Title: Super-resolution imaging with sparse modeling

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Abstract: The angular resolution is the most fundamental to imaging the event-horizon-scale structure of supermassive black holes, and in order to realize the highest angular resolution ever, the EHT has been developing a world-wide (sub)mm VLBI array under the international collaborations.
In order to boost the imaging capability of the EHT, we have been developing a new imaging method based on the technique so-called "sparse modeling", which allows us to directly solve the ill-posed Fourier-transform equations caused by incomplete sampling of visibilities.
We show that the images obtained based on such an approach indeed provide an angular resolution a few times better than that of the standard imaging. We report on our simulations and also preliminary results of its application to real data, and discuss its potential in imaging black hole shadows with the EHT.

Super-resolution imaging with sparse modeling

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Makoto Uemura (Hiroshima U.)
Shiro Ikeda (Institute of Statistical Mathematics)

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- Quick review of EHT-related activities in Japan
- Imaging with sparse modeling: a new technique to boost the imaging capability of EHT

EHT activities in Japan

- Science activities

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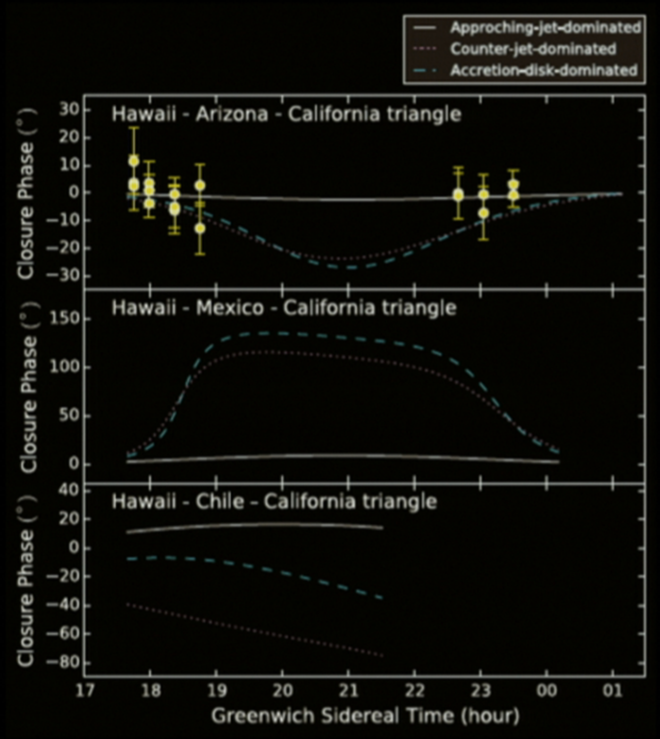
EHT data analysis M87 at 230G (Akiyama+)

Closure phase detected at 1mm !



EHT activities in Japan

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mm VLBI	M87 86G imaging (Hada+)

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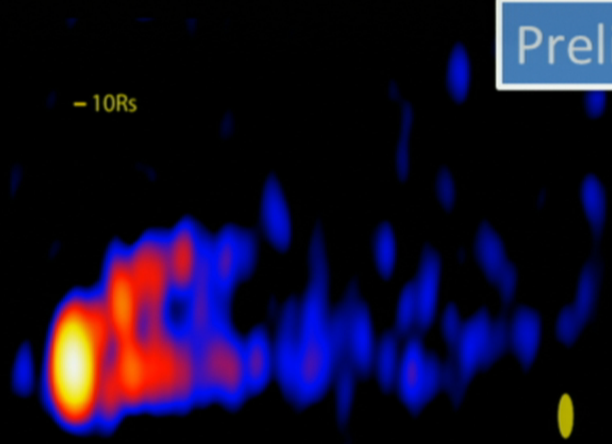
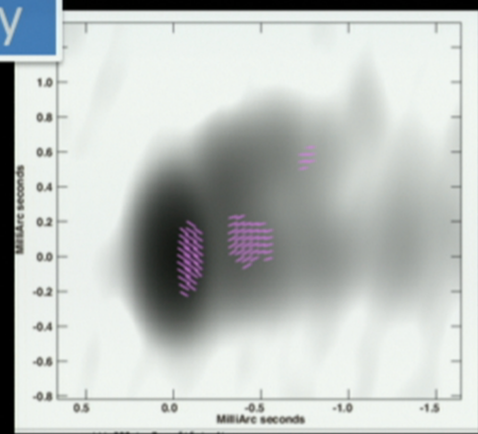
Preliminary



M87 with HSA at 86G



Possible polarization at 86G

M87 86G image: Hada+ in prep.

