中国科学院上海天文台
Shanghai Astronomical Observatory, Chinese Academy of Sciences

New science of next generation EHT

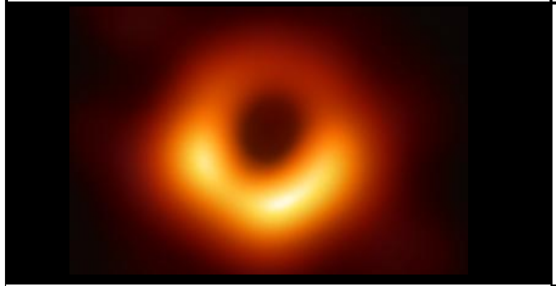
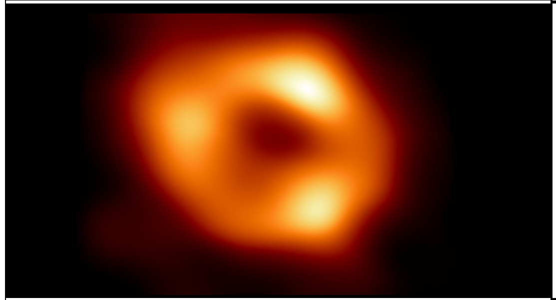
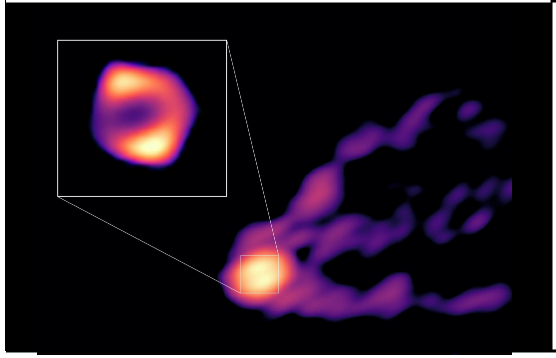
Speaker: Shan-Shan Zhao (赵杉杉)
Shanghai Astronomical Observatory

2023-12-02 北京 黑洞图像学术研讨会

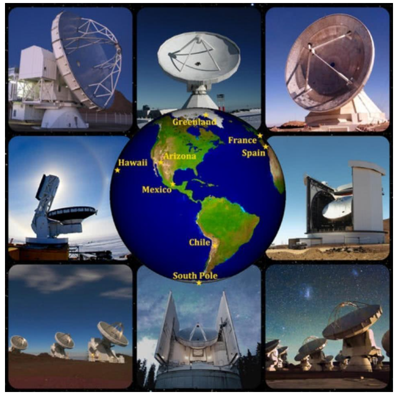
Outlines

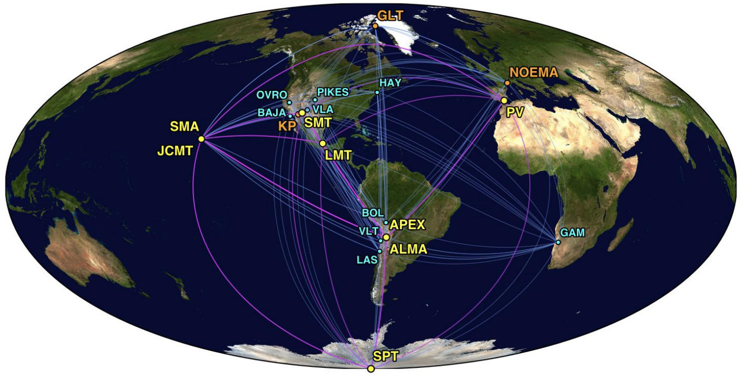
- **Background**
- **New science of next generation EHT (ngEHT)**
  - Test general relativity
  - Accretion flow / jet dynamics+radiation
  - more black hole images
  - supermassive black hole binaries detection
- **China in ngEHT**

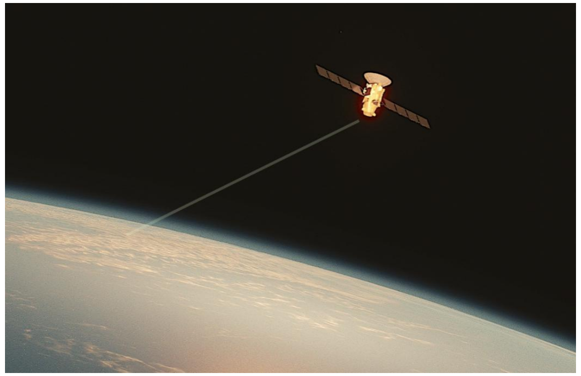
Current black hole images

image	black hole	array	frequency	publication
	M87*	Event Horizon Telescope (EHT)	230 GHz	EHTC et al. 2019,2021, ApJL
	SgrA*	EHT	230 GHz	EHTC et al. 2022, ApJL
	M87*	Global Millimeter VLBI Array (GMVA)	86 GHz	Lu et al. 2023, Nature

EHT -> ngEHT







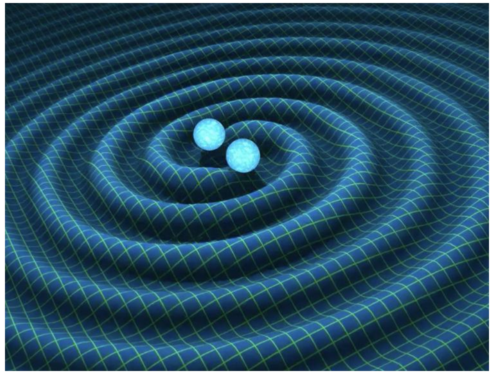
2017
8-element-array
230GHz

2021
11-element-array
230GHz (345GHz test)

2028
next generation EHT(ngEHT)
11-element-array
+ ~8 new sites (10-15m)
86/230/345GHz

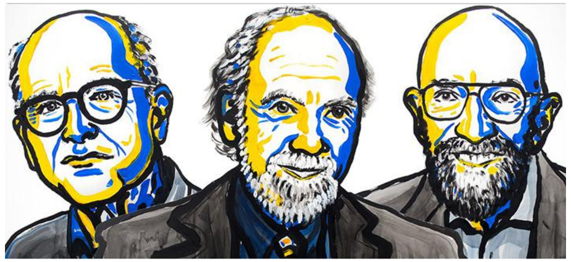
future
ngEHT-space VLBI
86-690GHz

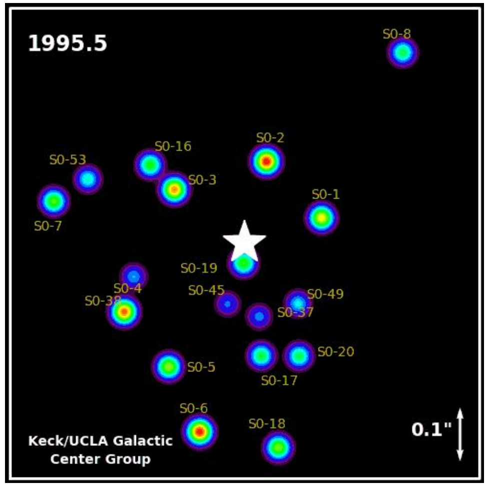
Test general relativity visual evidence of BH



“Hear” black hole

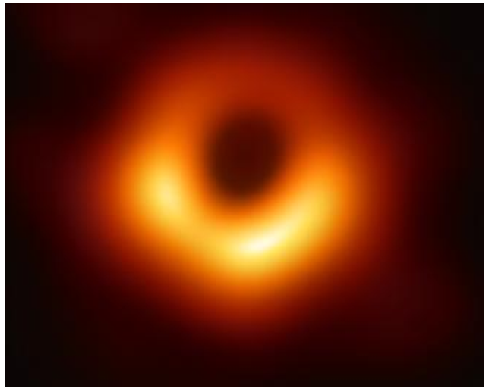
2017 NOBEL PRIZE





“Feel” black hole

2020 NOBEL PRIZE



“See” black hole

2020 BREAK THROUGH PRIZE

Dispute over black hole images

PHYSICAL REVIEW D **103,** 024023 (2021)

Can the EHT M87 results be used to test general relativity?

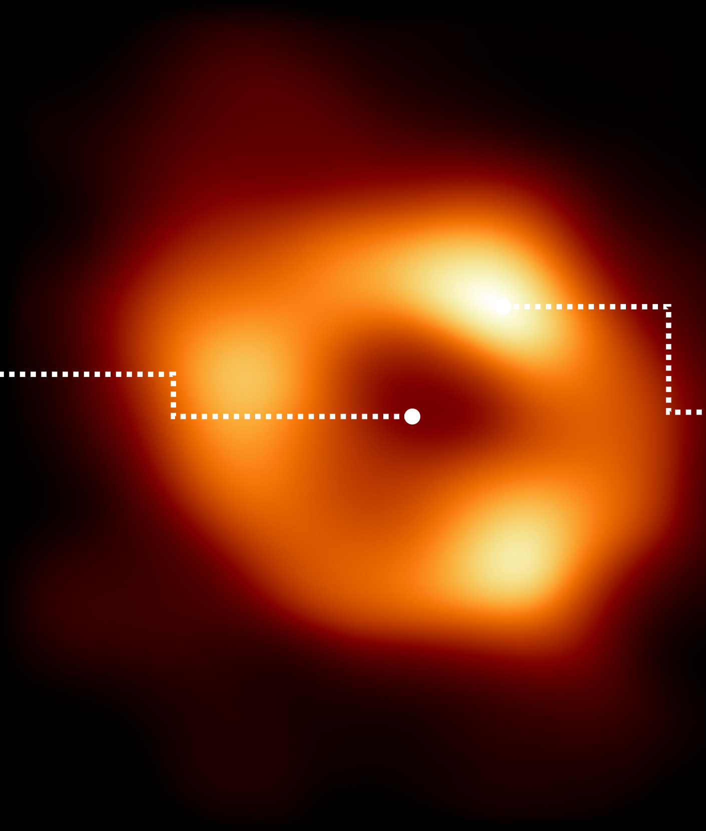
Samuel E. Gralla*

Department of Physics, University of Arizona, Tucson, Arizona 85721, USA

(Received 28 October 2020; accepted 21 December 2020; published 12 January 2021)

No. All theoretical predictions for the observational appearance of an accreting supermassive black hole, as measured interferometrically by a sparse Earth-sized array at current observation frequencies, are sensitive to many untested assumptions about accretion flow and emission physics. There is no way to distinguish a violation of general relativity from the much more likely scenario that the relevant "gastrophysical" assumptions simply do not hold. Tests of general relativity will become possible with longer interferometric baselines (likely requiring a space mission) that reach the resolution where astrophysics-independent predictions of the theory become observable.

