Imaging black holes with the EHT:
how does it complement studies of strong gravity (1)

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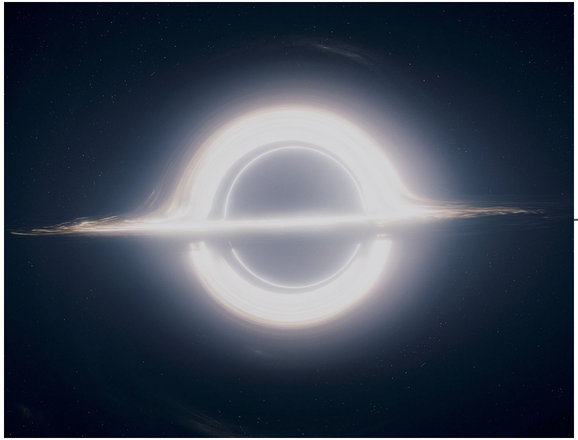
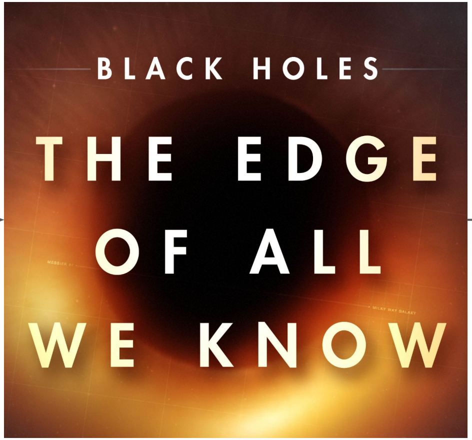
Acknowledgements: S. Issaoun, A. Chael, L. Medeiros, and the EHTC for presentation materials

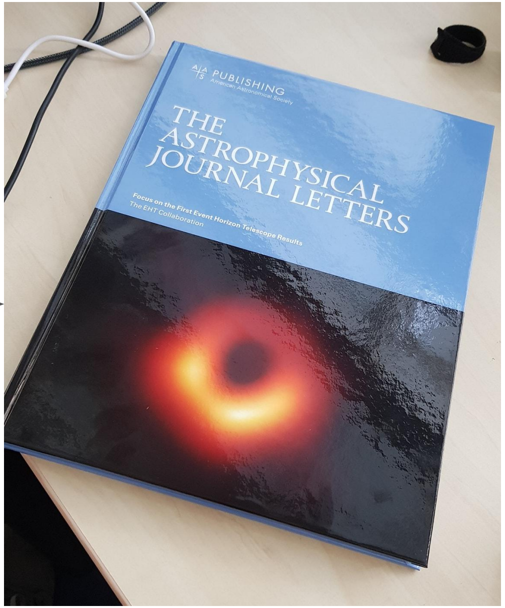
Main goal of this lecture



A black hole in an SF movie
(~5 min)



A scientific documentary
(~1 hr; available on Netflix)



The real EHT (>months)

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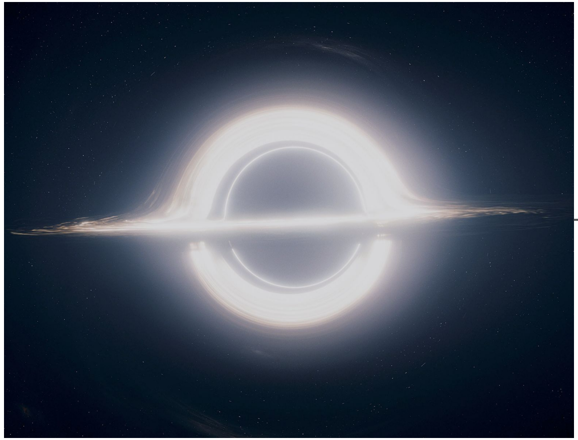

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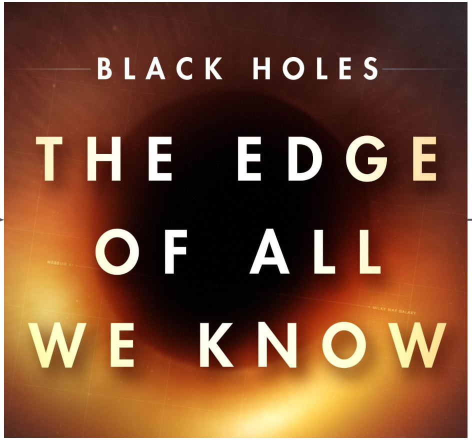

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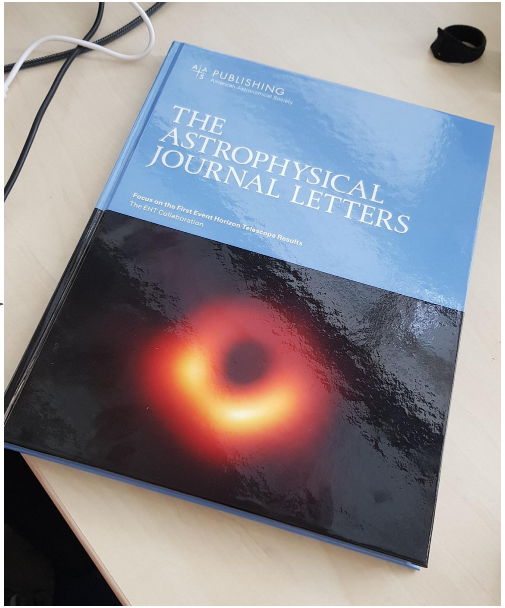


The real EHT (>months)

Where we could hopefully arrive at after this lecture

Outline

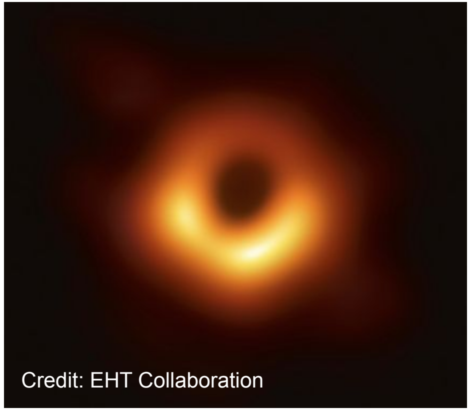
- **Intro -- Tests of GR, Supermassive black holes (SMBH), and VLBI/EHT**
- **Basics of radio interferometry and EHT data processing**
- Testing GR with the EHT image of M87*
- Astrophysics of M87(*) and numerical simulations
- Ongoing studies with/relevant to the EHT
- (Time permits) long-term future perspectives

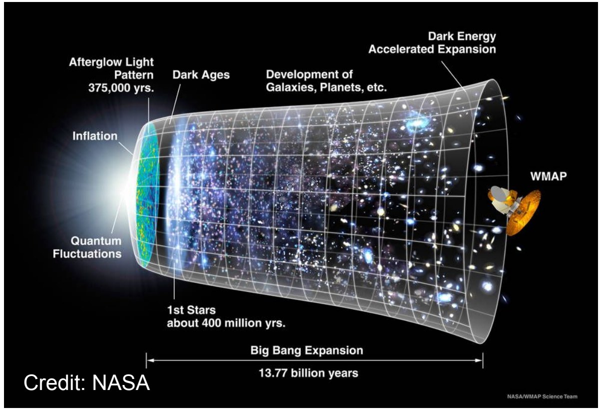
Introduction

GR, SMBH, and VLBI/EHT

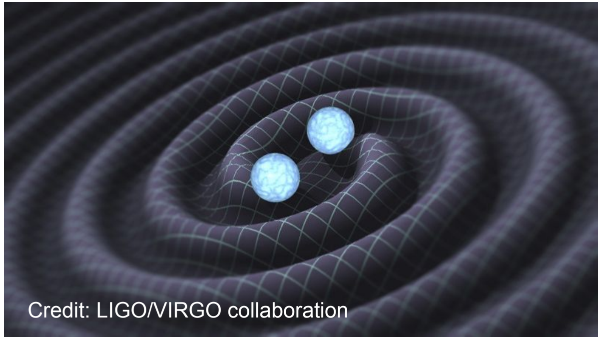
General relativity (GR) -- a very successful theory

- Describing space-time as curvature due to gravity, instead of a steady and stationary background
  - Becomes unavoidable when $GM/Rc^2 \sim 1$. In Astronomy:
    - Compact objects; White dwarfs, Neutron stars, Black holes, ...
    - Cosmology (the Universe)
    - Gravitational waves


Credit: EHT Collaboration



Credit: NASA


Credit: LIGO/VIRGO collaboration

Serious challenges still remain

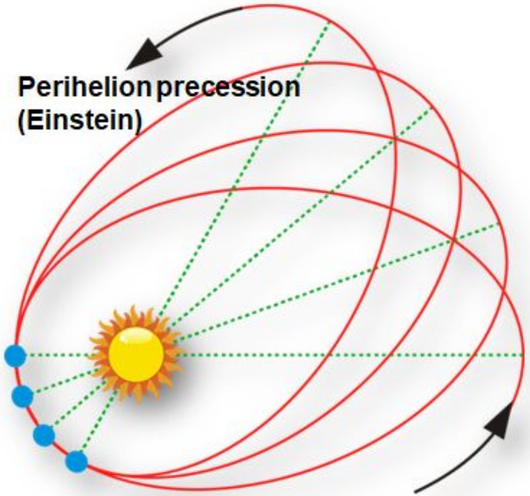
- Although most successful, GR still has challenges
  - On small scales where quantum physics matters (e.g., existence of event horizon, singularity, …)
  - Cosmological problems -- dark matter, dark energy, recent Hubble tension, …
- Many (*many!*) alternative theories exist (see right)
- New observational tests always required

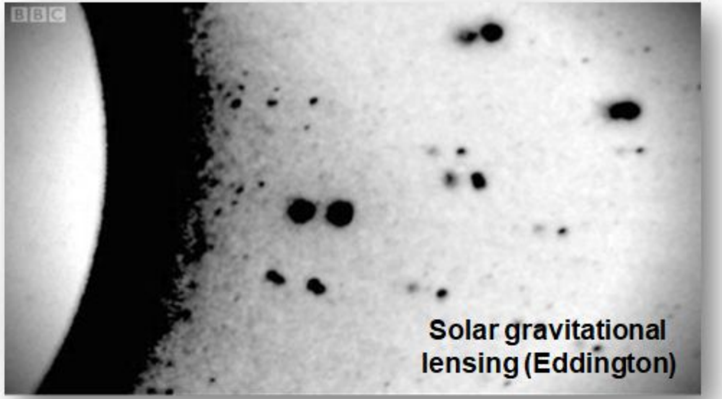
Theories from 1917 to the 1980s.

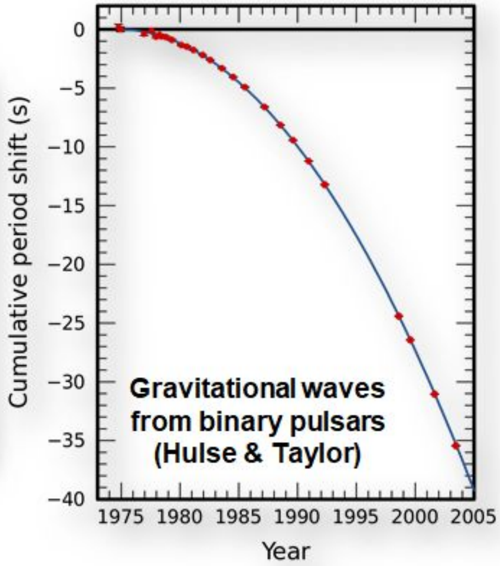
Publication year(s)	Author(s)	Theory name	Theory type
1922[5]	Alfred North Whitehead	Whitehead's theory of gravitation	Quasilinear
1922,[13] 1923[14]	Élie Cartan	Einstein–Cartan theory	Non-metric
1939[15]	Markus Fierz, Wolfgang Pauli		
1943[16]	George David Birkhoff		
1948[17]	Edward Arthur Milne	Kinematic Relativity	
1948[18]	Yves Thiry		
1954[19][20]	Achilles Papapetrou		Scalar field
1953[21]	Dudley E. Littlewood		Scalar field
1955[22]	Pascual Jordan		
1956[23]	Otto Bergmann		Scalar field
1957[24][25]	Frederik Belinfante, James C. Swihart		
1958,[26] 1973[27]	Huseyin Yilmaz	Yilmaz theory of gravitation	
1961[7]	Carl H. Brans, Robert H. Dicke	Brans–Dicke theory	Scalar-tensor
1960,[28] 1965[29]	Gerald James Whitrow, G. E. Morduch		Scalar field
1966[30]	Paul Kustaanheimo [de]		
1967[31]	Paul Kustaanheimo [de], V. S. Nuotio		
1968[32]	Stanley Deser, B. E. Laurent		Quasilinear
1968[33]	C. Page, B. O. J. Tupper		Scalar field
1968[34]	Peter Bergmann		Scalar-tensor
1970[35]	C. G. Bollini, J. J. Giambiagi, J. Tiomno		Quasilinear
1970[36]	Kenneth Nordtvedt		
1970[37]	Robert V. Wagoner		Scalar-tensor
1971[38]	Nathan Rosen		Scalar field
1975[39]	Nathan Rosen		Bimetric
1972,[10] 1973[40]	Ni Wei-tou		Scalar field
1972[41]	Clifford Martin Will, Kenneth Nordtvedt		Vector-tensor
1973[42]	Ronald Hellings, Kenneth Nordtvedt		Vector-tensor
1973[43]	Alan Lightman, David L. Lee		Scalar field
1974[44]	David L. Lee, Alan Lightman, Ni Wei-tou		
1977[45]	Jacob Bekenstein		Scalar-tensor
1978[46]	B. M. Barker		Scalar-tensor
1979[47]	P. Rastall		Bimetric

Taken from Wikipedia

(Some) classical tests of GR in the weak field regime





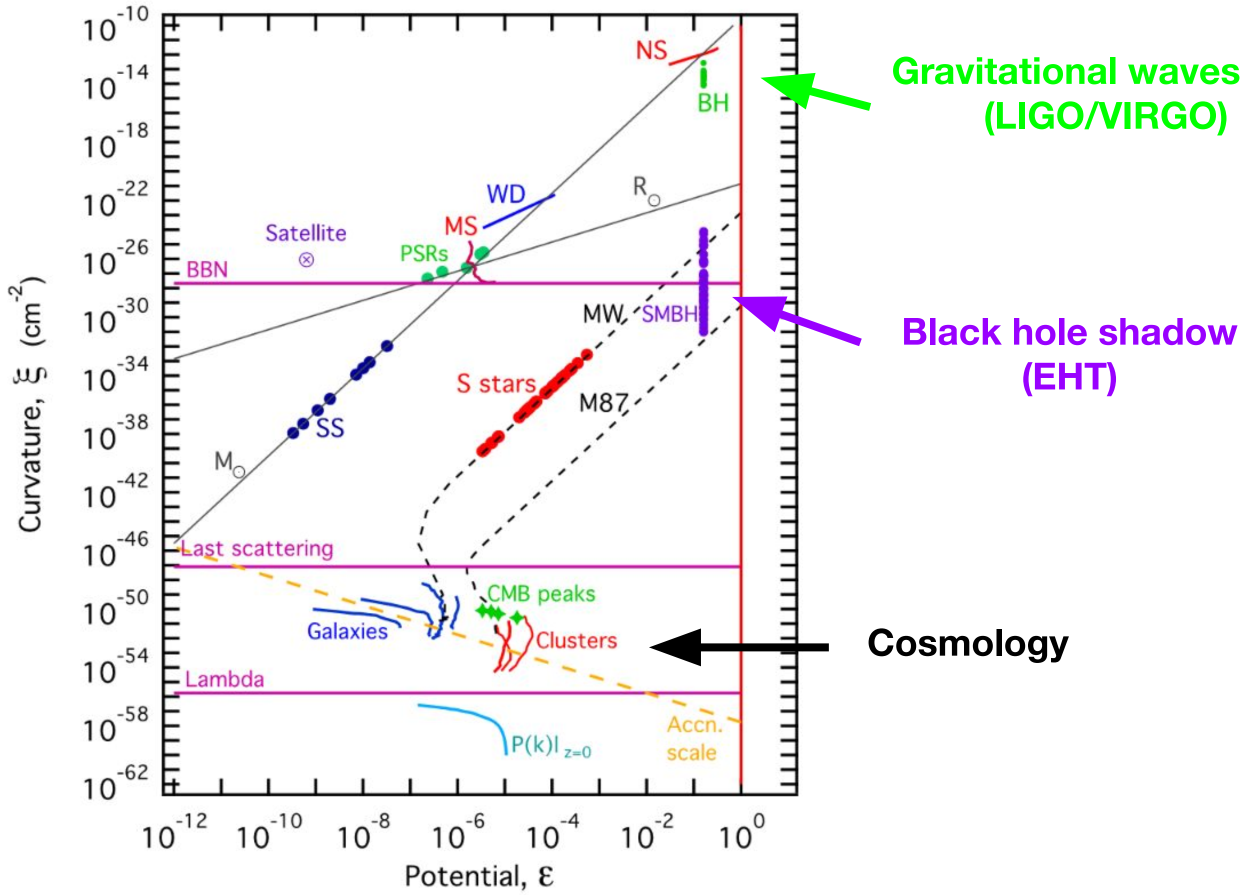


- GR predictions excellently matching observations (see also [here] for more tests)
- However, these tests do not probe well the “strong” field regime

Landscape of modern tests of GR

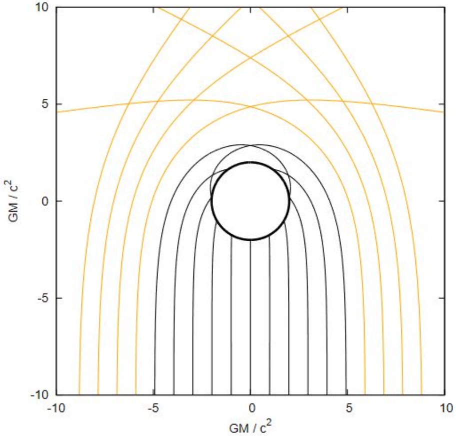
$$\epsilon \equiv \frac{GM}{rc^2}$$

$$\xi = \left(R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}\right)^{1/2} = \sqrt{48}\,\frac{GM}{r^3c^2}.$$



Baker+16

Black holes cast shadows of light



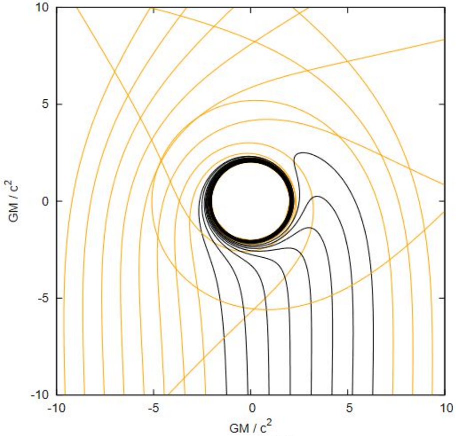
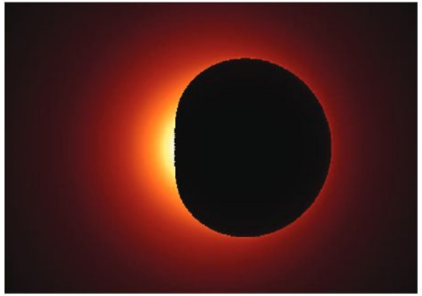
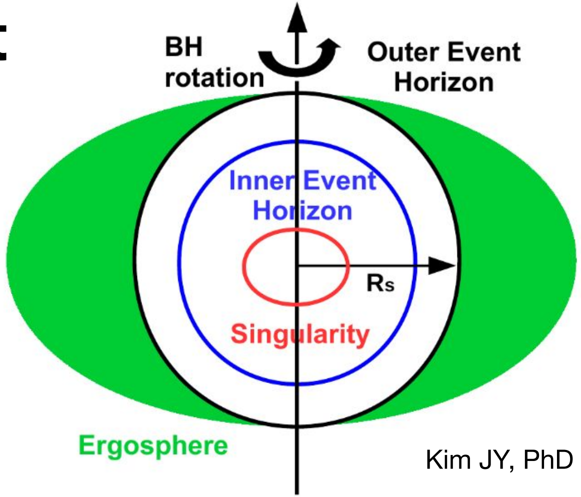


Figure from Asada+17



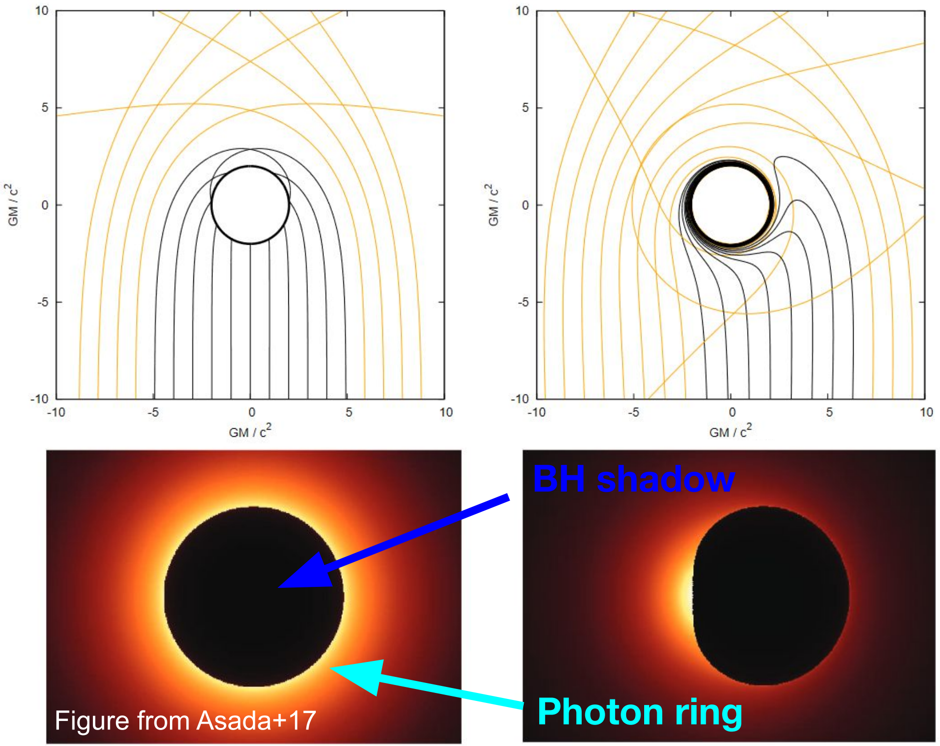
Non-spinning case (*a*=0) **Maximally spinning case (*a*~1)**



