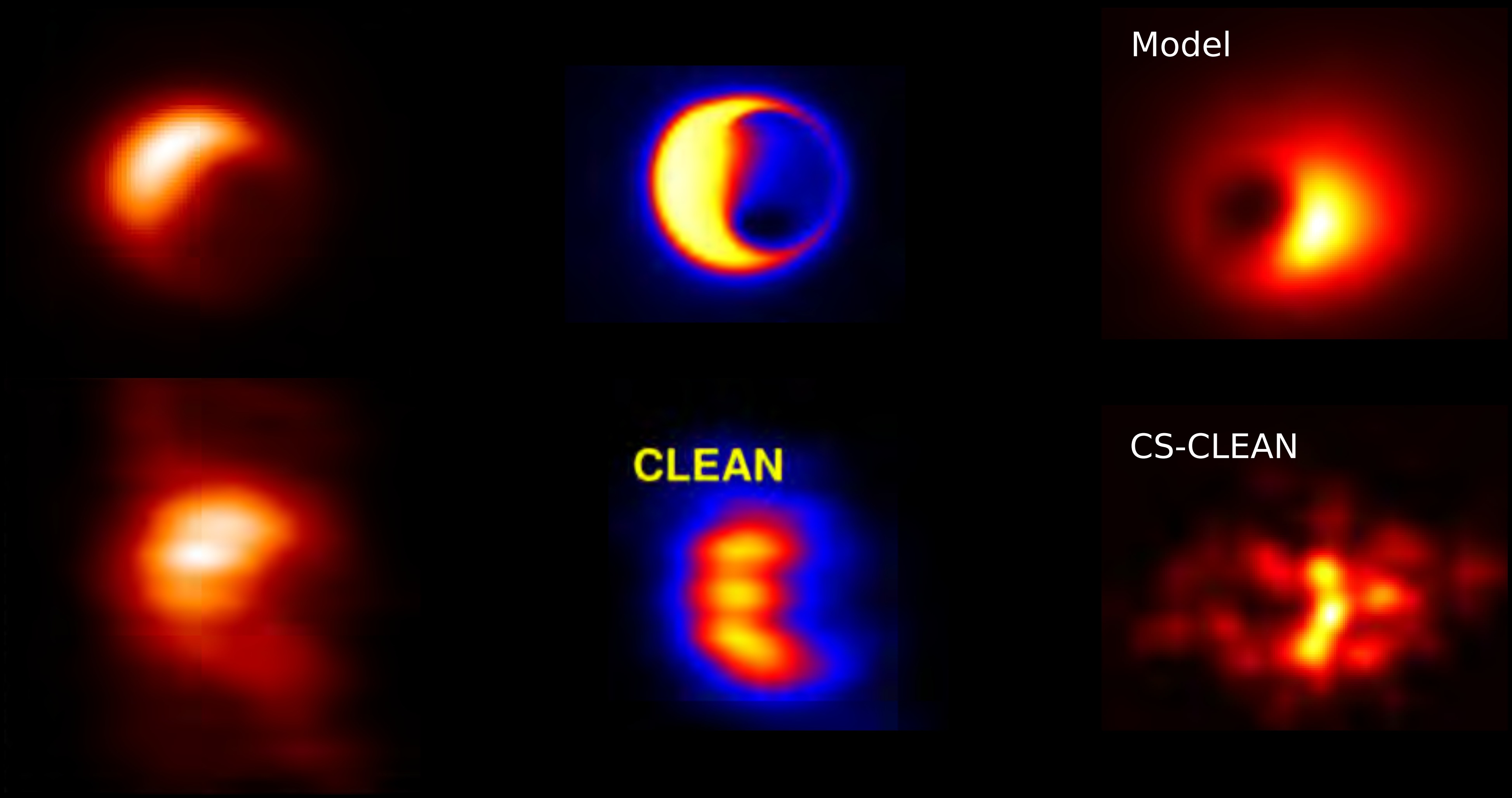
Sparse Reconstruction: CLEAN (greedy approach)

CLEAN (Hobgom 1974) = Matching Pursuit (Mallet & Zhang 1993)

CLEAN is problematic for the black hole shadows?