DOI: 10.1103/PhysRevD.103.024023



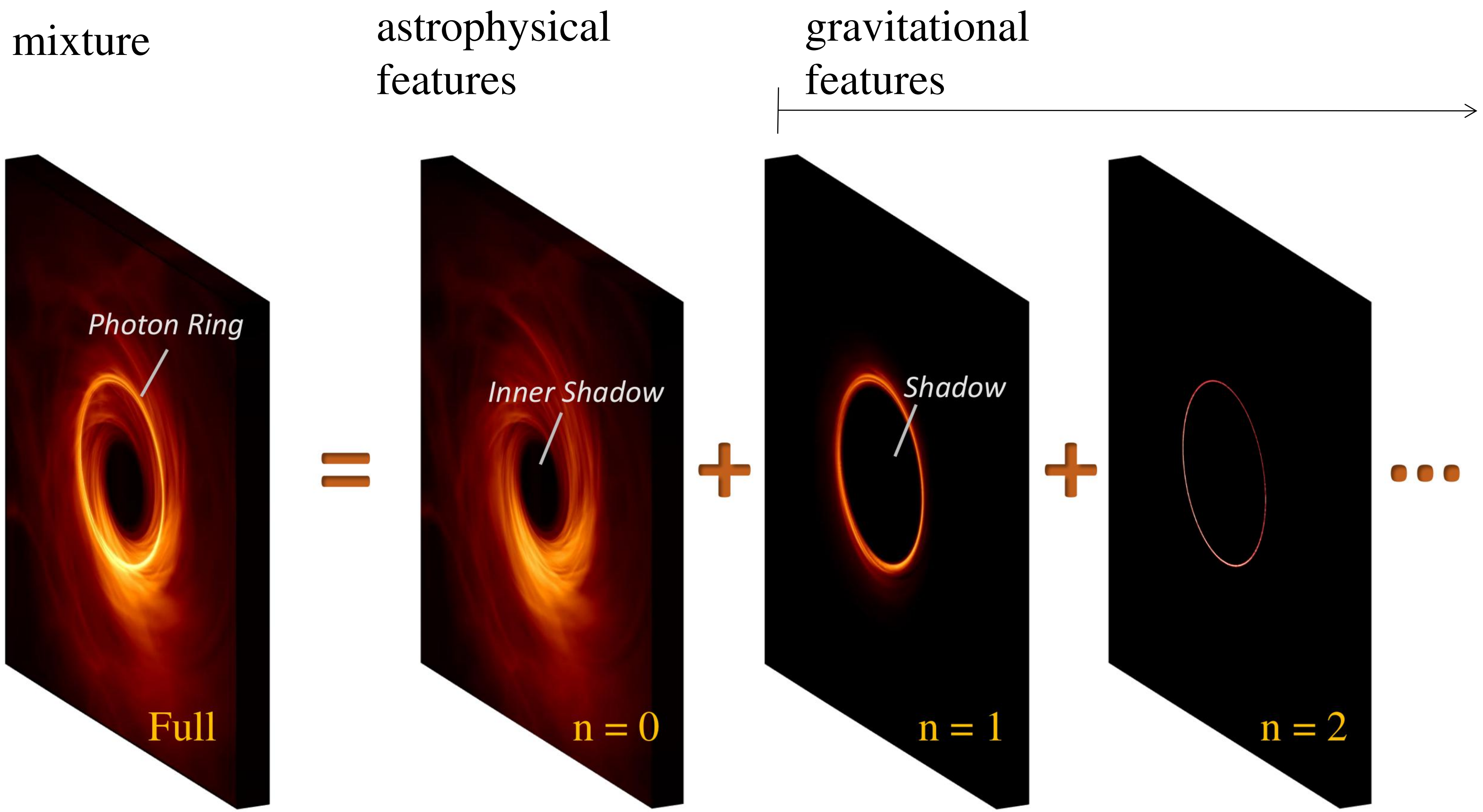
Fundamental Physics

Testing GR in strong gravitational field

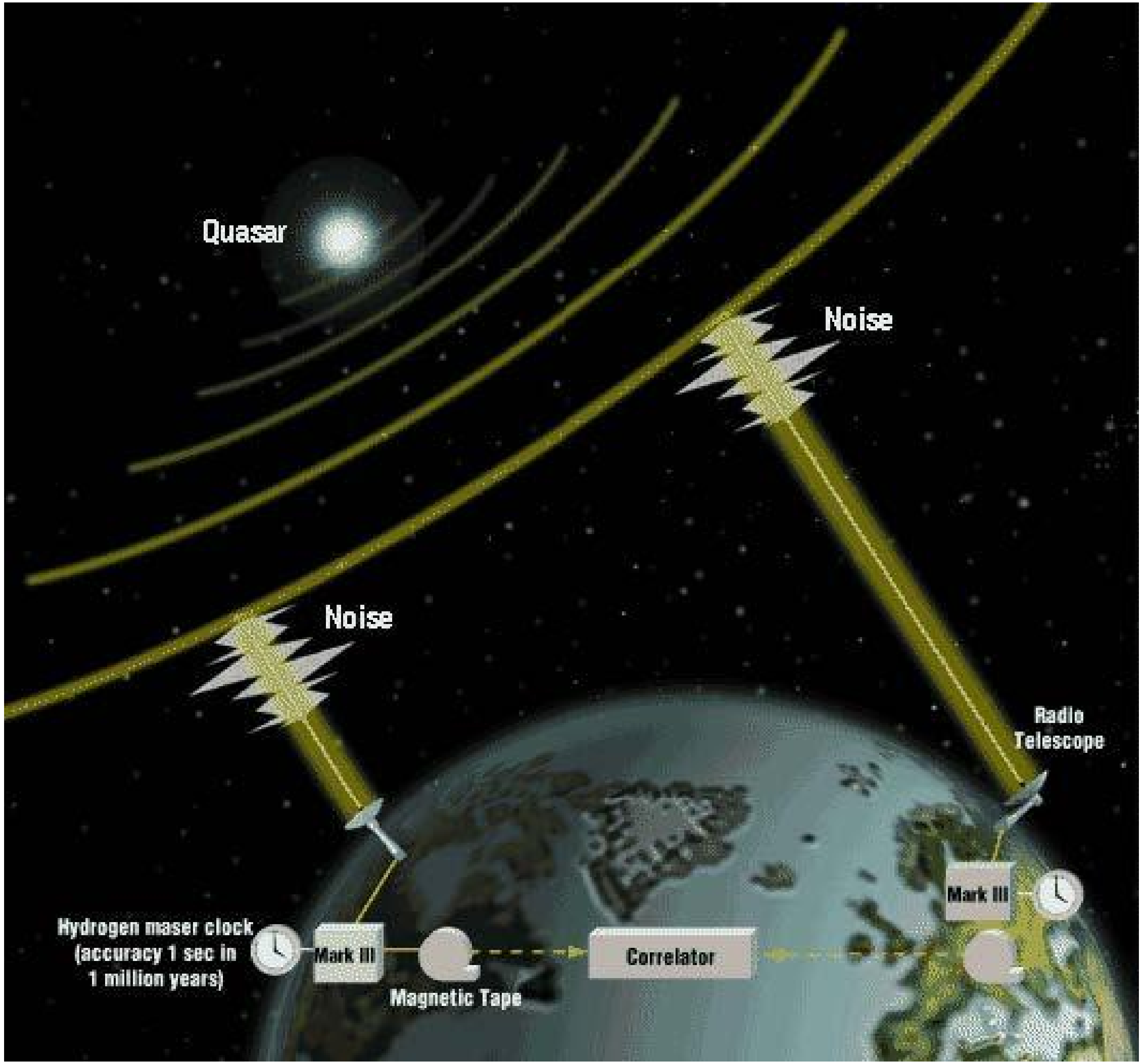
Astrophysics

dynamics+radiation of accretion flow/jet

EHT collaboration et al. 2022



mixture
astrophysical features
gravitational features
Photon Ring
Full
=
Inner Shadow
n = 0
+
Shadow
n = 1
+
n = 2
...

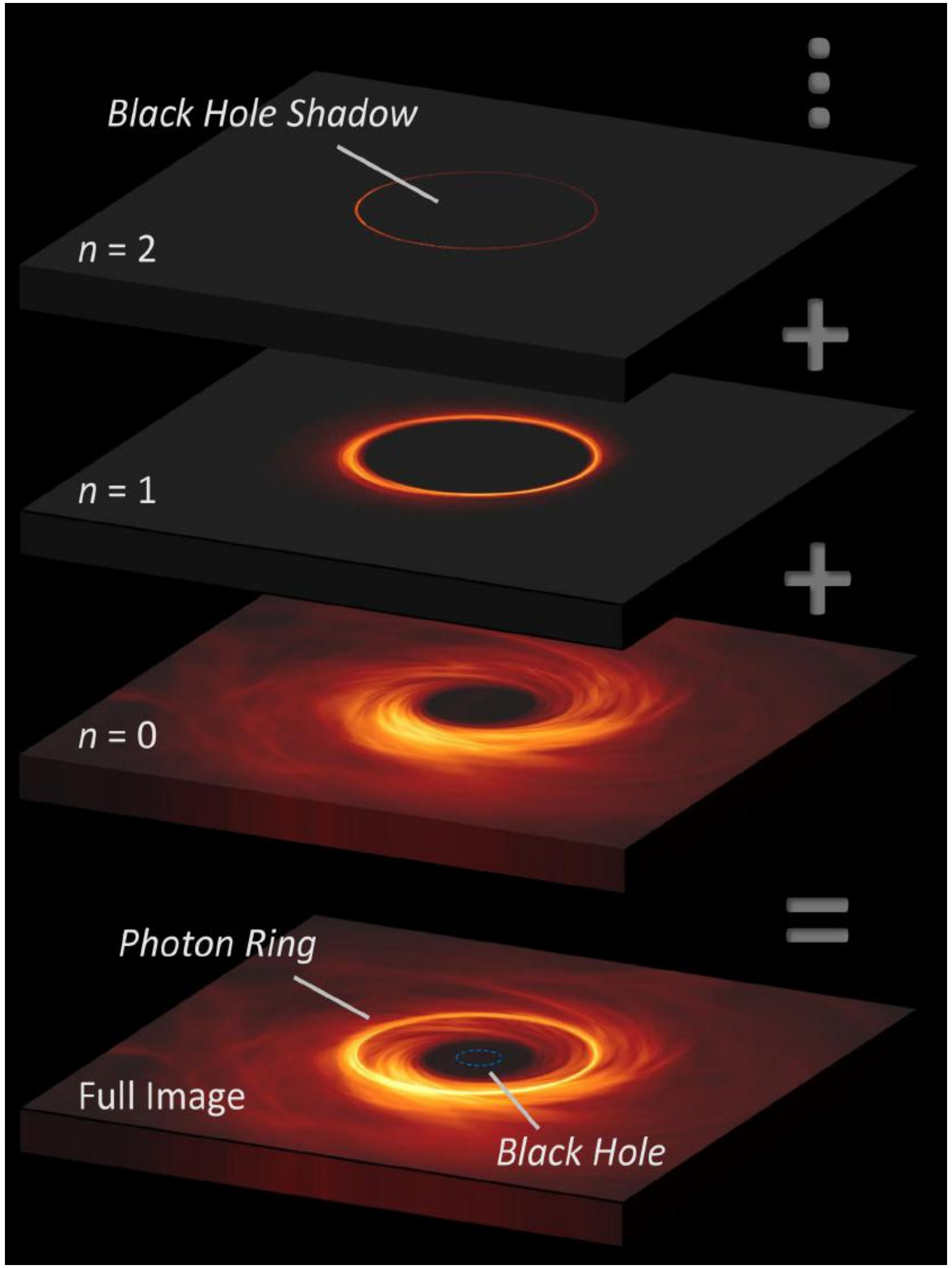


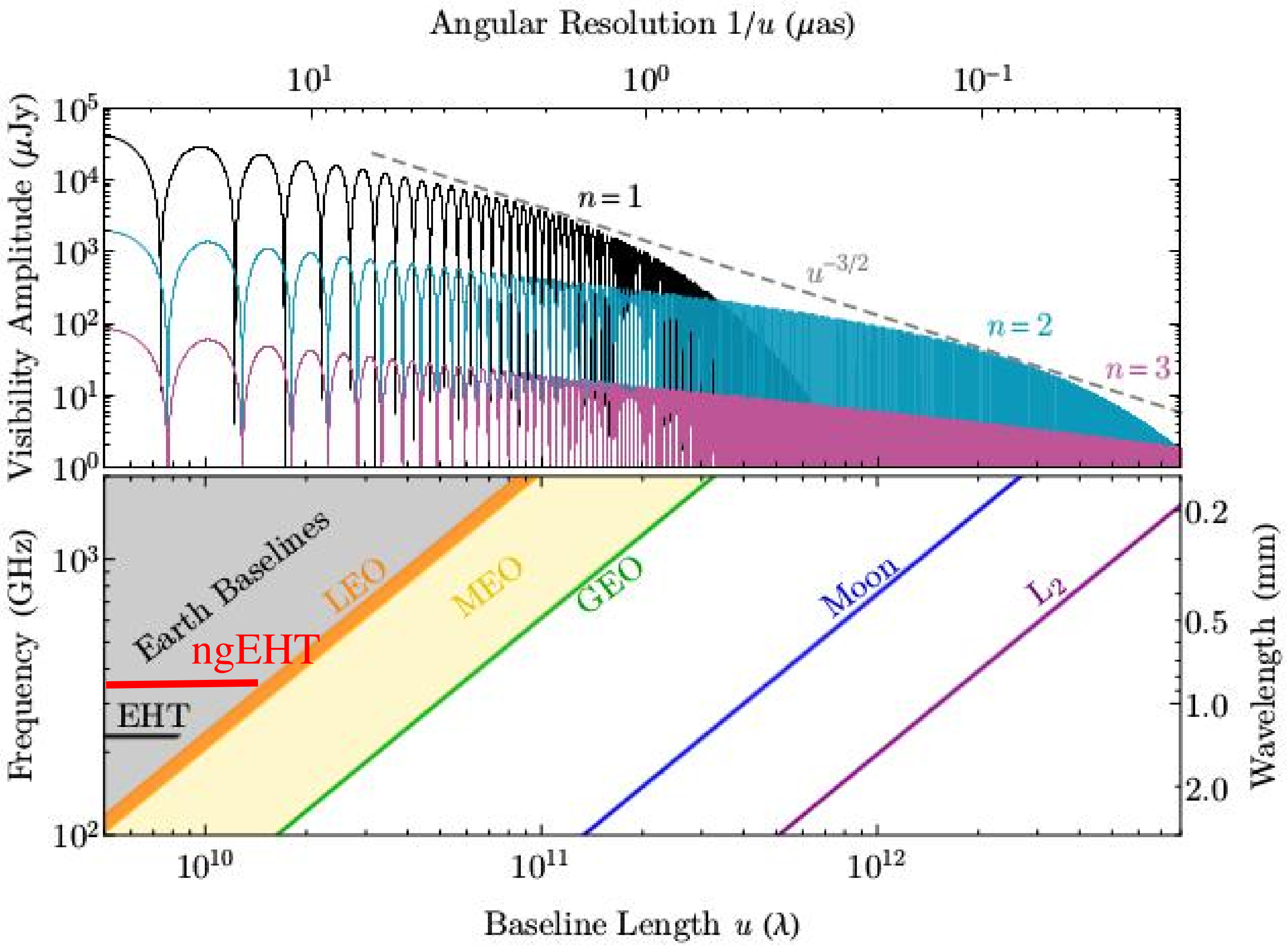
Very Long Baseline Interferometry (VLBI)

