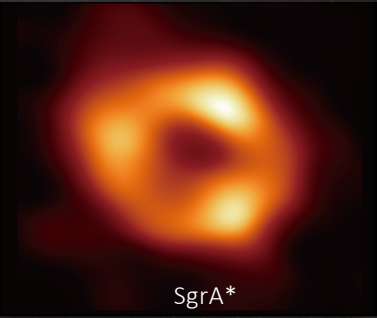
Astronomy and Data Science:

Building astronomical claims with modern data science



Shiro Ikeda

ISM, NAOJ, Kavli IPMU

About myself

- Mar.1996 Ph. D. Univ. of Tokyo
- Apr.1996 Brain Science Institute, RIKEN
- Apr.2001 Kyushu Institute of Technology
- Feb.2003 The Institute of Statistical Mathematics
- Information Geometry
- Signal Processing
- Information Theory
- Brain Data Analysis
- Fisheries Resources
- Astronomical Data Analysis

Institute of Statistical Mathematics (ISM)

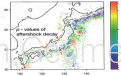
Unique institute focused on Statistical Science

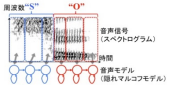
- Founded in 1944
- Located in Tachikawa, Tokyo
- On of the 22 Inter-University Research Institutes
- 49 faculty, 80 visitors, 70 part-time, 29 grad. Students.

Theory and Methodology

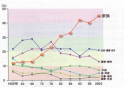
- Information Criterion
- Time series analysis
- Survey methodology
- Quantification theory
- Multivariate analysis

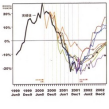
- Bayesian modeling
- MCMC, particle filter
- Ensemble machine
- Sparse modeling
- Kernel method
- Meta-analysis
- Data assimilation method





Promote the development of human resources capable of decision making based on data





Data Science

Data

Medical

Biology

Astronomy

Finance

Government

Data Science

(Statistics)

People

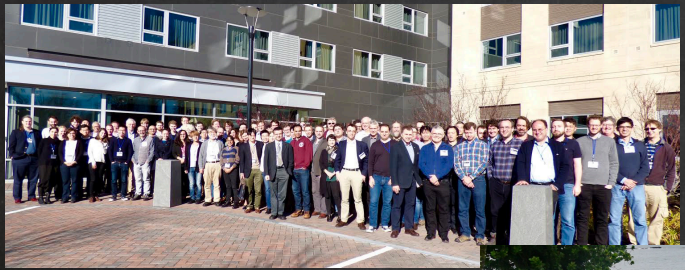
(Researchers)

Scientific Claim

Making Decisions

Deliberate

International Collaboration



EHT Collaboration Meeting 2016@Boston

13 Stakeholder Institutions

EHT Collaboration Meeting 2019@Hilo, Hawaii

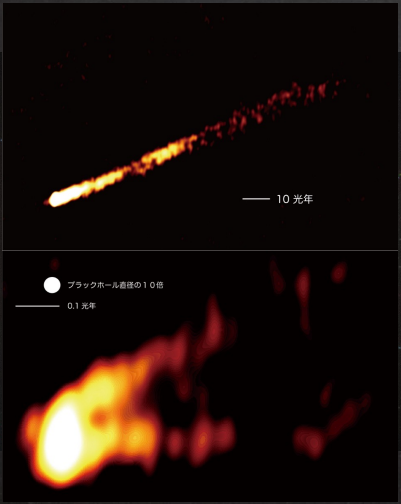
more than 300 members

80 institutes from

21 countries (2022)

M87*

M87 Supermassive Blackhole (?) : Before EHT Results



Credi: ESO, NAOJ

Center of M87 Galaxy

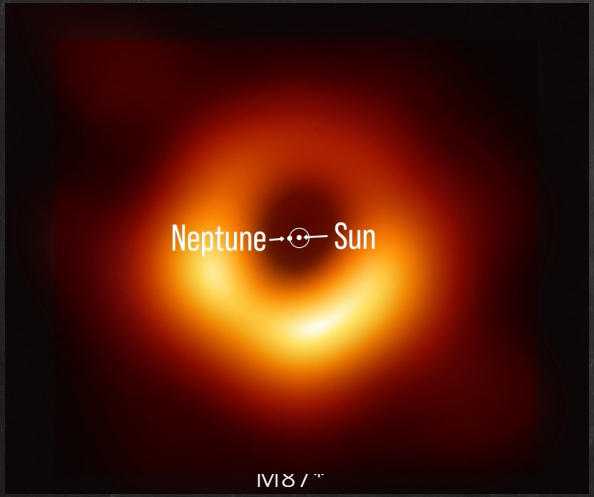
Distance : 55×10^6 Light year

Mass : $\begin{matrix} 3.2 \\ 6.2 \end{matrix} \times 10^9$ Solar Mass

Strong emission with different wavelength

Strong Jet is observed.

M87 Supermassive Blackhole : Astronomical Claim



Credit: H.Falcke/Radboud University/L.Krüger, EHT Collaboration

- Ring

  Black hole

- Size ~ 42μas

  6.5×10^9 Solar Mass

- Brighter Part (South)

  Rotation → Jet

Credit: EHT Collaboration

EHT Results

The First M87 EHT Results : 6 papers, 200 pages, 300 authors.