Ground Truth

CLEAN



Fabian Baron, EHT 2012

Chael+2016 ApJ

Akiyama+2017a, ApJ
Akiyama+2017b, AJ

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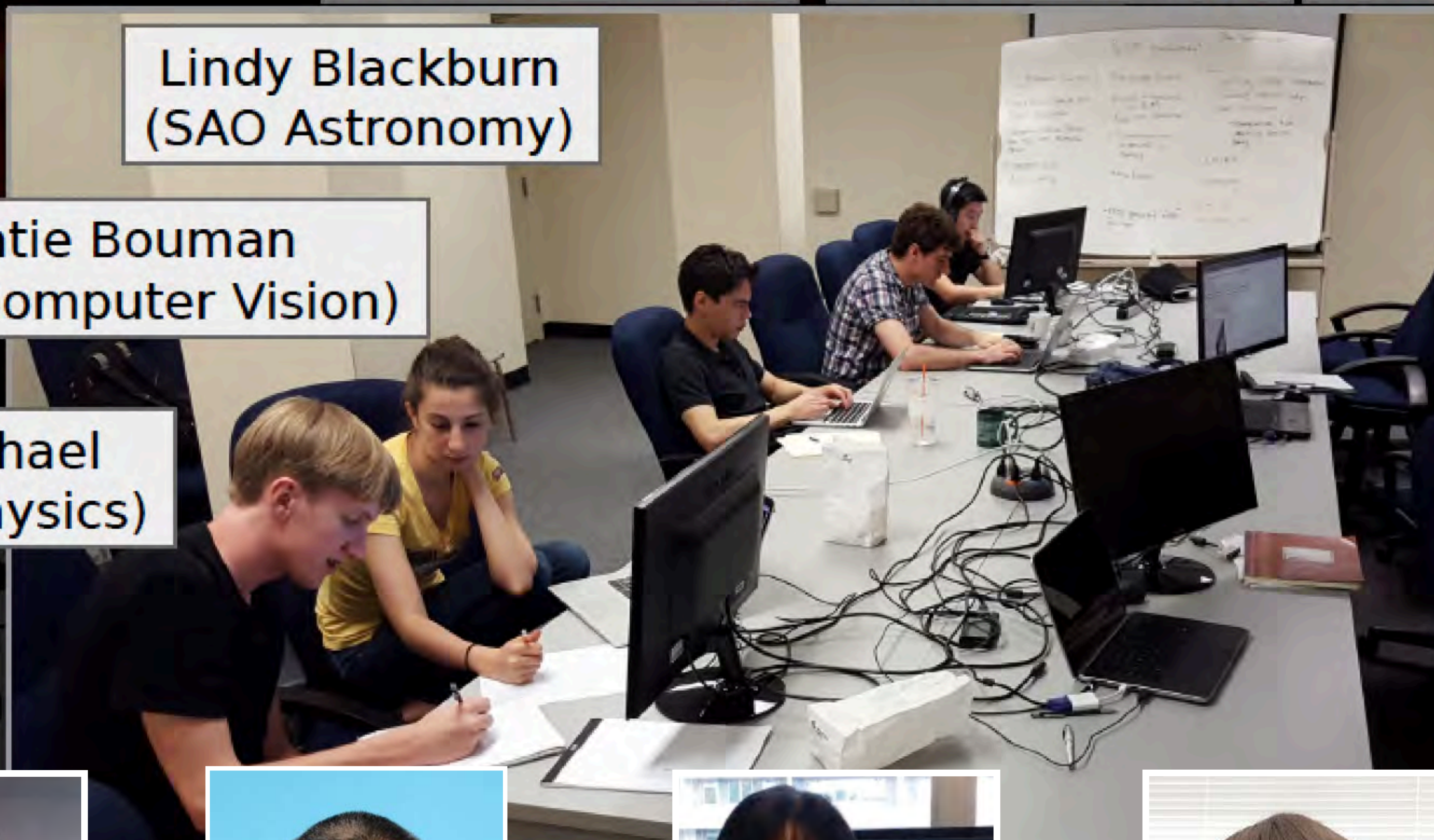
EHT Imaging: Fusion of Young Powers & Divergence

Andre Young
(SAO Astronomy)

Kazu Akiyama
(MIT Astronomy)

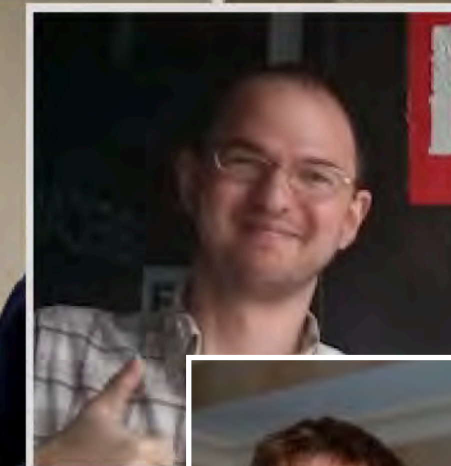
Julian Rosen
(UGA Mathematics)



Lindy Blackburn
(SAO Astronomy)

Katie Bouman
(MIT Computer Vision)

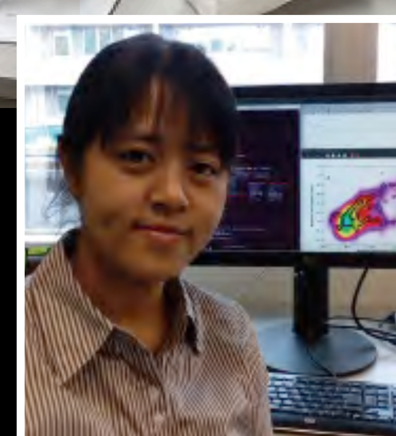
Andrew Chael
(Harvard Physics)



Michael Johnson
(SAO Astronomy)

Marki Honma
NAOJ
Astronomy

Shiro Ikeda
ISM Statistical
Mathematics



Fumie Tazaki
NAOJ Astronomy

Kazuki Kuramochi
U.Tokyo Astronomy

Approach 1: Sparse Modeling (Compressed Sensing)