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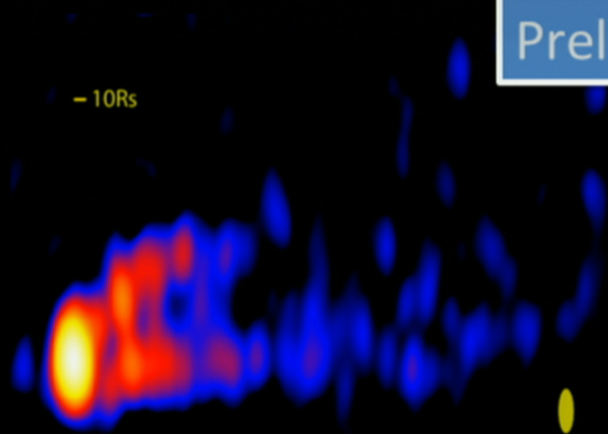

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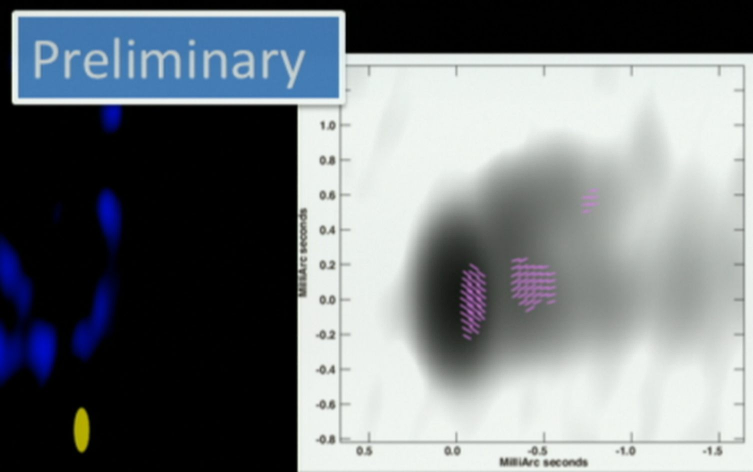

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  contribution to APP: optical fiber link (AOS-OSF)

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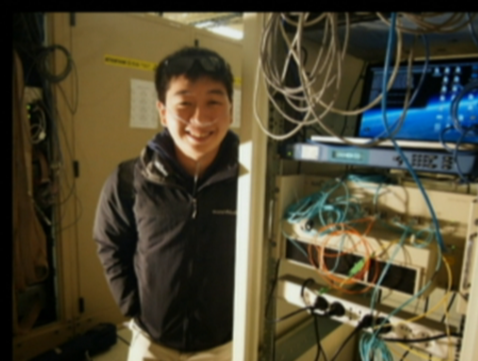

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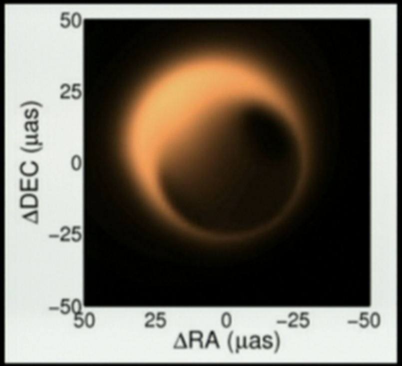
  contribution to APP: optical fiber link (AOS-OSF)

  new imaging technique to boost image capability (Honma+, see also Tazaki's poster)

Motivation



- We definitely need high resolution !
- Resolution is given by

$$\Theta \sim \lambda / D$$

- If there is an imaging technique to obtain resolution better, it would significantly boost the imaging capability of EHT.

Super-resolution technique is equivalent to building a larger array !!