Each claim : image analysis
direct data analysis
General Relativity simulation

multiple approches

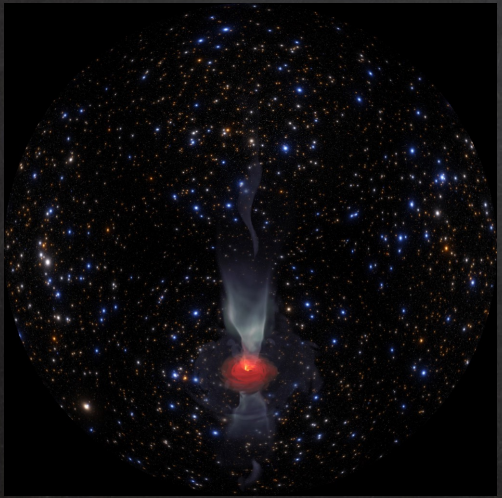
Each process : multiple methods

(To create M87 image : 3 different softwares)

Ring and Blackhole Shadow

Credit: From Kip Thorne's talk at Cardiff Univ., on youtube

EHT Results



Credit: Jordy Davelaar et al./Radboud University/BlackHoleCam

GR Prediction : Blackhole Shadow

Ring Shape

Blackhole Size

6.5×10^9 SM

Blackhole Rotation

Bright edge.

Supermassive BHs are small from our sight

Credit: ESO/M. Kornmesser/L. Calçada

Event Horizon Telescope

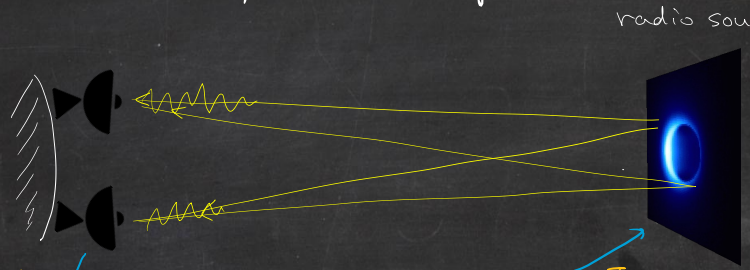
- Observation

April, 2017

6 locations

8 telescopes

Radio Interferometry and Image Reconstruction



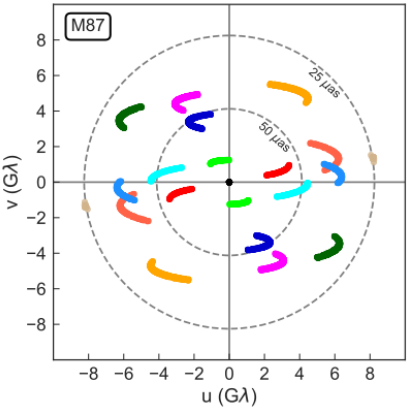
$$V(u,v) = \iint I(x,y)\, e^{2\pi i k(ux+vy)}\, dx\, dy$$

$\Uparrow$

Observe Fourier components

Reconstruct Image.

Radio Interferometry : Sampling Points for M87 & SgrA*



EHT M87 Paper IV

Fourier points are small

Imaging is an ill-posed problem

CLEAN : traditional

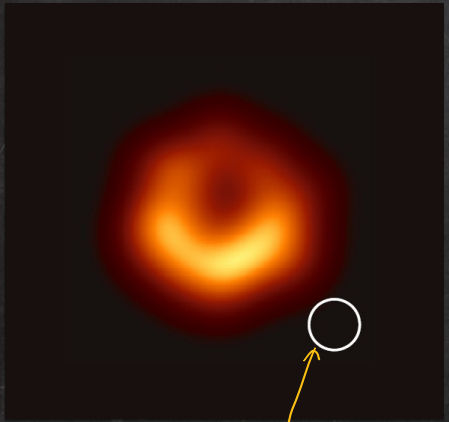
RML : New for EHT

Regularized Maximum Likelihood

(Bayesian MAP estimate)

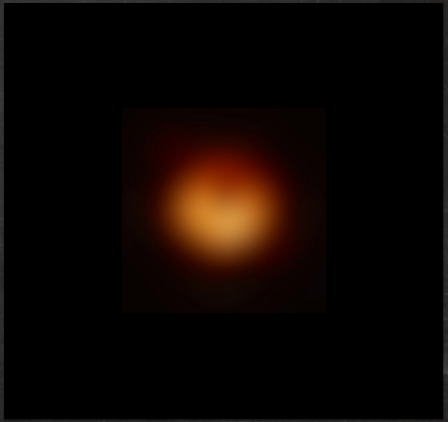
Before EHT results : CLEAN is enough for M87?

6.5×10^9 SM



Limited Resolution

3.2×10^9 SM



We needed Plan B.

New Imaging Methods : Regularized Maximum Likelihood

Data

Image

Newly introduced parameters

$$\underset{x}{\text{minimize}} \quad \underbrace{L(y, x)}_{\text{Likelihood}} + \underbrace{R(x; \theta)}_{\text{Regularization}}$$

Likelihood

Fidelity

Regularization

Prior

Constraints

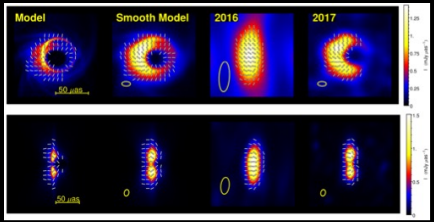
Nonlinear Nonconvex

Negative Entropy, Sparsity, Smoothness.