Kim JY, PhD thesis

- Photon trapping due to strongly curved spacetime around black hole
  - the **BH mass** dominates the size
- The exact shape can depend on **BH spin** (Bardeen 1973), but not dominant
- **Light source** also matters, but not dominant for the presence of photon ring (next lecture)

Black holes cast shadows of light



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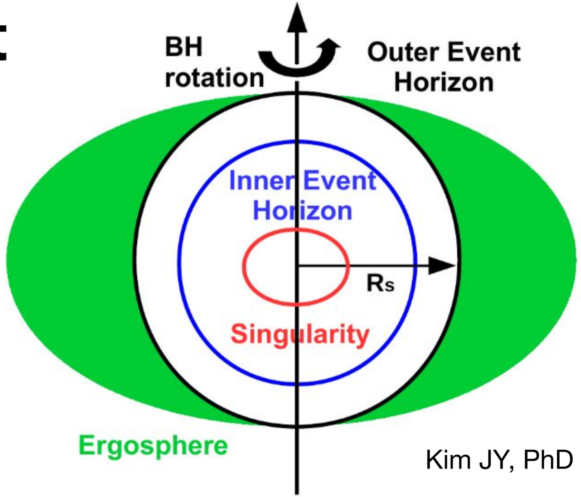

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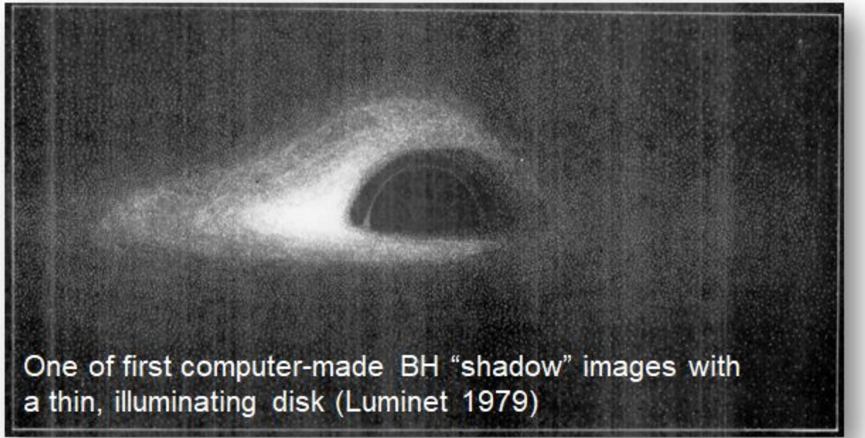
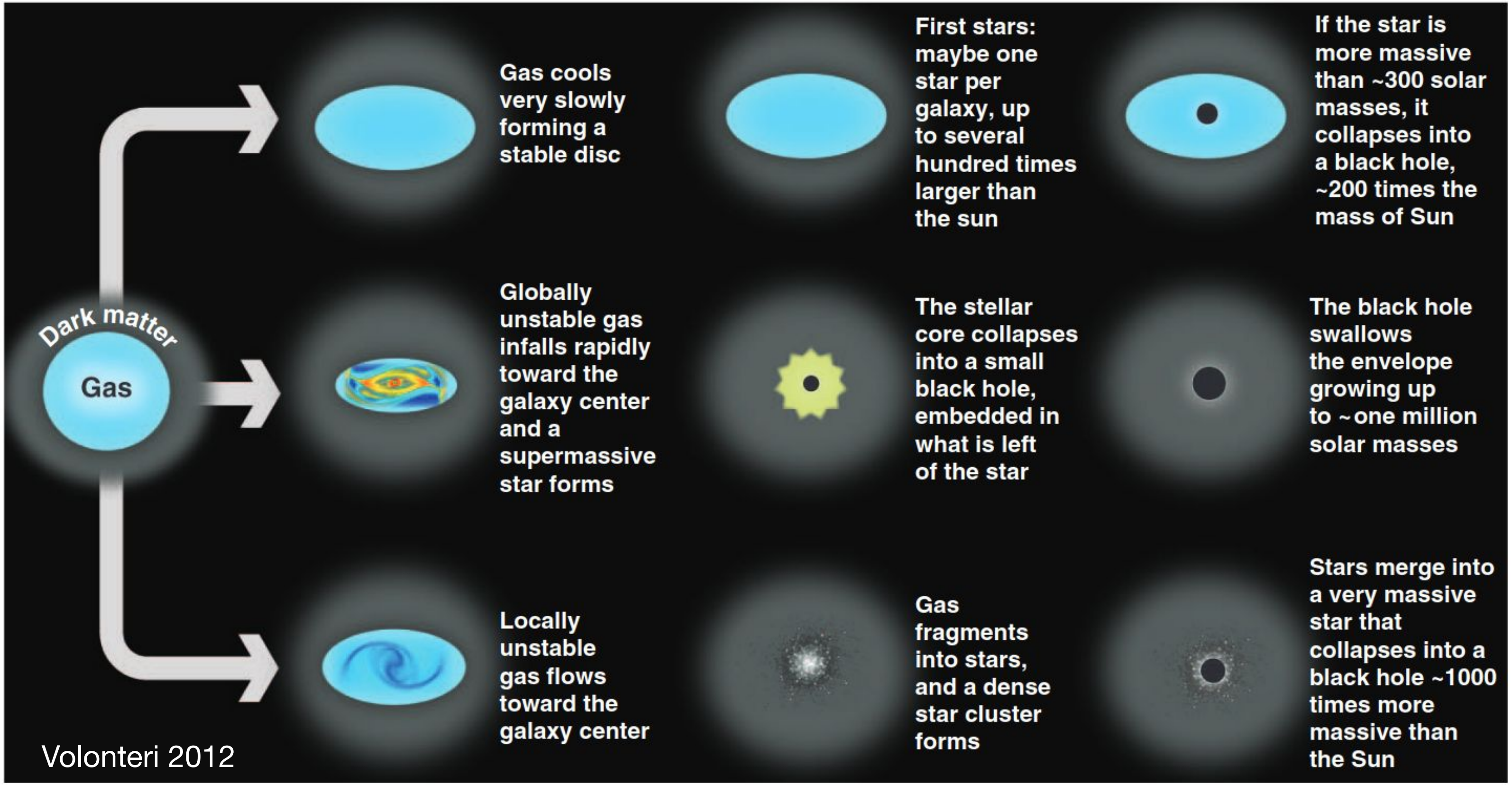
Early studies of BH shadow (theory, selective)



One of first computer-made BH "shadow" images with a thin, illuminating disk (Luminet 1979)

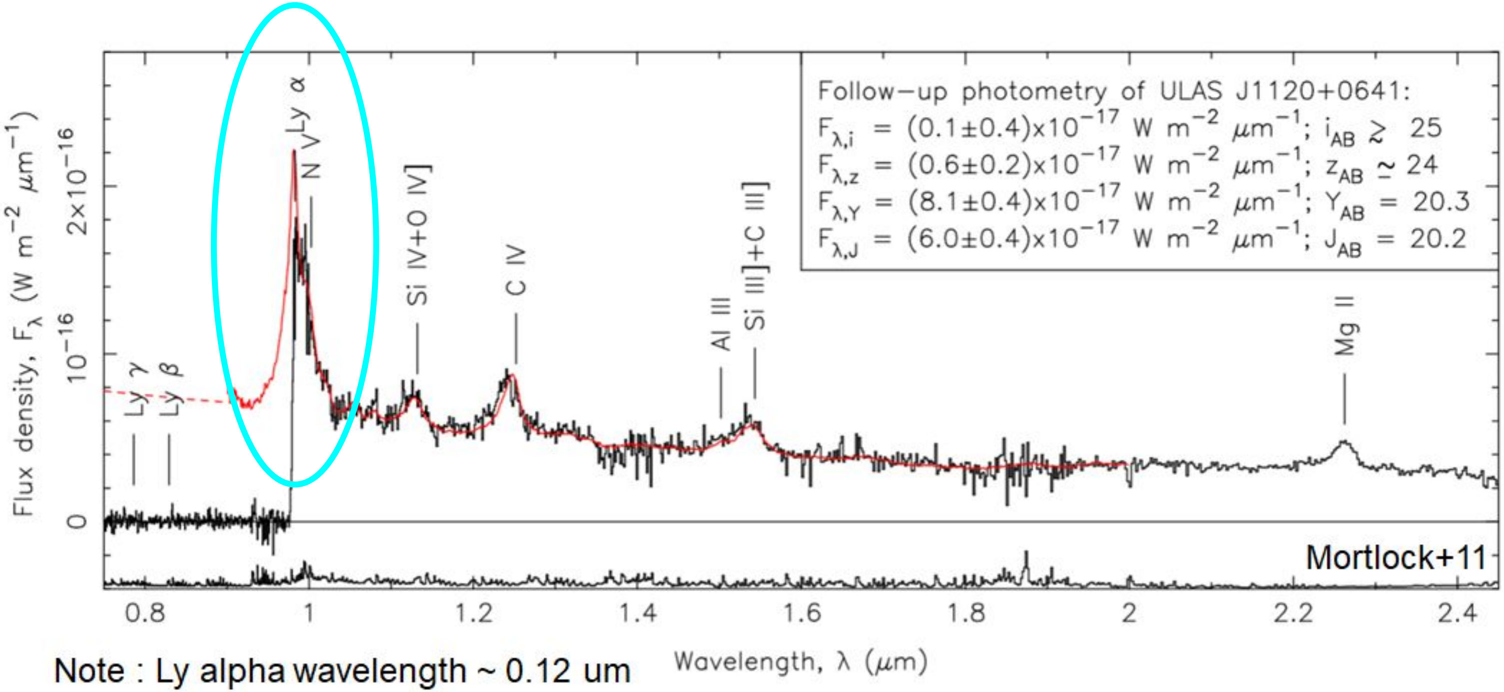
- Schwarzschild solution (Schwarzschild 1916)
- Kerr solution (Kerr 1963)
- Wheeler coins the term "Black Hole" (1967)
- Initiating studies of gravitational lensing by BH (Cunningham & Bardeen 1972; Bardeen 1973)
- First simulations of a thin disk around non-spinning BH (Luminet 1979)
- First simulations of a thin disk around spinning BH (Viergutz 1993)
- First simulations of astrophysical SMBH image for Sgr A* (Falcke et al. 2001)

Origin of astrophysical “supermassive” black holes (SMBHs) (10^6 -- 10^9 Msun)



(See also lectures by Minjin Kim)

Evidence for the presence of SMBHs in the early Universe

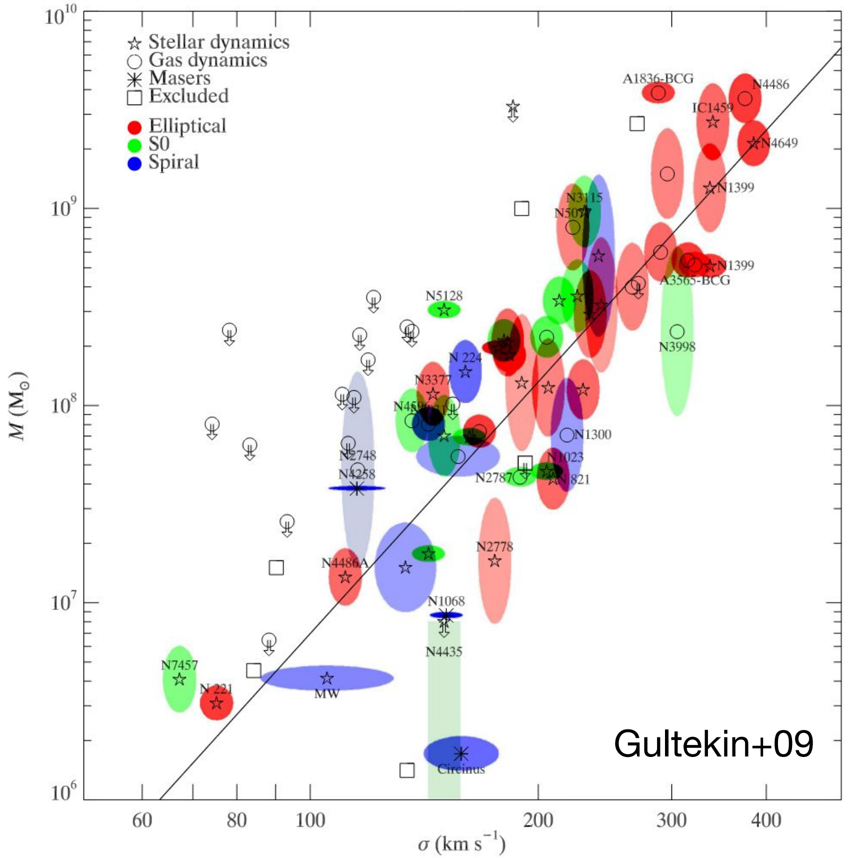


Note : Ly alpha wavelength ~ 0.12 um

Redshift ~ 7 (0.7 billion yr; **less than 6% of the age of the Universe**),
inferred SMBH mass ~ 10^9 Msun.

(See also lectures by Minjin Kim)

Evidence for the evolution of SMBHs through cosmic time



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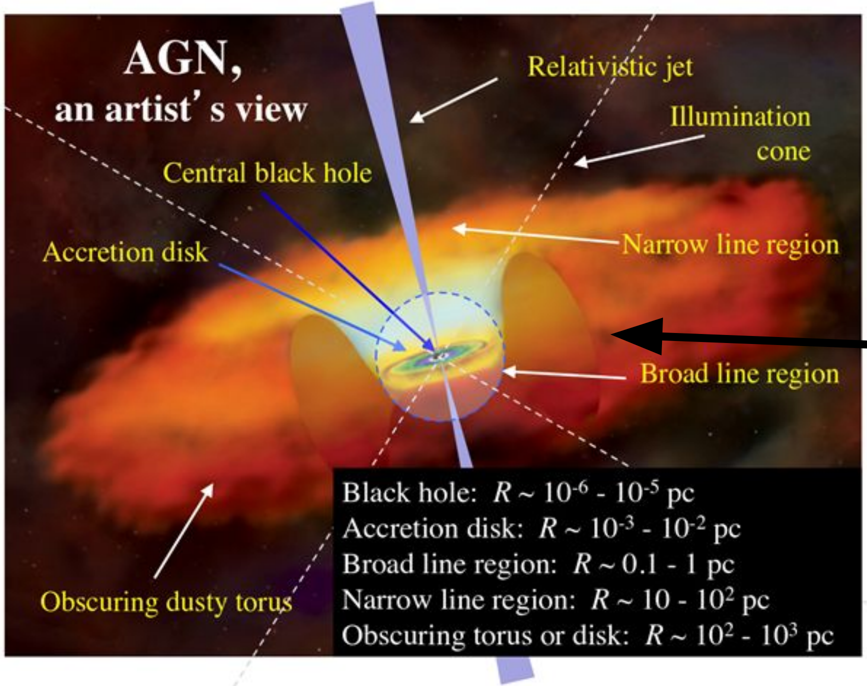
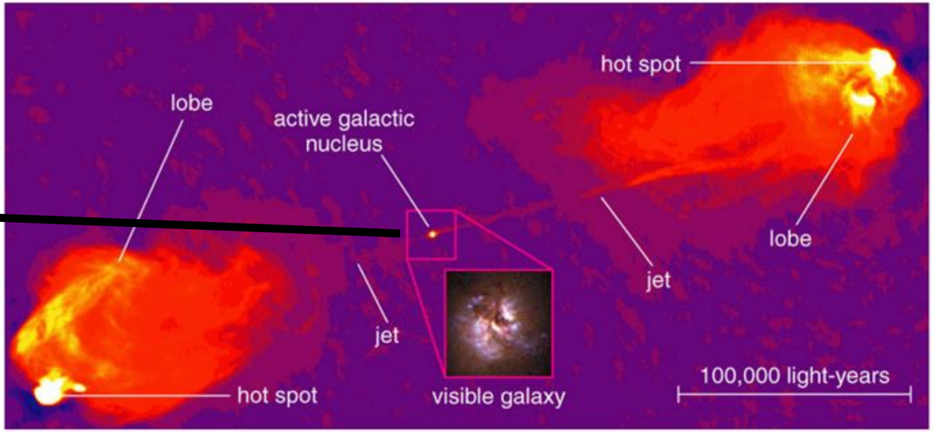
Anatomy of an astrophysical, accreting SMBH



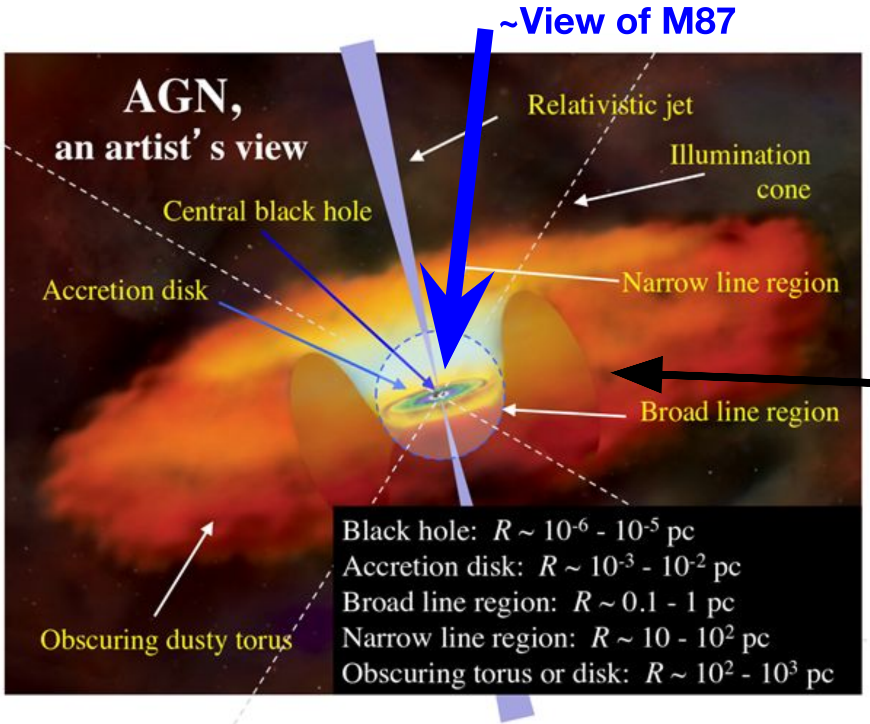
Urry & Padovani 1995



There are no black holes in "vacuum"; astrophysical SMBHs are surrounded by complex environments

(See also lectures by Minjin Kim)

Anatomy of an astrophysical, accreting SMBH



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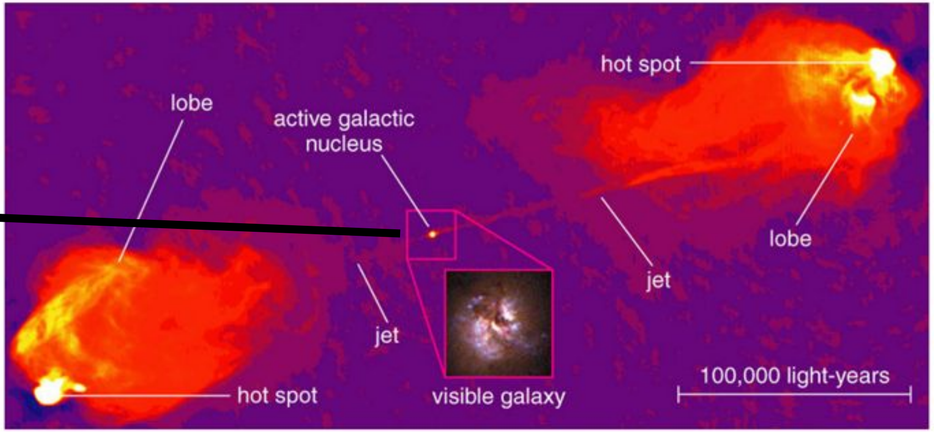

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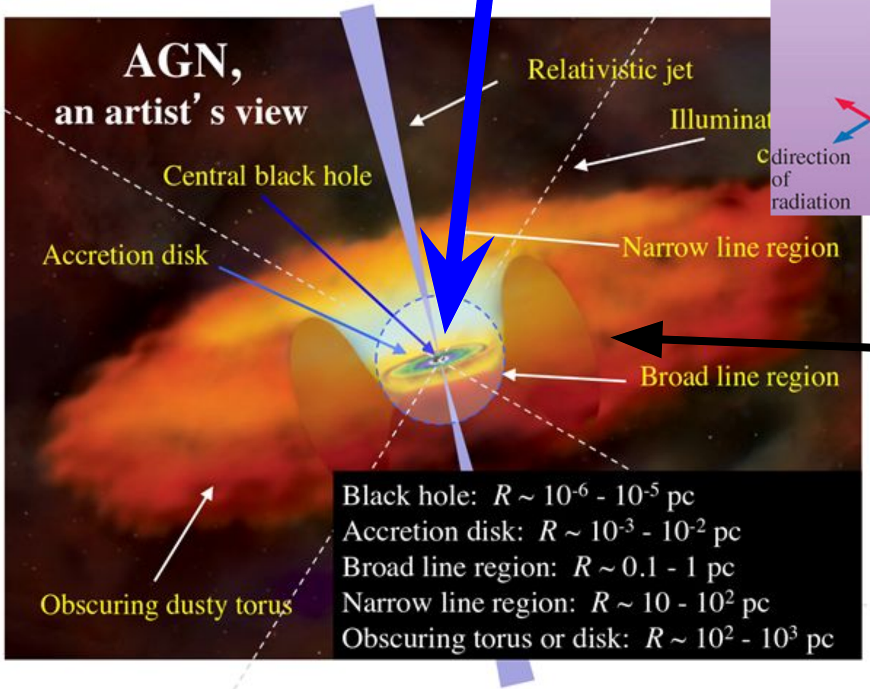
Anatomy of an ast… , accreting SMBH