Interferometry imaging

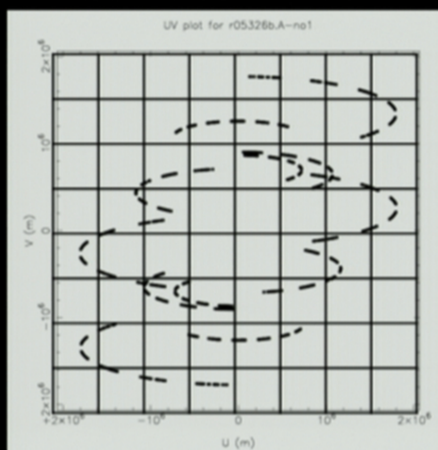
Discrete Fourier transform of 2-D grid data

- Limited (u, v) coverage needs 0 padding of grids
- As a result, there will be finite-size beam and side lobes

beam size $\Theta \sim \lambda / B$ (λ : wavelength, B : baseline length)

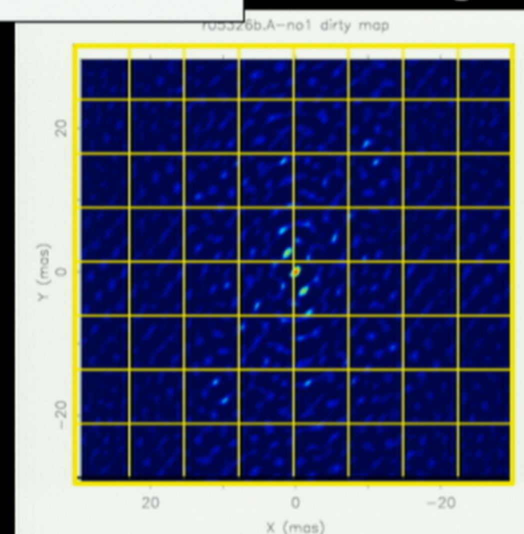
$$I_\nu(x,y) = \iint S_\nu(u,v) e^{-2\pi i(ux+vy)} du dv$$

Visibility S(u,v)



N² points
2-D FT

Image I (x,y)