New Imaging Methods for EHT

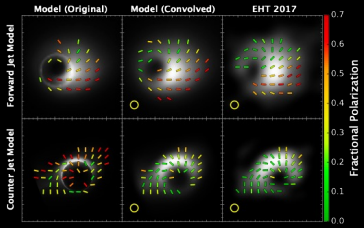
Maximum Entropy Method (MEM)

Chael et al. 2016, Fish et al. 2014,
Lu et al. 2014, 2016



Sparse Modeling

Akiyama et al. 2017a, 2017b
Ikeda et al. 2016, Honma et al. 2014

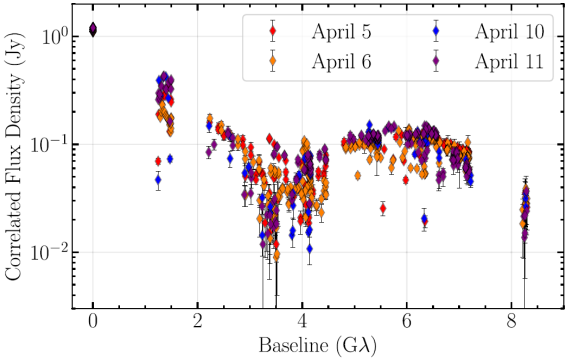


Two New Imaging Libraries

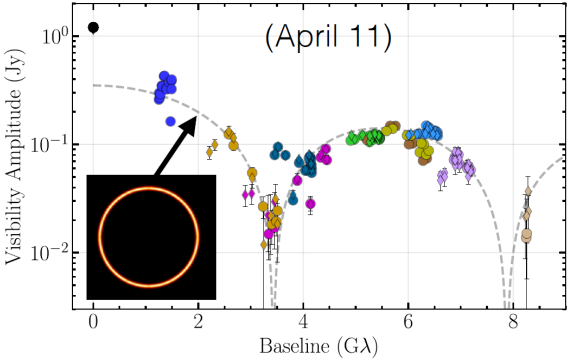
eht-imaging (Chael+2016,2018) : https://github.com/achael/eht-imaging

SMILI (Akiyama+2017a,b) : https://github.com/astrosmili/smili

Calibrated data sets (6, June 2018)



EHT Collaboration 2019c, ApJL, 875, L3



EHT Collaboration 2019a, ApJL, 875, L1

EHT M87Paper IV, Fig.2

June – July, 2018. Imaging by 4 teams.

Team 1

Americas

US & Chile

(SAO, U. Arizona, U. Conception)

Leader: K. Bouman & A. Chael

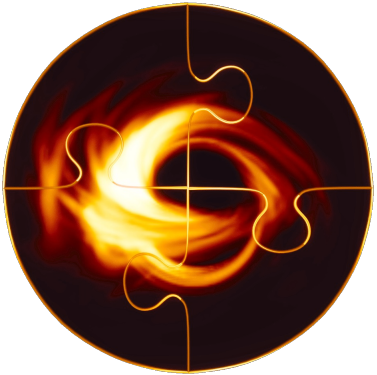
Team 2

Global

US, Japan, Netherland

(MIT, NAOJ, Hiroshima U., Radboud U.)

Leader: K. Akiyama & S. Issaoun



Team 4

East Asians

Korea, Japan & Taiwan

(ASIAA, KASI, NAOJ)

Leader: S. Koyama

Team 3

Cross Atlantic

US, Spain, Germany, Finland

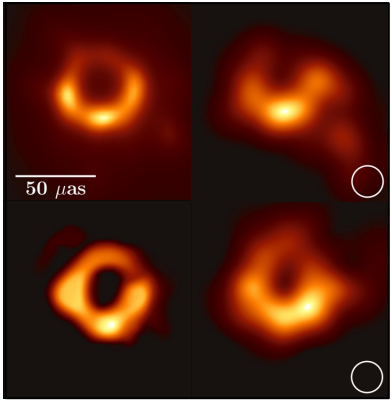
(Boston U, MPIfR, IAA, Aalto)

Leader: A. Marscher

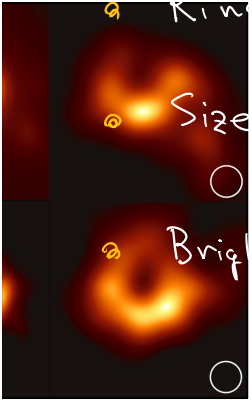
Image
Train
1
1.0
1.06
1.06
1.07
2
1.06
1.0
1.07
1.06
3
1.07
1.06
1.06
1.0

July 2018. 4 results

April 11



April 11



Team 4

East Asians

Korea, Japan & Taiwan
(ASIAA, KASI, NAOJ)

Leader: S. Koyama

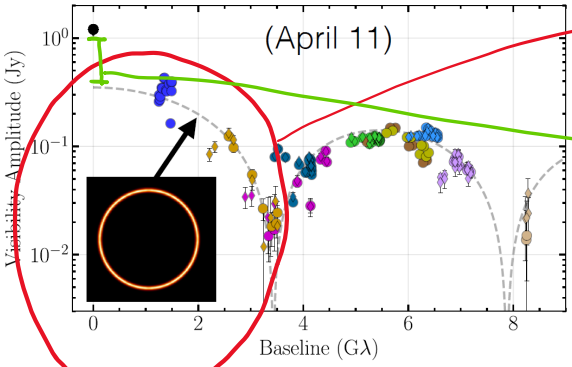
Team 3

Cross Atlantic

US, Spain, Germany, Finland
(Boston U, MPIfR, IAA, Aalto)

Leader: T. Krichibaum & A. Marscher

Calibrated data sets (June 2018)



EHT Collaboration 2019a, ApJL, 875, L1

Indicate a compact object

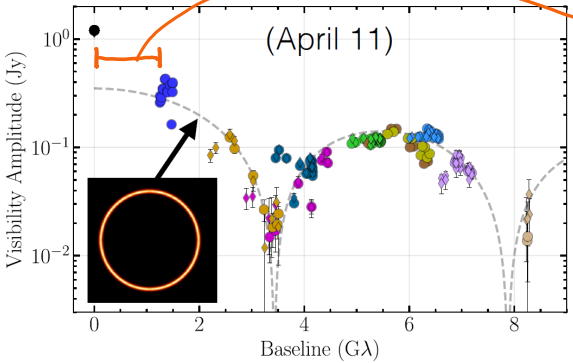
Not be explained with a compact object

Big Structure

+

a Compact object

Calibrated data sets (June 2018)