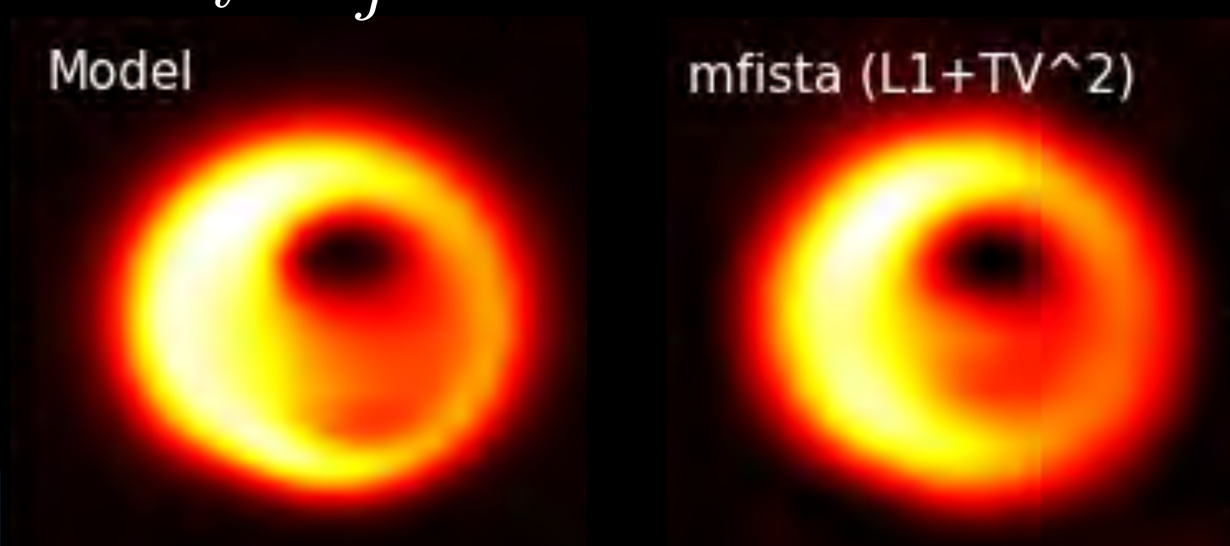
$$\min_{\mathbf{x}} \left(||\mathbf{y} - \mathbf{A}\mathbf{x}||_2^2 + \Lambda_l ||\mathbf{x}||_1 + \Lambda_t ||\mathbf{x}||_{\mathrm{tv}} \right)$$

Chisquare

L1 norm — Regularization on *sparsity*

Total Variation: — Regularizing the *sparsity on the gradient domain*

$$||\mathbf{x}||_{\mathrm{tv}} = \sum_i \sum_j \left(|x_{i+1,j} - x_{i,j}|^2 + |x_{i,j+1} - x_{i,j}|^2 \right).$$



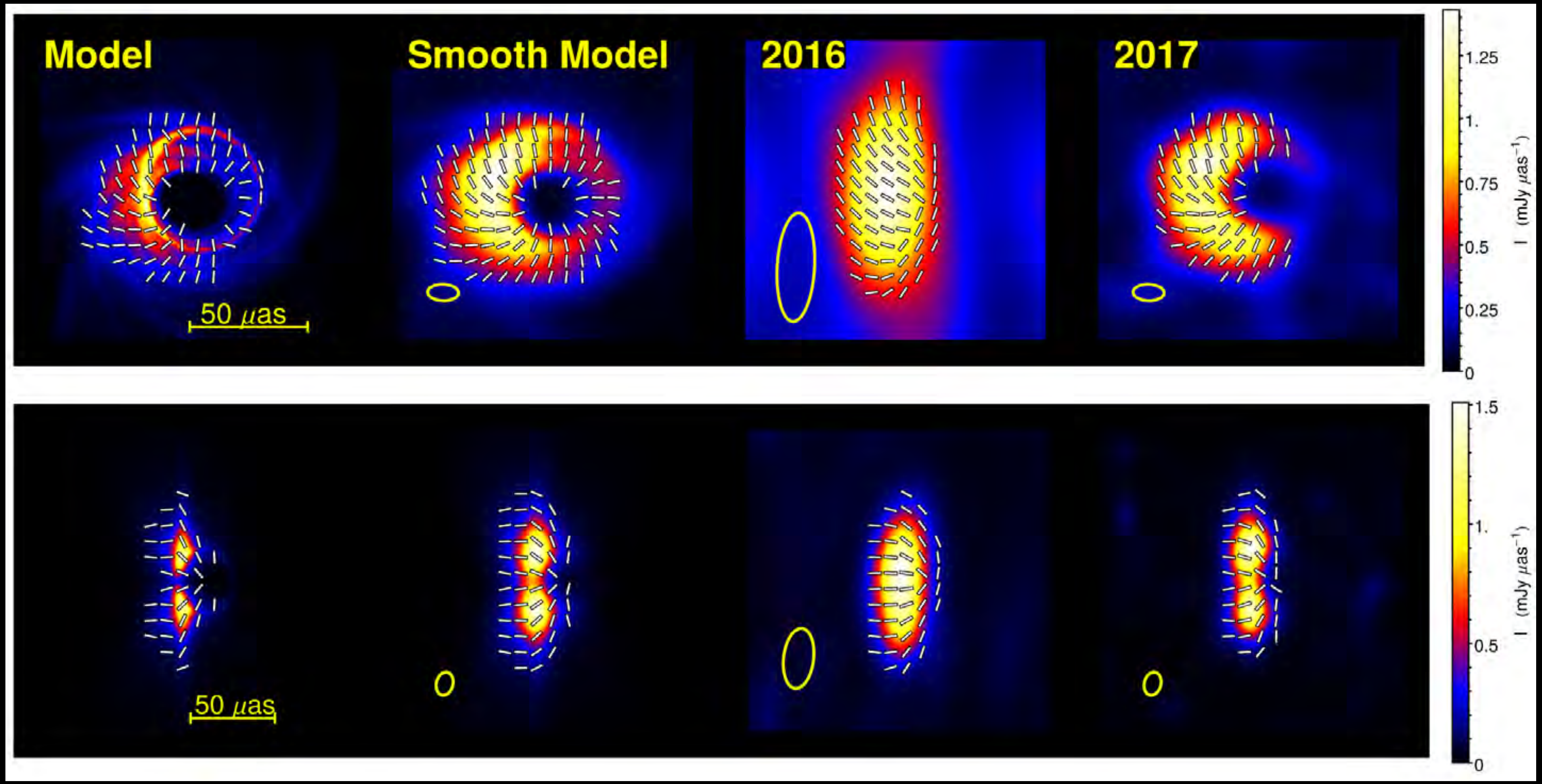
Honma+2014
Akiyama+2017a,b
Kuramochi+2017
submitted to ApJ