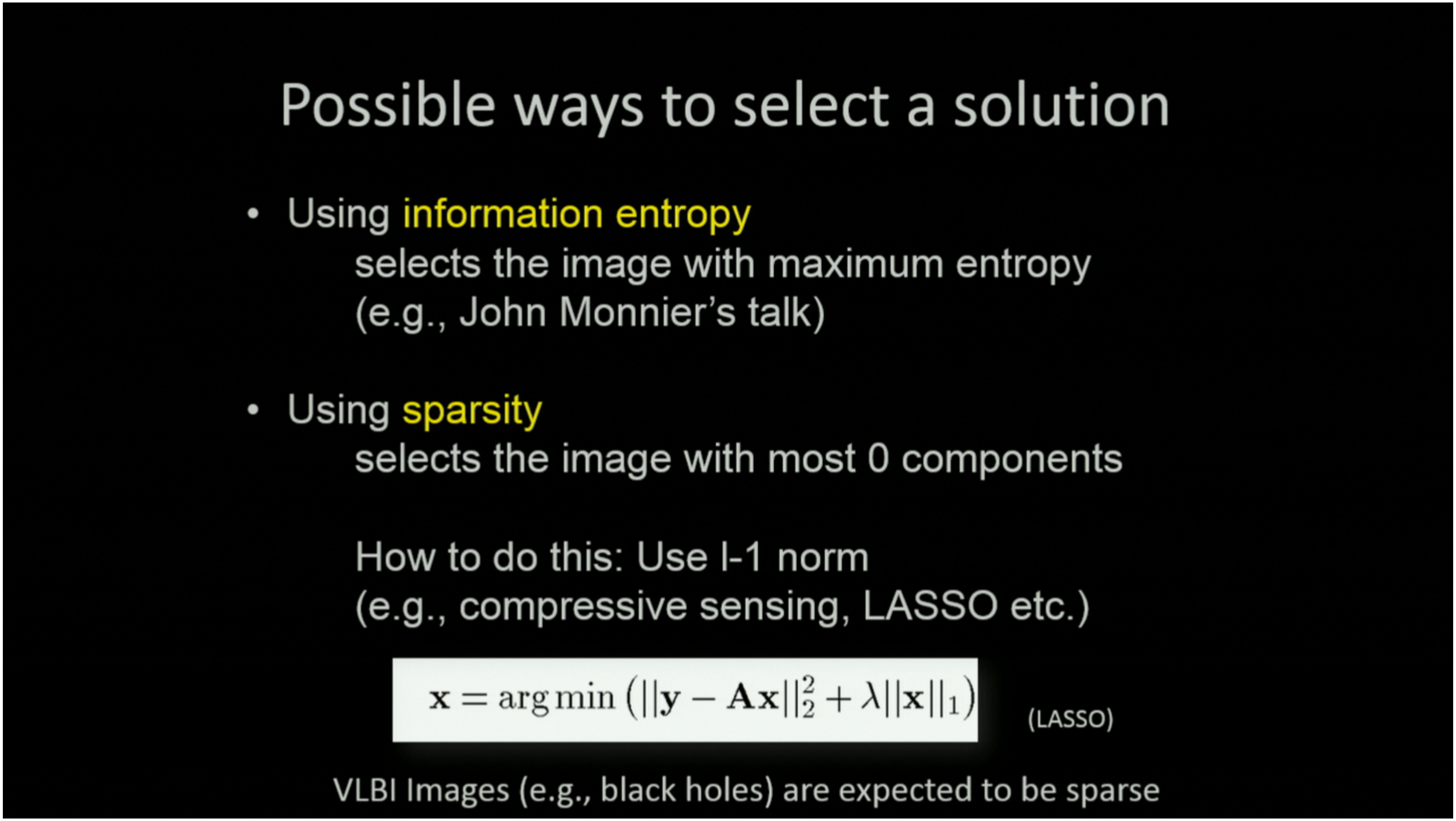


Standard imaging: FFT with 0-filling

visibility = A x image

$$\underbrace{\begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ \cdots \\ V_M \\ 0 \\ 0 \end{pmatrix}}_{\text{Observed data } (V_1 \ldots V_M)\text{; 0-fill } (0, 0)} = \underbrace{\mathbf{A}}_{\text{FT matrix}} \times \underbrace{\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ \cdots \\ \cdots \\ \cdots \\ I_N \end{pmatrix}}_{\text{Solution (Image)}}$$

0-filling process causes both finite beam size and numerous side-lobes.

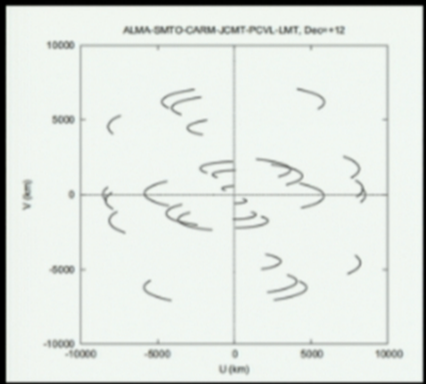


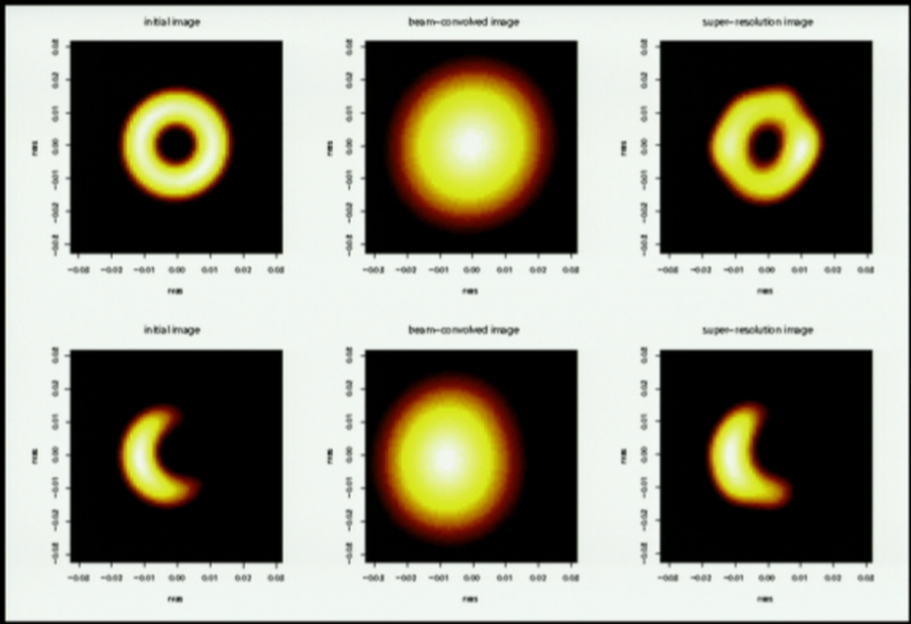
Possible ways to select a solution
• Using information entropy
selects the image with maximum entropy
(e.g., John Monnier's talk)
• Using sparsity
selects the image with most 0 components
How to do this: Use l-1 norm
(e.g., compressive sensing, LASSO etc.)
$\mathbf{x} = \arg\min \left(||\mathbf{y} - \mathbf{A}\mathbf{x}||_2^2 + \lambda ||\mathbf{x}||_1 \right)$
(LASSO)
VLBI Images (e.g., black holes) are expected to be sparse