EHT Collaboration 2019a, ApJL, 875, L1

~~Big Structure~~

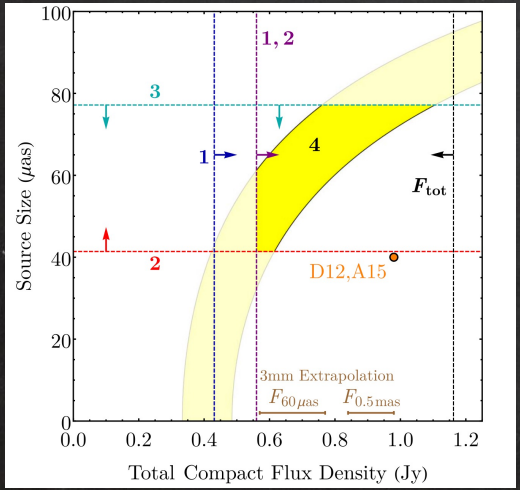
~~Lack of Fourier components~~

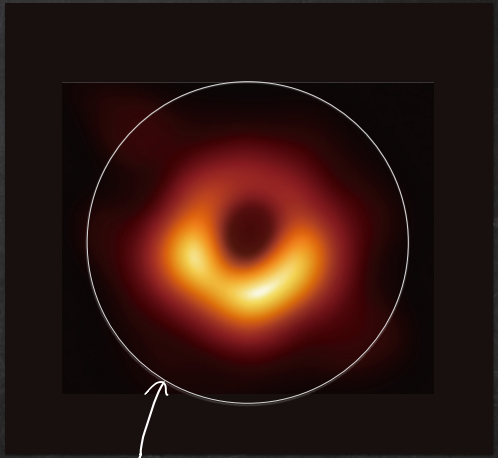
~~Faint structure~~

~~Low S/N~~

Imaging of a Compact Object

Compact Object





50~90% of the emission lives here

Imaging methods used for M87* images

Traditional Method

CLEAN

DIFMAP (Shepherd+97, 98, 03)

Model

General Pixelated Images
Residual Calibration Gains

Hyper Parameters

Sparse reconstruction

Compact flux
Size

New Imaging Methods

Regularized Maximum Likelihood (RML)

eht-imaging (Chael+16, 18)

Model

General Pixelated Images

Hyper Parameters

Sparse
Smooth
Maximum Entropy

Compact flux
Size

SMILI (Akiyama+17a, b)

Model

General Pixelated Images
Residual Calibration Gains

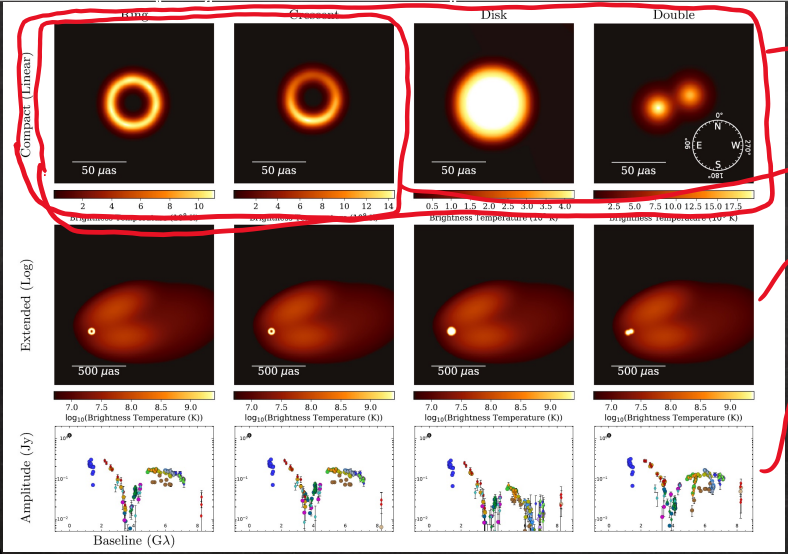
Hyper Parameters

Sparse
Smooth

Compact flux
Size

Credit: K. Akiyama, MIT

Can imaging methods distinguish these?



Ring ?

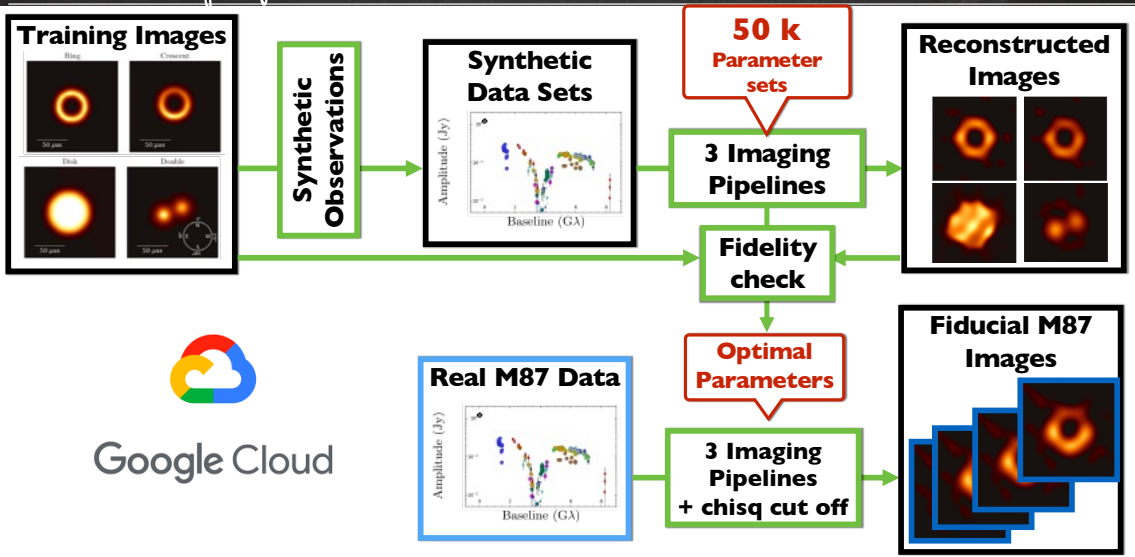
Bright edge ?