~View of M87



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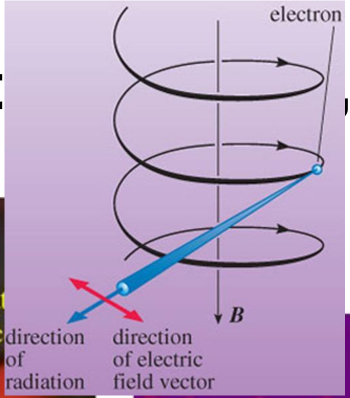
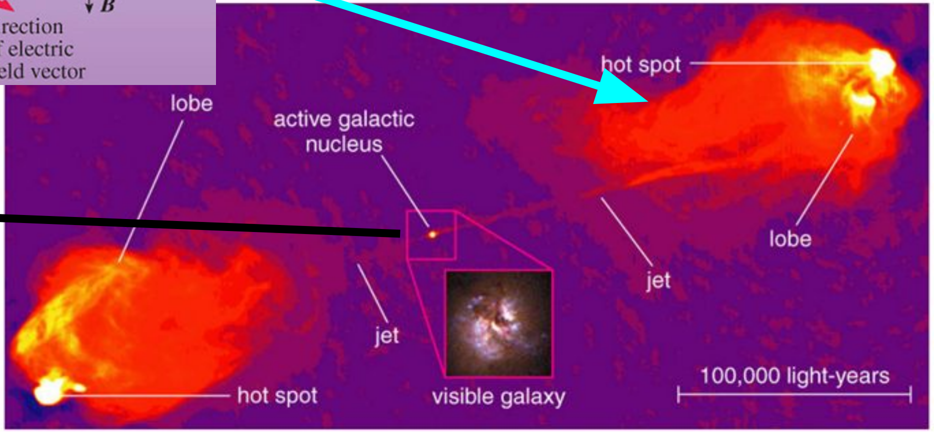


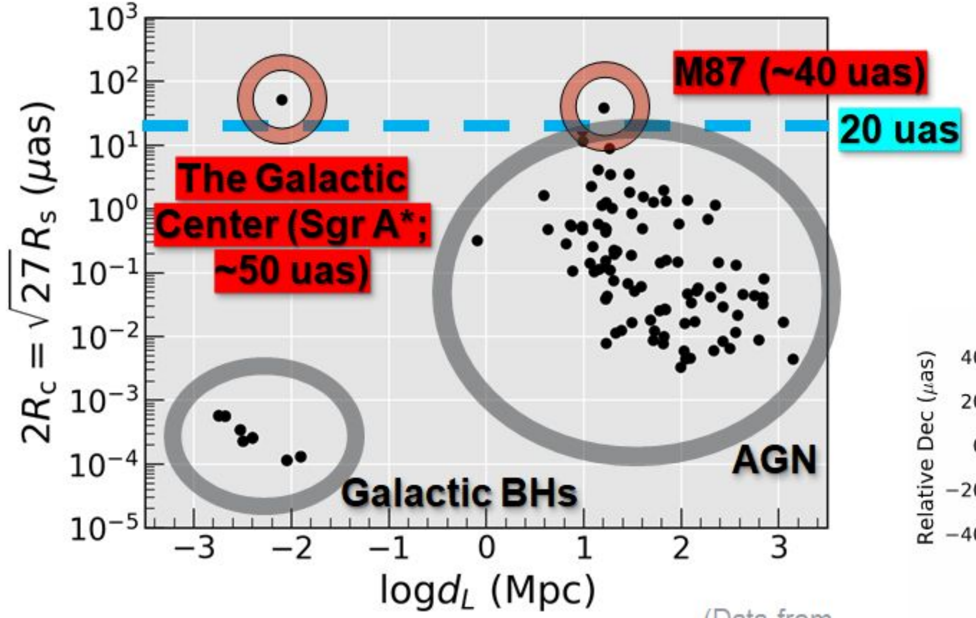
Synchrotron radiation primarily at radio frequencies (Credit: Open University)



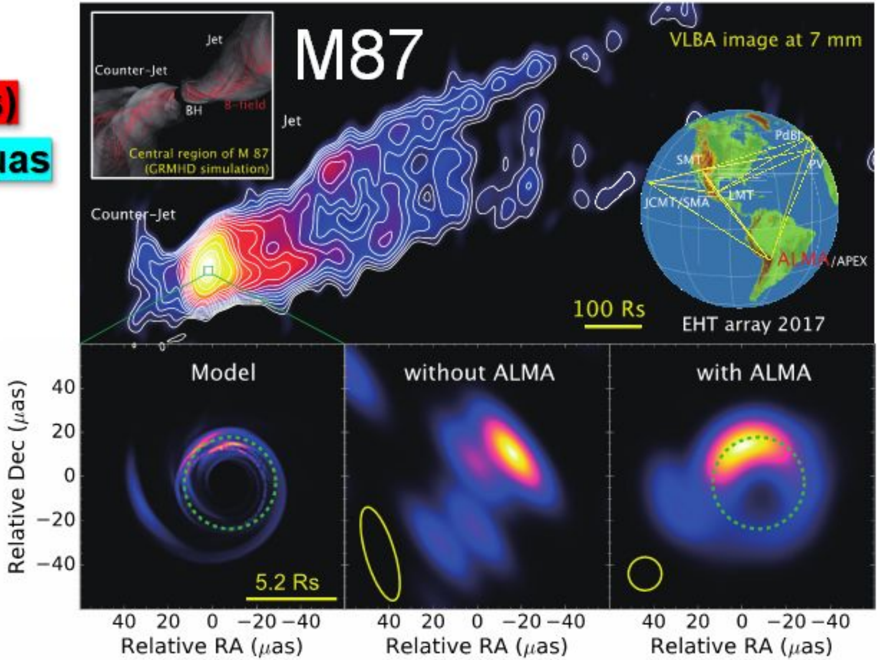
There are no black holes in "vacuum"; astrophysical SMBHs are surrounded by complex environments

(See also lectures by Minjin Kim)

Imaging a SMBH: calculating the apparent angular sizes of the photon capture diameter



(Data from Merloni+03)



Prediction for the EHT 2017 M87 (from ALMA Cy 4 proposal; credit EHTC)

- 1 arcsec=1/60 deg
- 1 milliarcsec (1mas) = 1e3 arcsec
- 1 micro-arcsec (1 uas) = 1e3 mas

How to achieve a very high angular resolution?

- Fundamental angular resolution in optics:

$$\theta \sim \frac{\lambda}{D}$$

where

λ **: observing wavelength**

D **: aperture size**

- To achieve very high angular resolution:
  - As short wavelength as possible (radio? NIR? optical? X-ray?)
  - As large aperture as possible (few meters? Kilometers? Earth-size?)
- **Technical limitations exist**; need to find an optimal point

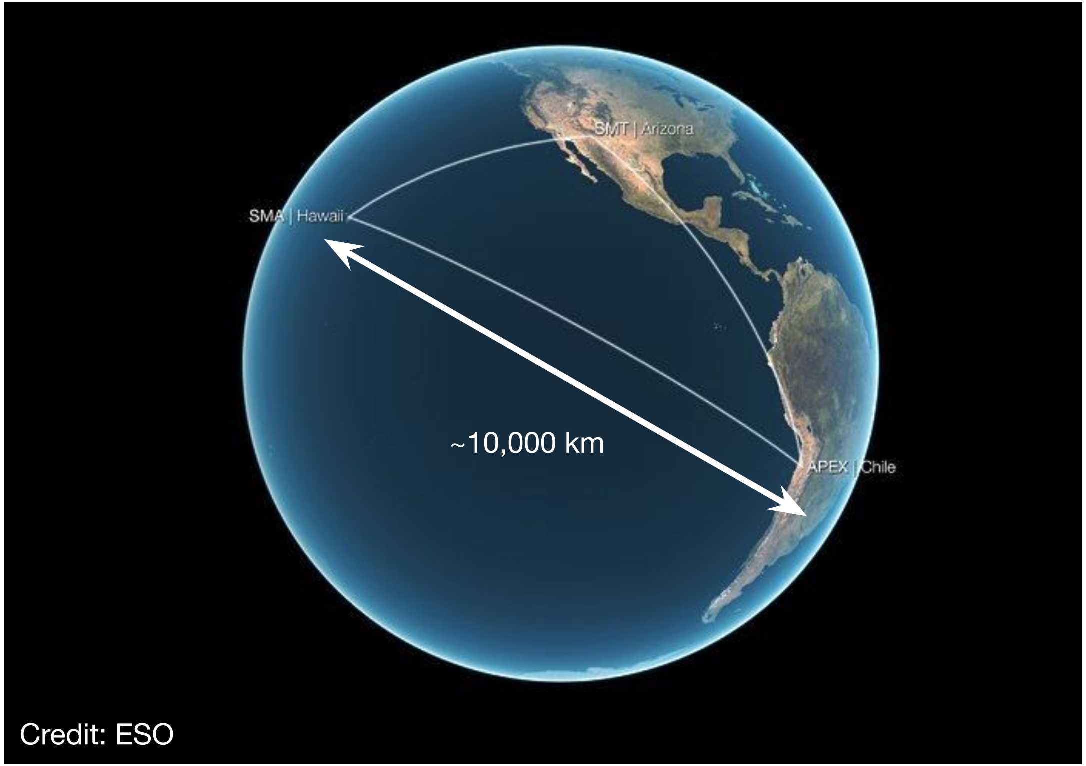
Also need to see through the opacity barrier

GRMHD+GRRT
simulation
(next lecture)

Observing EM freq.:
86 GHz → 230 GHz

Video credit:
CK Chan

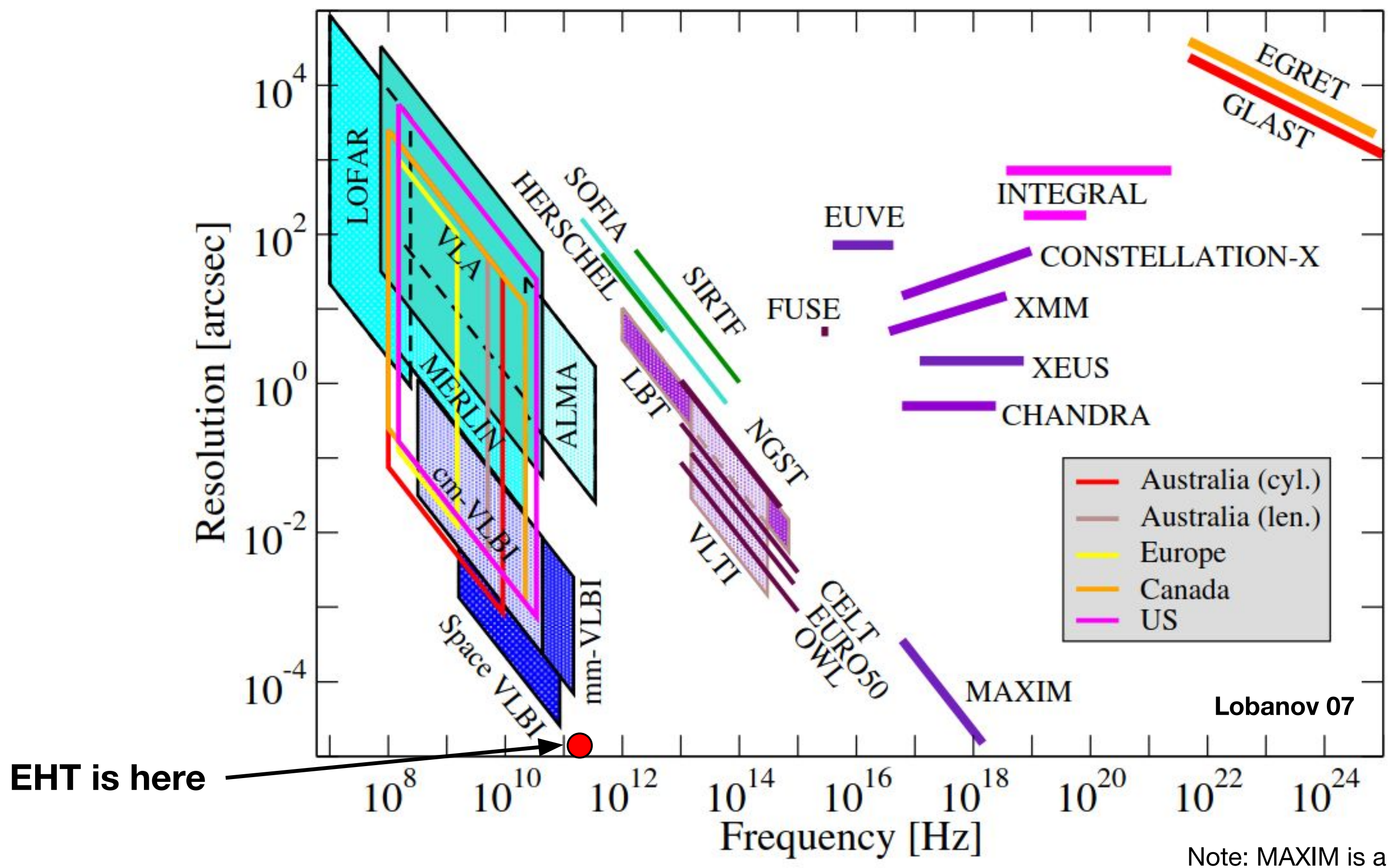
Optimal point: Earth-sized synthetic aperture observing at 1.3 mm wavelength



$$\theta \sim \frac{\lambda}{D} = \frac{1.3mm}{10^4 km} \sim 10^{-10}\mathrm{rad}$$

~ 20 micro-arcsec (uas);
Possible to image M87 and Sgr A*!

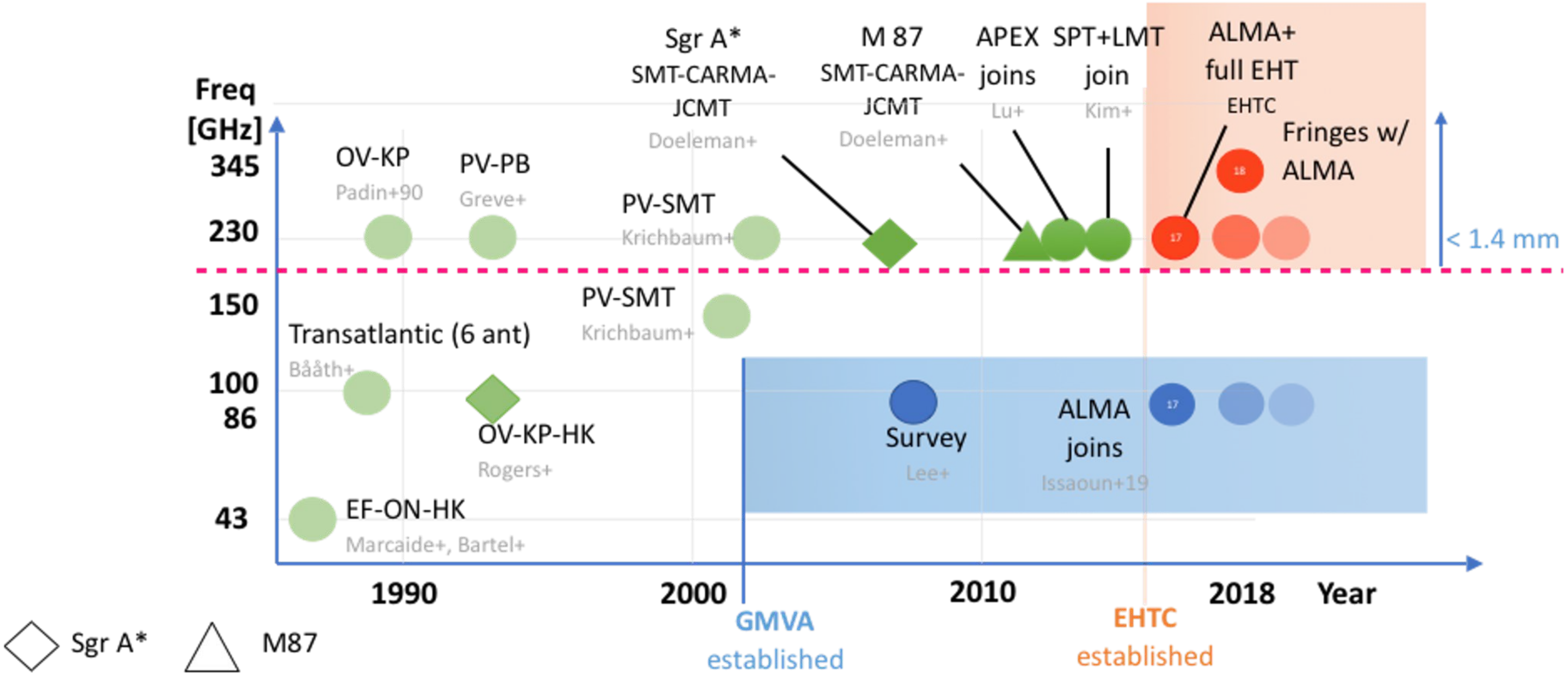
Very Long Baseline Interferometry (VLBI): microscope to dissect the Universe



- 1 arcsec=1/60 deg
- 1 milliarcsec (1mas) = 1e3 arcsec
- 1 micro-arcsec (1 uas) = 1e3 mas
- EHT resolution: ~20 uas

Note: MAXIM is a conceptual X-ray interferometer

Developing mm-VLBI over >30 years

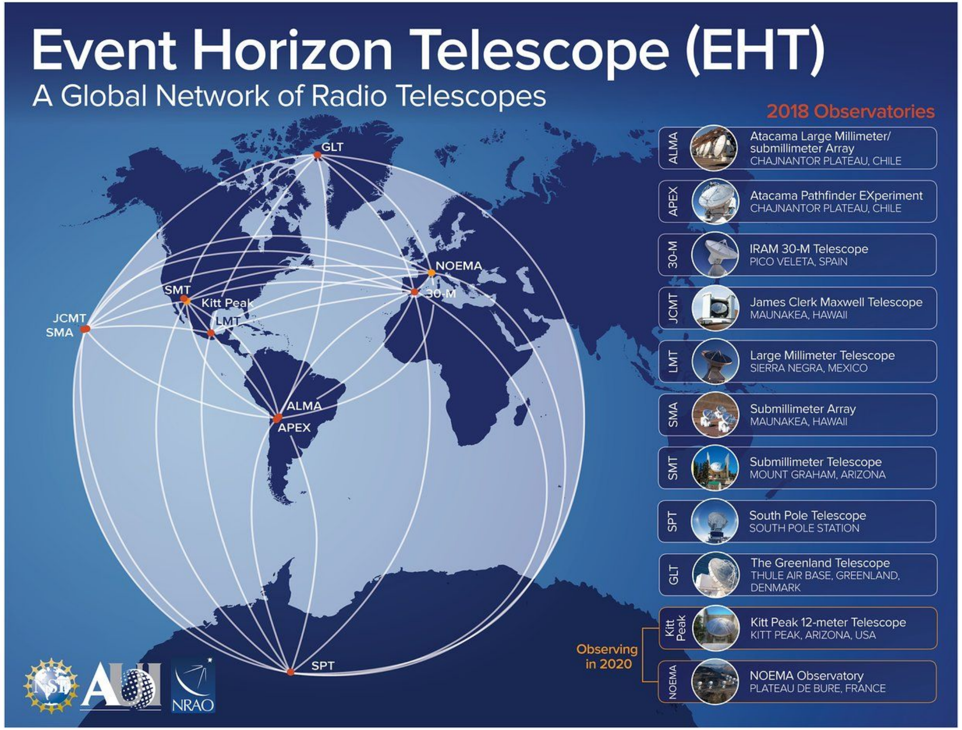


Observatories:

APEX: Atacama Pathfinder Experiment (North Chile) **CARMA**: Combined Array for mm Astronomy (California) **EF: Effelsberg (MPIfR Bonn) HK:** Haystack (Massachusetts) **JCMT:** James Clerk Maxwell Telescope (Hawaii) **KP**: Kit Peak (Arizona) **LMT**: Large mm Telescope (Mexico) **ON**: Onsala (Sweden) **OV**: Owens Valley (California) **PB**: Plateau de Bure (France) **PV**: Pico Veleta (Spain) **SMT**: Submm Telescope (Arizona) **SPT**: South Pole Telescope

Credit: E. Ros

The Event Horizon Telescope (EHT)



- A network of 8 telescopes (+1 in 2018, +3 in 2021) observing at 230 GHz (and higher)

- **Prime science goals**
  - **Imaging black holes**
  - **Testing General Relativity**
  - **Understanding BH accretion**
  - **Understanding jet genesis**

- FYI: operated by 13 board institutes (Korea engaging as a part of the East Asian Observatory)

The Event Horizon Telescope Collaboration (EHTC)

Regular EHTC meeting, Dec 2019, Hawaii

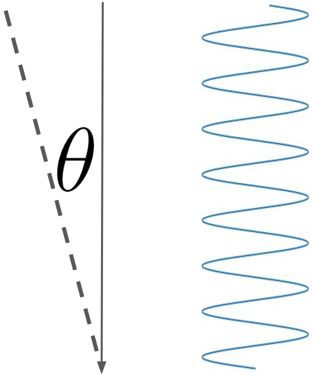
- Foundation of the formal collaboration in 2017 (the year of the first official observing run)
- >200 affiliated scientists from the world (incl. those from Korea)

Basics of radio interferometry

with EHT as an example

Let’s observe M87*: a single radio telescope

A far-field **point source** of power (P)=1 Jy at zenith



Monochromatic EM wave (30 GHz frequency; **lambda=1cm**)

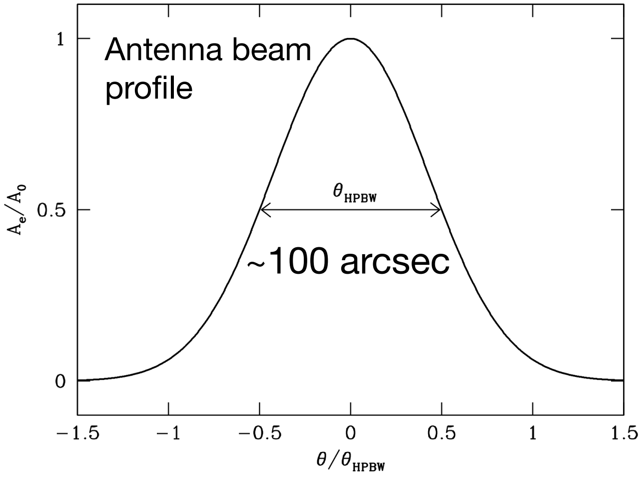
A telescope (**D=20m**)