$$\text{angular resolution} \propto \frac{\text{wavelength}}{\text{baseline}}$$

GMVA 86 GHz 40 muas
EHT 230 GHz 20 muas (15 muas)
ngEHT 345 GHz 10 muas

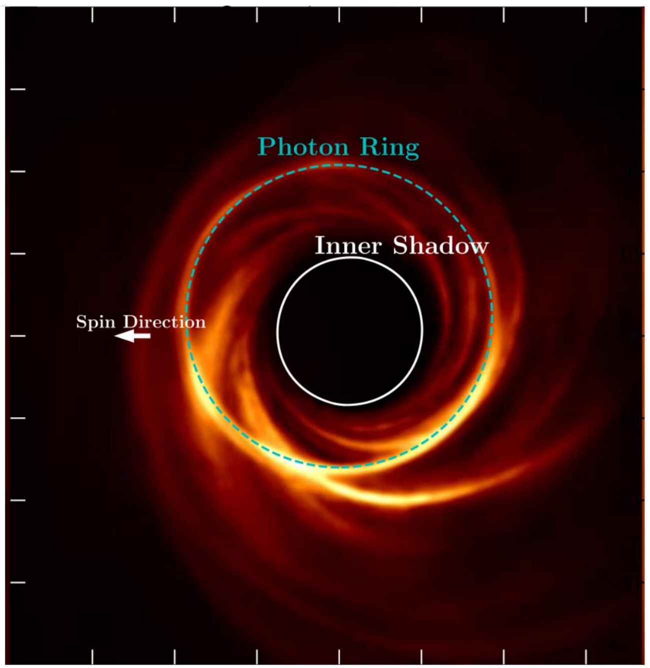
Test GR: Sub photon rings

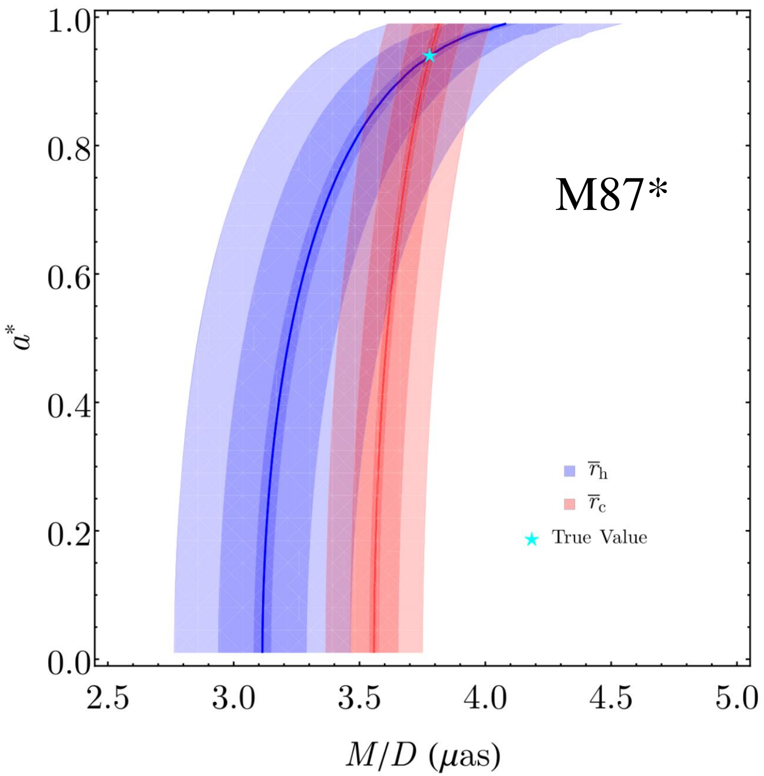




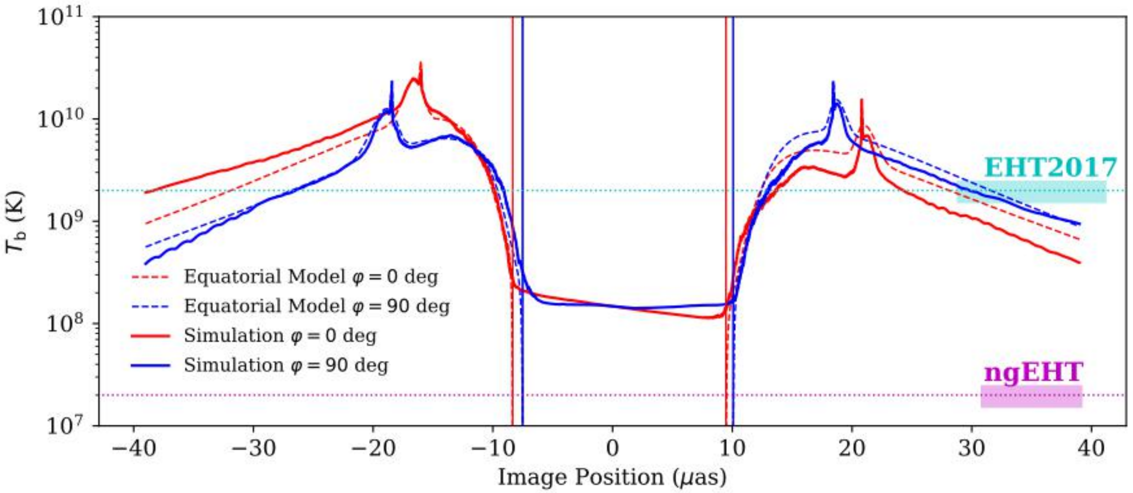
(Johnson et al. 2020)

Test GR: inner shadow / lensed horizon





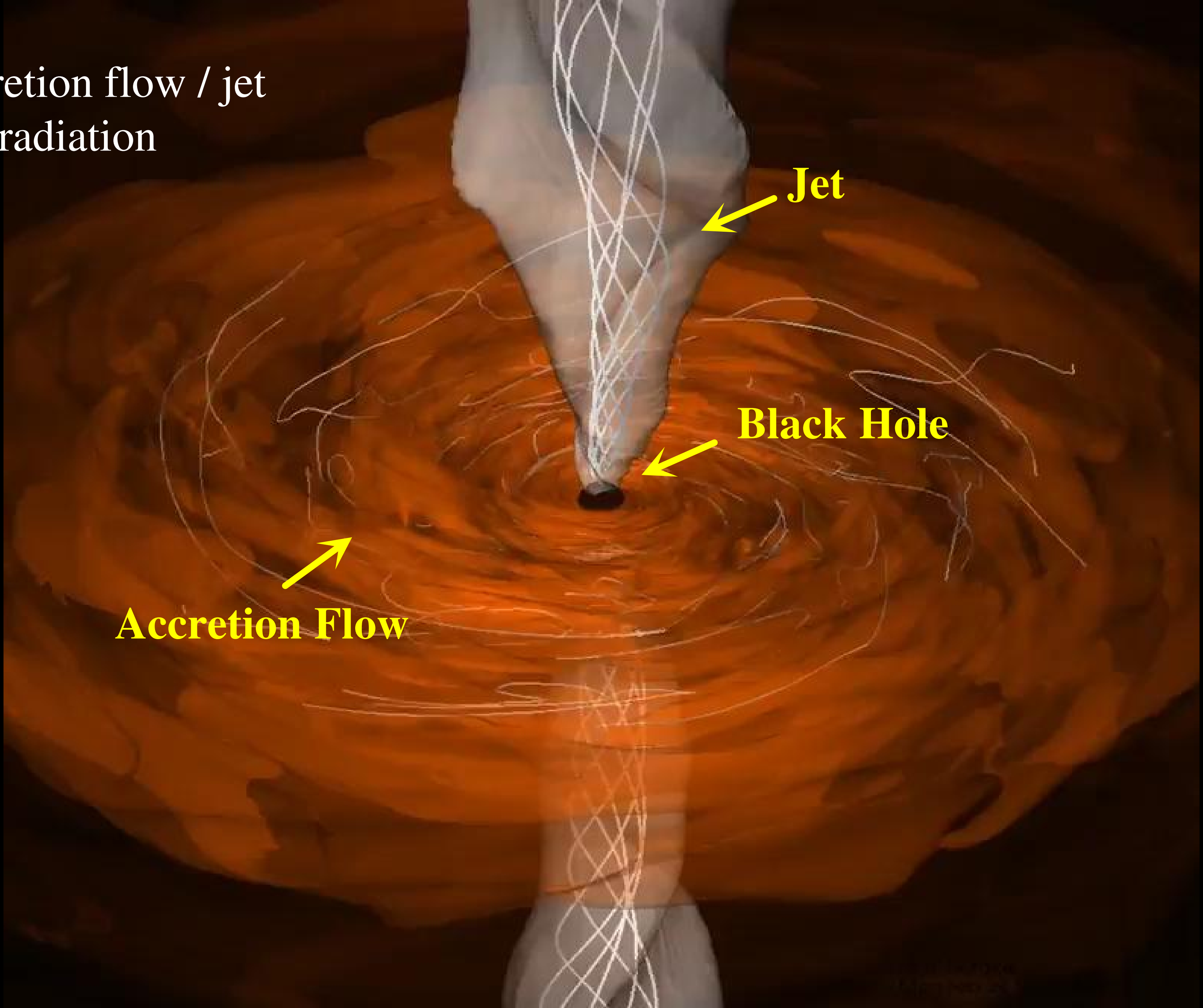
inner shadow size
photon ring size
shades refer to 1μas, 0.5μas, 0.1μas



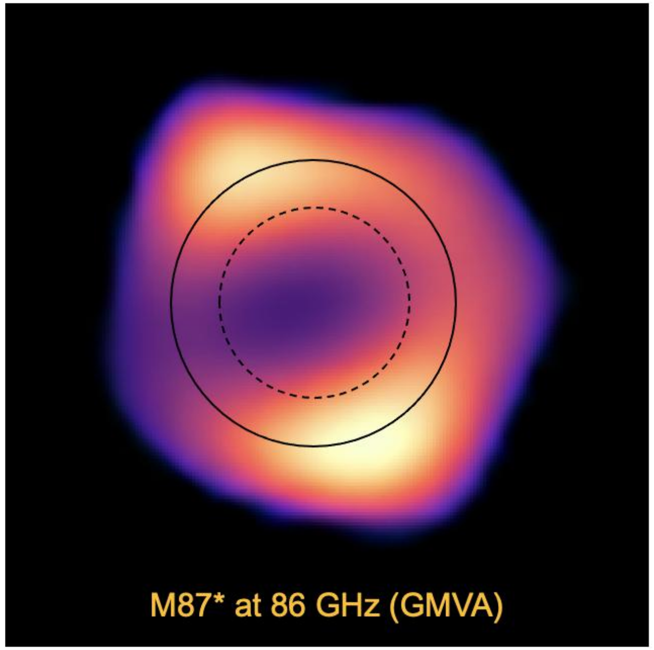
ngEHT dynamic range
improves 2 order than EHT

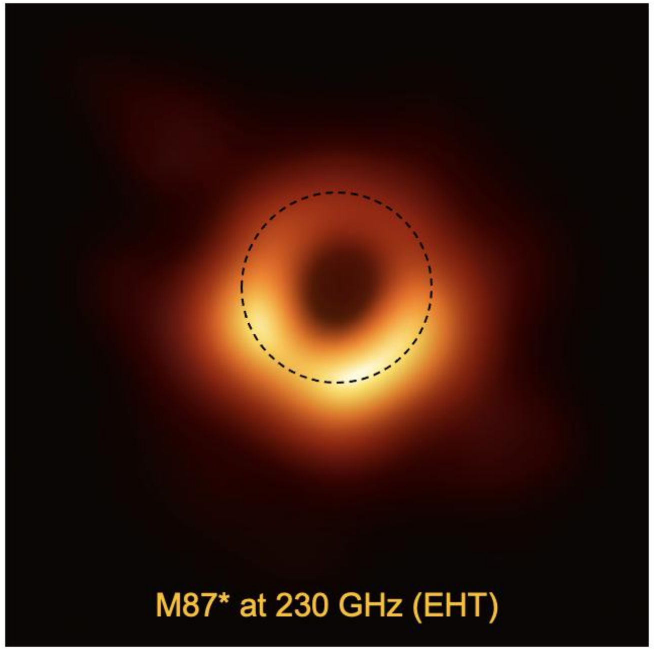
(Chael, Johnson, & Lupsasca 2020)