Big structure matters?

Similar to observation

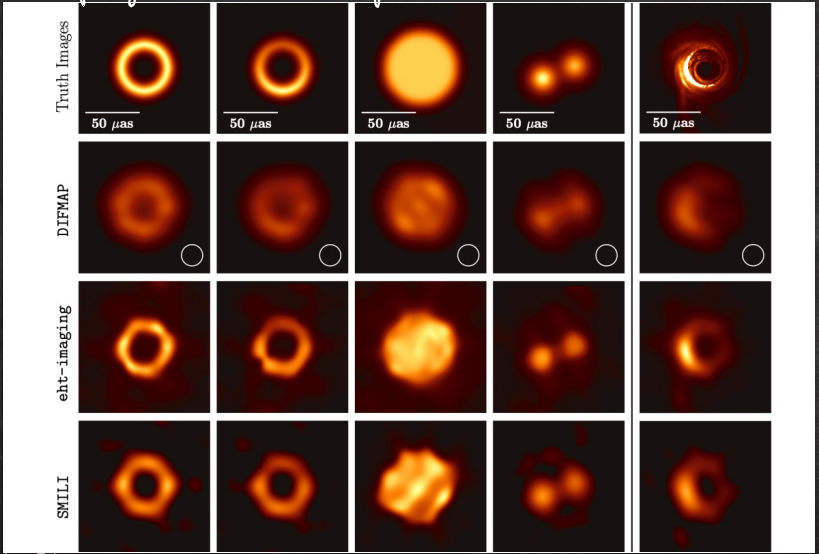
EHT M87 Paper IV

Imaging Process



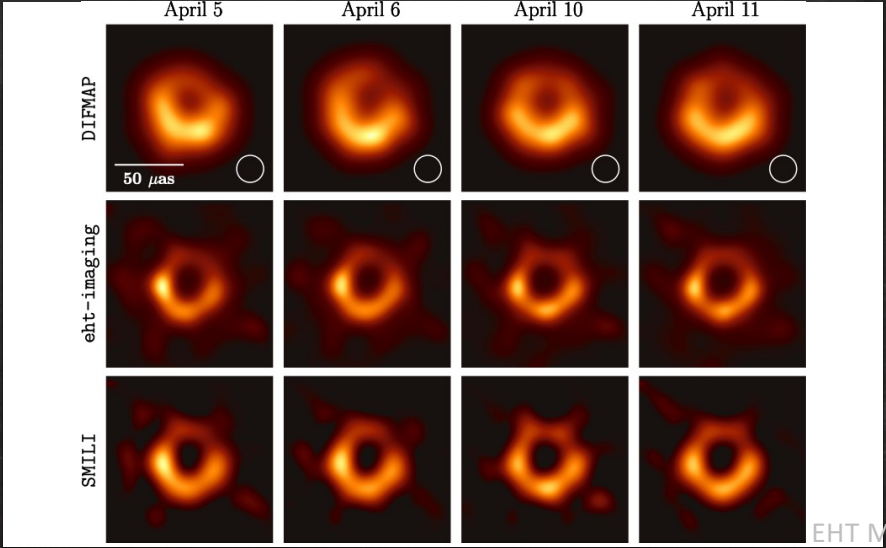
Google Cloud

Can imaging methods distinguish these? Yes they can!