Voltage

Square — **< >**

Picture: a Korean VLBI Network (KVN) antenna

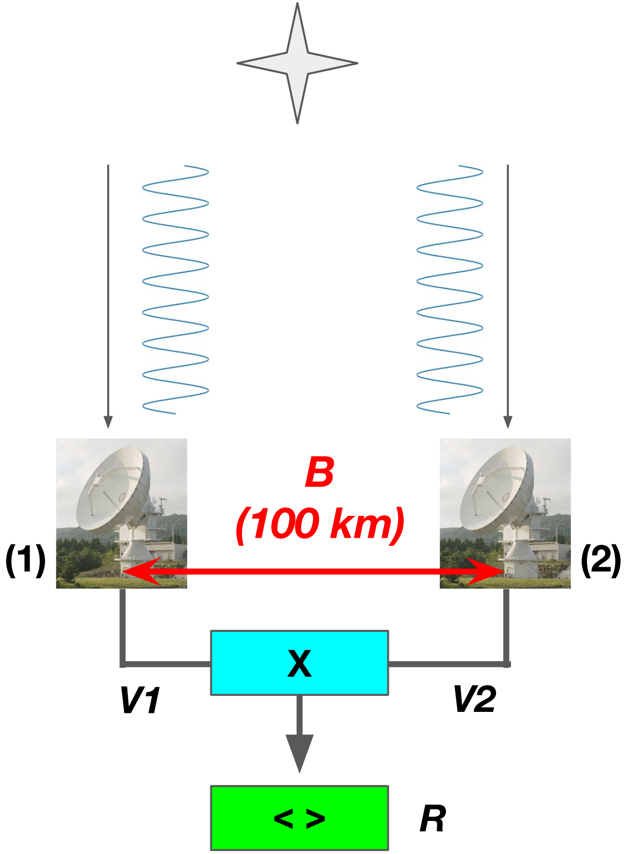
- Amplitude/power measured by the radio telescope:
  - **Voltage = *A**Cos(2**pi***nu**t)**
  - ***P*=<*V(t)*^2>=1 Jy** (with proper calibration)
- Angular resolution towards the source:
  ~ *lambda/D* ~ 5e-4 rad ~ 100 arcsec = 10^5 mas



Credit: NRAO

$$1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W \cdot m^{-2} \cdot Hz^{-1}}$$

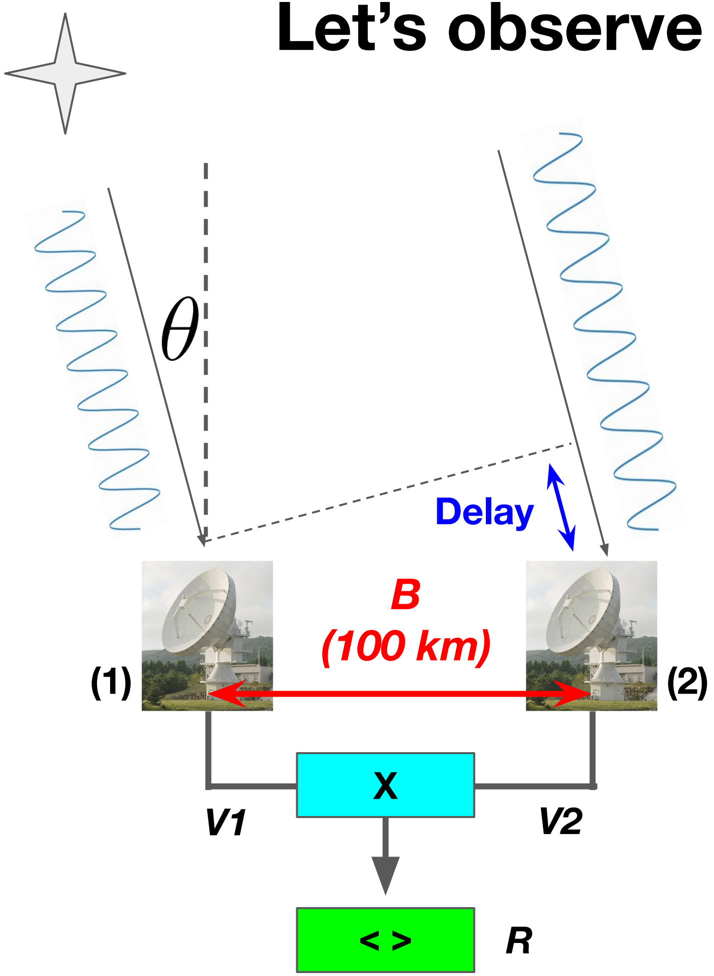
Let’s observe M87*: two separated telescopes



- Setup:
  - Two identical telescopes of D=20m
  - Observing frequency = 30 GHz (lambda=1cm)
  - **Telescope separation (baseline length) *B* = 100 km**
    - Ignore all the electronics errors and Earth’s curvature
  - **Backend: multiply voltages from the two telescopes and do time-averaging**

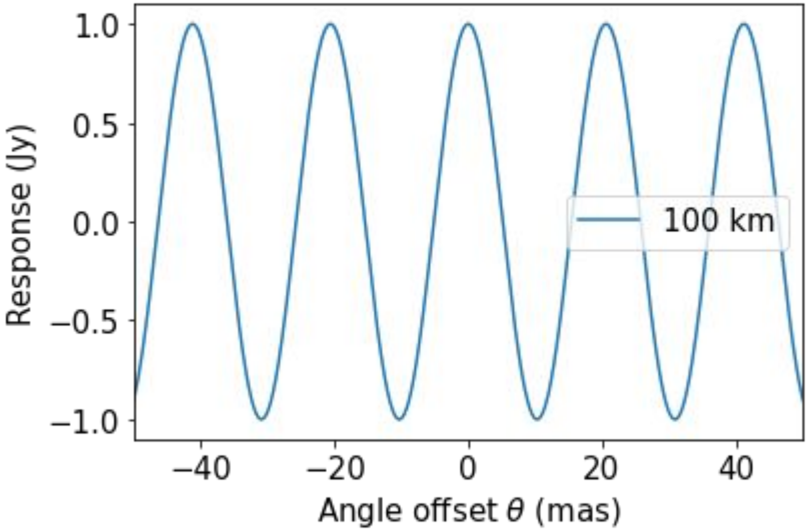
- Result:
  - ***R*=<*V1***V2*>=1 Jy** (note no delays of wave arrival timings at the two telescopes)
  - **What about the angle dependence of this response (light coming from off-axis)?**

Let’s observe M87*: small angular offsets



- **The wavefront arrives late at Telescope 2!**
  - This delay is a function of the angular offset from the zenith
  - Also causing constructive/destructive interference

- **With a bit of geometry and calculations...**



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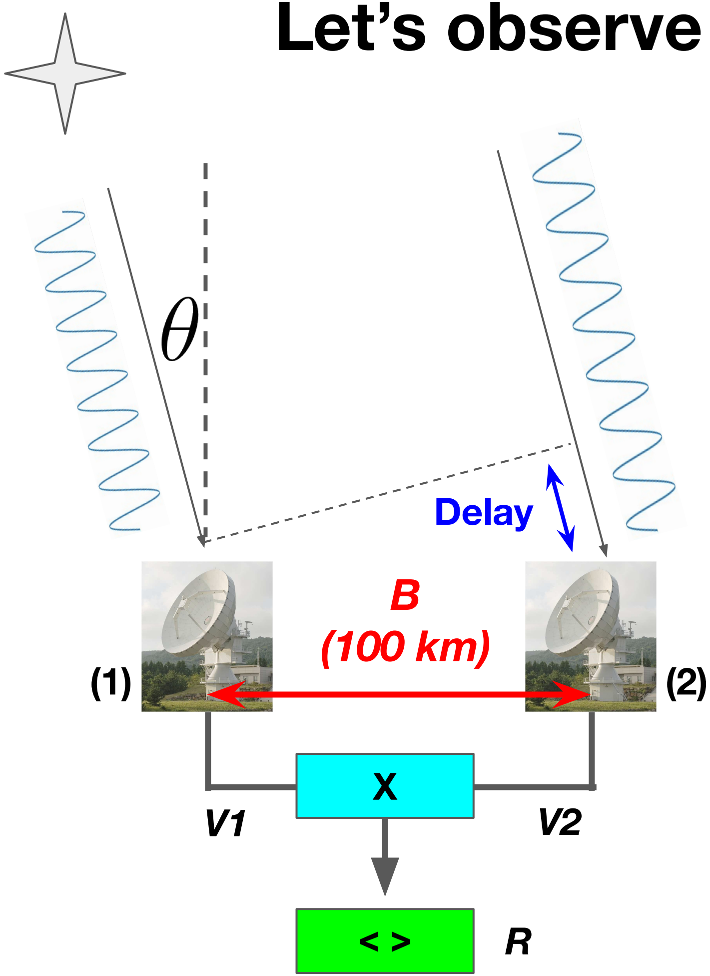
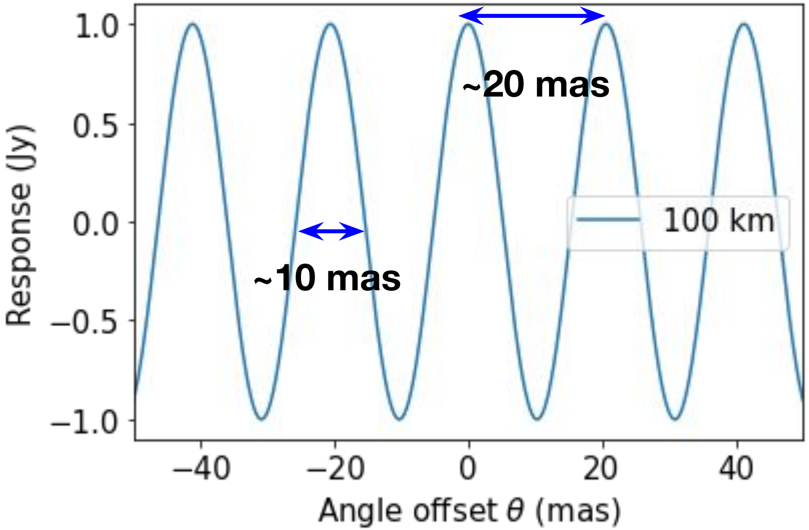
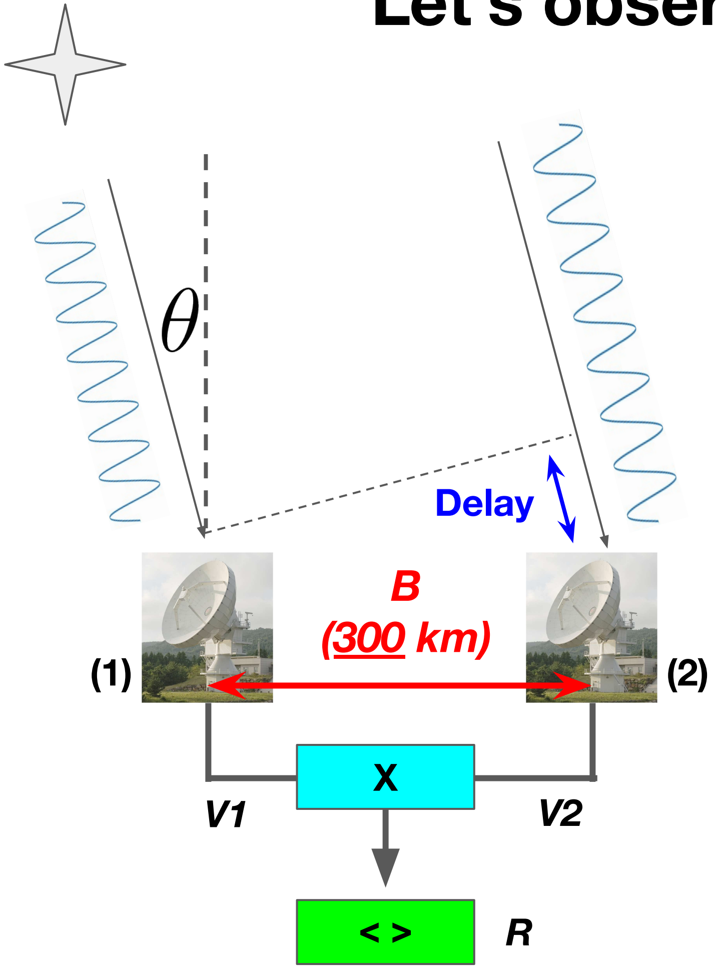


- **The response is very sensitive to the angle**
  - Peak-to-peak: ~20 mas, read from the plot
  - **Notice *lambda/B* ~ 20 mas!**

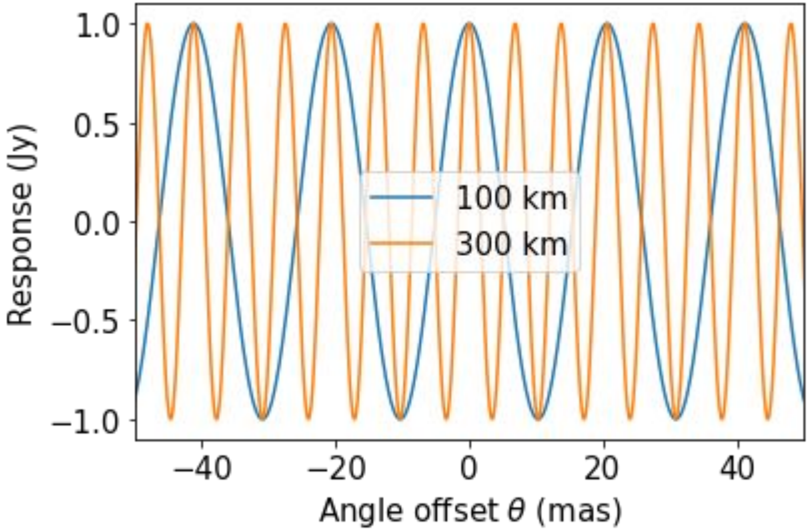
- **This *R* function allows a very precision position localization on the sky**



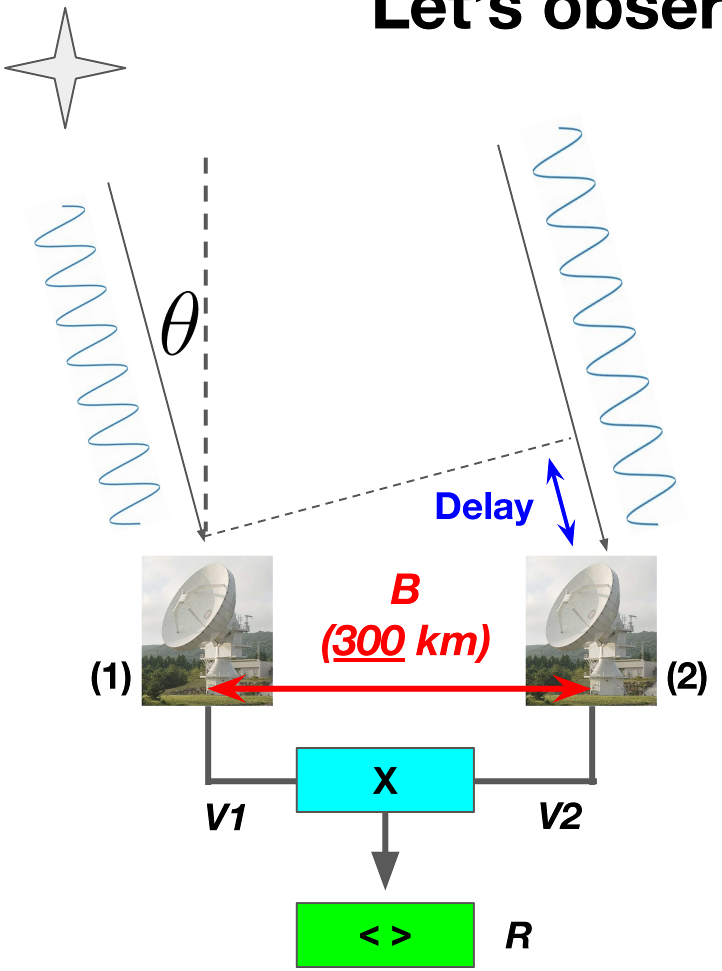
Let's observe M87*: longer spacing



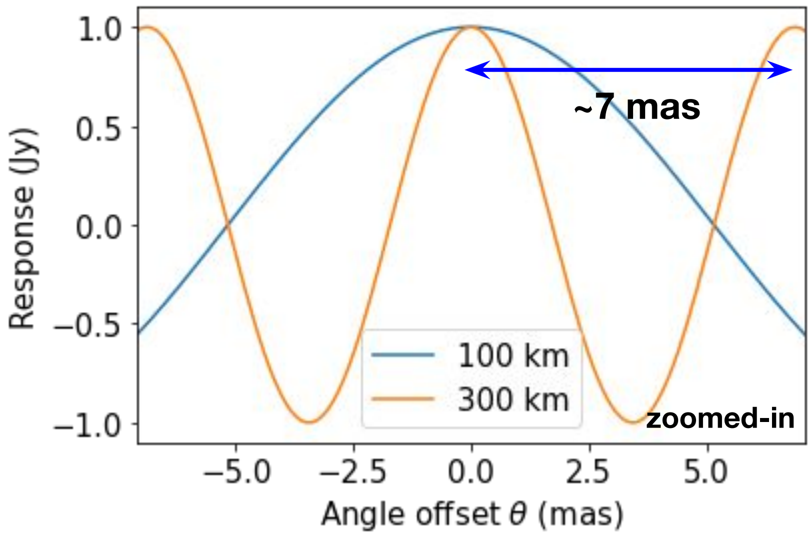
- The same setup as before, **but increase *B* from 100km → 300km**
- The angular response is sharpened ~3 times



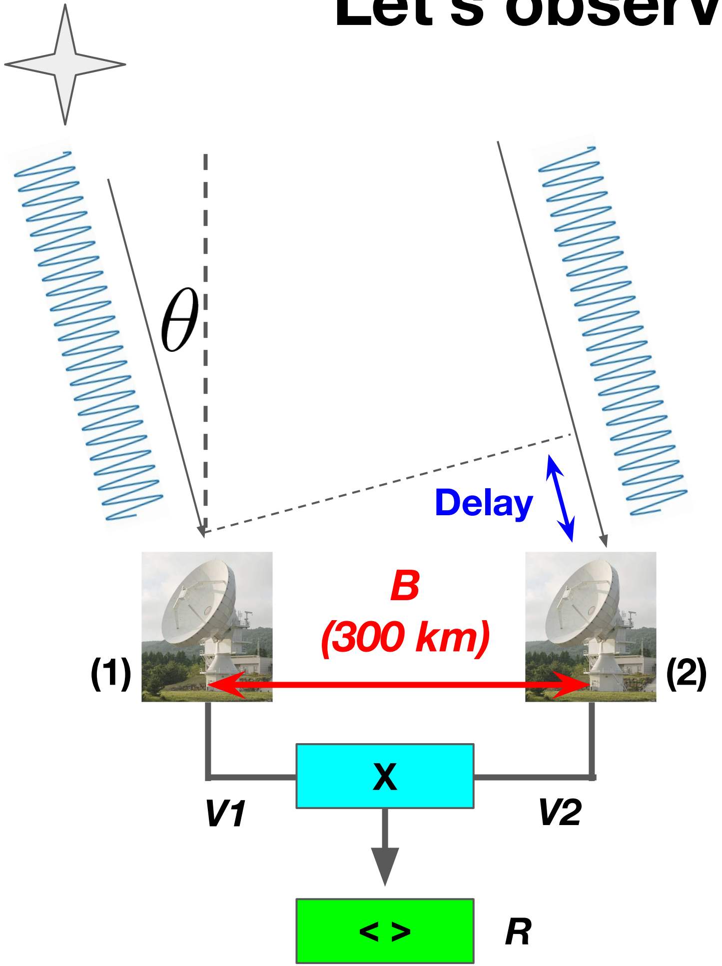
Let’s observe M87*: longer spacing



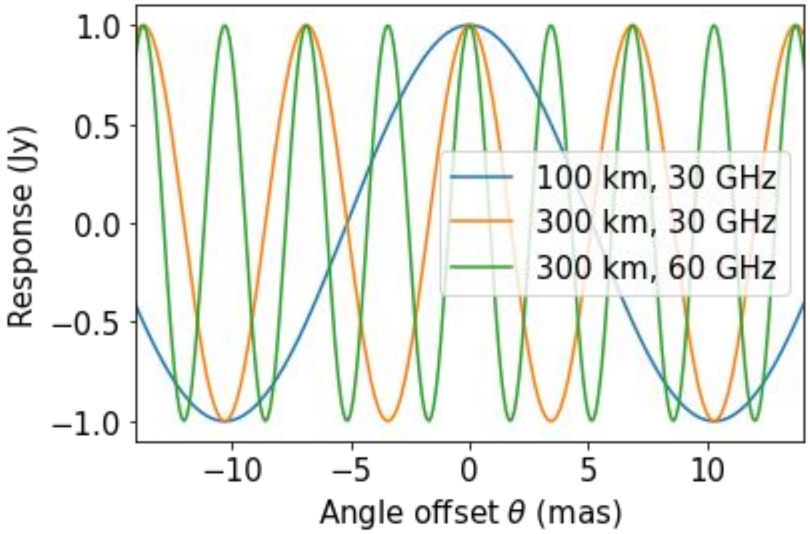
- The same setup as before, **but increase *B* from 100km → 300km**
- The angular response is sharpened ~3 times
- **Notice *lambda/B* ~ 7 mas**