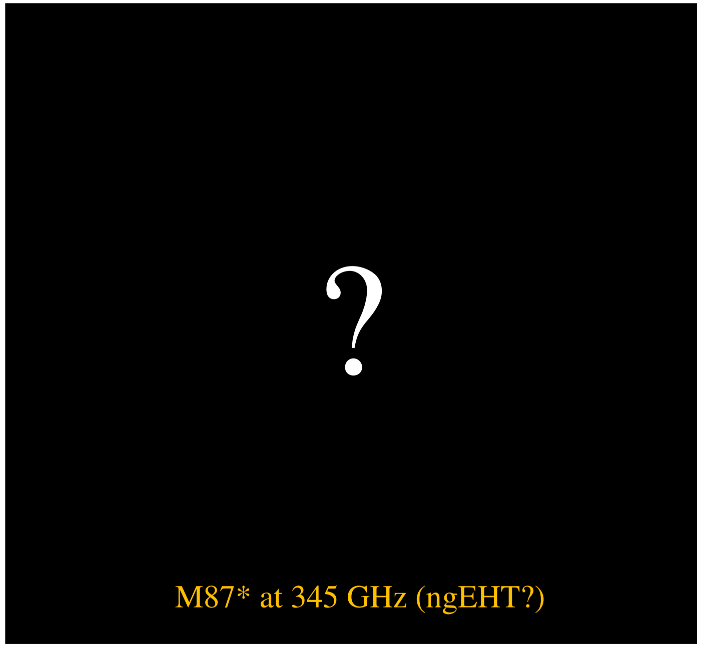
Study Accretion flow / jet dynamics+radiation



ngEHT will provide multi-frequency black hole images



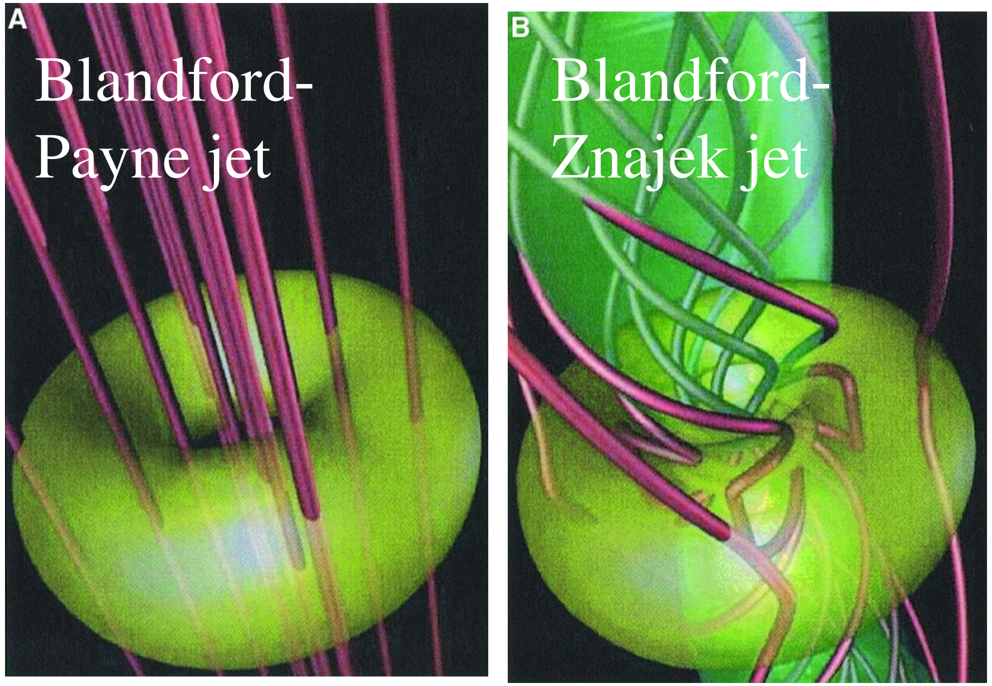




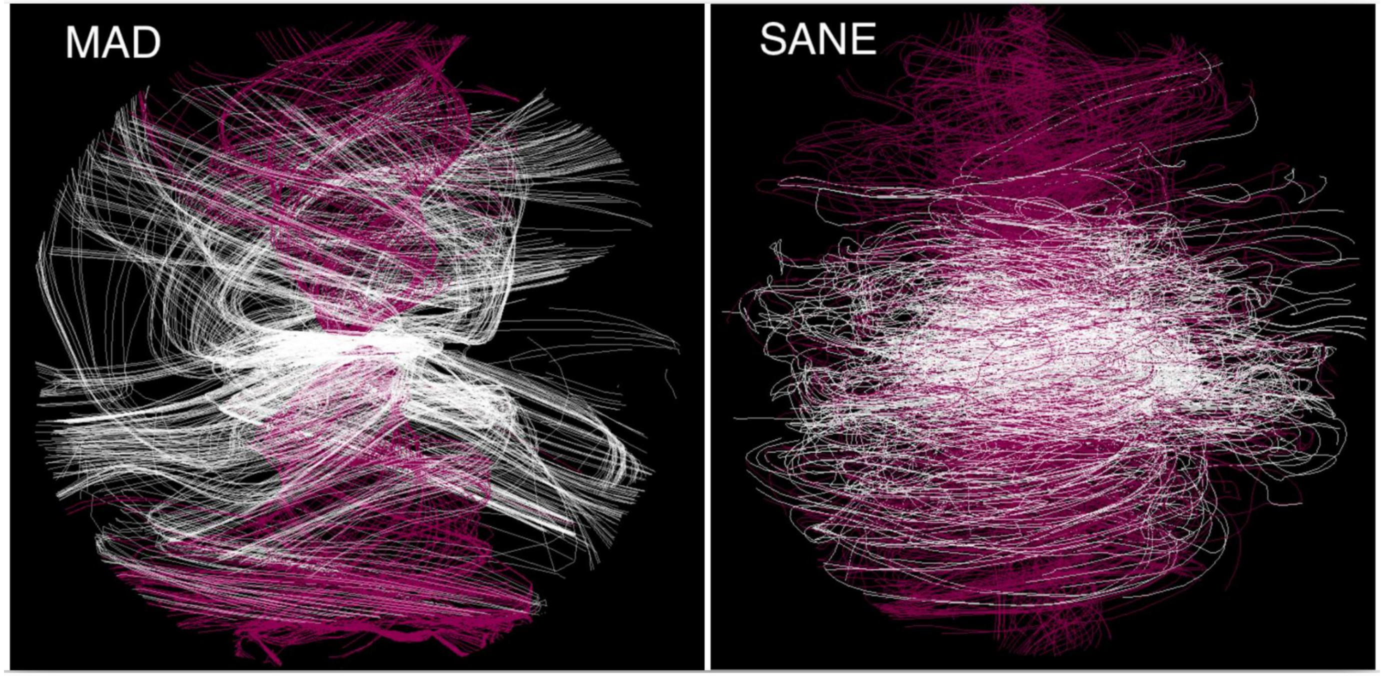
separate astrophysical ring (frequency-dependent) and gravitational ring (frequency-independent)

Study Accretion flow / jet dynamics+radiation

Jet dynamics



Accretion flow dynamics

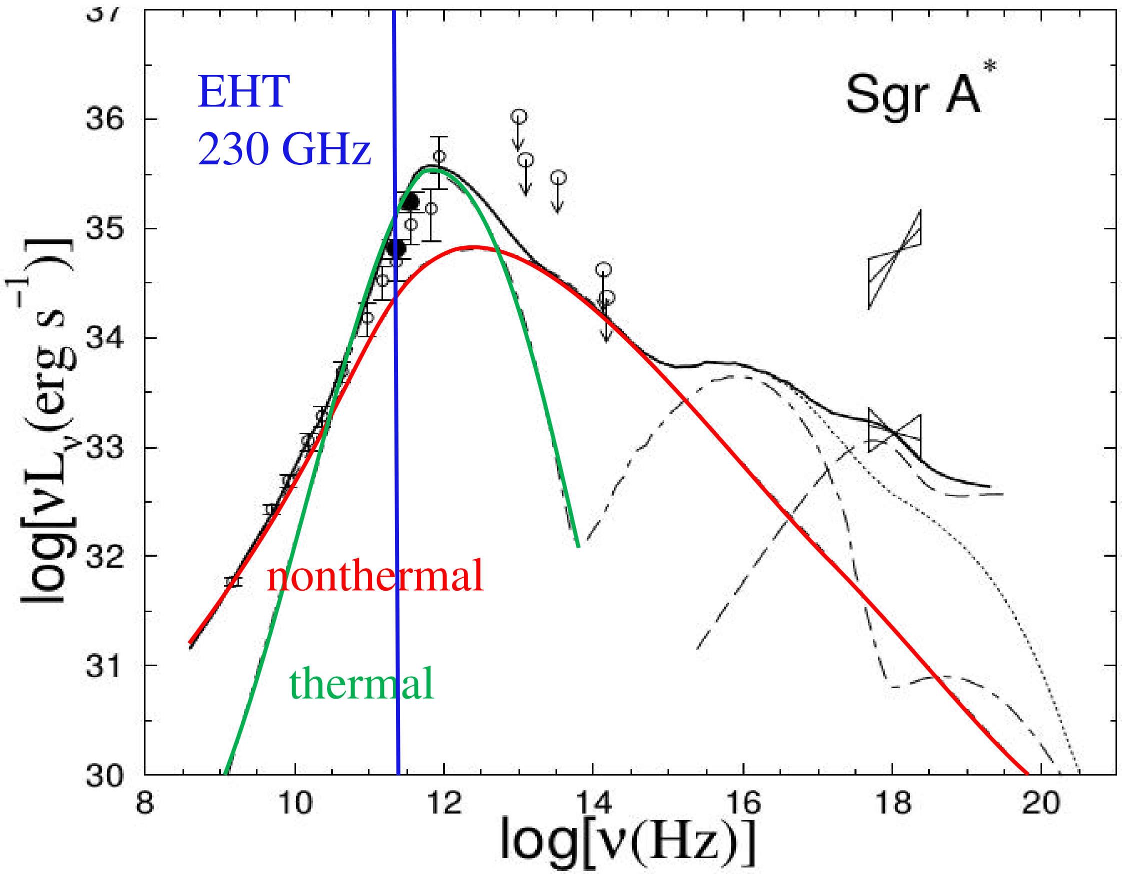


EHT2017 observation of M87* prefer BZ jet, MAD model

Study Accretion flow / jet dynamics+radiation

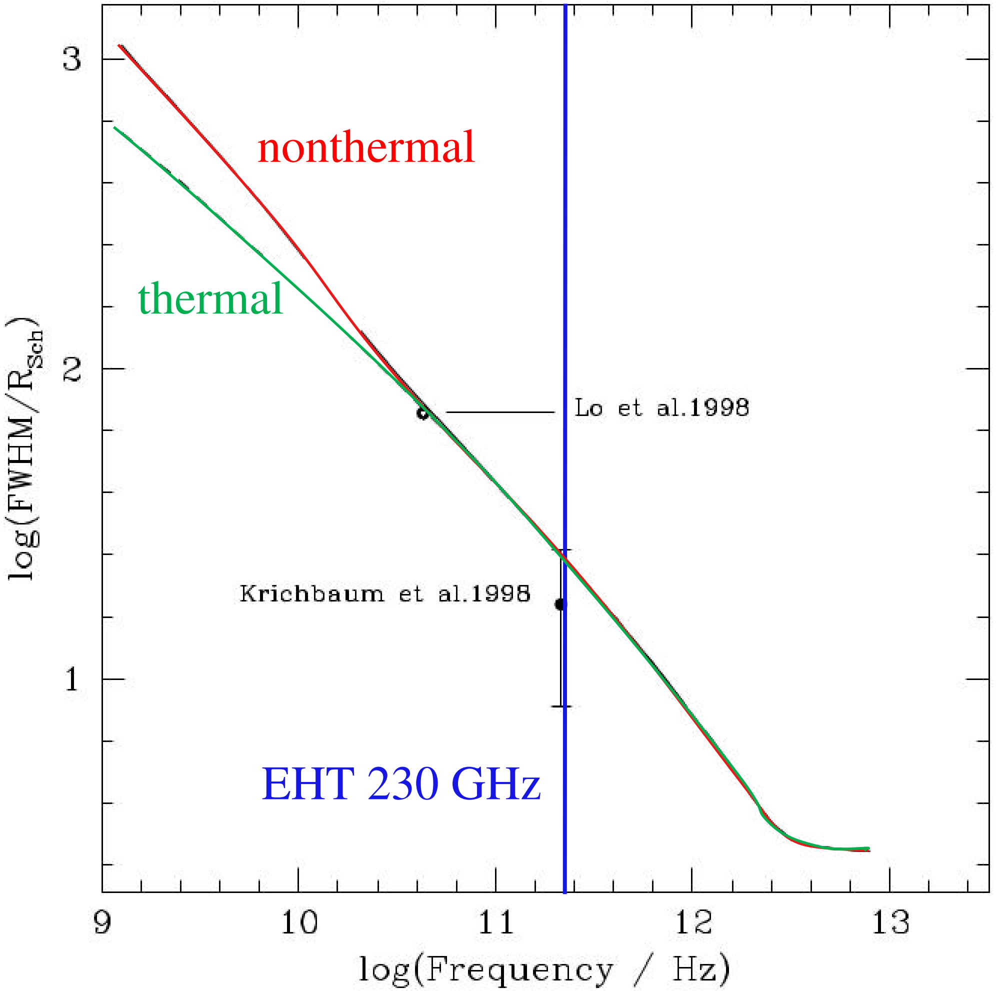
Nonthermal electron radiation

spectrum



(Yuan et al. 2003)

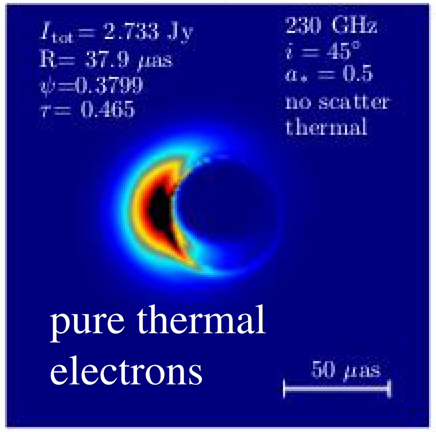
SgrA* source size

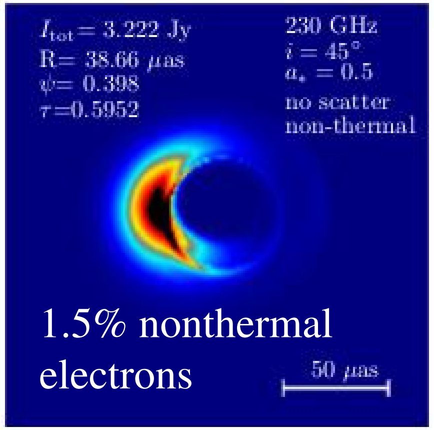


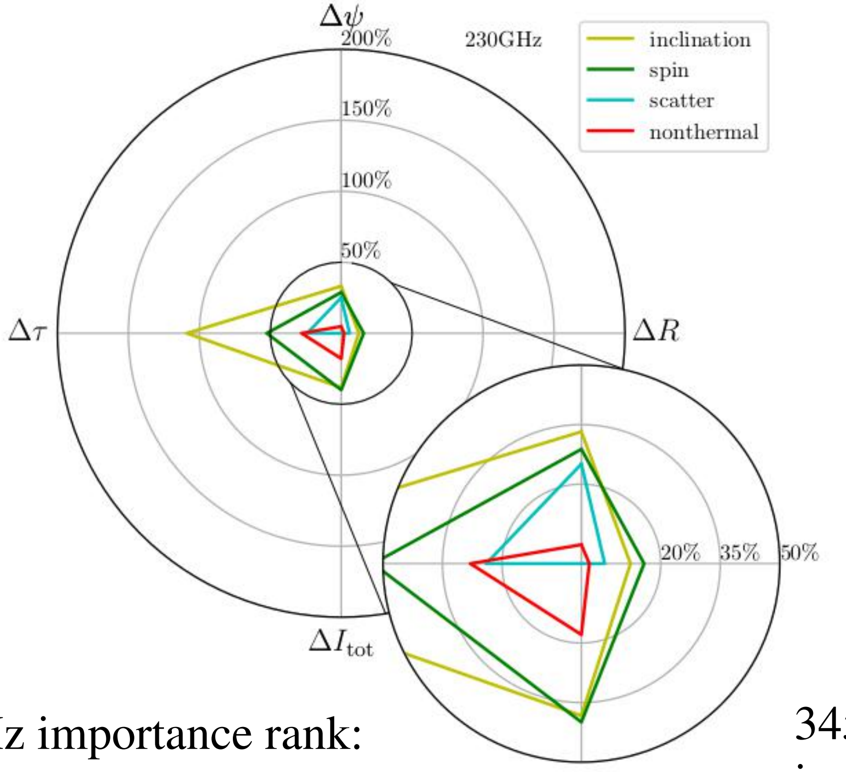
(Ozel et al. 2000)