Approach 2: Maximize the Information Entropy

Maximum Entropy Methods (MEM; Frieden 1972; Gull & Daniell 1978)

$$\min_{\mathbf{x}} \left(||\mathbf{y} - \mathbf{A}\mathbf{x}||_2^2 - \Lambda f_{\mathrm{entropy}}(\mathbf{x}) \right)$$

$$f_{\mathrm{entropy}}(\mathbf{x}) = -\sum_i x_i \log\left(\frac{x_i}{m_i}\right)$$



(Chael et al. 2016, ApJ)

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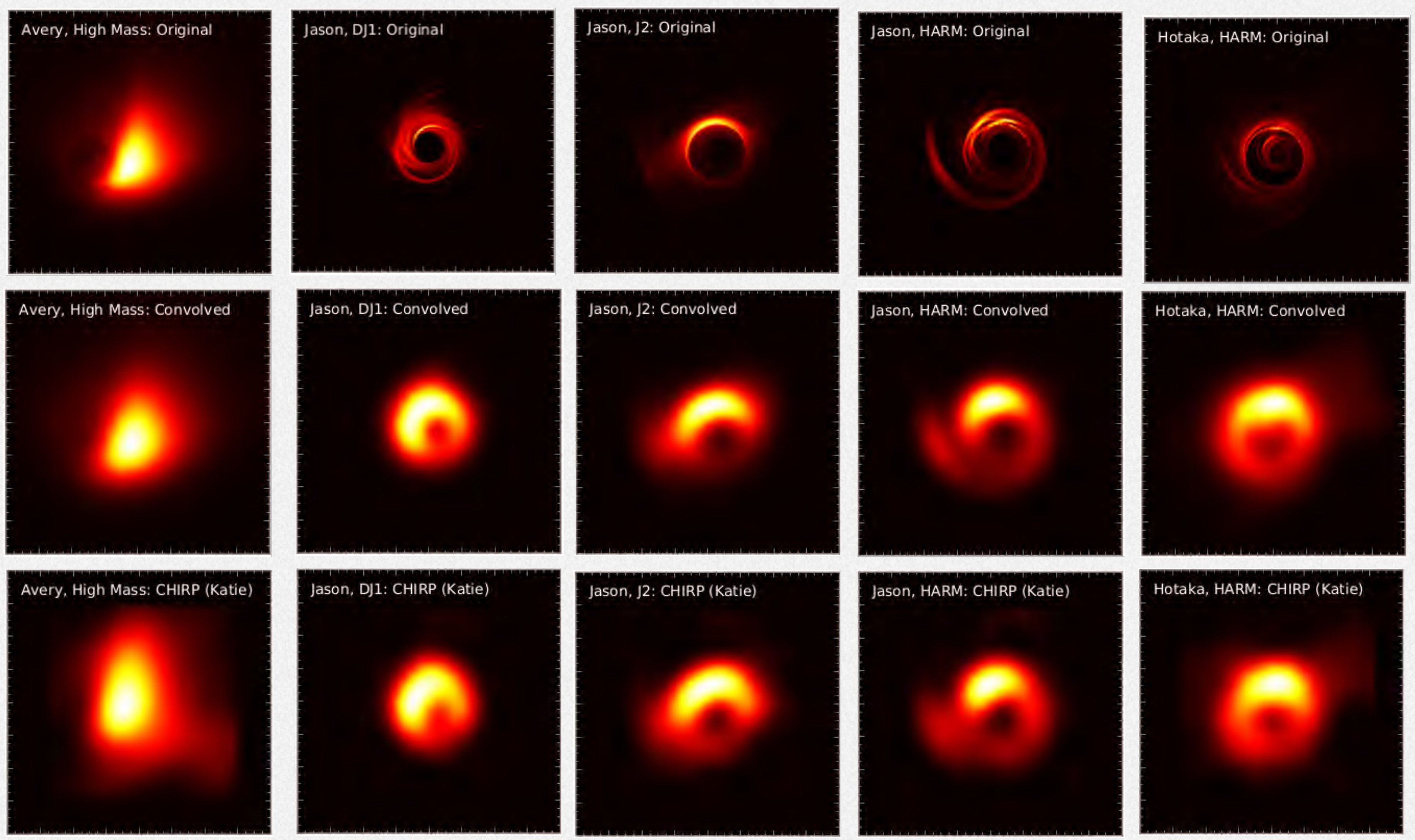
Approach 3: Machine-learn Distributions of Image Patches