Simulation

- Simulated 6-station EHT observations of M87 (including noise)

M=3x10^9 M_sun



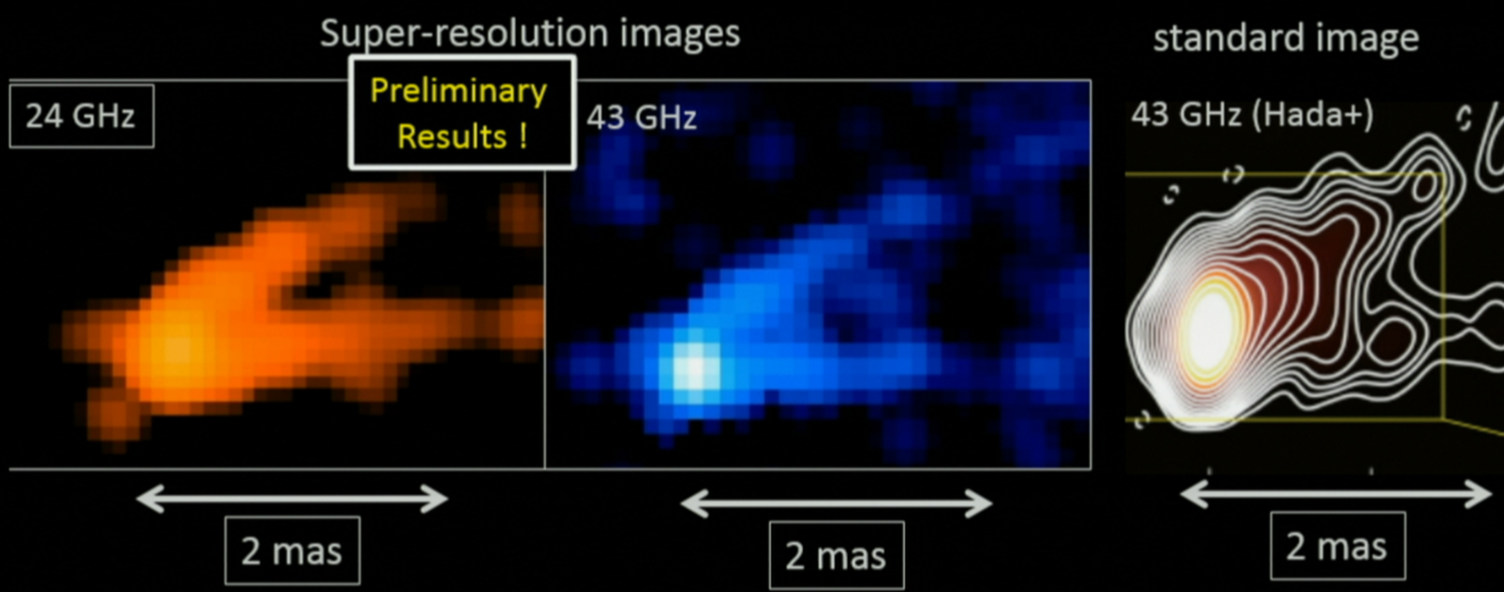


Initial model   Standard image   Sparse modeling

Honma et al.(2014), PASJ, arXiv 1407.2422

Application to real data: M87 case

- M87 with VLBA at 22G/43G (Tazaki's poster)



Jet's limb structure is clearly seen even near the core.