Impact of nonthermal electron radiation effects on the horizon scale image structure of Sagittarius A*

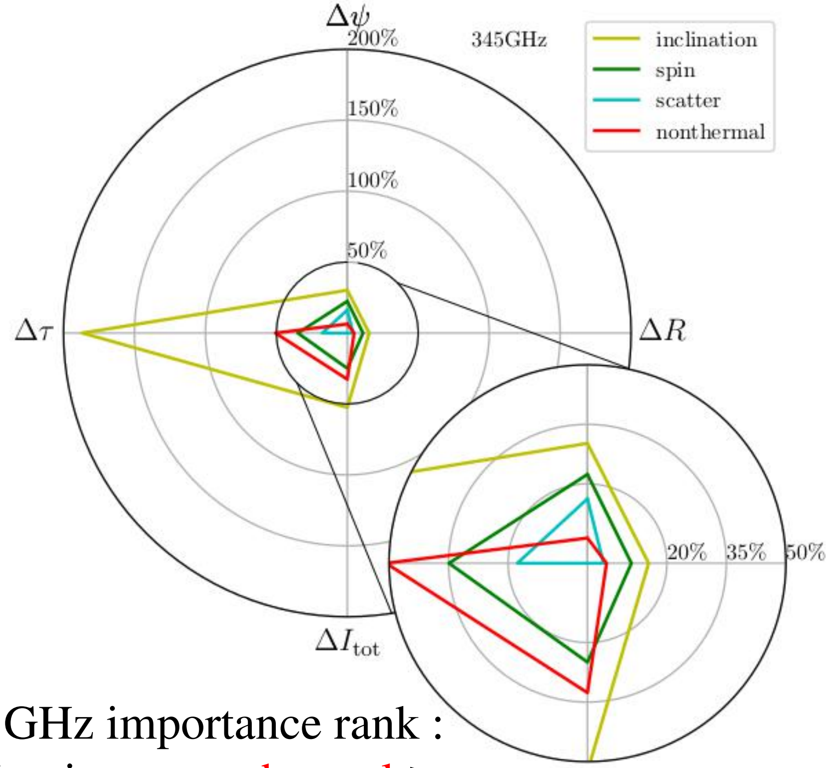
Shan-Shan Zhao,[1★] Lei Huang,[1,2] Ru-Sen Lu[1,3,4] and Zhiqiang Shen[1,3]







230 GHz importance rank: inclination > spin > scatter ≈ nonthermal



345 GHz importance rank : inclination > nonthermal ≳ spin > scatter

(Zhao et al. 2022)

Importance of the nonthermal electron radiation at 230/345 GHz

	$\Delta I_{\rm tot}$ (%)		ΔR (%)		$\Delta\psi$ (%)		$\Delta\tau$ (%)	
	230 GHz	345 GHz	230 GHz	345 GHz	230 GHz	345 GHz	230 GHz	345 GHz
inclination	38.29	52.47	12.37	15.41	33.23	30.2	108.8	186.9
spin	39.92	24.94	15.81	11.07	28.8	22.39	52.47	34.9
scatter	0	0	5.882	4.044	25.08	16.23	23.98	17.67
nonthermal electrons	17.9	32.63	2.001	4.806	4.767	6.351	27.99	50.75

Table 1
Measured Parameters of Sgr A*

Parameter	EHT Estimate
Emission ring:[a]	
Diameter, d	51.8 ± 2.3 μas
Fractional width, W/d	~30–50

-> 4.4% uncertainty

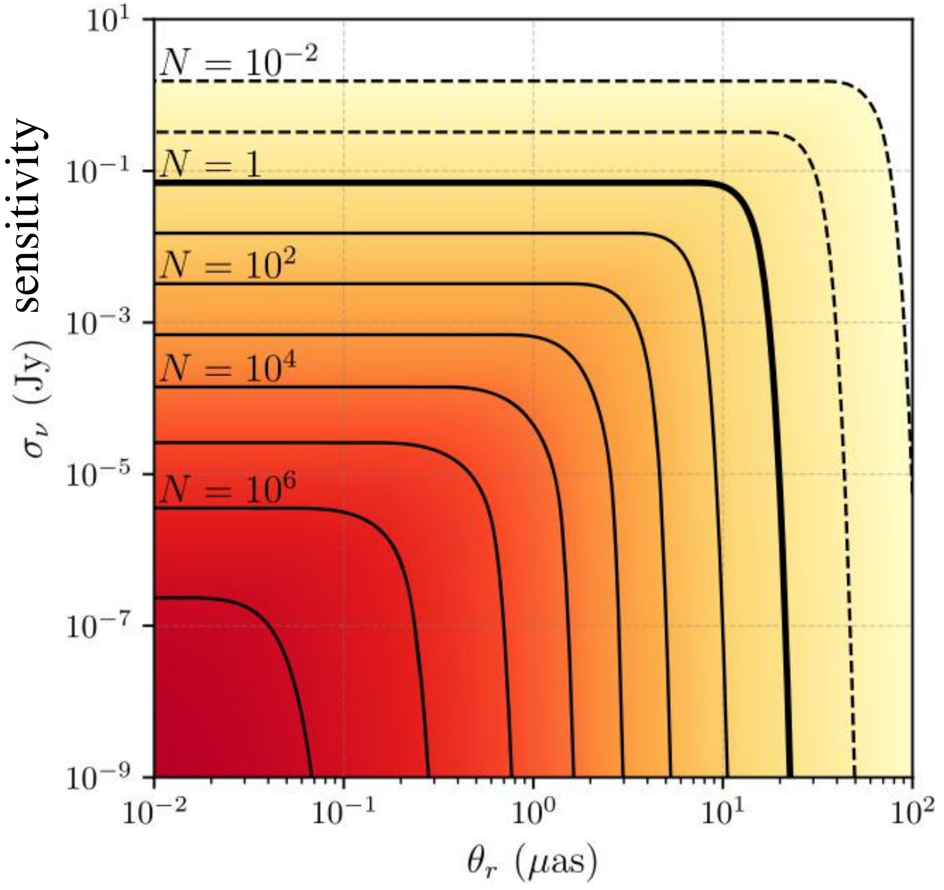
(EHTC+ 2022)

- current 230 GHz: ~2% size difference, twice smaller than the ring size measurement uncertainty by EHT
- future 345 GHz: ~5% size difference, may detectable.

(Zhao et al. 2022)

More BH images

number of observable black hole shadows



photon ring size

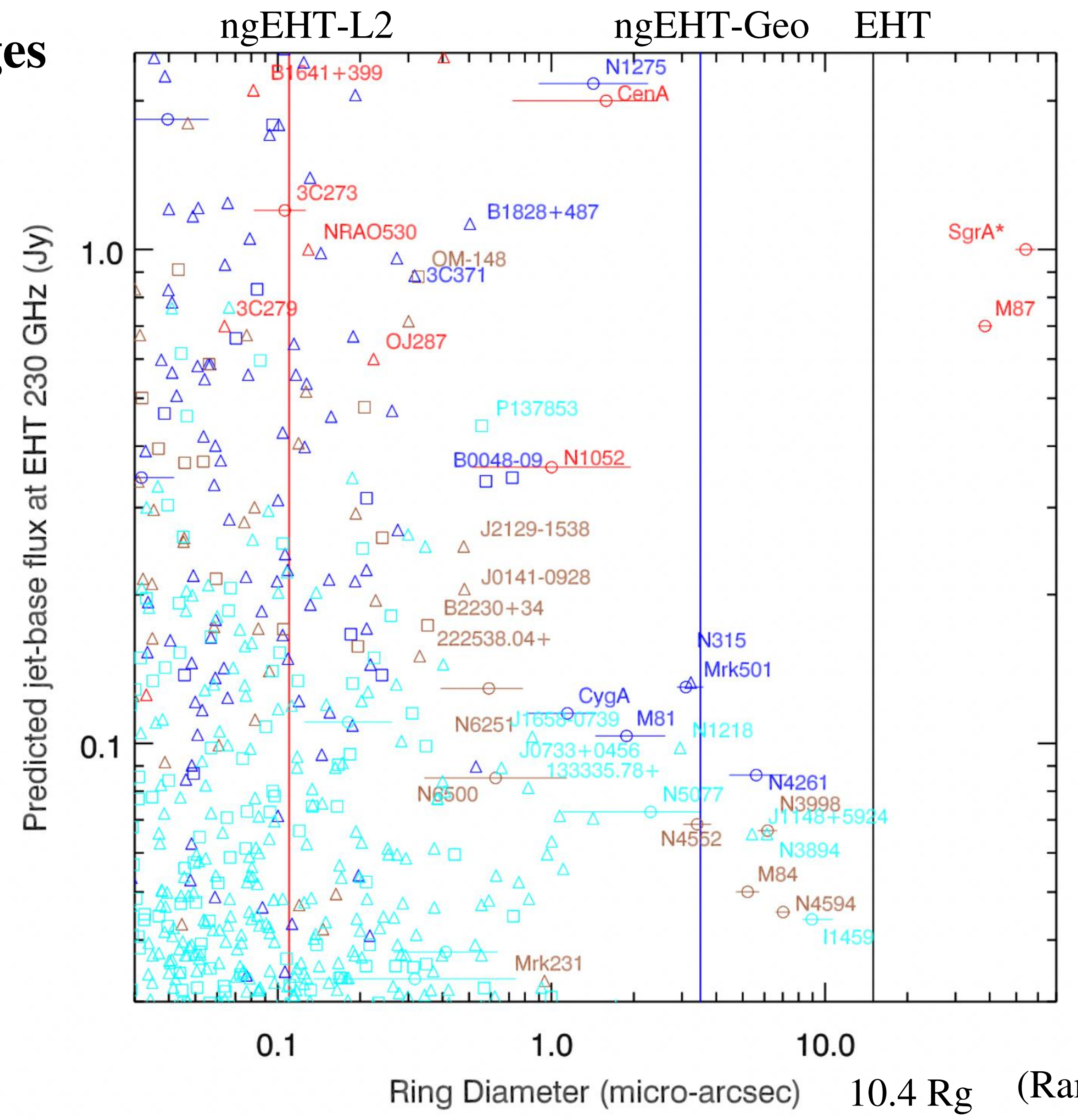
Table 1
Population Characteristics at 230 GHz

Target Population	How many?	Properties	
		ϑ (μas)	S_ν (Jy)
	M87	40	0.5
	1	(12.8, 24.5)	(3.8, 16.5) $\times 10^{-2}$
Black hole shadows	10^2	(3.1, 5.4)	(1.6, 5.5) $\times 10^{-3}$
	10^4	(0.81, 1.1)	(7.9, 17.0) $\times 10^{-5}$
	10^6	(0.15, 0.23)	(1.9, 4.9) $\times 10^{-6}$

- sensitivity<70mJy, EHT (20 μas) can find ~5 more black hole shadows
- ≲1μas, ≪1mJy can observe a lot of black hole shadows

(Pesce et al. 2021)

More BH images



(Ramakrishnan et al. 2023)