A patch prior (CHIRP; Bouman et al. 2015 CVPR)

CHIRP: Continuous High Image Resolution using Patch priors

Reconstruct the image so that it maximizes consistency with a machine-learned patch prior distribution

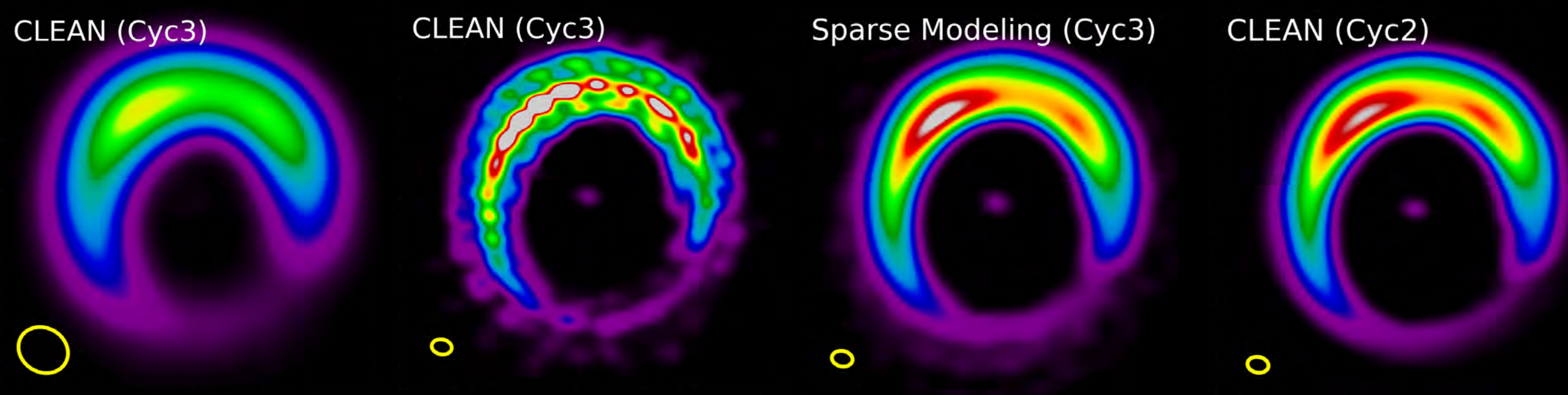


(courtesy of Katie Bouman)

Application to Real Data: Protoplanetary Disk

ALMA Observations of Protoplanetary Disk HD 142527 (345 GHz)

Compact configuration		Intermediate config.
Nominal Resolution	Superresolution (same to the intermediate configuration)	Nominal Resolution



Kataoka et al. 2016, ApJ

Fukagawa et al. in prep.

(Yamaguchi, Akiyama, & Kataoka et al. in prep.)