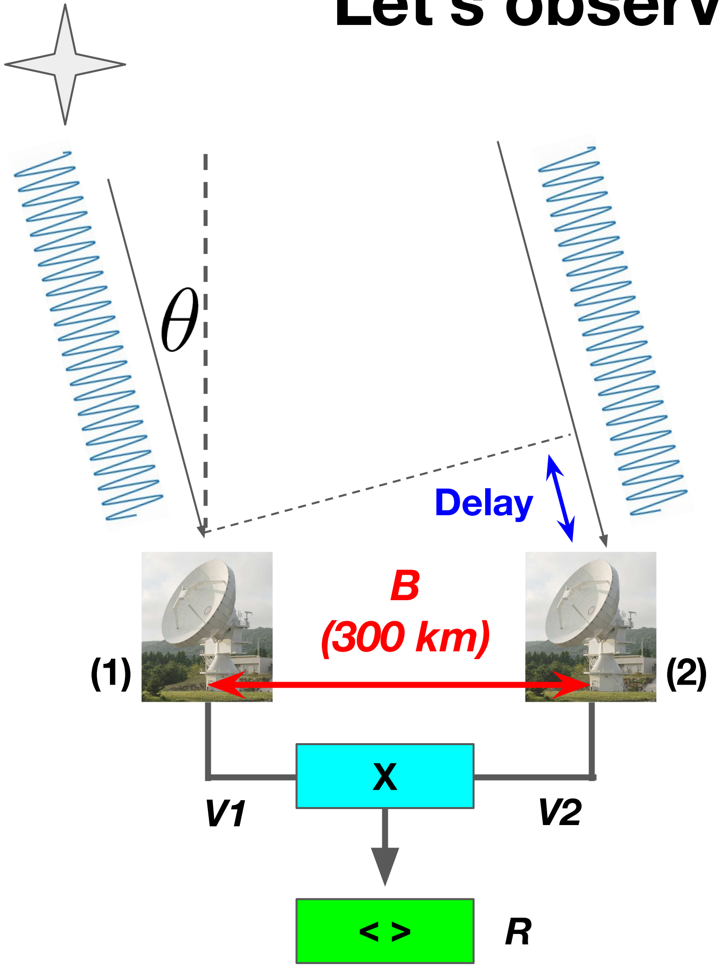
Let's observe M87*: Higher frequency



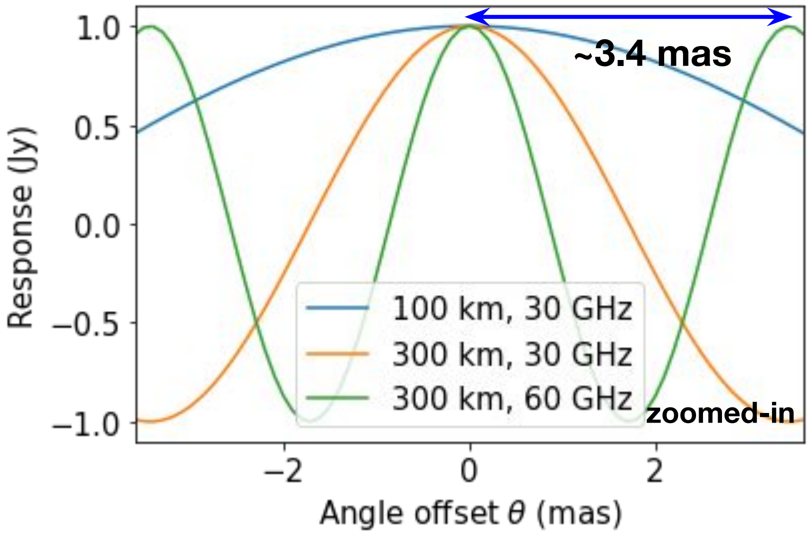
- B=300 km, now ***nu*: 30 → 60 GHz**
  - lambda=0.5 cm
- ***lambda/B* ~ 3.4 mas**

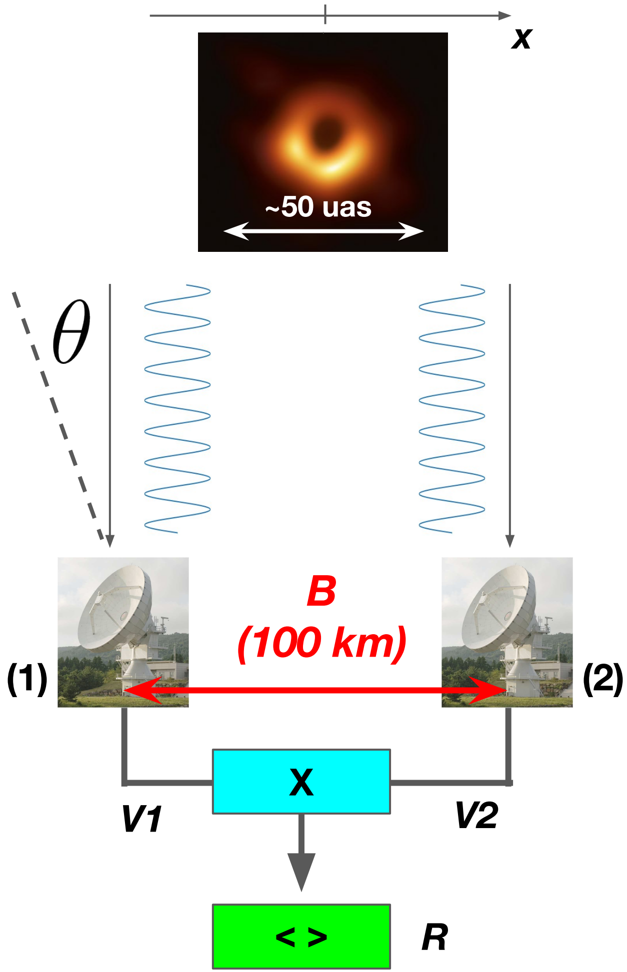


Let’s observe M87*: Higher frequency



- B=300 km, now ***nu*: 30 → 60 GHz**
  - lambda=0.5 cm
- ***lambda/B* ~ 3.4 mas**
- This response is called **“fringe”**

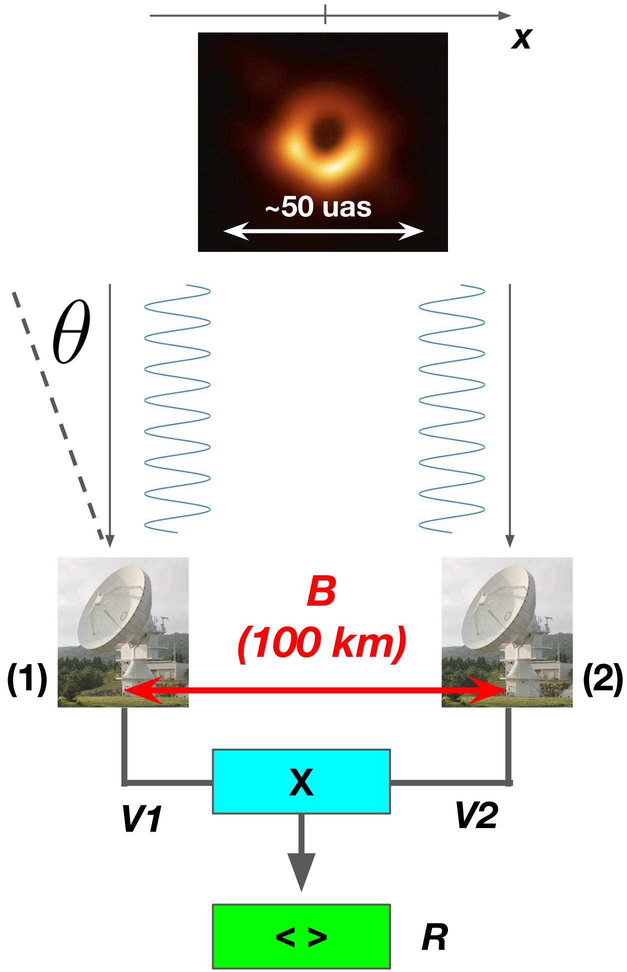




Let’s observe M87*: extended source

- Assume: M87* is at zenith (BH at *x*=0) and has 0.5 Jy total flux
    - Total flux can be known from single-dish obs.
- Setup: 100 km baseline, *nu*=230 GHz (*lambda*=1.3mm)

- What will be the output signal of this baseline?



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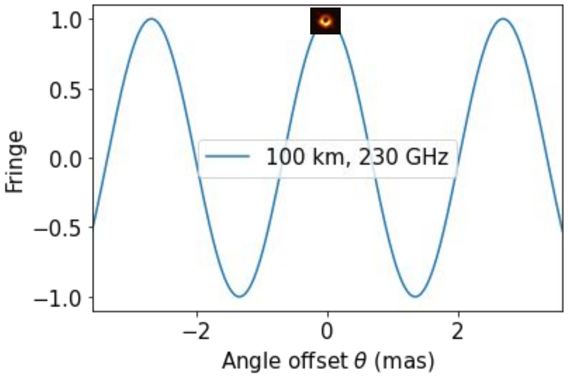
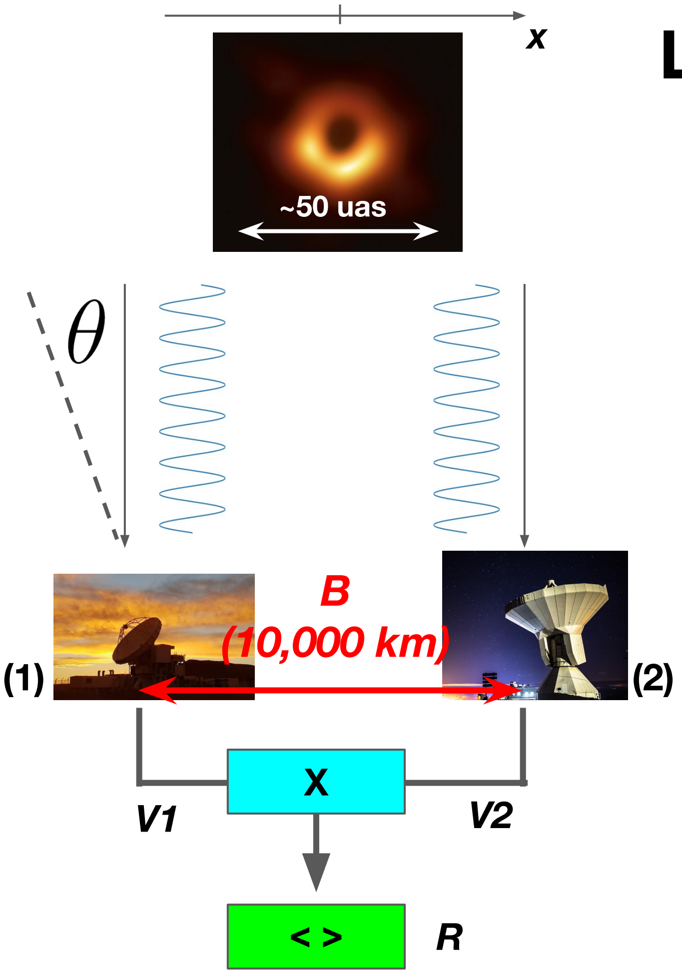
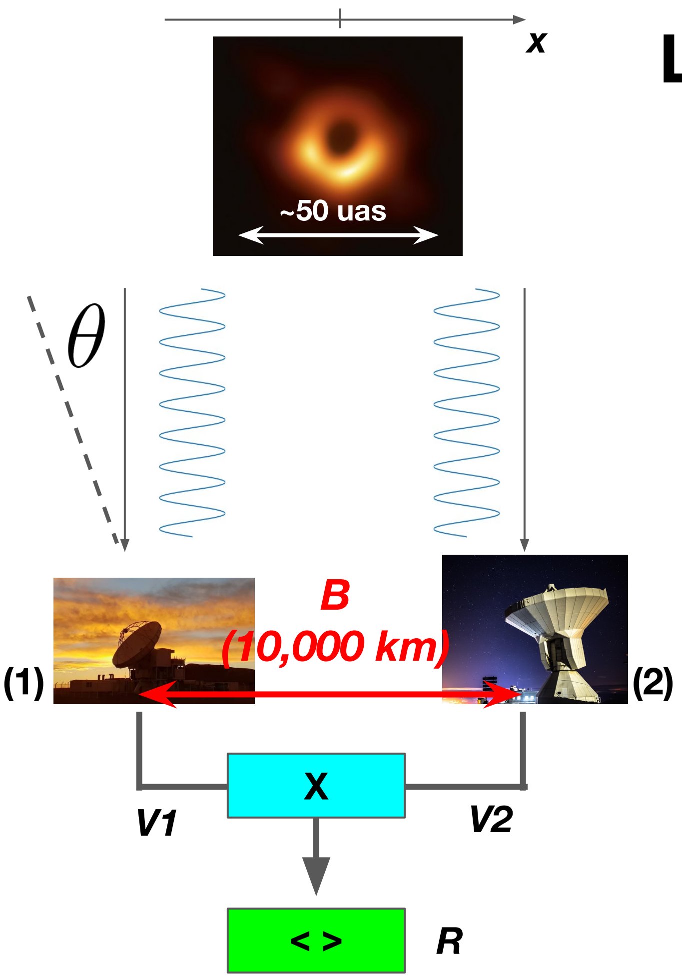


- Extended structure = collection of point sources
- Response = <Fringe(*theta*) **x** M87* image(*x*)> = 0.5 Jy
  - Here the averaging runs over the angle offset



Let's observe M87*: extended source

- Assume: M87* is at zenith and has 0.5 Jy total flux
- Setup: 10,000 km baseline, *nu*=230 GHz (*lambda*=1.3mm)
  - (left) APEX at Chile and (right) IRAM 30m at Spain
- What will be the output signal of this baseline?



Let’s observe M87*: extended source

- Assume: M87* is at zenith and has 0.5 Jy total flux
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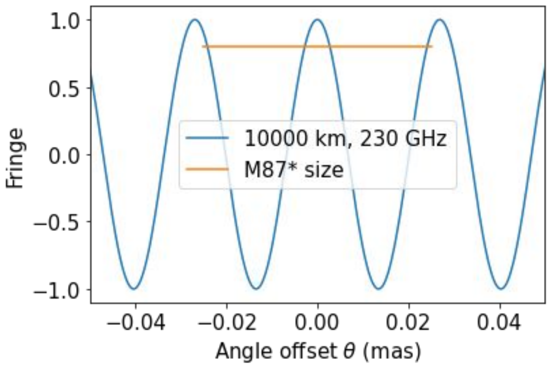
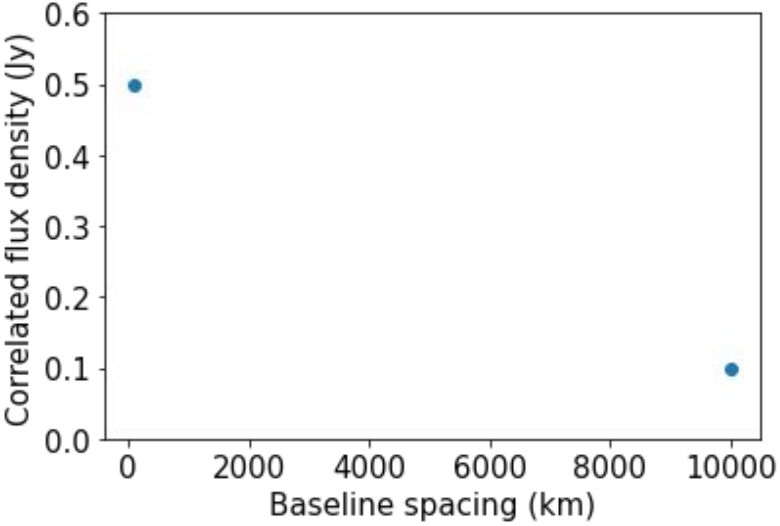


- Response = <Fringe(*theta*) **x** M87* image(*x*)> ~ 0.1 Jy (very rough rounding)

How to interpret these measurements?



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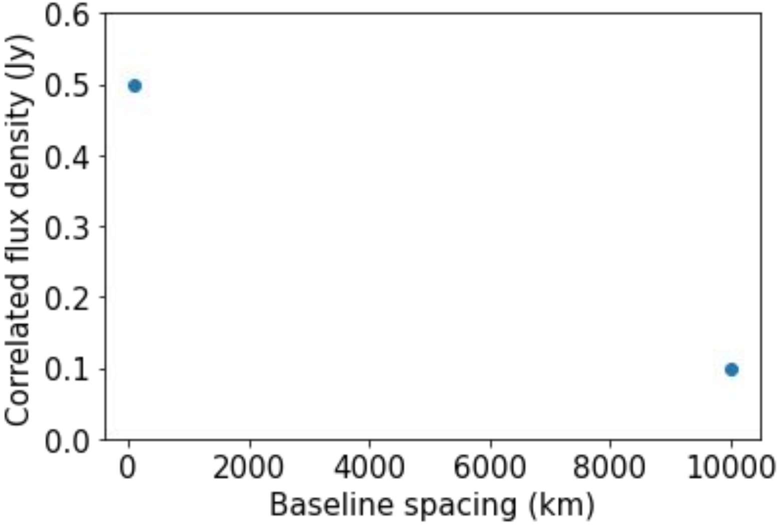
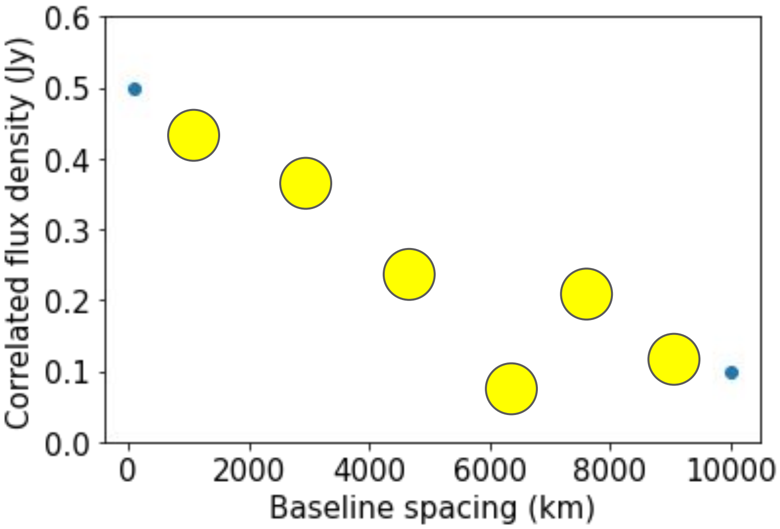


- The source is “**unresolved**” at 100km baseline with 0.5 Jy correlated flux
- The source is **“resolved”** at 10,000km length with 0.1 Jy correlated flux
  - Evidence for some structure at 1.3mm/10,000km ~ **30 uas scale**
- Each baseline measures the source structure and flux on their corresponding resolution
  - **“Fourier decomposition”**
- Is the source a Gaussian? ring? disk?

How to interpret these measurements?



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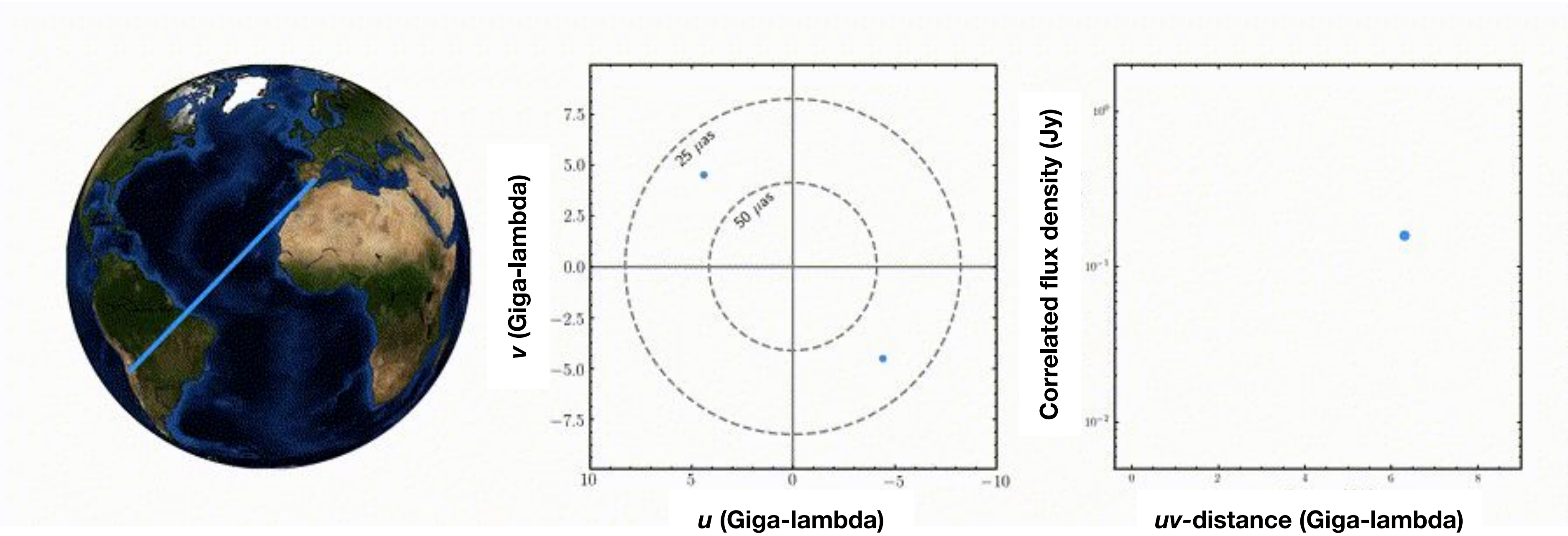
    - Evidence for some structure at 1.3mm/10,000km ~ **30 uas scale**
- Each baseline measures the source structure and flux on their corresponding resolution
    - **“Fourier decomposition”**
- Is the source a Gaussian? ring? disk?
    - **Need more measurements at various baseline lengths**

Real EHT M87 observations with Earth rotation



More baselines with Earth rotation
(Ryle 1974; Nobel prize in Physics)

Filling-in a synthetic aperture (Fourier space coverage)

Correlated flux at each spatial scales

Animation credit: D. Palumbo, M. Wielgus

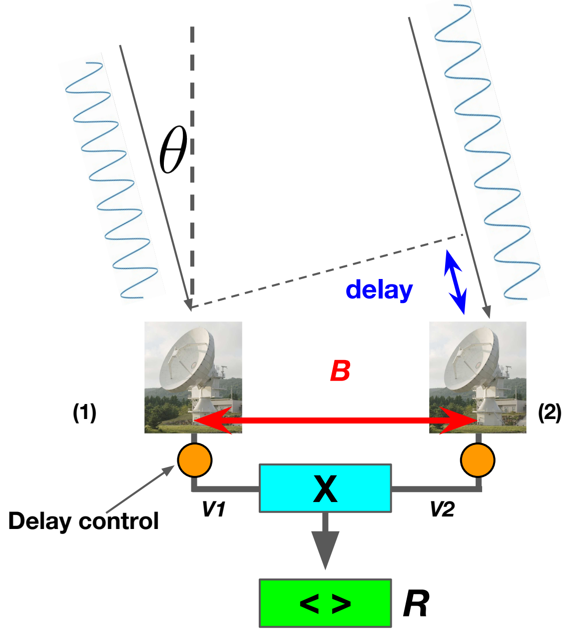
Some further remarks (advanced topics)

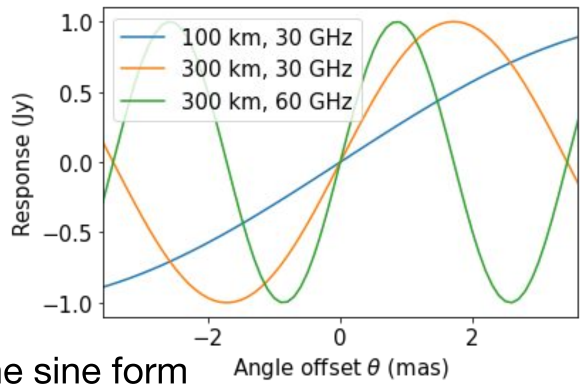
- **Pointing:** we can electronically add "delays" to *V1,* to move our "zenith" to any sky position (note: real waves are not monochromatic)

- **Response:** in practice, two *R* values are computed with different artificial lags, to catch both even and odd-symmetric parts
  - Complex *R*: "amplitudes" and "phases"

- **Dimensions:** sky brightness *I(x,y)* and baseline measurements *V(u,v)* are 2D: ***V(u,v)=FT(I(x,y))*** (van Cittert-Zernike theorem)

- For deeply interested students, see [this] textbook (open access)





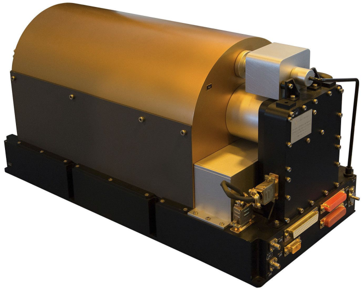
Notice the sine form

VLBI data acquisition...