More BH images: independent mass measurement

black hole shadow measurements -> a sample of black hole mass

black hole and galaxy co-evolution

black hole mass

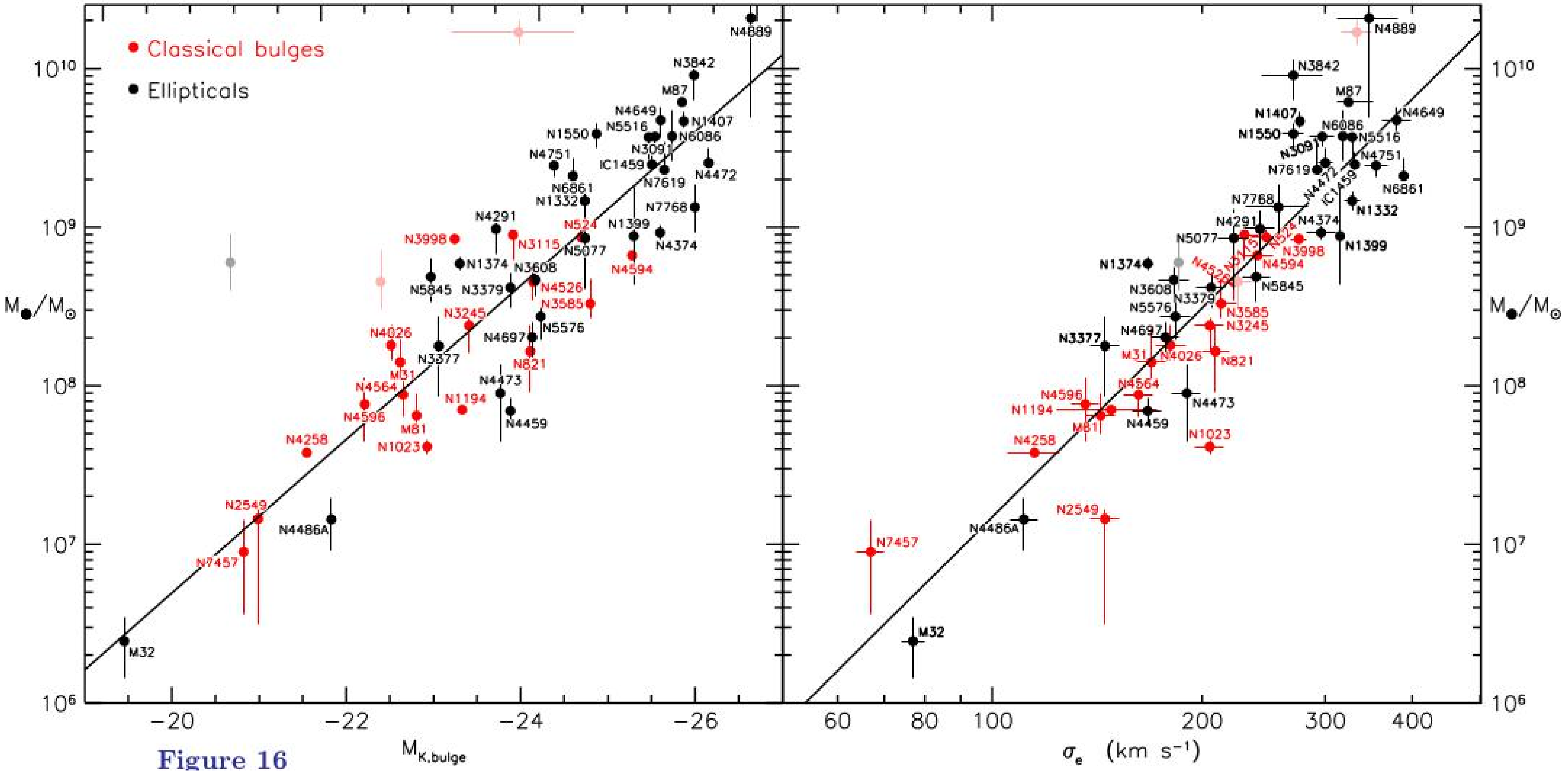


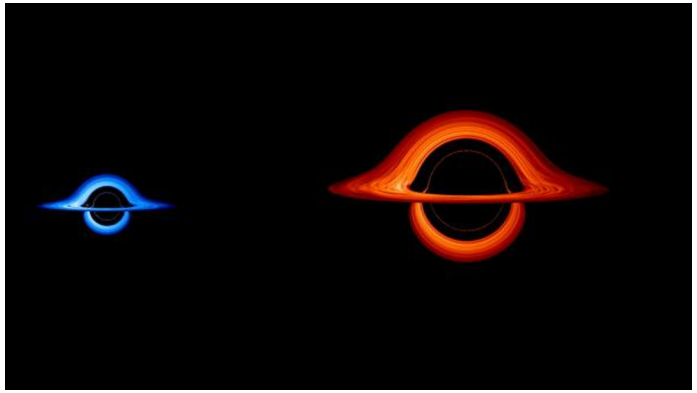
Figure 16

bulge magnitude

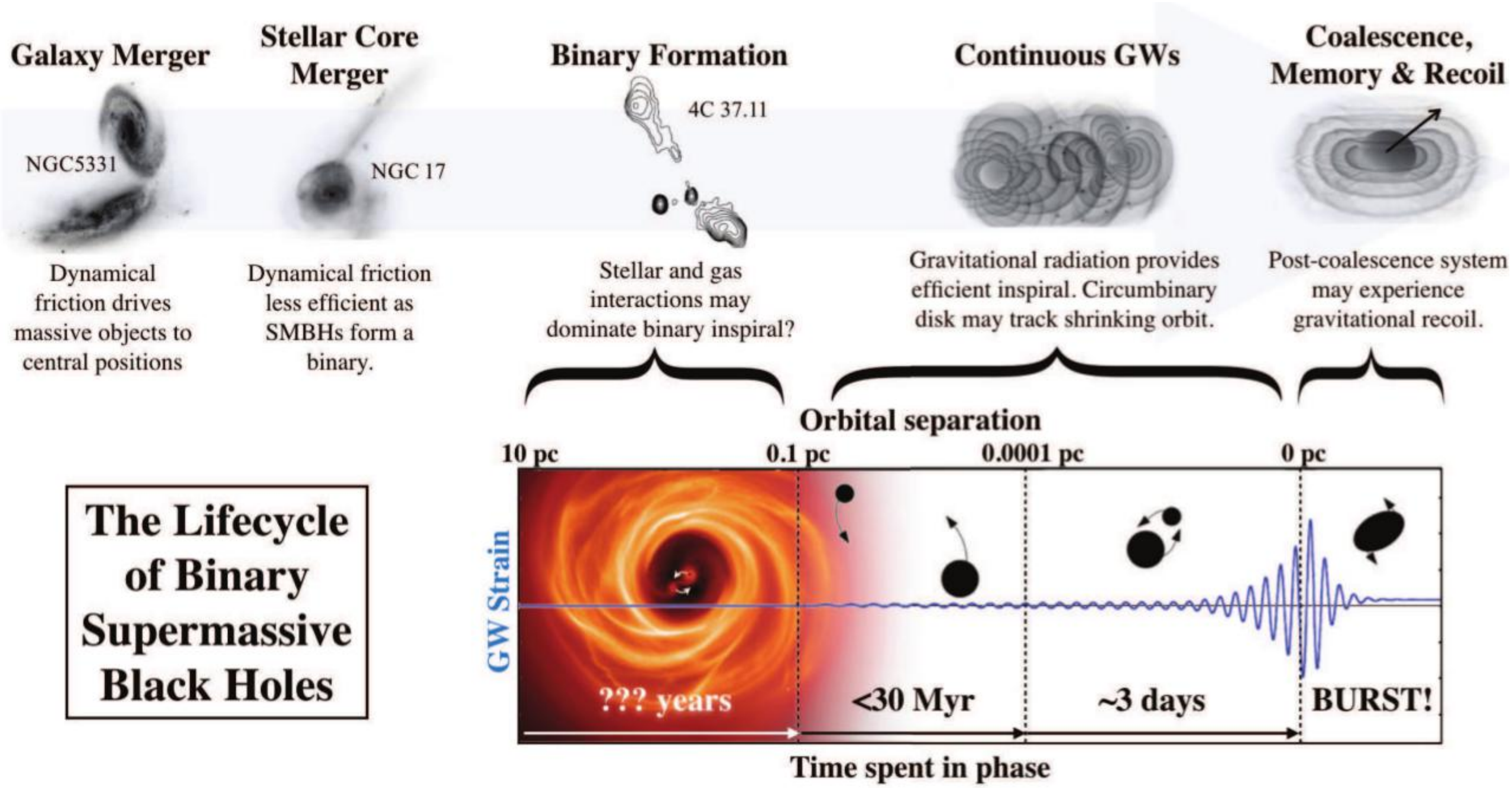
velocity dispersion

(Kormendy & Ho 2013)

supermassive black hole binaries (SMBHBs) detection

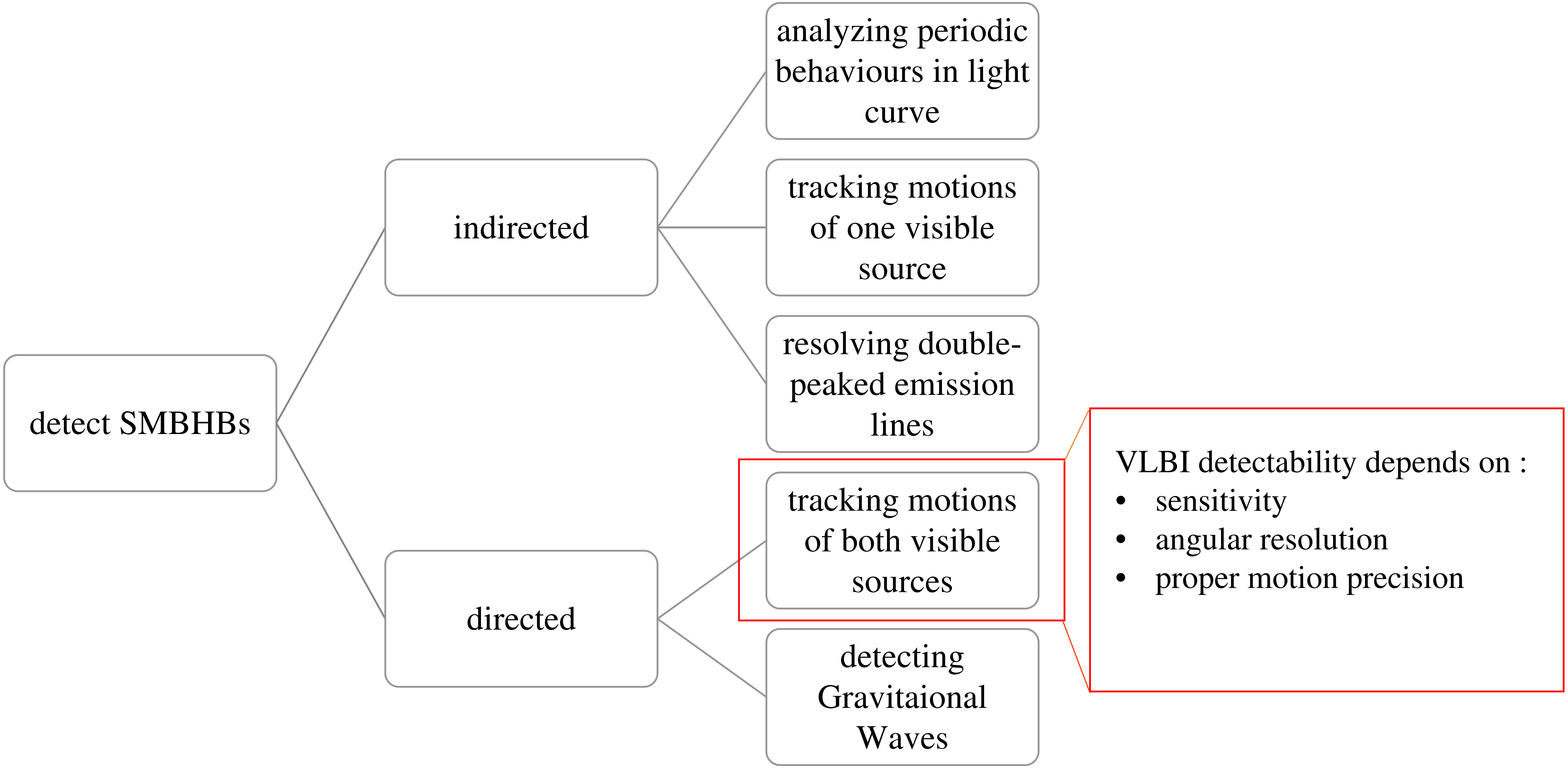


(Image credit: NASA's Goddard Space Flight Center/Jeremy Schnittman and Brian P. Powell)