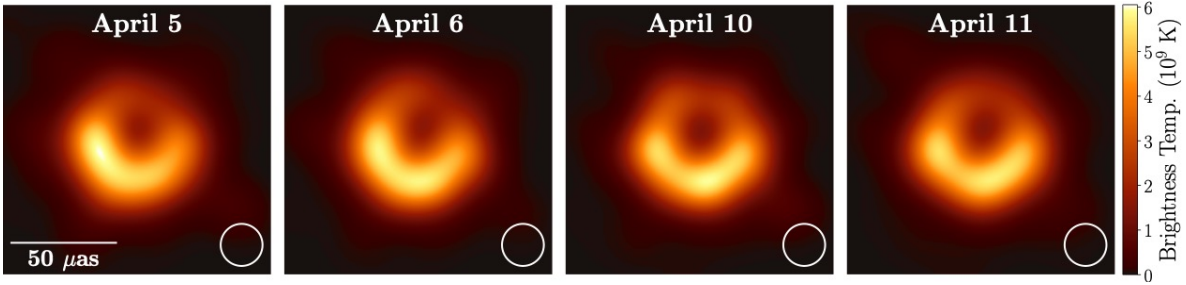
EHT M87 Paper IV

M87* results with 3 imaging methods



EHT M87 Paper IV

Averaged Images

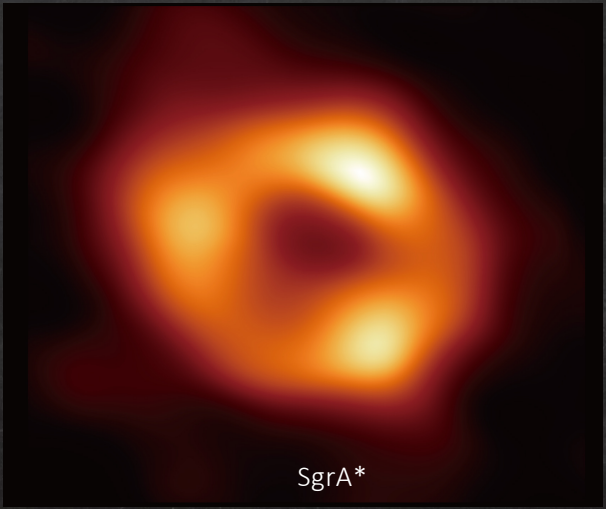


EHT M87 Paper IV

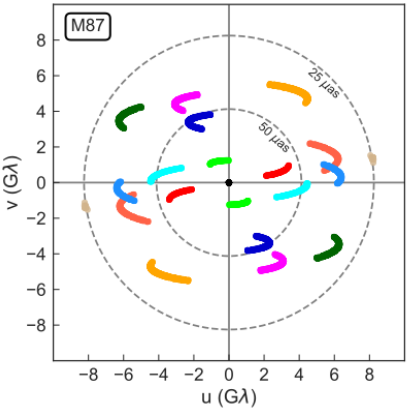
Releast M87* image

EHT Collaboration

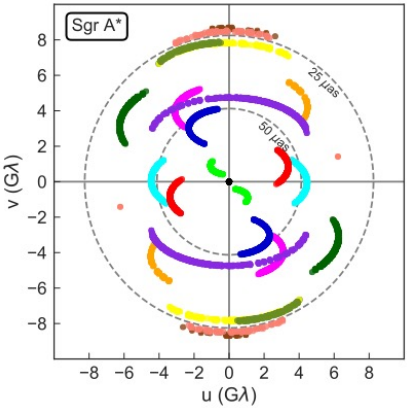
SgrA*



Radio Interferometry : Sampling Points for M87 & SgrA*

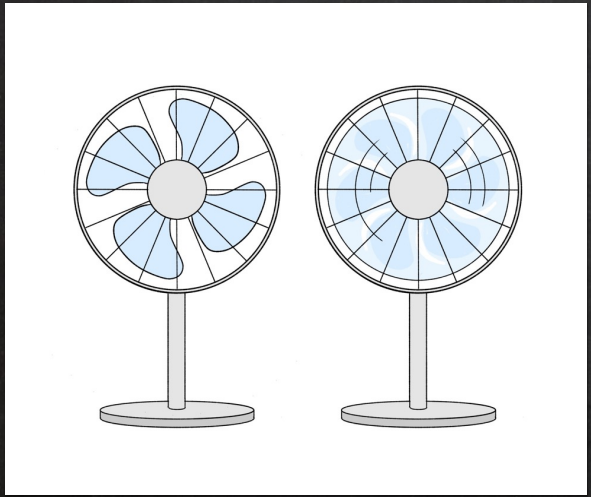


EHT M87 Paper IV



EHT SgrA* Paper III

Imaging of Sgr A* is more difficult : Time variability



Credit: Hanae Ikeda

Sgr A* is time varying.

- Rotation, Shape change

Theoretically : few ~ 30 min.

EHT observation

10 hours / night

Imaging of Sgr A* is more difficult : Scattering

Credit: NASA/JPL-Caltech

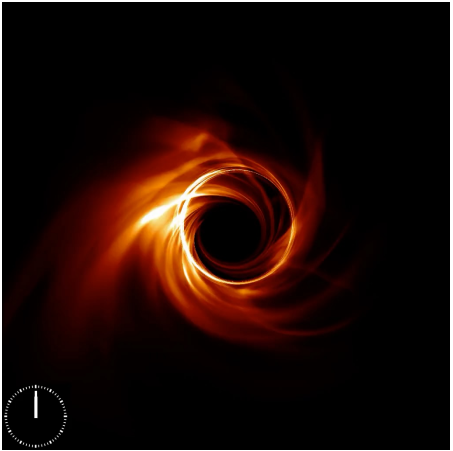
Seeing through Milkyway Galaxy

Interstellar medium ⟹ Scattering

Credit: ESO/S. Brunier

How they influence the images?

Time variability



Simulation: EHT Collaboration et al. 2022, Sgr A* Paper V
Credit: Abhishek Joshi, University of Illinois at Urbana-Champaign

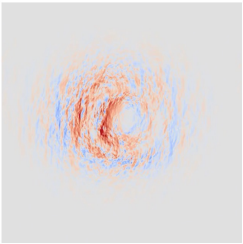
Slide by Kazu Akiyama@MIT

Dealing with Scattering : Scattering Mitigation

On-Sky Image = **Angular-broadened Image** + **Refractive Substructure**

=

+



*

Refractive substructures appear as Gaussian noises in the Fourier domain

Johnson & Gwinn 2014, Johnson & Narayan 2016, Johnson et al. 2018, Psaltis et al. 2018

Credit: Kazu Akiyama@MIT

Image methods used for Sgr A* imaging

Traditional Method

CLEAN

DIFMAP (Shepherd+97, 98, 03)

Model

General Pixelated Images
Residual Calibration Gains

Hyper Parameters

Image Assumptions

Scattering Parameters

Variability Parameters

New Imaging Methods

Regularized Maximum Likelihood (RML)

eht-imaging (Chael+16, 18)

Model

General Pixelated Images

Hyper Parameters

Image Assumptions

Scattering Parameters

Variability Parameters

SMILI (Akiyama+17a, b)