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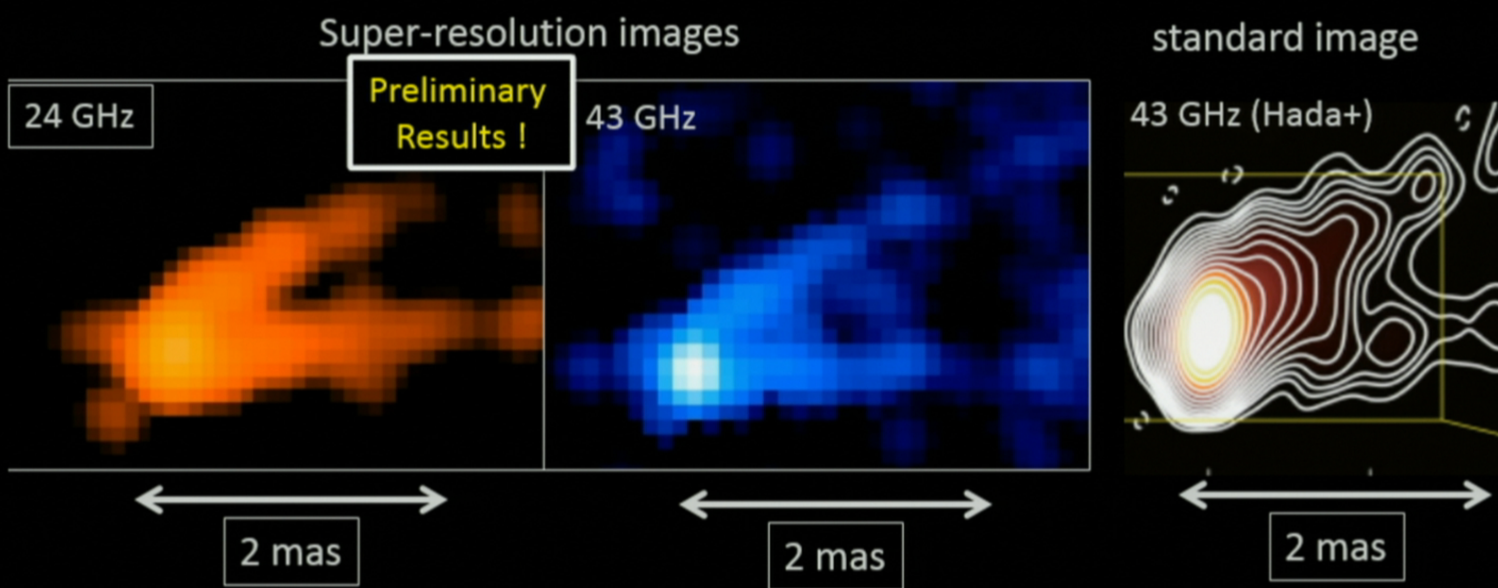
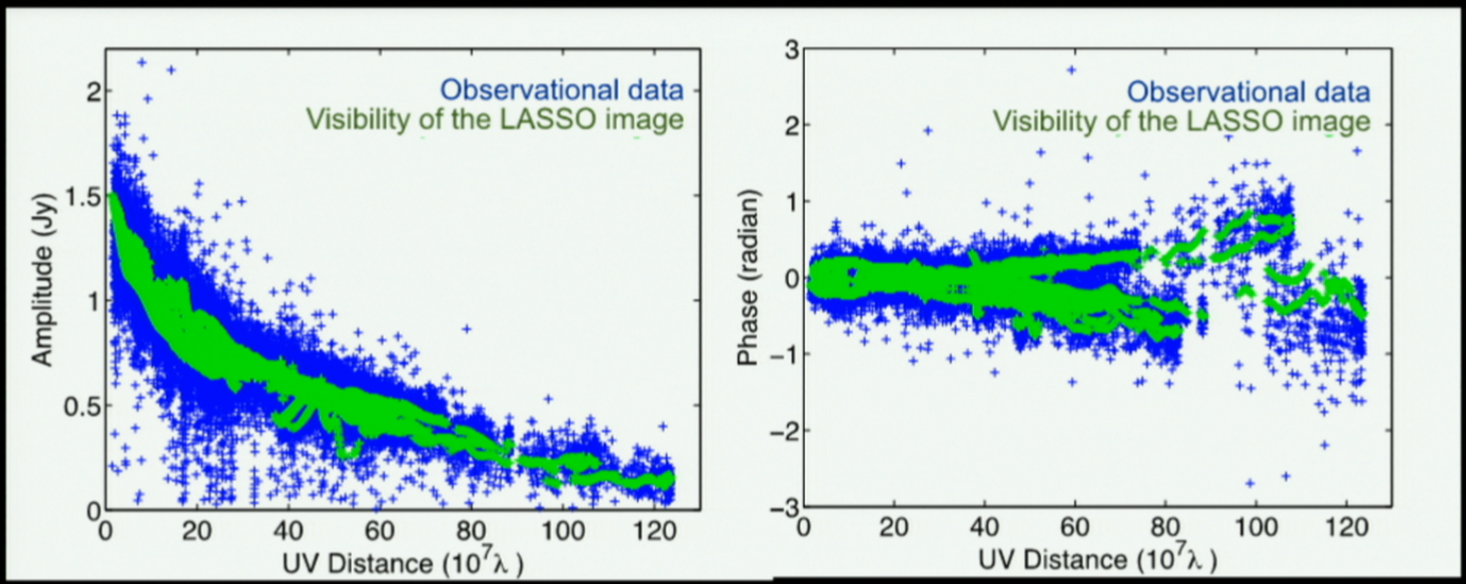