Digitizers

Downconverters

Recorders

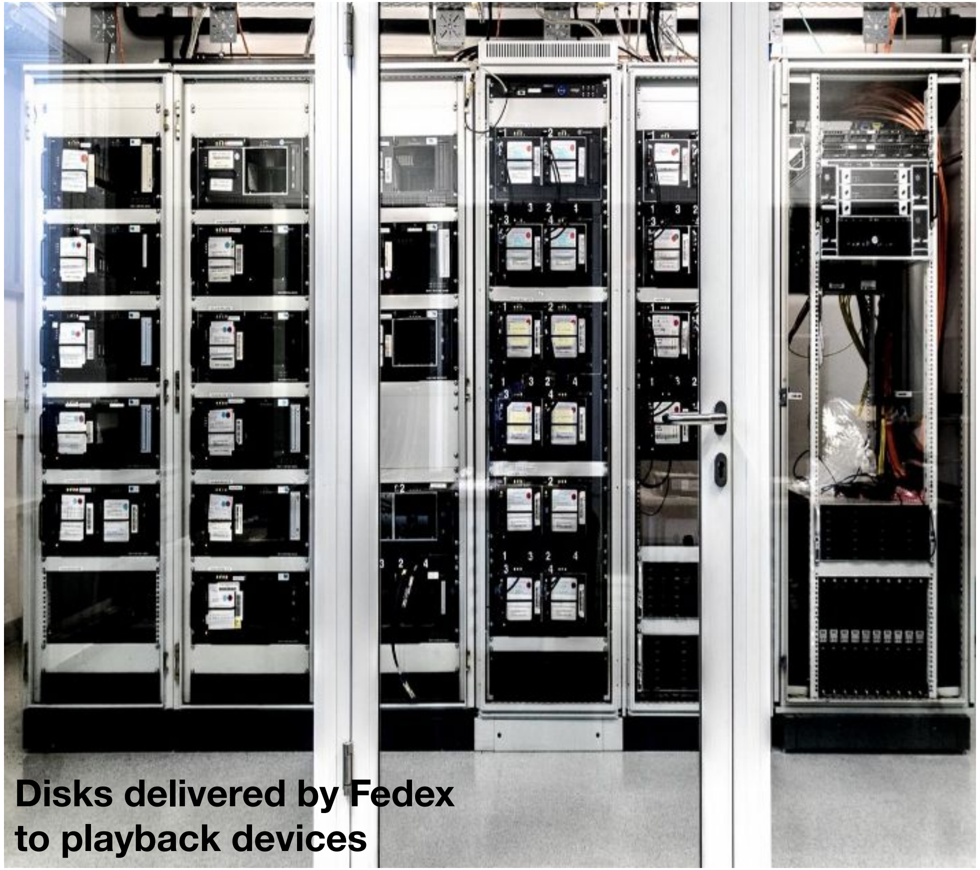


Hydrogen maser (atomic clock, ~pico-sec level accuracy): generate precise timestamps of each voltage record

Image from Wikipedia

… and processing (the “X” and “<>”)

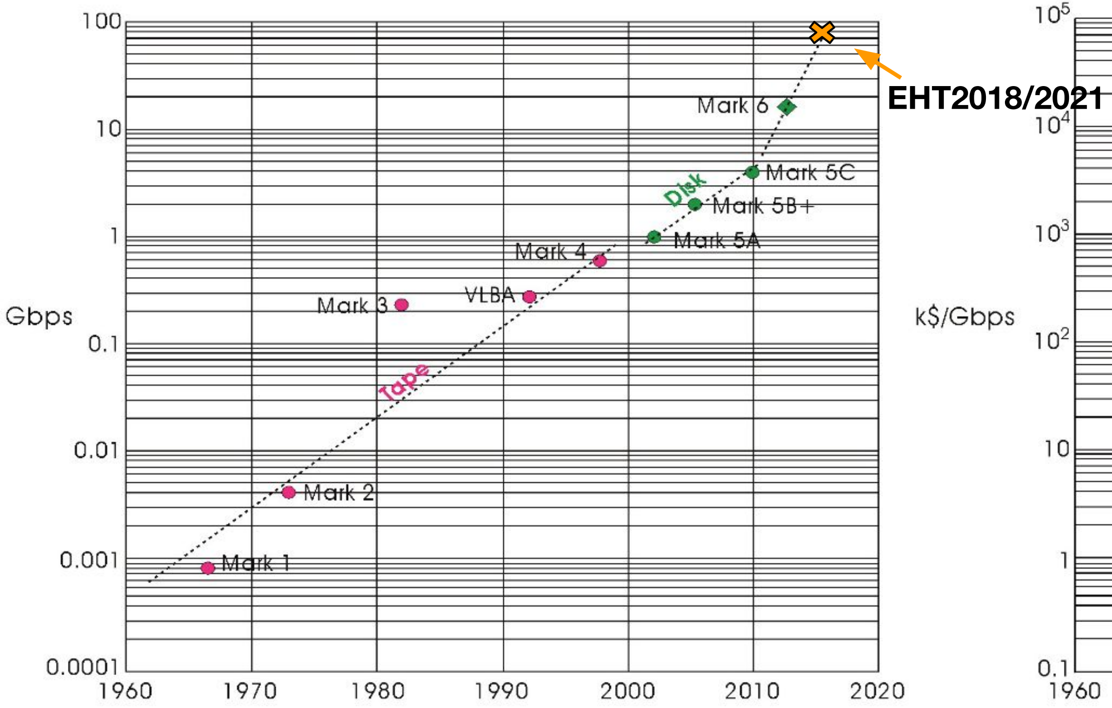
carefully with Earth geometry and clock models

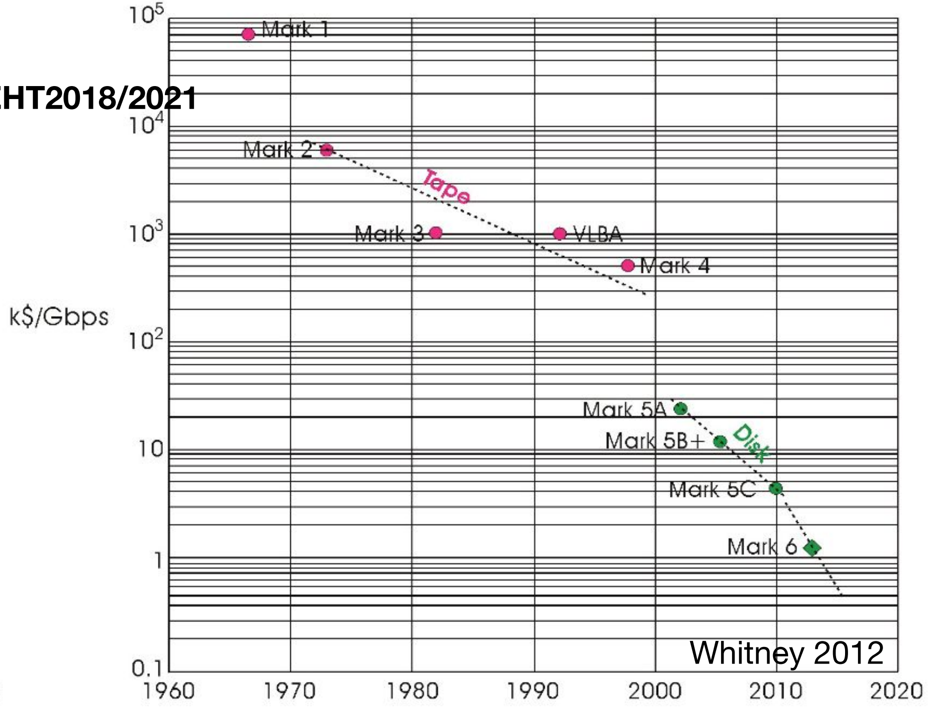


An example VLBI correlator at MPIfR, Bonn, Germany
(1360 cores, 56 Gbps interconnection, > 1PB storage)
Image credit: MPIfR

BTW, why big discoveries now?

Drastic improvements in data recording



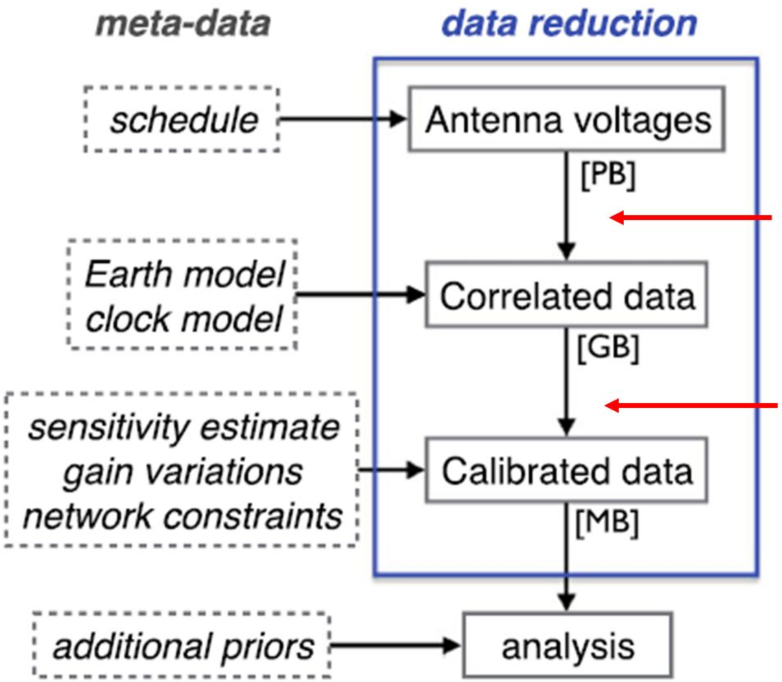


~1 TB in 2 min; ~700 TB per day per station

<u>Five orders of magnitudes</u> improvement over the last 5 decades!

Origin of errors and need for calibration

- **Not ideal antennas** -- surface error, receiver noise, polarization impurity, antenna position errors, ...
- **Electronics** -- analog/digital conversion, bandpass filters, frequency down-conversion, …
- **Atmosphere** -- opacity changes, phase attenuation, …
- **Human/machine errors** -- scheduling/observation failures, ...

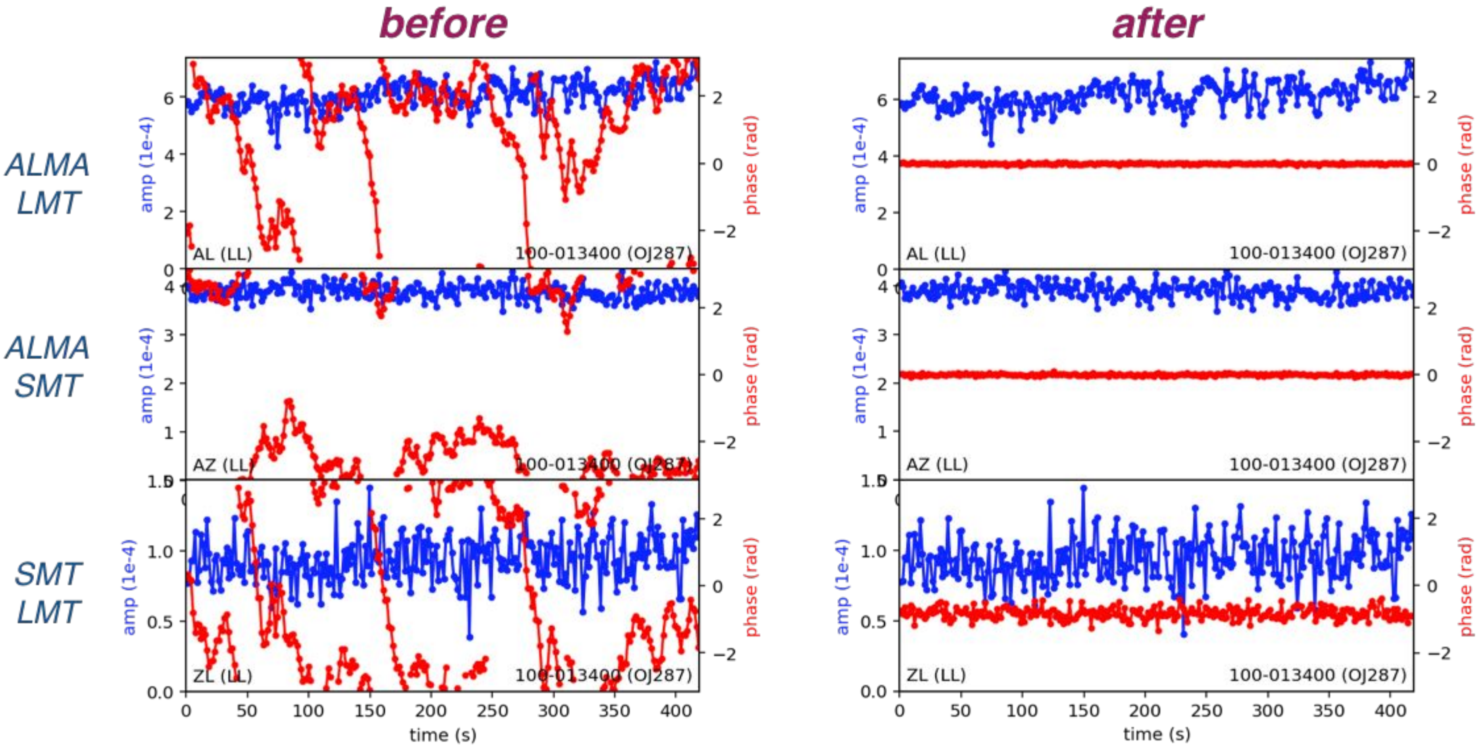


Several revisions

ER 1-5

EHTC+2019c

VLBI data calibration example (advanced topic)

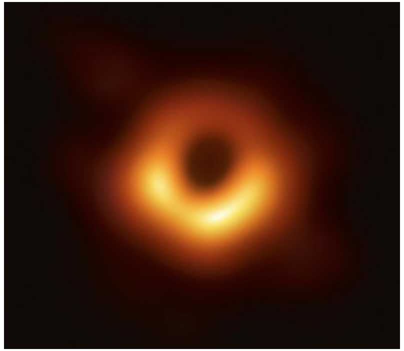


source structure phase varies on ~hour
but can only average for ~few seconds due to atmosphere

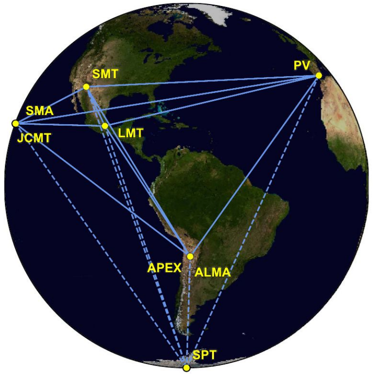
can average for entire scan

Slide credit: Blackburn, Issaoun, EHTC

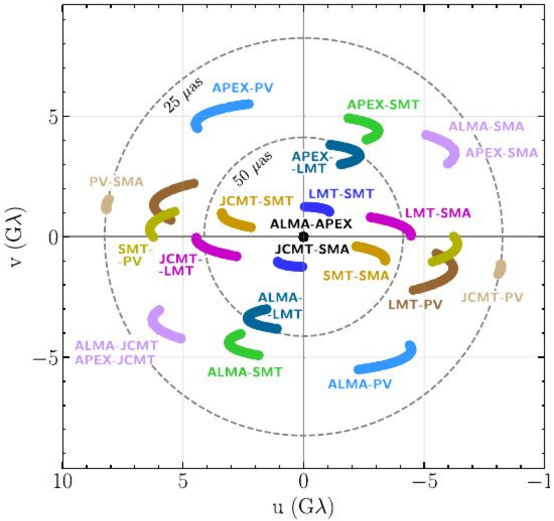
So far...

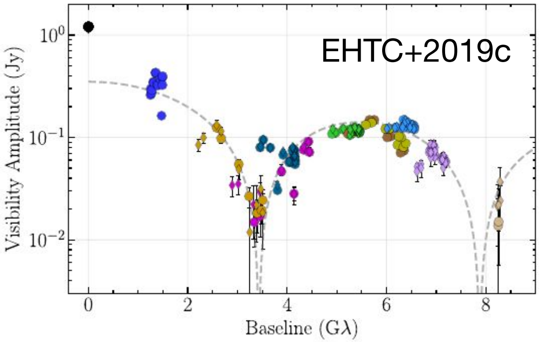


Obs.

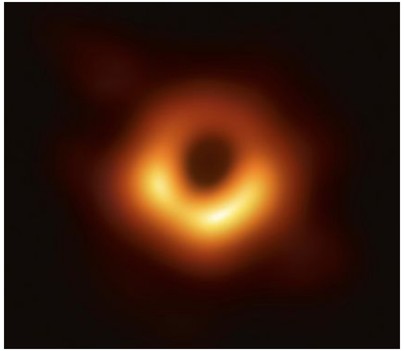


2D FT





Making an *image* from VLBI data



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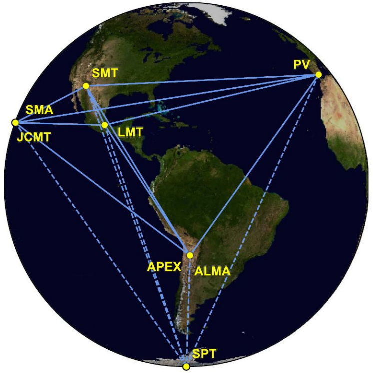
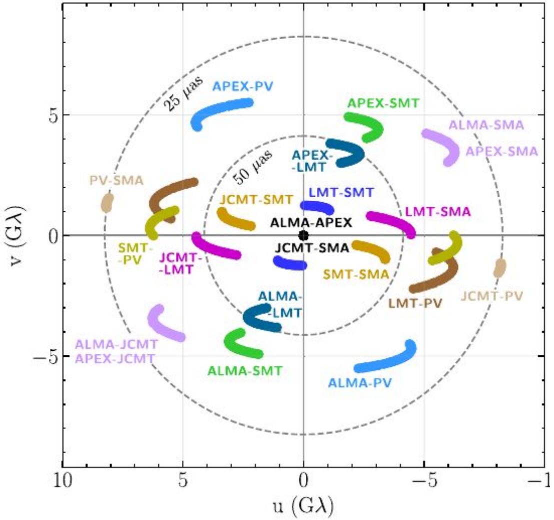
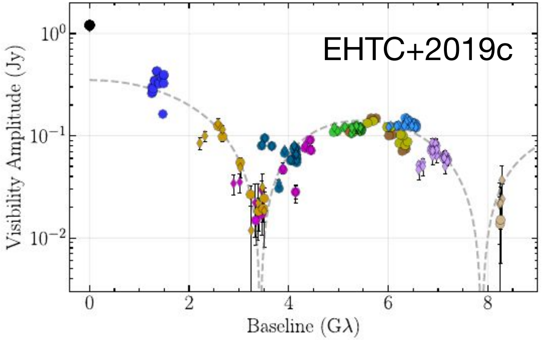


2D FT



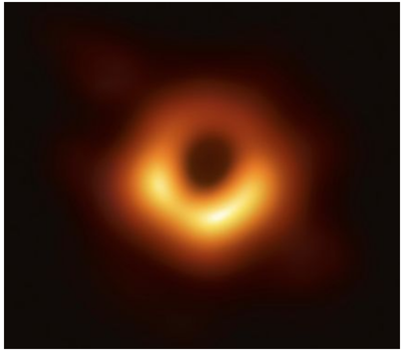


Reconstructed image?

Simply Inverse Fourier-Transform?

