Physics of μas structures of AGN

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Next Generation Space VLBI (ngSVLBI) Workshop
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JIVE
Joint Institute for VLBI
ERIC

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

EXCELENCIA SEVERO OCHOA

CSIC

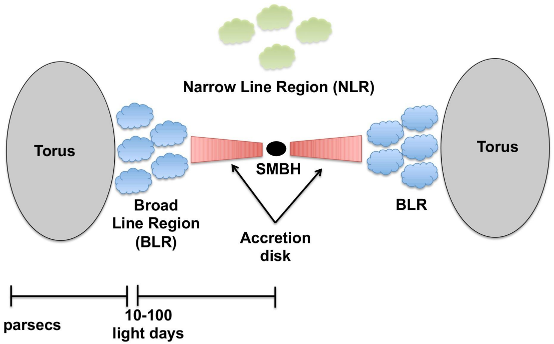
Credits: NASA’s Goddard Space Flight Center

The relevance of being active: the AGN phenomenon

- ❖ AGN are the most luminous persistent sources of electromagnetic radiation in the universe.

Main AGN Components:

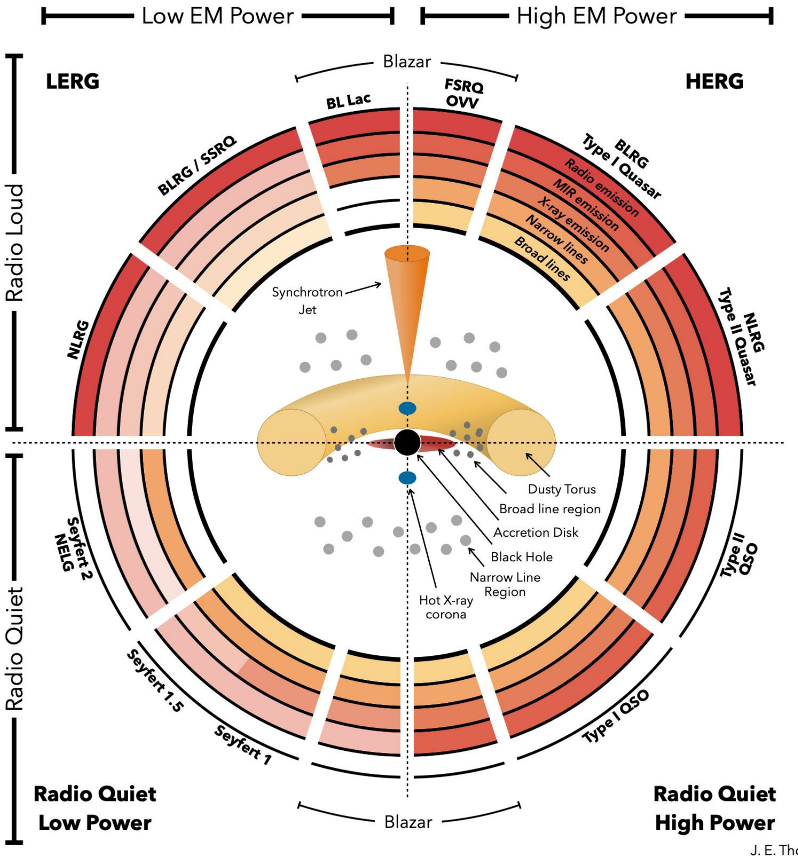
- ❑ Central Engine (one or more supermassive black holes)
- ❑ Accretion disk
- ❑ BLR
- ❑ Torus
- ❑ NLR
- ❑ Corona