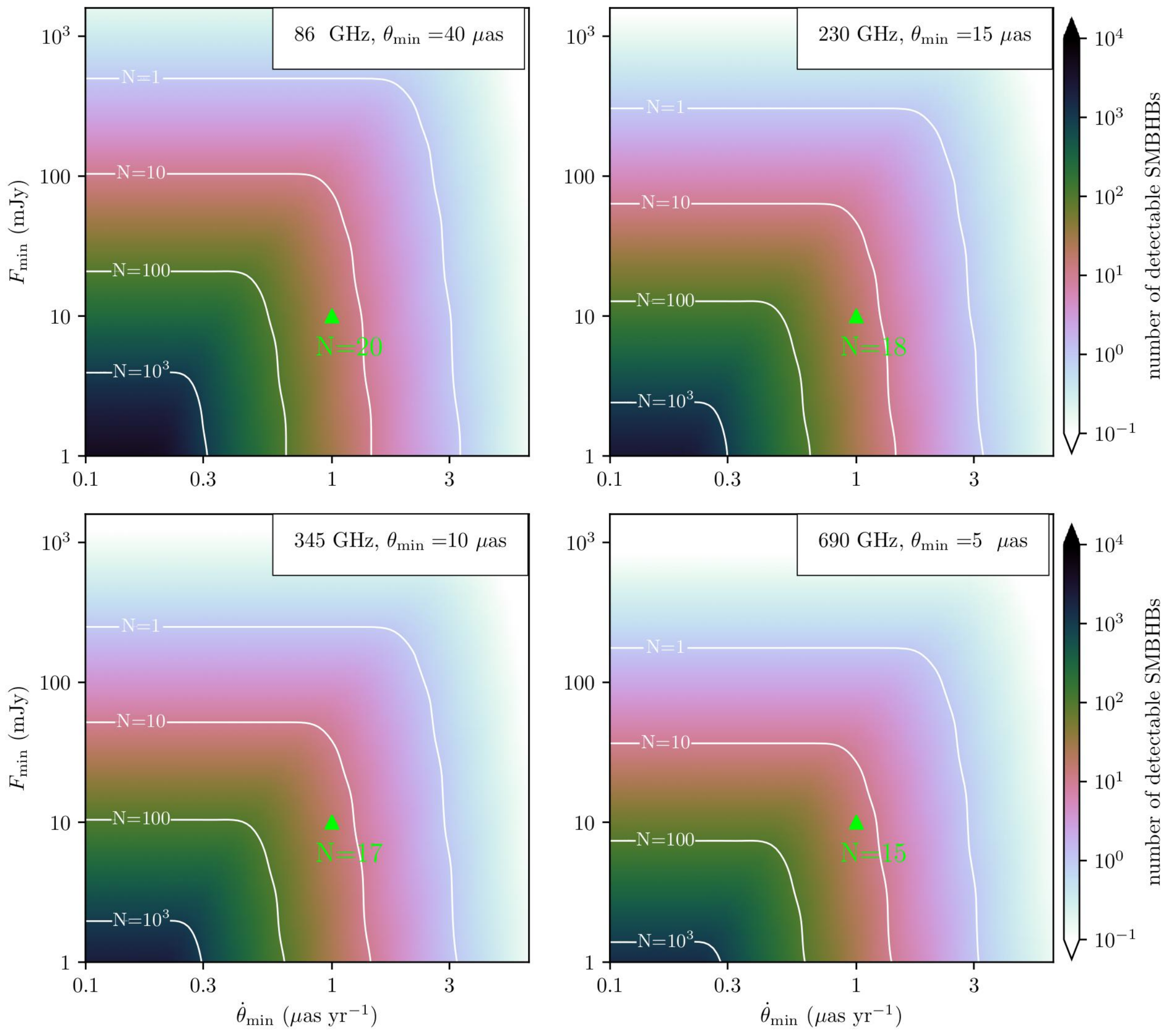
Burke-Spolaor et al. (2018)

SMBHBs binaries



How many SMBH binaries are detectable through tracking relative motions by (sub)millimeter VLBI

Shan-Shan Zhao, Wu Jiang, Rusen Lu, Lei huang, Zhiqiang Shen



$\dot{\theta}_{\min}$ (μas/yr)	Num. of detect. SMBHBs* 86 GHz	230 GHz	345 GHz	690 GHz
3	1	0	0	0
1	20	18	17	15
0.1	279	140	105	64

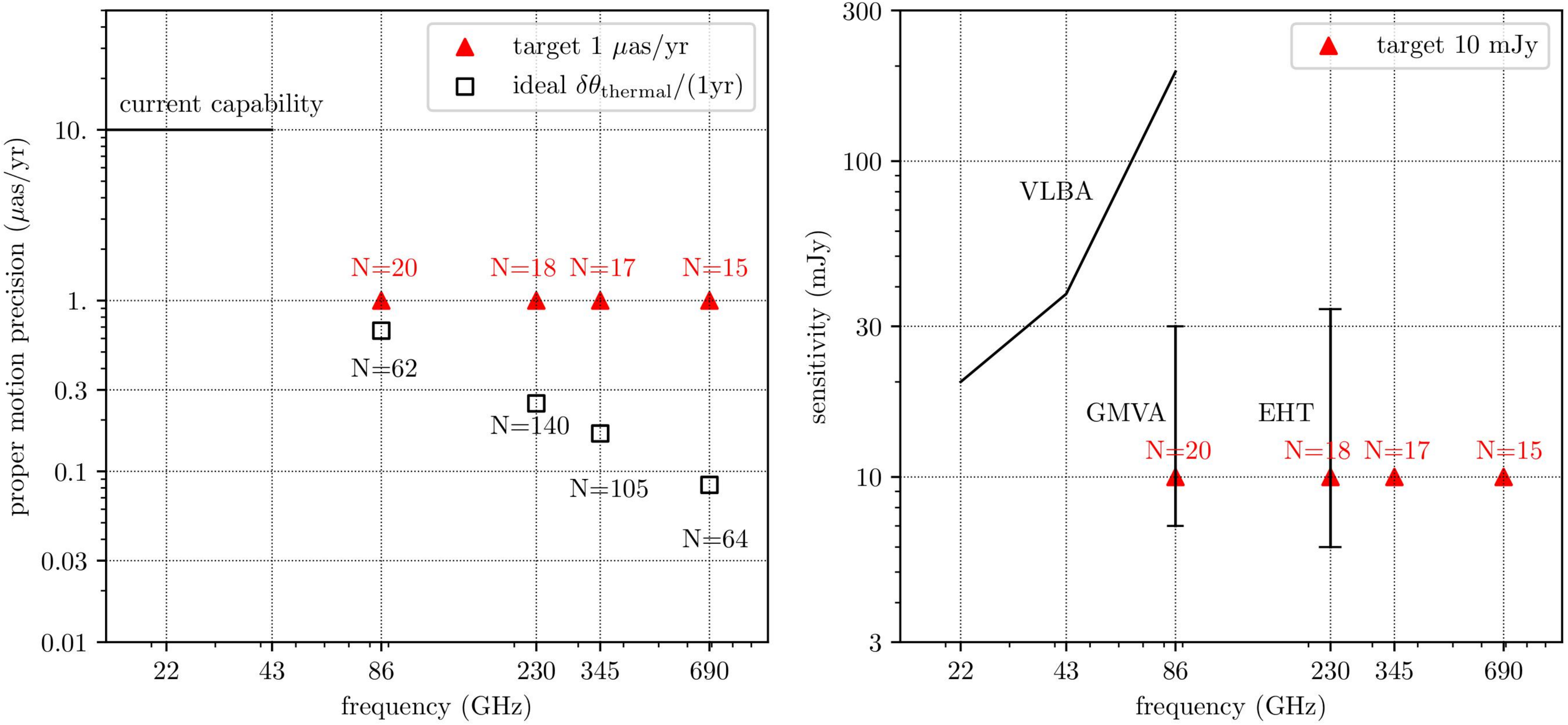
$F_{\min} = 10$ mJy

By using simultaneous multi-frequency technique, (sub)millimeter VLBI can achieve

- 1 muas/yr astrometry
- 10 mJy sensitivity
- better than 40 muas resolution

=> ~20 SMBHB systems can be detected

(Zhao et al. 2023, accepted)



(Zhao et al. 2023, accepted)

also see ngEHT white paper (Jiang et al 2023)

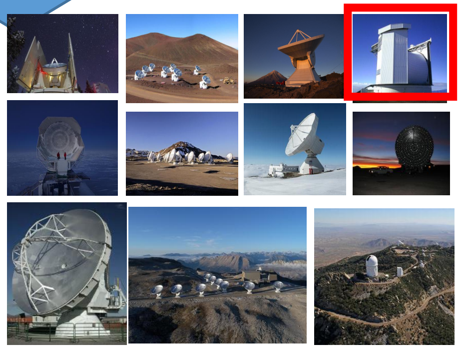
Applications of the Source-Frequency Phase-Referencing Technique for ngEHT Observations

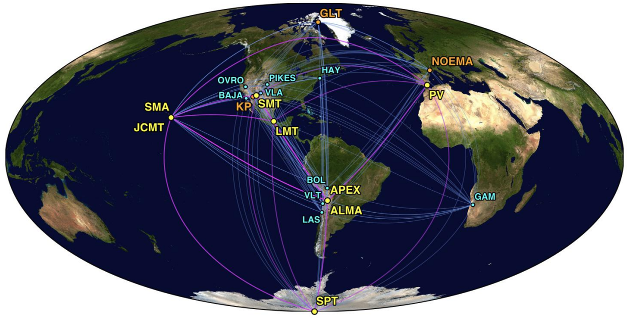
by Wu Jiang [1,2,*], Guang-Yao Zhao [3,*], Zhi-Qiang Shen [1,2], María J. Rioja [4,5,6], Richard Dodson [4], Ilje Cho [3], Shan-Shan Zhao [1,2], Marshall Eubanks [7] and Ru-Sen Lu [1,2,8]

China’s role in ngEHT

- scientists
- telescope(s)
- key techniques

more important role





EHT2017
8-element-array
230GHz

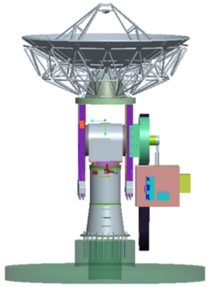
EHT2023
11-element-array
230GHz (345GHz test)

ngEHT
86/230/345GHz

space ngEHT
86-690GHz

China sub-millimeter VLBI: develop plan

STEP1

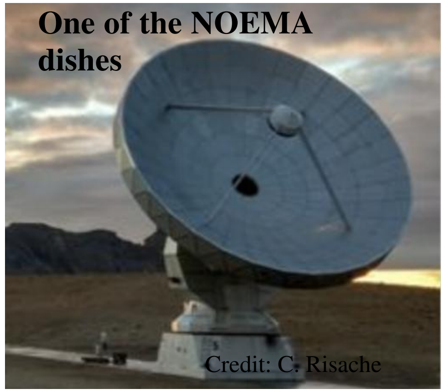


end of 2023

5m telescope in shanghai

for 86 GHz test

STEP2



in 5 years

15m sub-millimeter telescope in Tibet

86-345GHz

join ngEHT

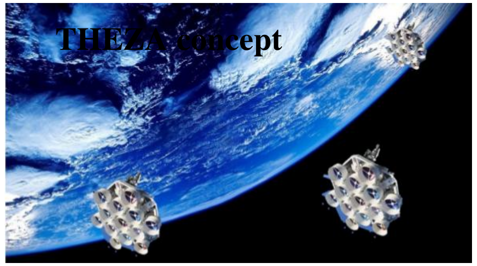
STEP3

in 10 years

3 such telescopes

to form an array

STEP4

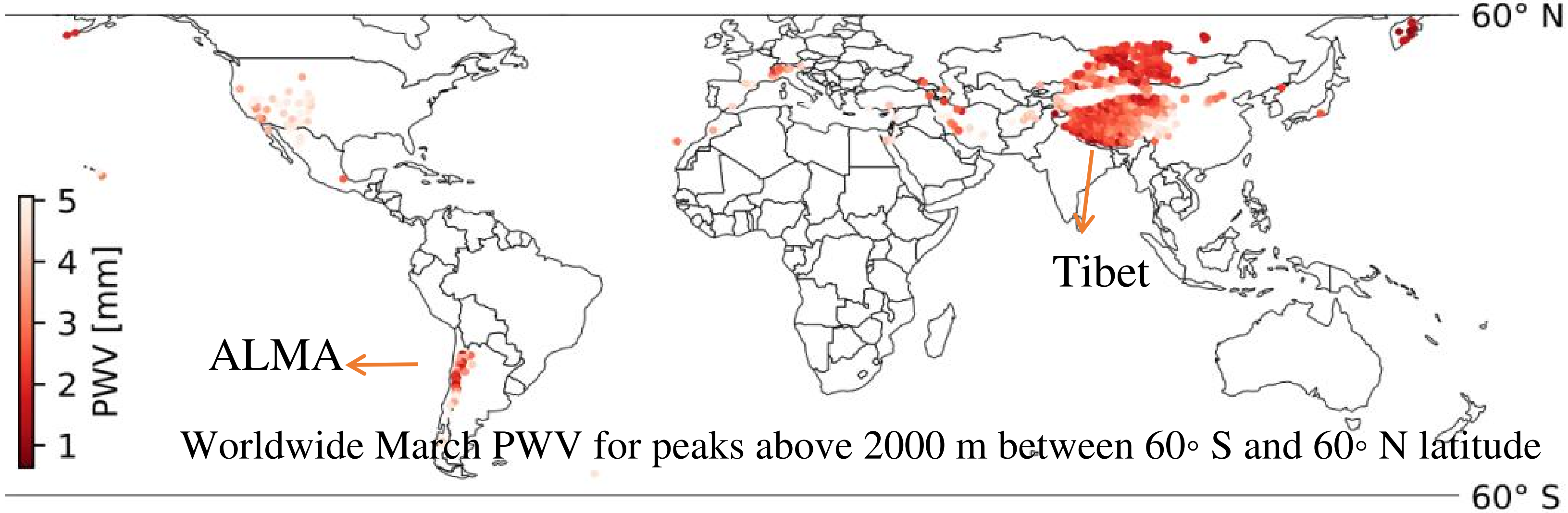


in 20 years

space VLBI

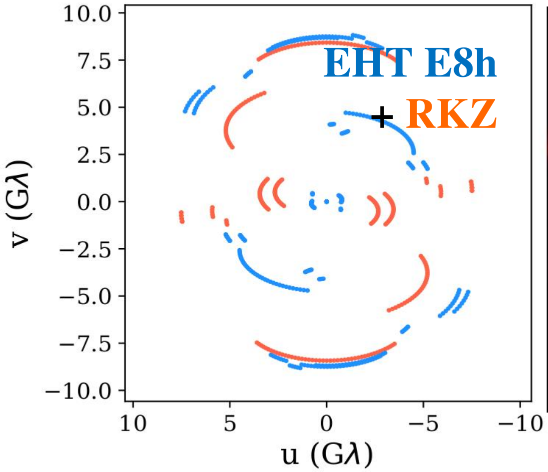
China sub-millimeter VLBI: telescope(s)