Image Credit: Bouman

Making an *image* from VLBI data



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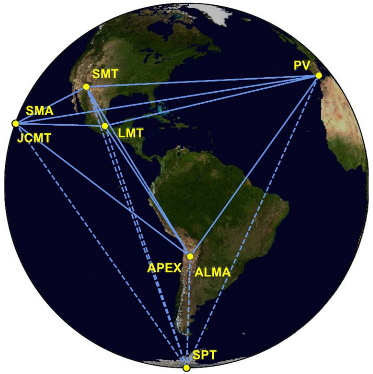
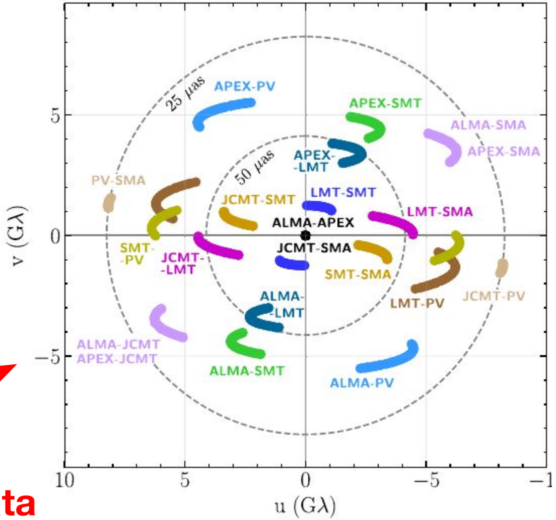
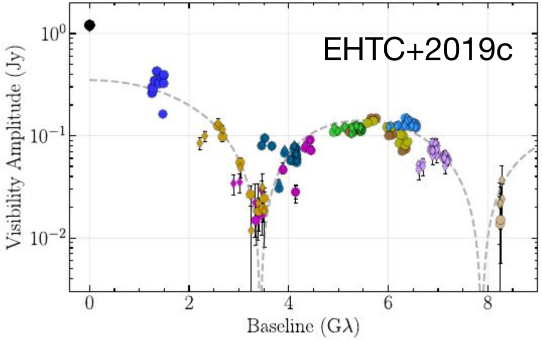


2D FT



Fundamentally undersampled;
infinitely many images can equally fit this data



Simply Inverse
Fourier-Transform?

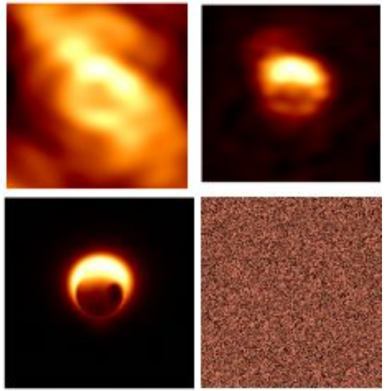
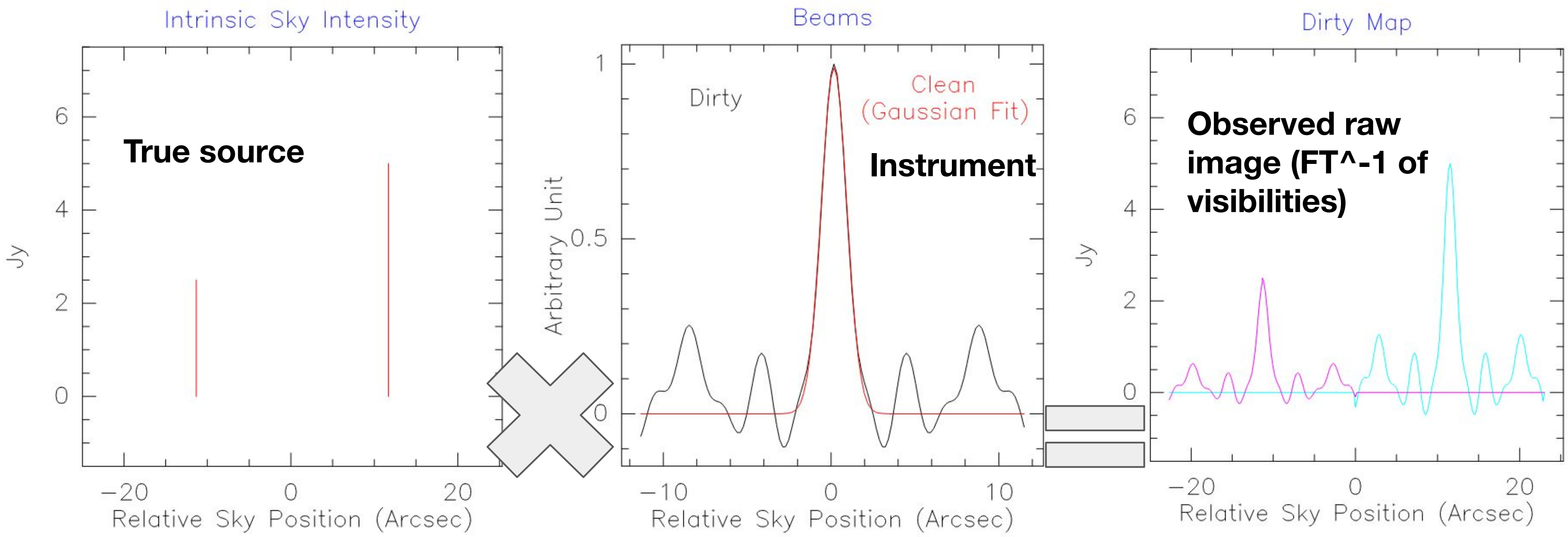


Image Credit: Bouman

CLEAN: classical image reconstruction algorithm (advanced topic)



Credit: J. Pety, IRAM interferometry school

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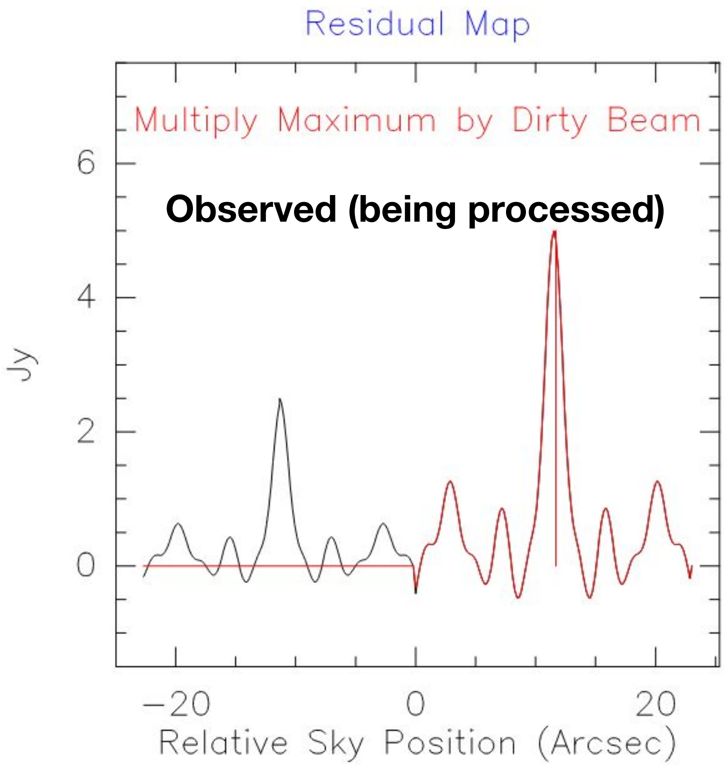

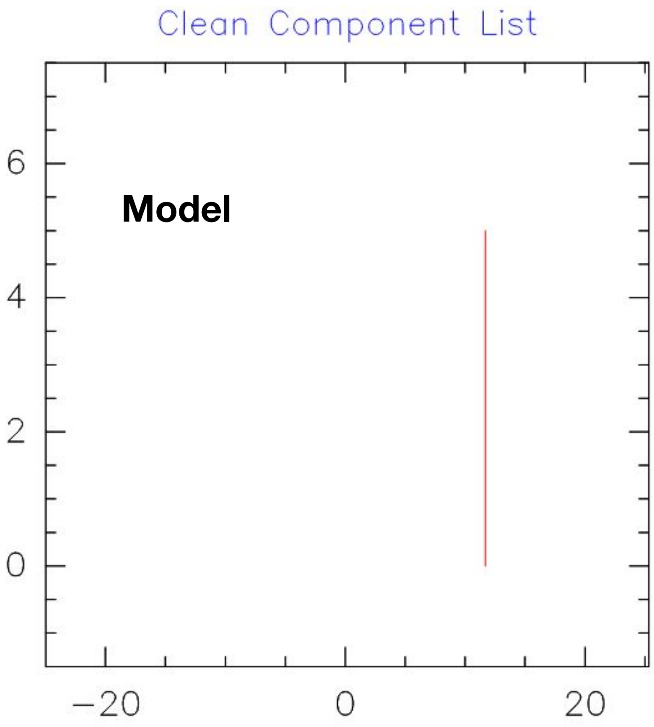

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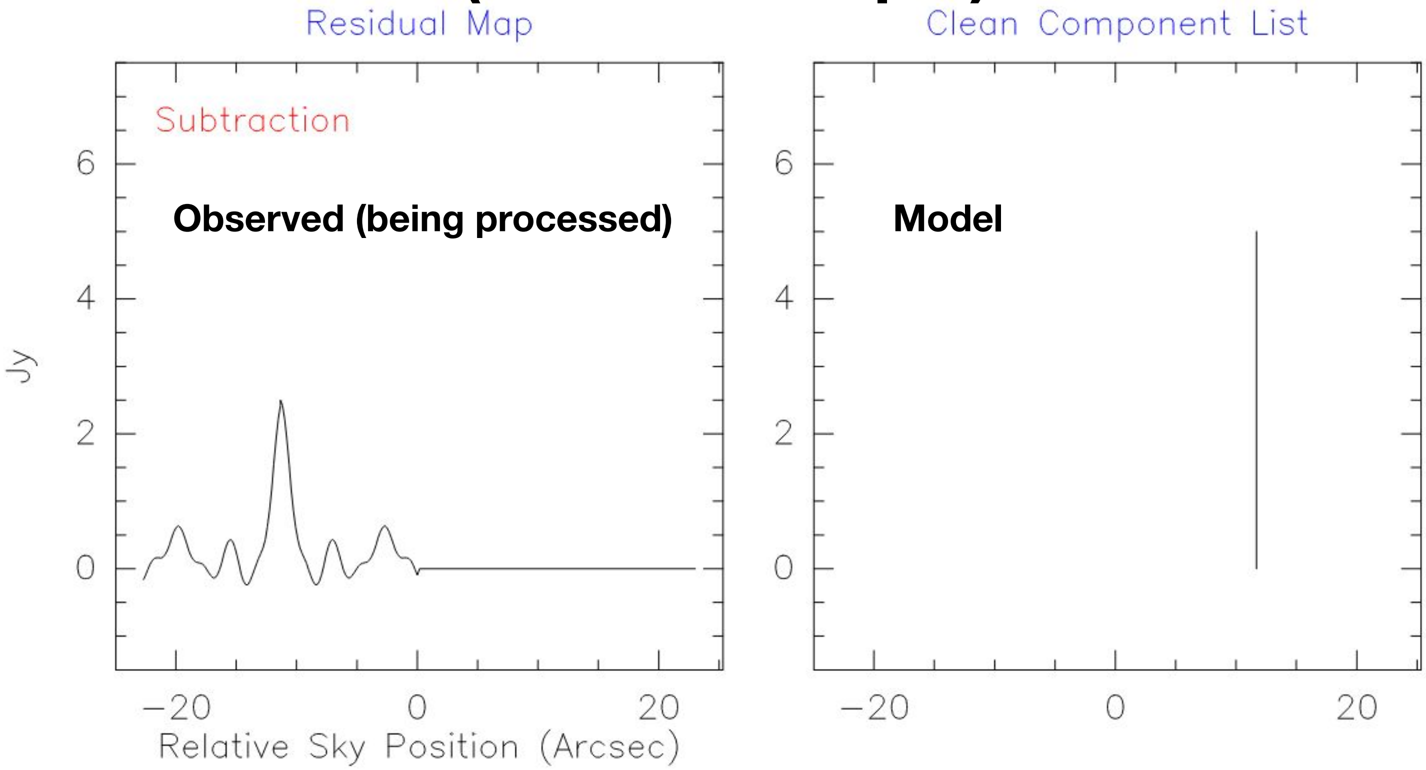

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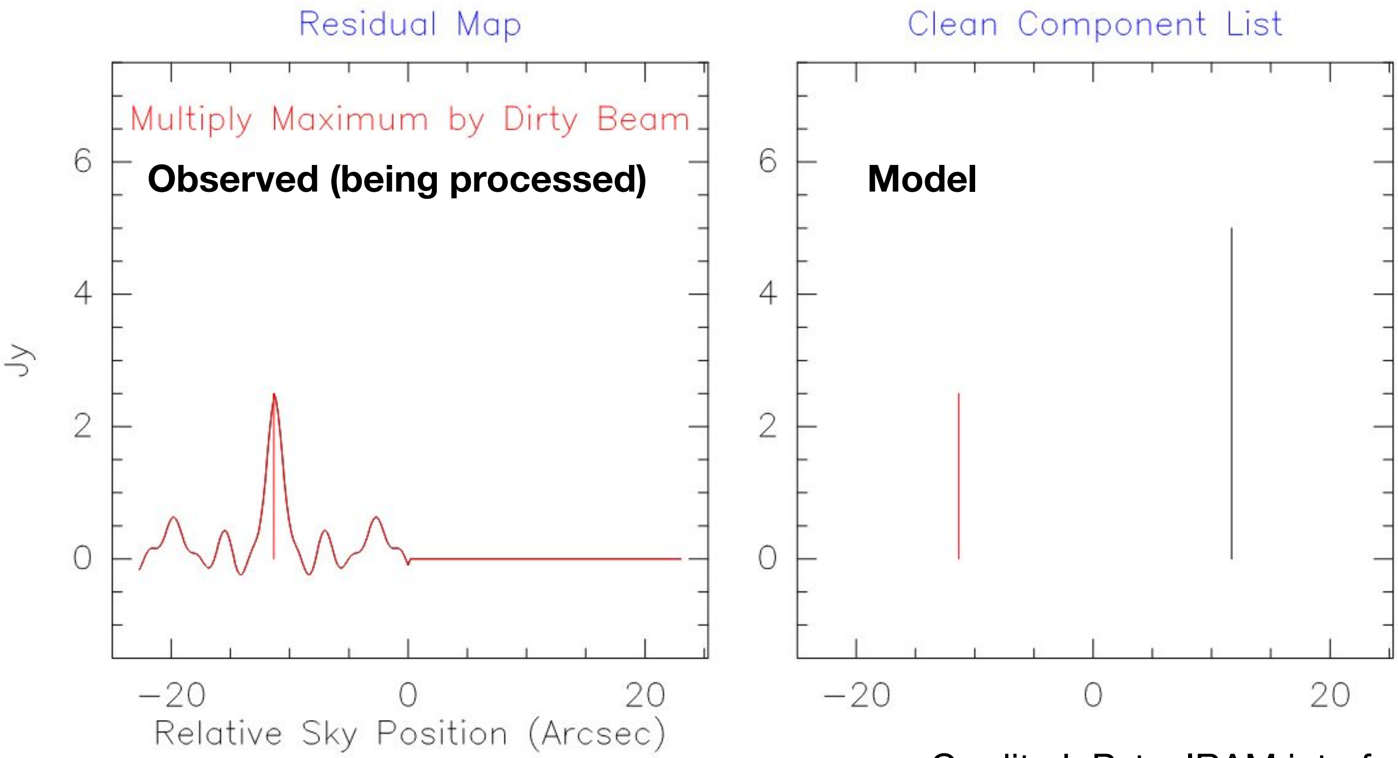

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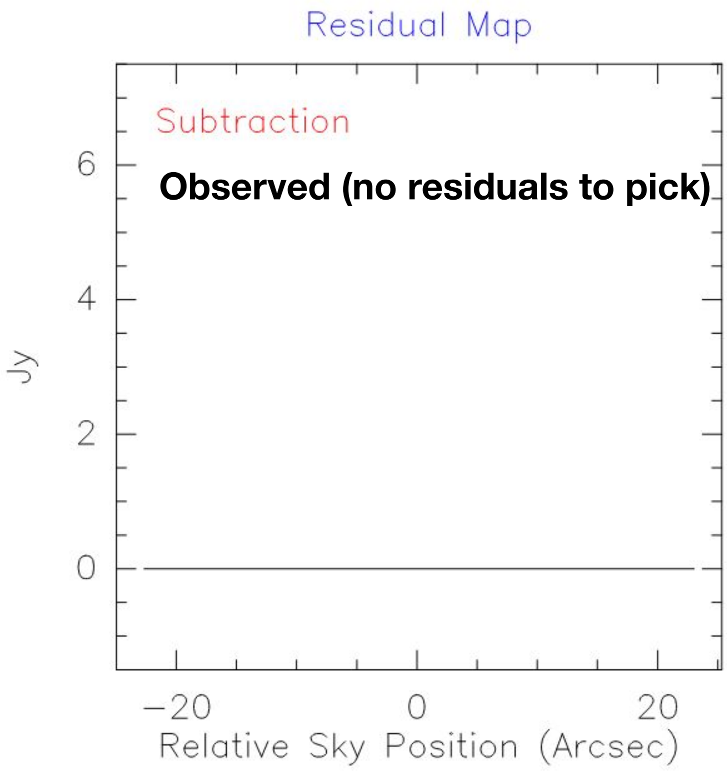

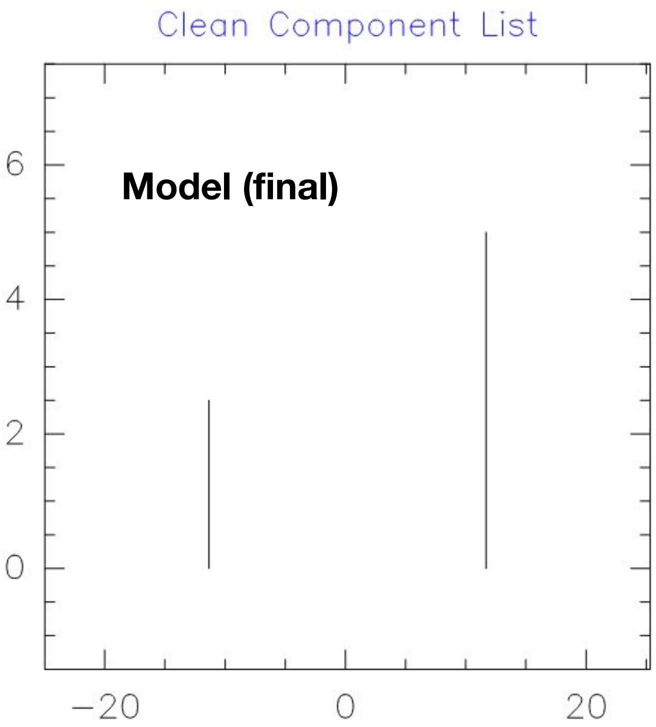

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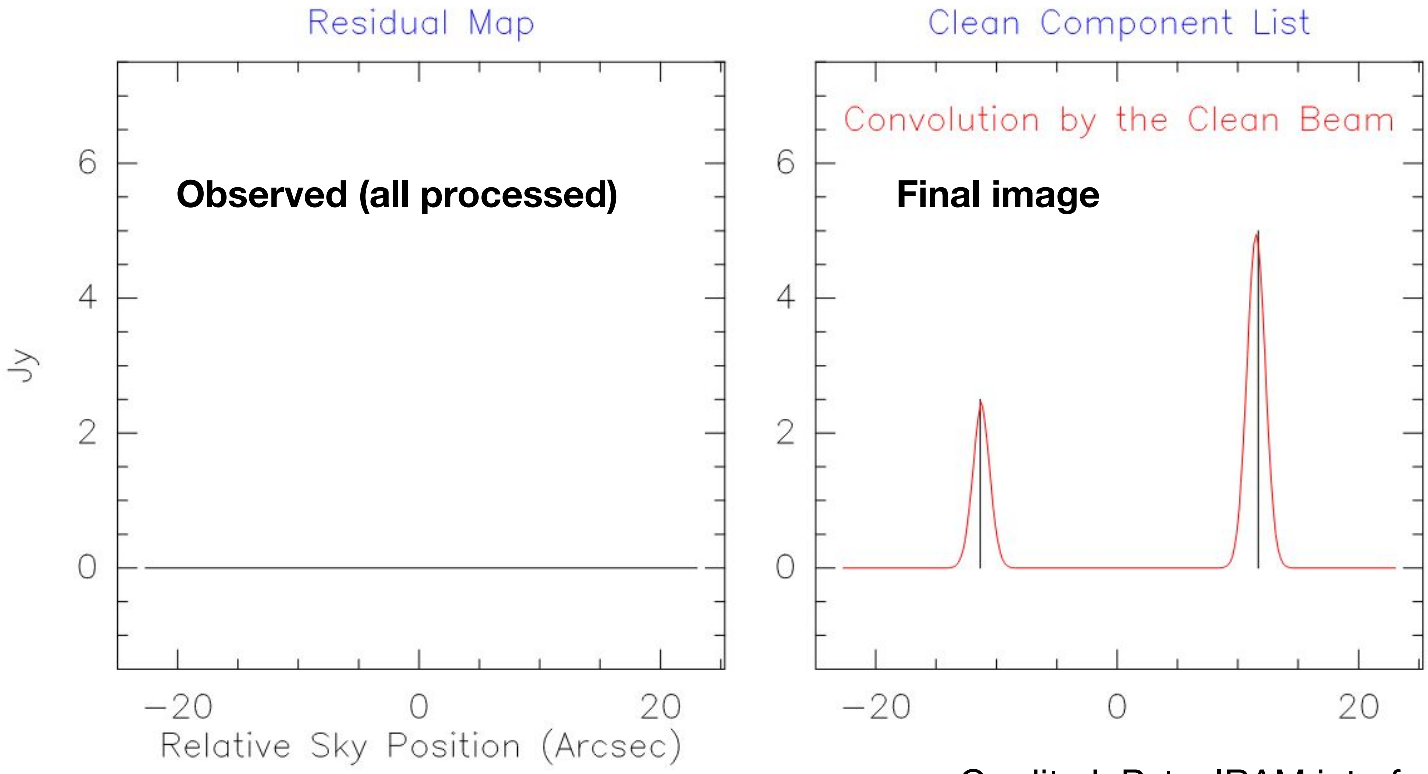


Credit: J. Pety, IRAM interferometry school

How to overcome ambiguity: blind imaging

The Imaging WG was divided into four independent teams

Team 1

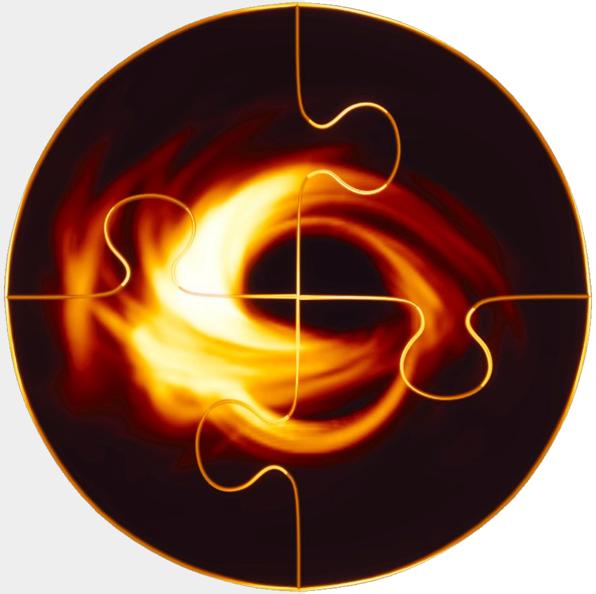
Americas

US & Chile
(SAO, U. Arizona, U. Concepcion)

Team 4

East Asians

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



Team 2

Global

US, Japan, Netherlands
(MIT, NAOJ, Hiroshima U., Radboud U.)