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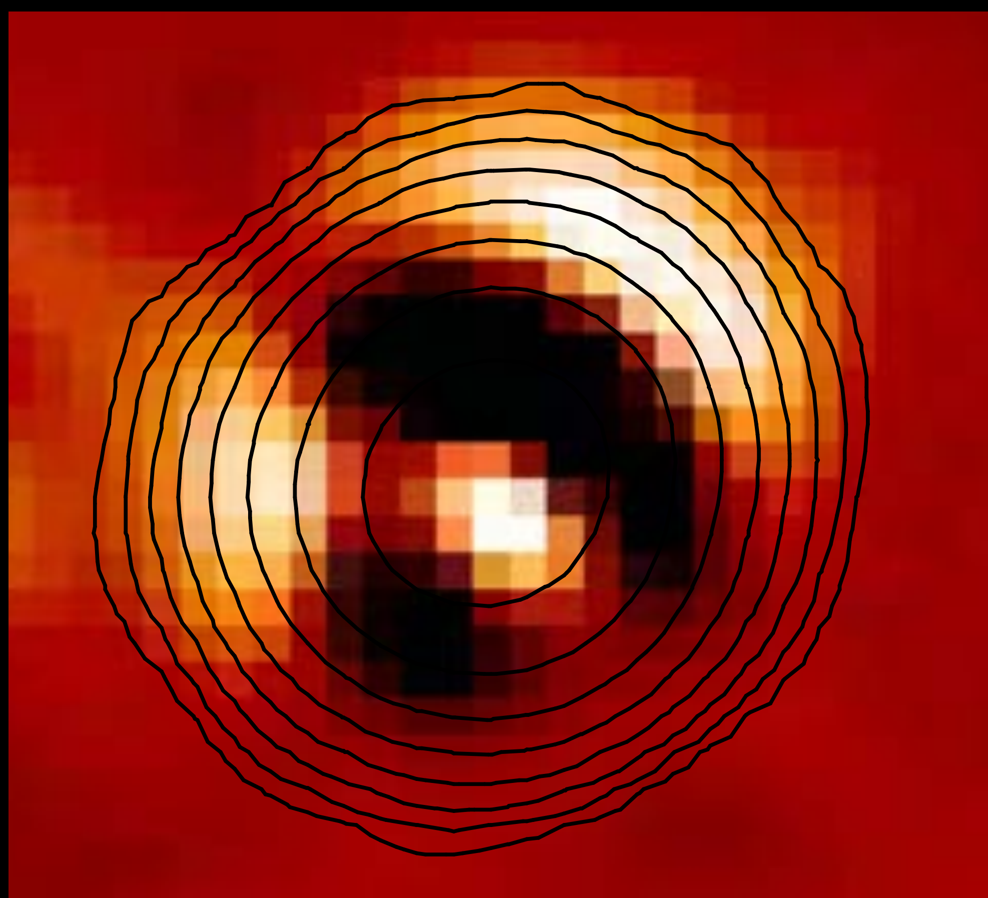
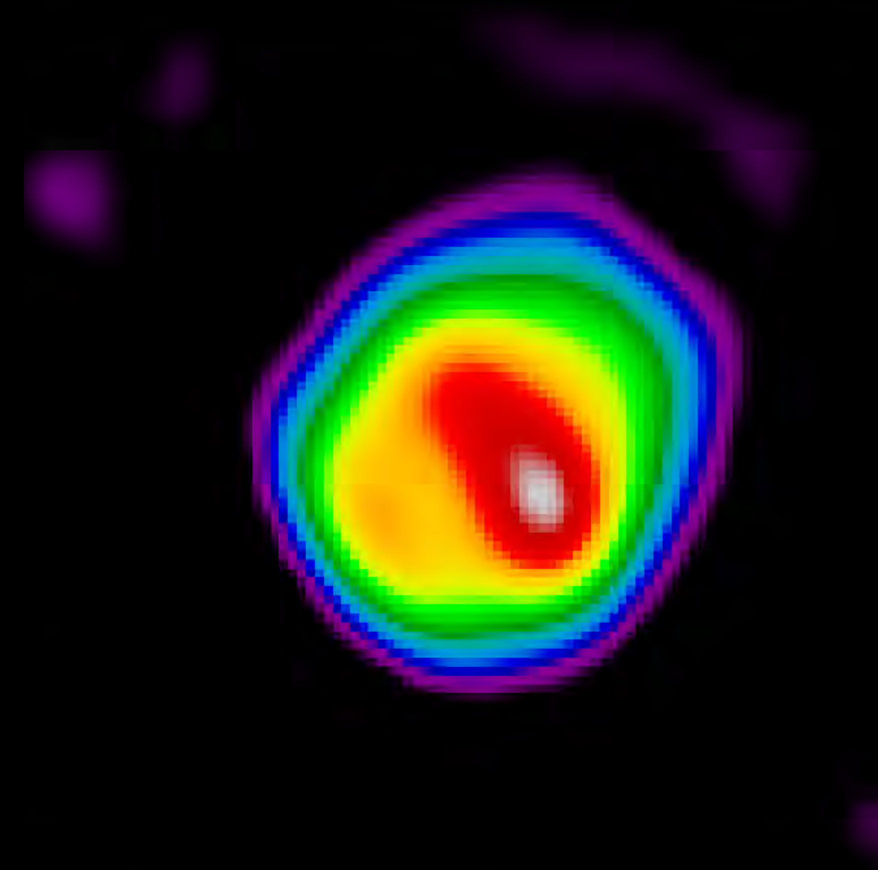
Application to Real Data: Radio Stars

Resolving Asymmetric Shape & Temperature Distribution of Stellar Photosphere with JVLA

Residual Map
of a Uniform Disk model



Contour lines: CLEAN MAP



(Matthews et al. in prep.)

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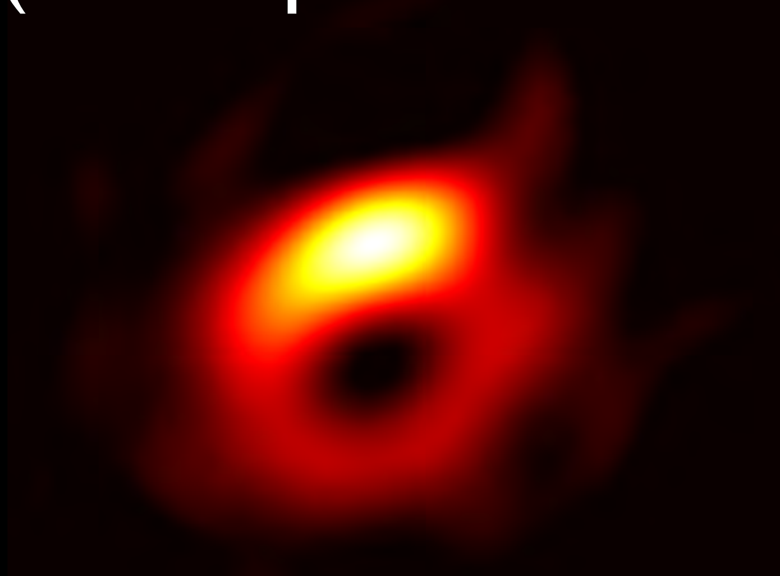
Challenges for VLBI Imaging

No good phase & amplitude calibrations!