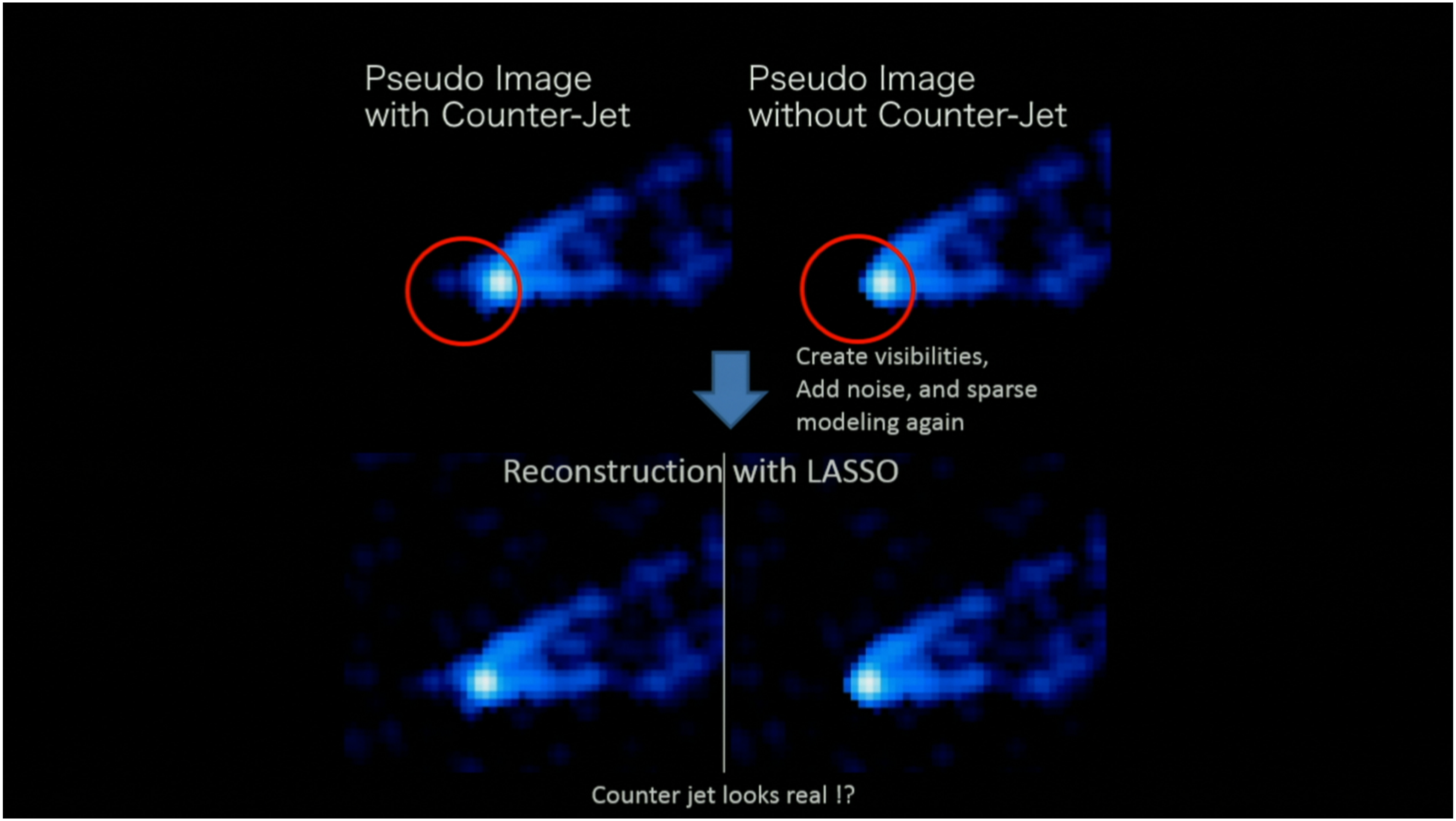
Jet's limb structure is clearly seen even near the core.

Reproduced visibilities

- Visibilities are well modeled with the images



amplitude   phase


Pseudo Image
with Counter-Jet
Pseudo Image
without Counter-Jet
Create visibilities,
Add noise, and sparse
modeling again
Reconstruction with LASSO
Counter jet looks real !?