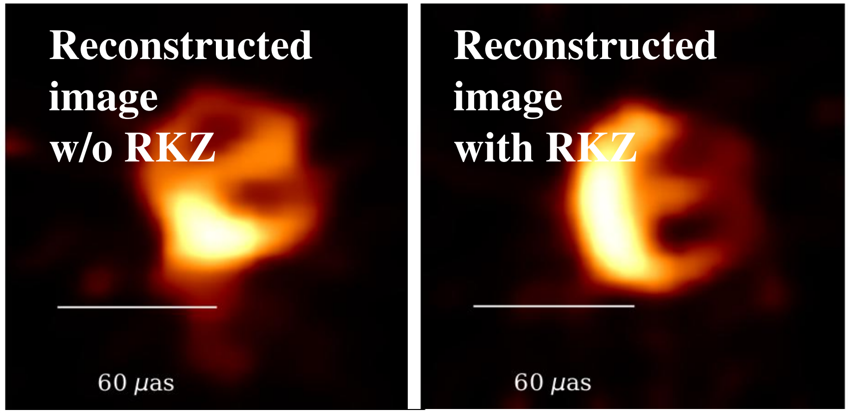
1. West China has very good sites for sub-millimeter observation
2. Realize 24h-observation to capture SgrA* movie



Worldwide March PWV for peaks above 2000 m between 60◦ S and 60◦ N latitude

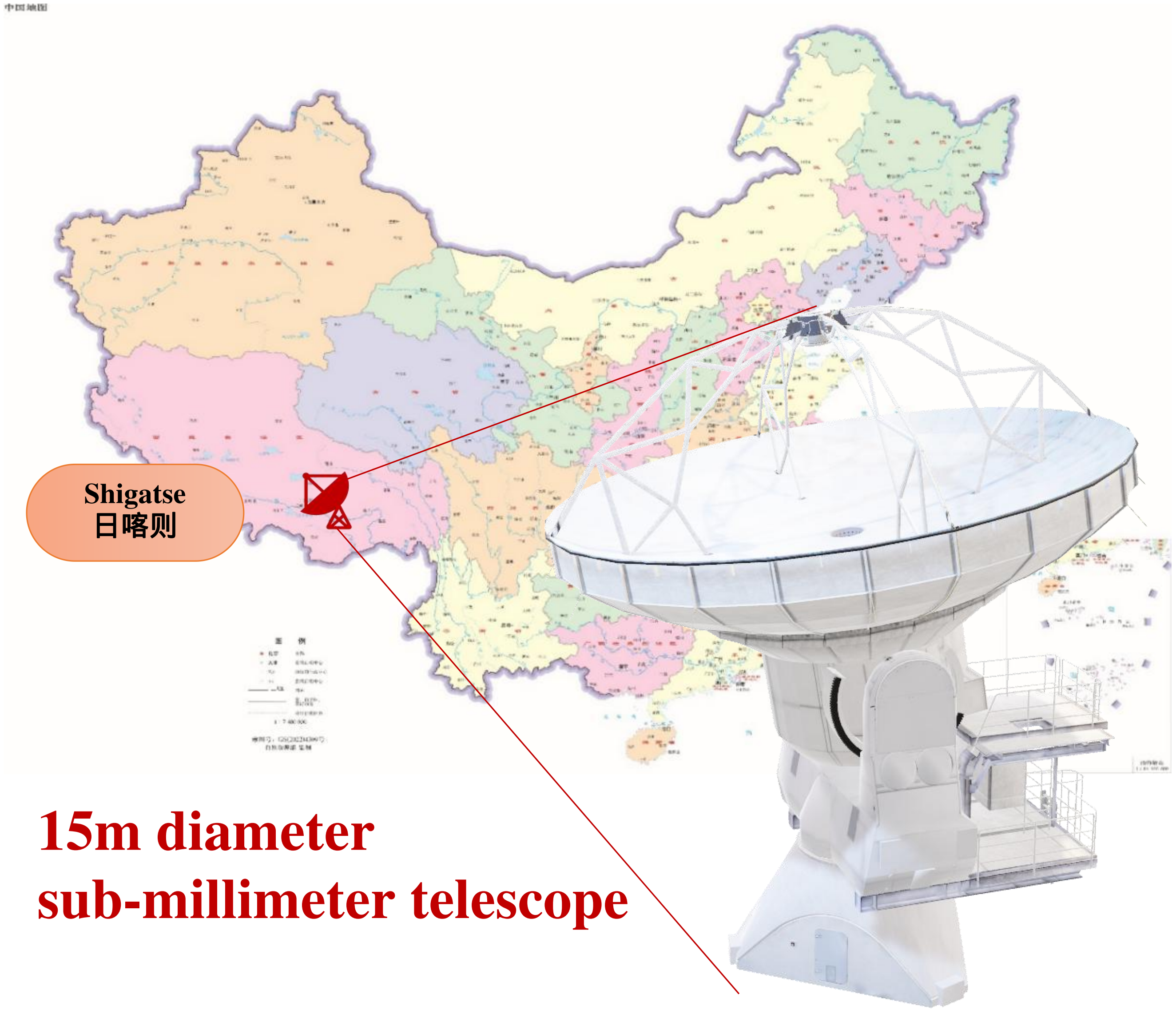
(Raymond et al. 2021)





(Yu et al. 2023)

China sub-millimeter VLBI: telescope(s)

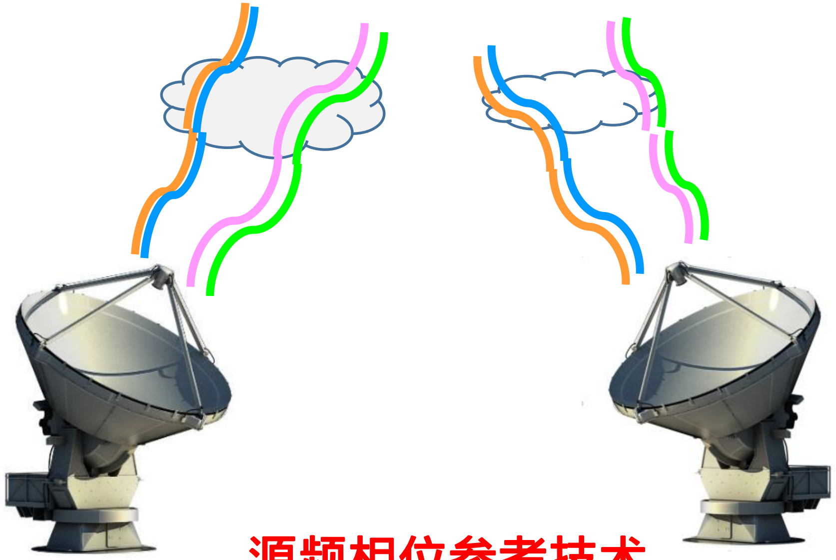


15m diameter
sub-millimeter telescope

China sub-millimeter VLBI: Key techniques

Simultaneous multi-frequency observation

- Reduce atmospheric errors
- Boost sensitivity
- Unlock high frequency Astrometry

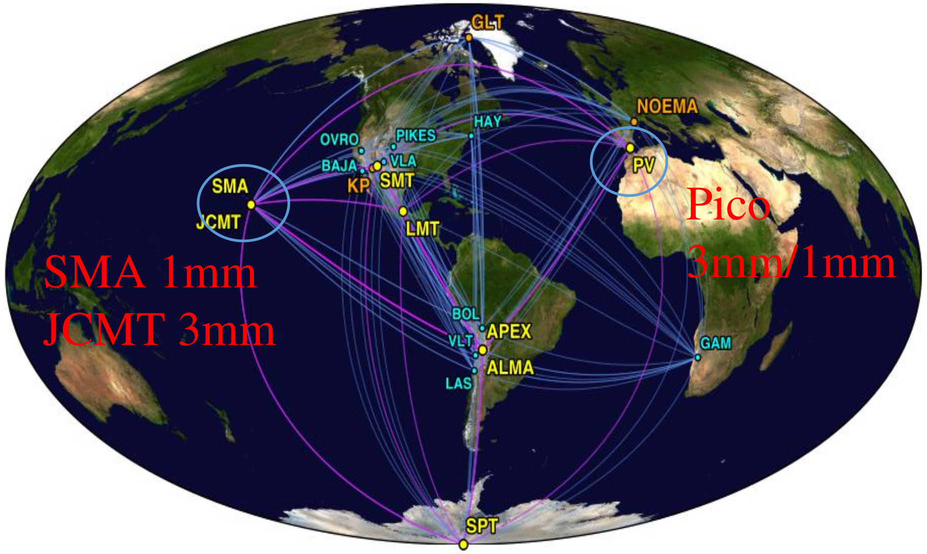


源频相位参考技术

Source Frequency Phase Reference

详见江悟的报告：Techniques and sciences for simultaneous multi-frequency VLBI observations

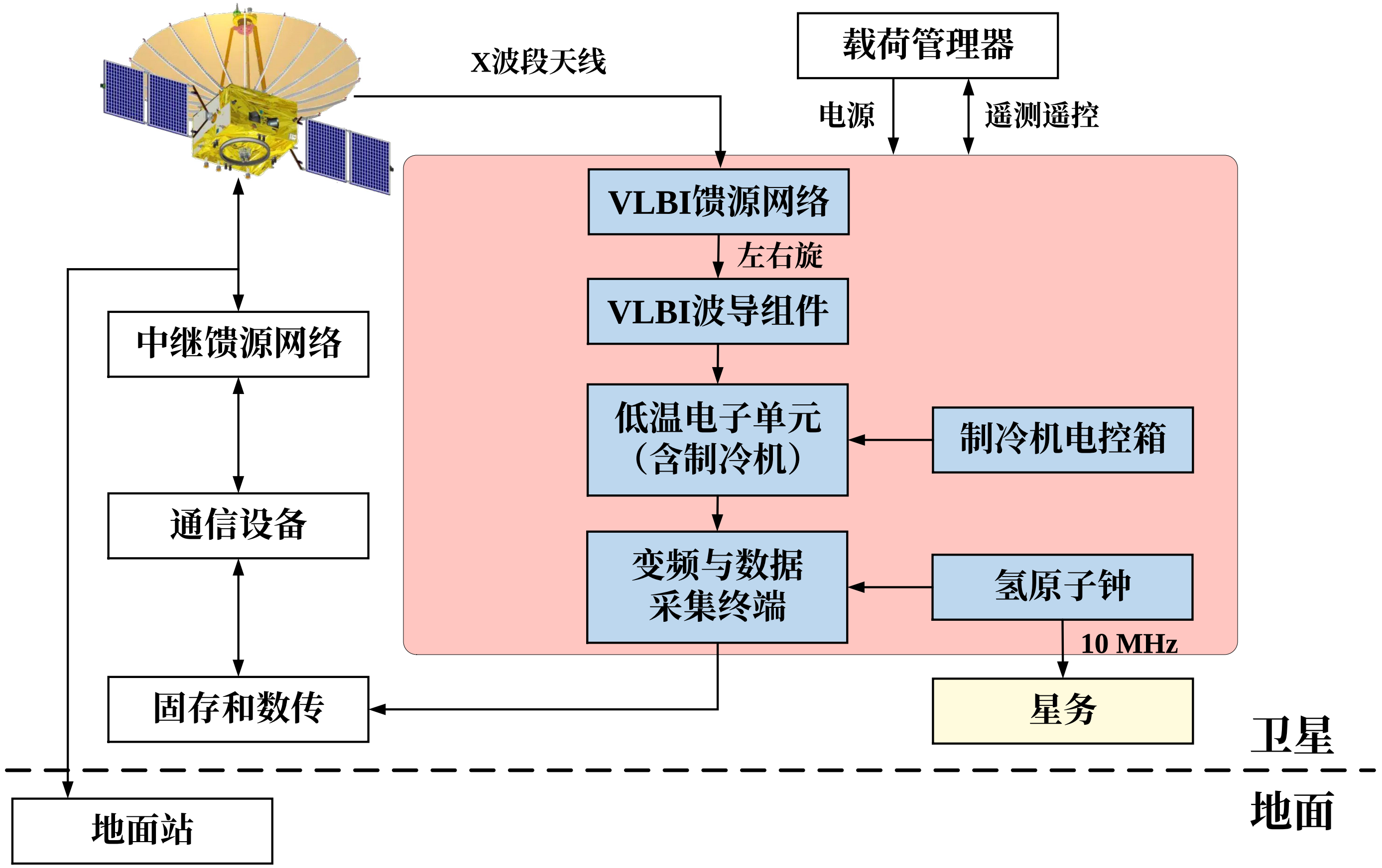
First 85/215GHz was done! (Nov. 22 2022)



China space VLBI: first moon-earth cm-VLBI test

Lunar Orbit VLBI EXperiment (LOVEX)

a 4.2m 8GHz telescope on Lunar orbit satellite (Queqiao II)



Summary

- ngEHT:
  - ground ngEHT (in 5 years) : 86/230/345 GHz, ~10 muas angular resolution;
  - space ngEHT (in 20 years): ~1 muas;
- new science of ngEHT:
  - M87* & SgrA*: separate gravitational structure from astrophysical structure;
  - other targets: capture more black hole images; detect SMBHBs;
- China in ngEHT:
  - telescopes: build sub-millimeter telescopes in Tibet and join ngEHT;
  - technique: simultaneous multi-frequency observation;

Thank you very much!