We need to carefully CLEAN
so that images are consistent with
amplitude gains of ~10-30 %. …., etc….

Solution: Full Closure Imaging (Cl. Amplitudes + Cl. Phase)

M87 Jet Model
(Moscibrodzka+17)



EHT 2017/2018
Full Closure Imaging

Sparse Modeling: Akiyama et al. in prep.
MEM & CHIRP: Chael et al. in prep.

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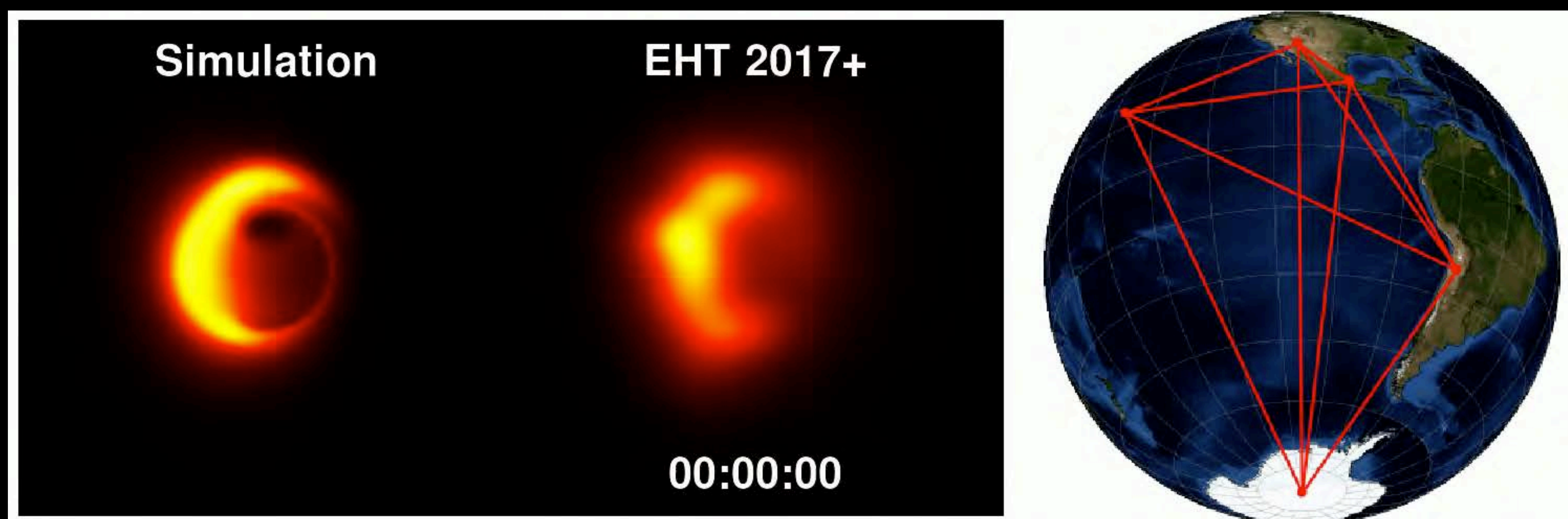
Challenges for VLBI Imaging

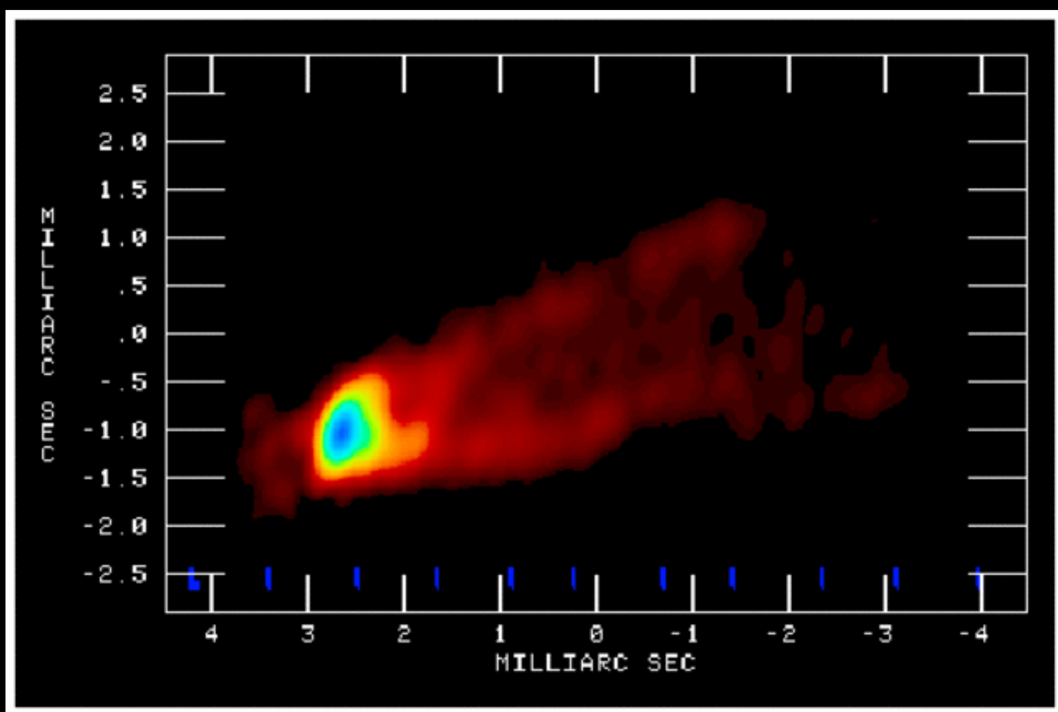
Sgr A* has a time variability.