Model

General Pixelated Images
Residual Calibration Gains

Hyper Parameters

Image Assumptions

Scattering Parameters

Variability Parameters

Bayesian Imaging

THEMIS (Broderick+20a, b)

More Restrictive Model

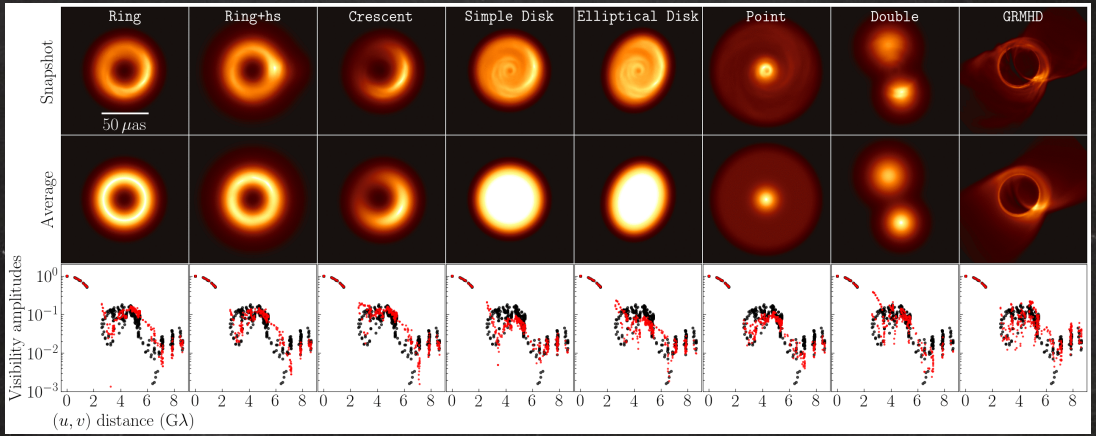
Low-resolution Pixel Images
Residual Calibration Gains
Scattering Parameters
Variability Parameters
Field of View / Grid
Orientations

Hyper parameters

Number of Image Pixels

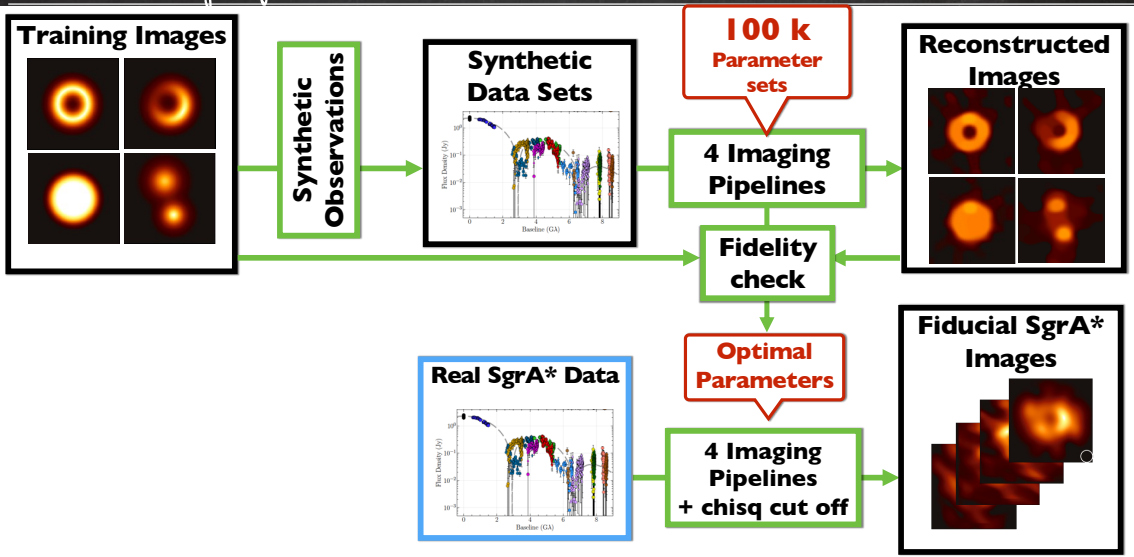
Credit: K. Akiyama, MIT

Can imaging methods distinguish these?