Team 3

Cross Atlantic

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

New Techniques

Traditional Techniques

Each team <u>blindly</u> reconstructed images

Goal: Assess human bias

Slide credit: K. Akiyama

How to overcome ambiguity: blind imaging

Team 1

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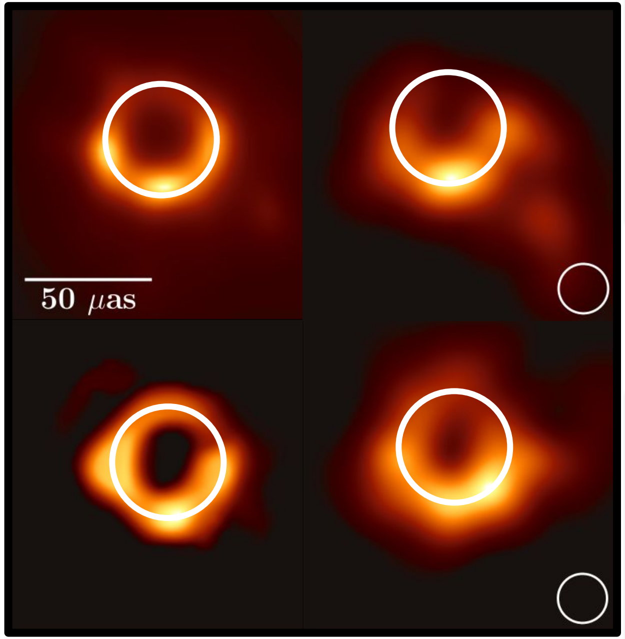
April 11



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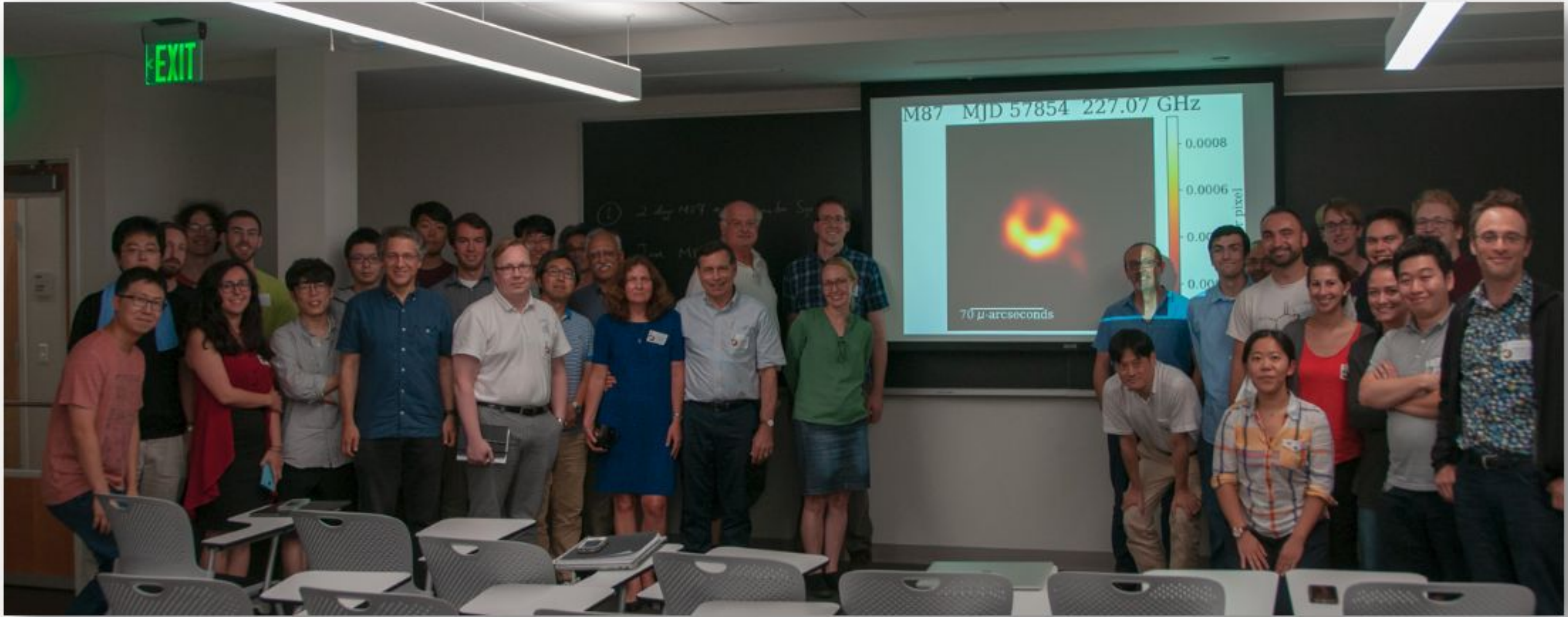
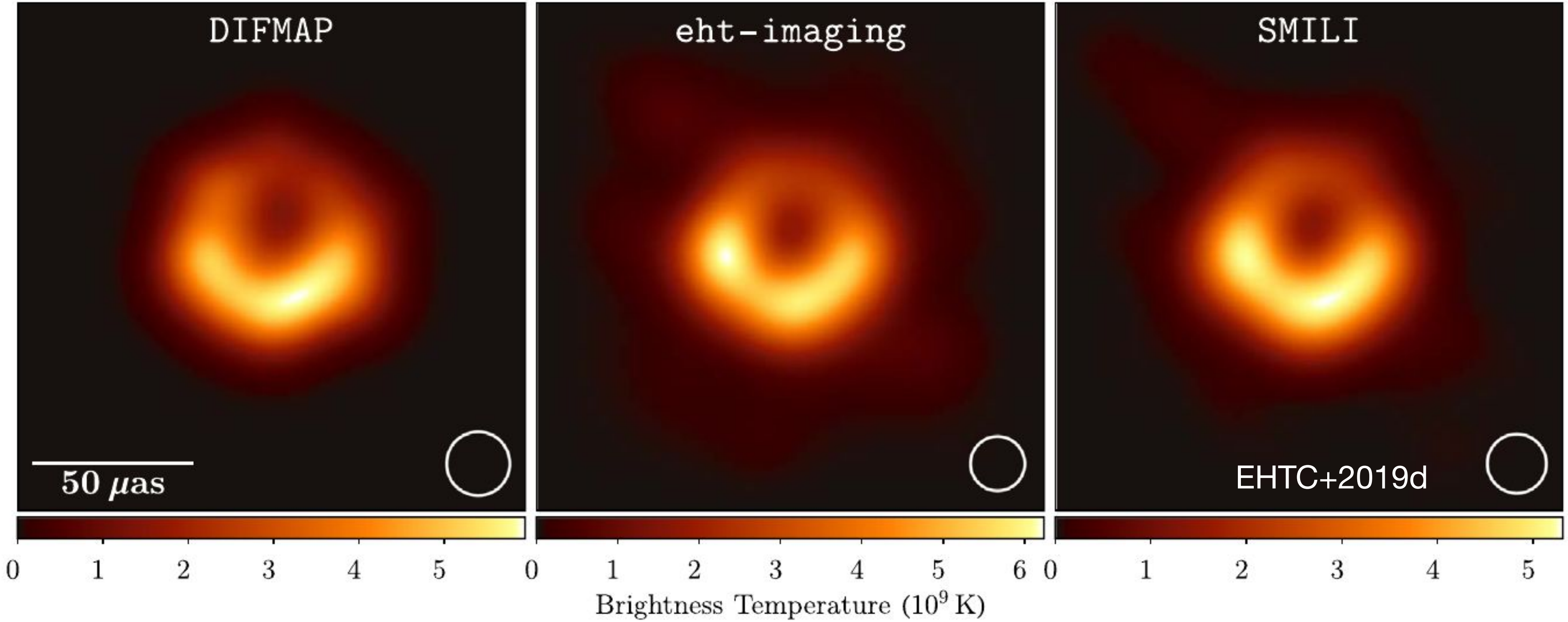
Slide credit: K. Akiyama



2nd EHT Collaboration imaging workshop on M87*

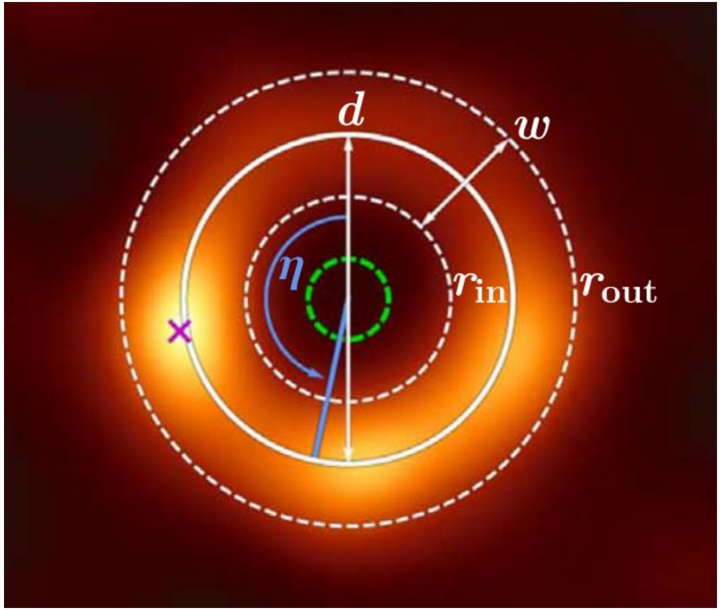
July 2018 at Harvard, Cambridge

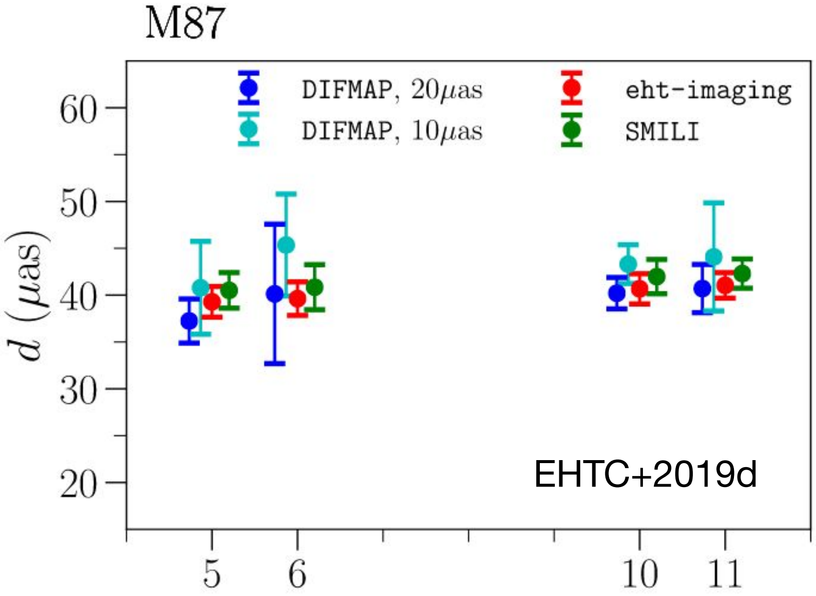
Fiducial (i.e., best) maps from the three pipelines
(after optimization)



The best out of ~50,000 images

Image-domain feature extraction





Describe the ring by (1) the width, (2) r_in, (3) r_out,
(4) diameter, and (5) the (intensity-weighted) position angle

Parameter extraction by simple geometric modeling

Start with a circular disk and remove a smaller circular disk from the interior to produce a ring

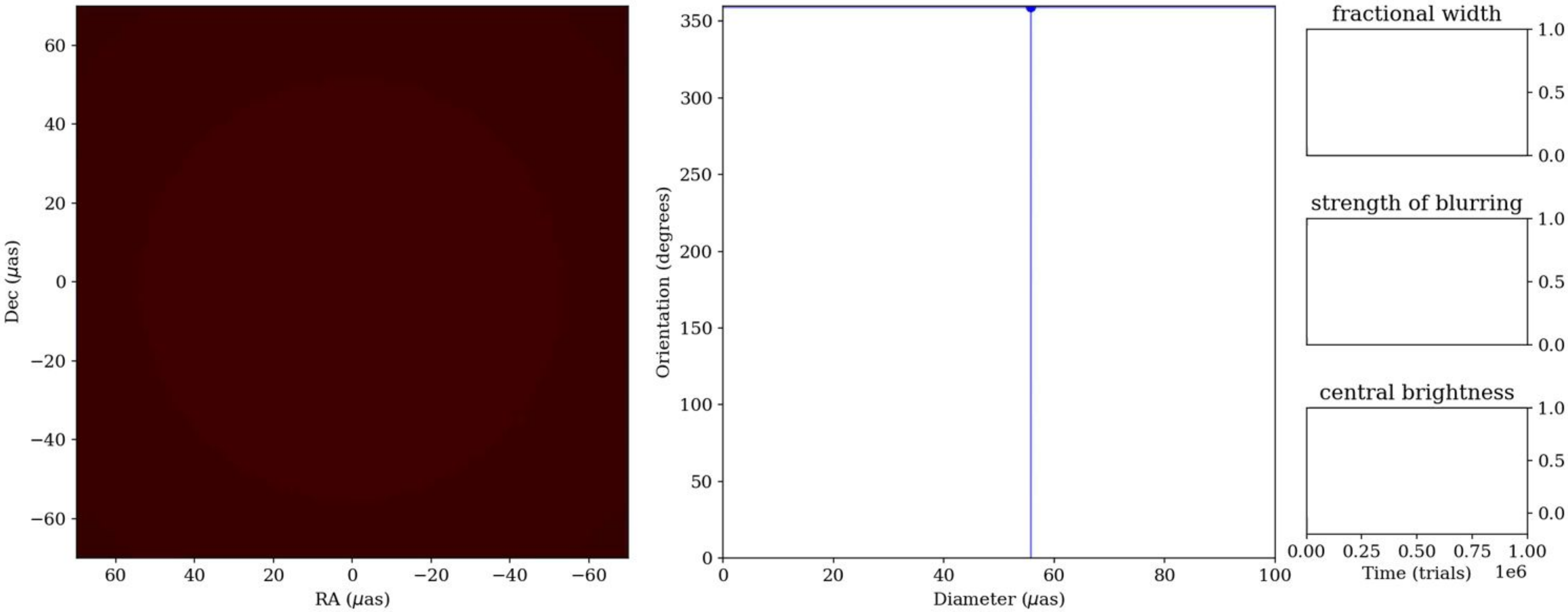
Shift the inner hole of the ring to produce a crescent

Change the crescent orientation by rotating it

Blur the entire image to soften the artificially sharp edges

Animation credit: D. Pesce
Slide credit: S. Issaoun

Parameter extraction by simple geometric shapes



An example MCMC run on the real EHT visibility dataset

Animation credit: D. Pesce
Slide credit: S. Issaoun

EHTC+ 2019f

Final images and extracted parameters of M87*

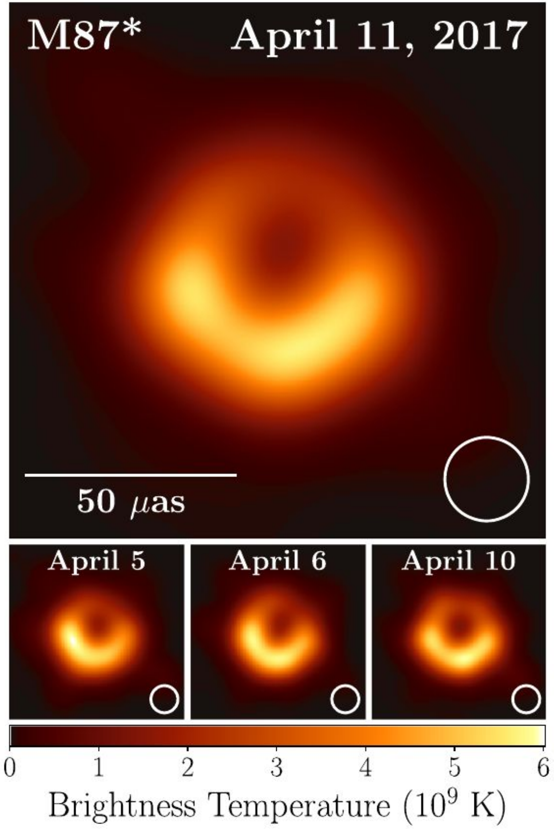


Table 1
Parameters of M87*

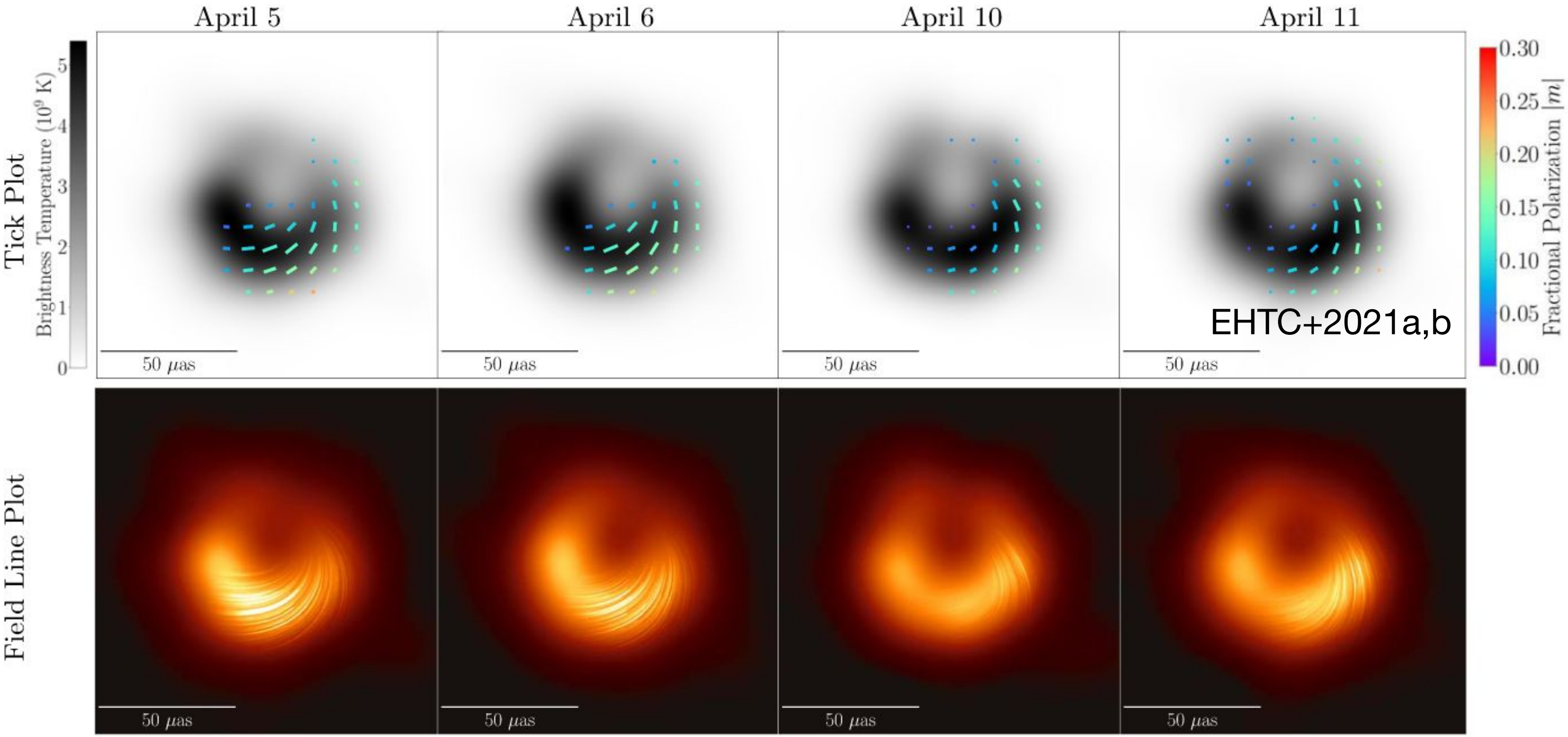
Parameter	Estimate
Ring diameter [a] d	42 ± 3 μas
Ring width [a]	<20 μas
Crescent contrast [b]	$>10:1$
Axial ratio [a]	$<4:3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	3.8 ± 0.4 μas
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M[c]	$(6.5 \pm 0.7) \times 10^9 M_\odot$
Parameter	**Prior Estimate**
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9 M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9 M_\odot$

Notes.
[a] Derived from the image domain.
[b] Derived from crescent model fitting.
[c] The mass and systematic errors are averages of the three methods (geometric models, GRMHD models, and image domain ring extraction).
[d] The exact value depends on the method used to extract d, which is reflected in the range given.
[e] Rederived from likelihood distributions (Paper VI).

EHTC+2019a

Newspapers/journals after 11 April 2019

… and 2 years later: M87* polarimetry



<u>Interpretations and EHT science cases to follow in the next lecture</u>