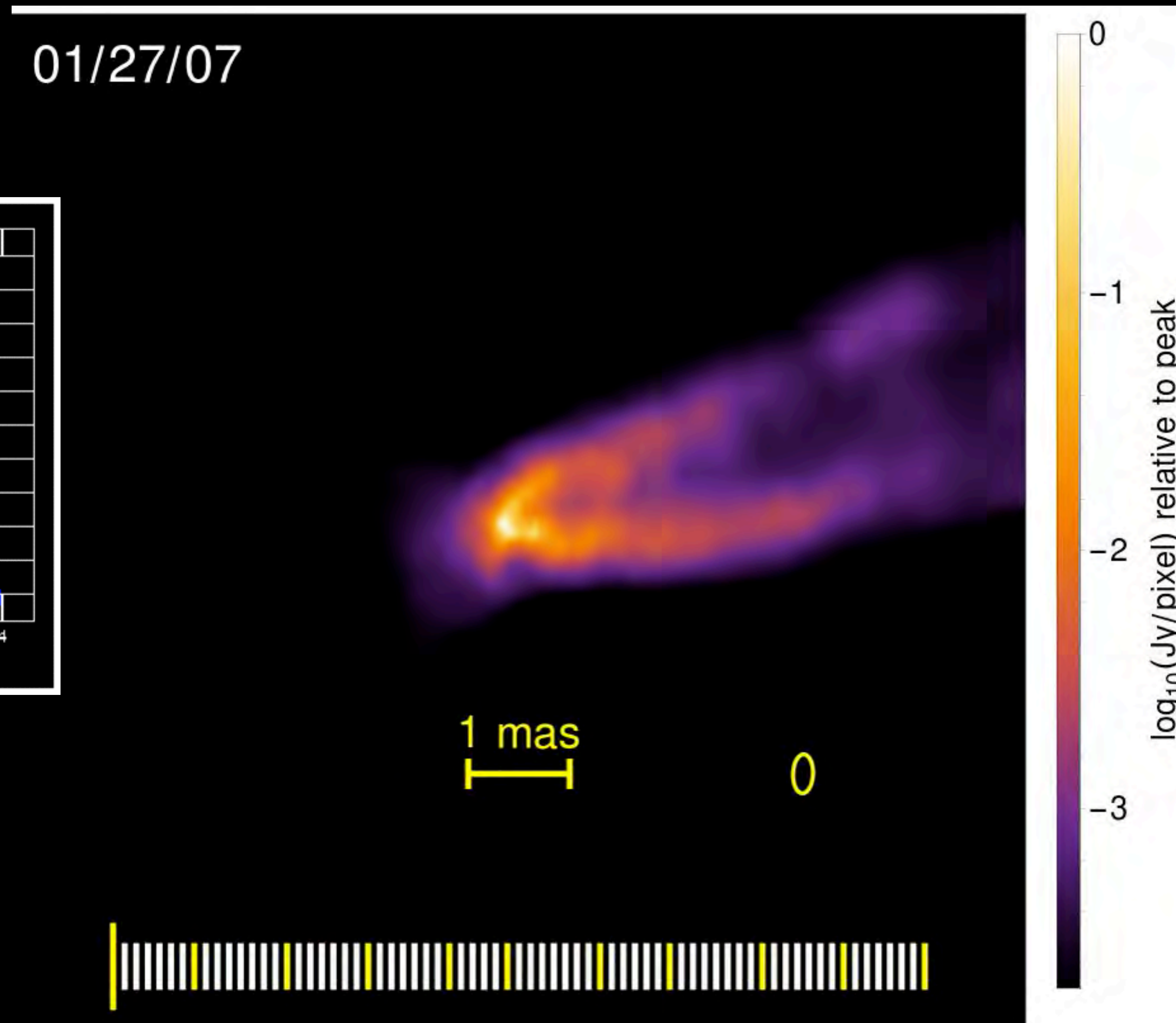
Solution: regularize and solve movies.
(extension of sparse and other regularizers in time direction)



(Johnson et al. 2017, ApJ in press;
Bouman et al. 2017, IEEE in press)

Applications of Dynamical Imaging of M87 data





(Johnson et al. 2017, ApJ in press)

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Summary

- EHT imaging techniques provide a new opportunity to obtain high-quality, high-resolution images (and movies) from various type of interferometric data sets.
- On-going wide application to various sources and other problems
  - Radio Stars, Protoplanetary disks, Jets
  - Faraday Tomography