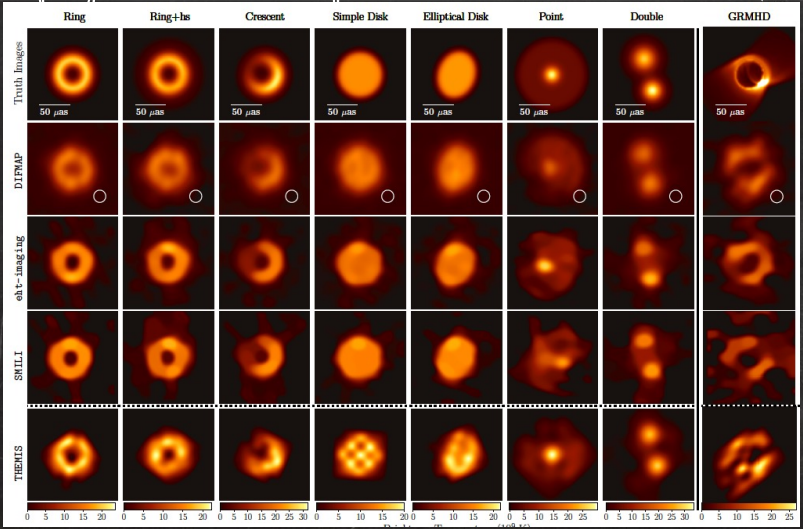


Credit: K.Moriyma, Frankfurt

Imaging Process

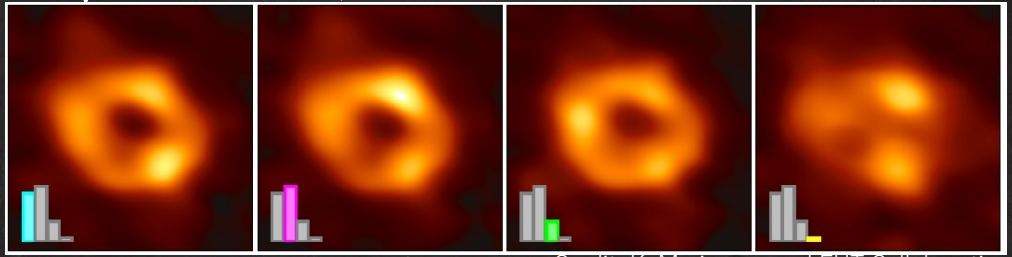


Can imaging methods distinguish these? Yes they can!



EHT SgrA* Paper III, 2022

Ring or Non-ring ?



Credit: K. Moriyama, and EHT Collaboration

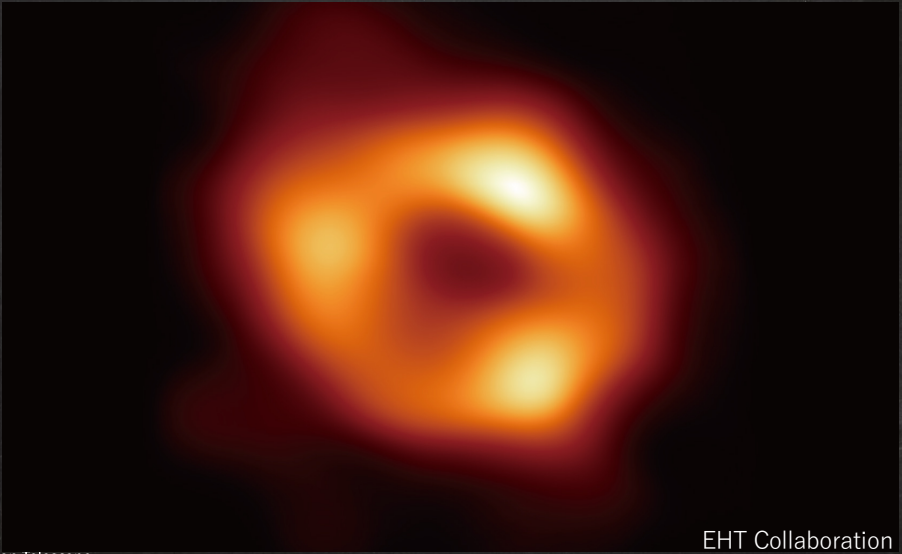
Among 10,000 reconstructions, 3 % are non-ring.

Sgr A* is non-ring? ..... Not likely - GRMHD simulations

Scattering made it non-ring? .. Not likely .. w/o scattering mitigation most of images are ring

Time variability made it no-ring .. Very Likely .. GRMHD

Release Sgr A* image



EHT Collaboration

Event Horizon Telescope

Credit: NRAO, AUI, NSF

- Observation

April, 2018

7 locations

9 telescopes

Event Horizon Telescope

Credit: Thalia Traianou

- Observation

April, 2021, 2022

9 locations

11 telescopes

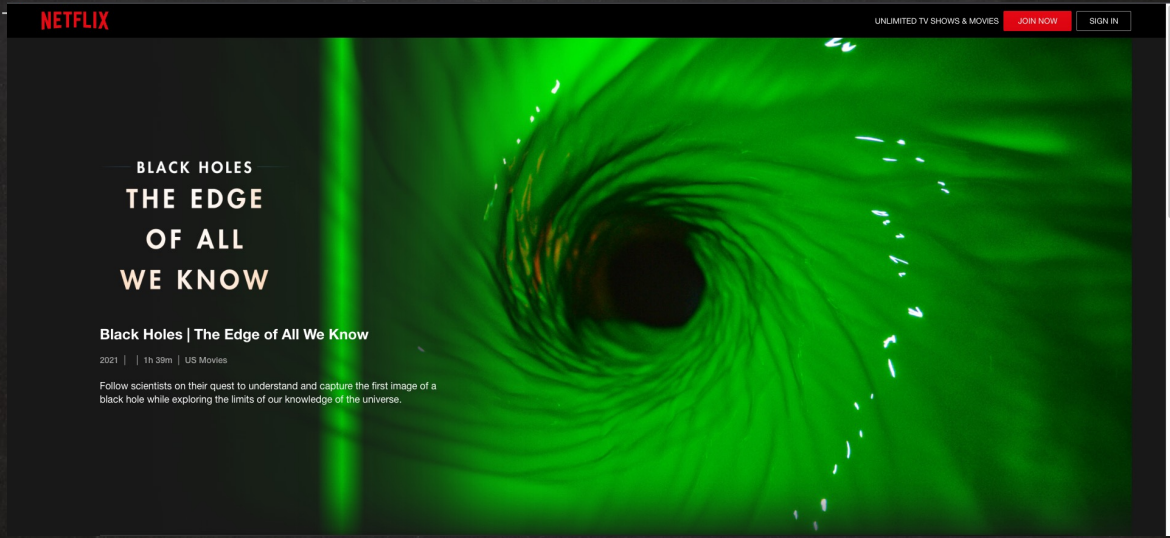
Conclusion

Data Science is getting more important for Astronomy / Physics (Biology, Medical Science)

Discussion, Respect, ---- important for collaboration.

Setting a "good" goal is important.

More data science in the future.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