Concluding remarks

- Introduction of sparse modeling allows us to obtain super-resolution images and to boost imaging capability.

- Application to the real data seems that the technique is promising, and hopefully make significant contribution to understand the event-horizon-scale structure in the AGNs.

- Issues:

  to evaluate to which extent the map is reliable.

  to make this applicable to non-linear case (e.g., bi-spectrum, closure phase)

Imaging is wonderful !

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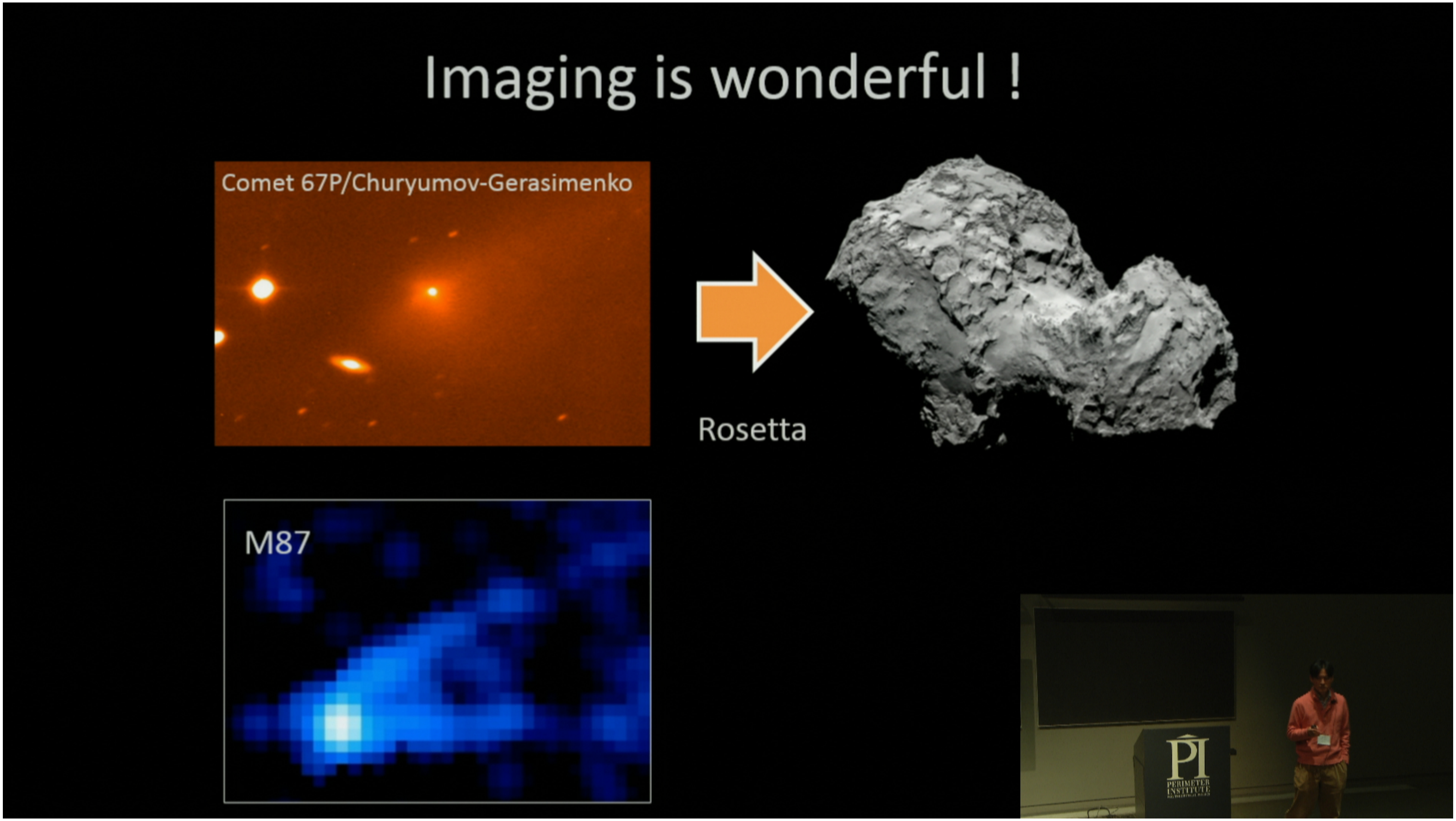
Rosetta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Rosetta
M87
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