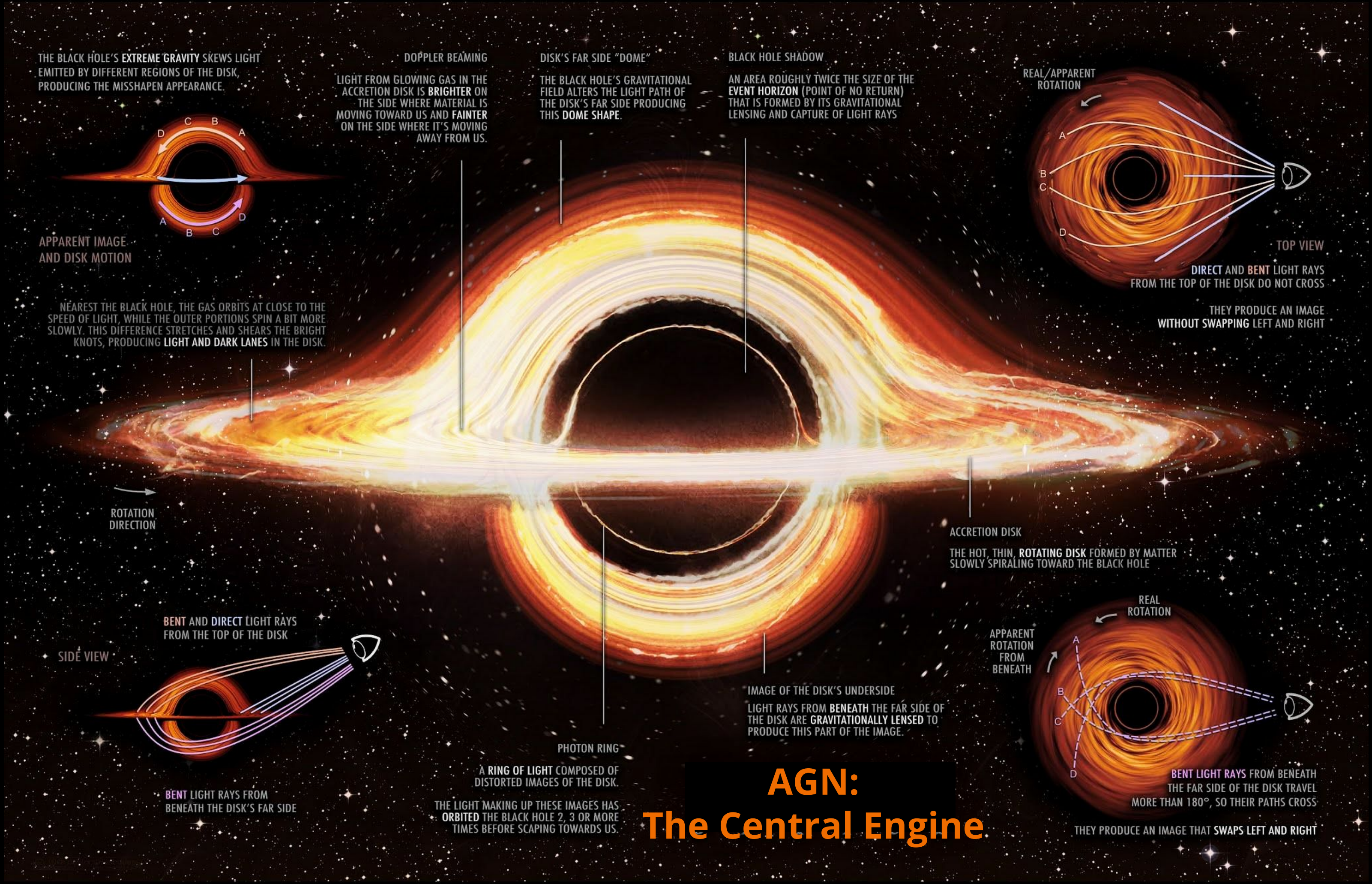
Credit:Claudio Ricci

Open questions:

- ❖ Accretion models: alpha-disk and Bondi accretion, ADAFs.
- ❖ Other forms of spherical symmetric accretion?
- ❖ Geometry of torus?
- ❖ Patchy corona?



AGN: The Central Engine



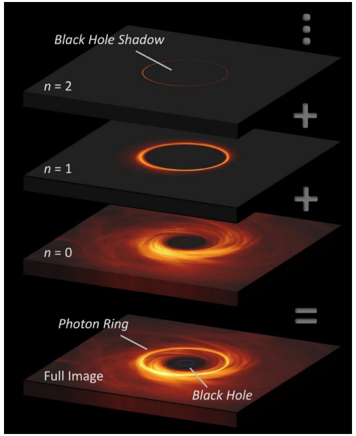
The AGN phenomenon: Central Engine

Open questions:

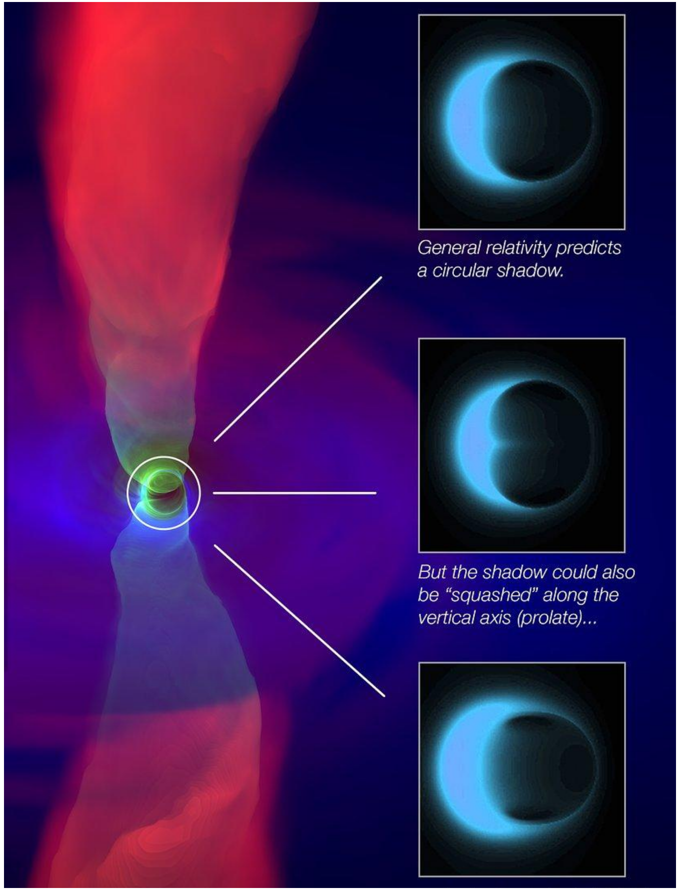
- ❖ Black hole-galaxy coevolution?
- ❖ SMBH masses and spins?
- ❖ The outline of the shadow is expected to be nearly circular, if the central object is a black hole described by the Kerr metric. Spacetime metric?

GR predicts that all black holes are described by the same metric, independent of their mass.

How do SMBHs form and grow?

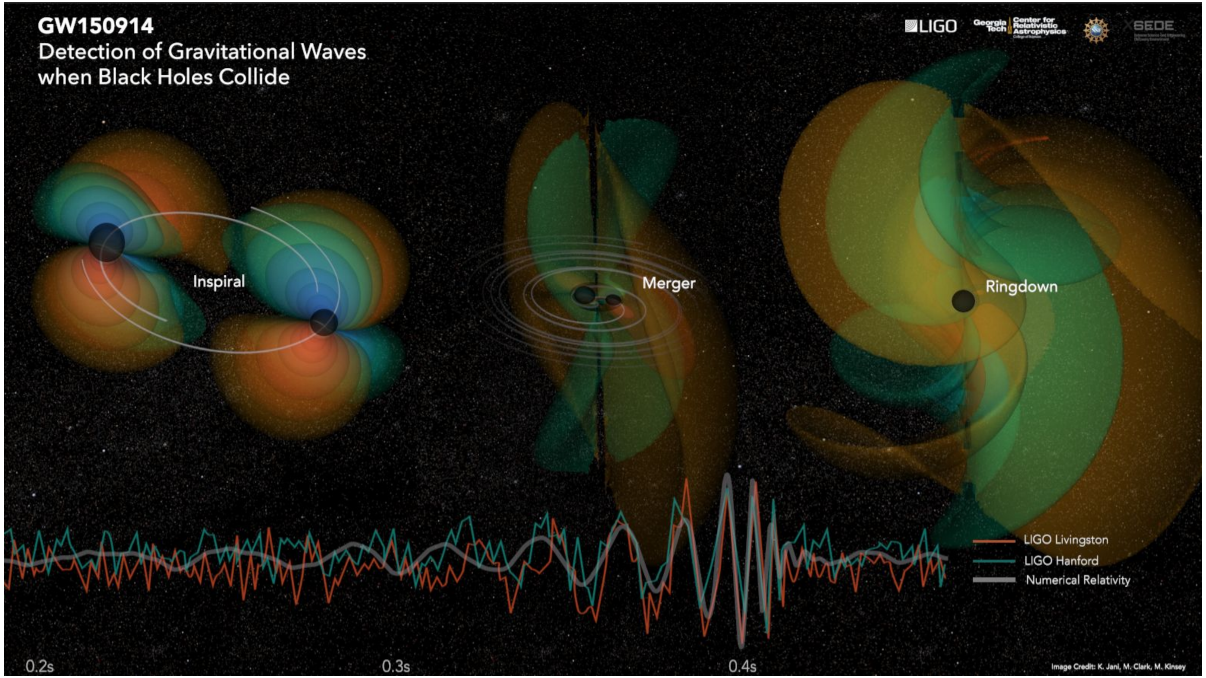


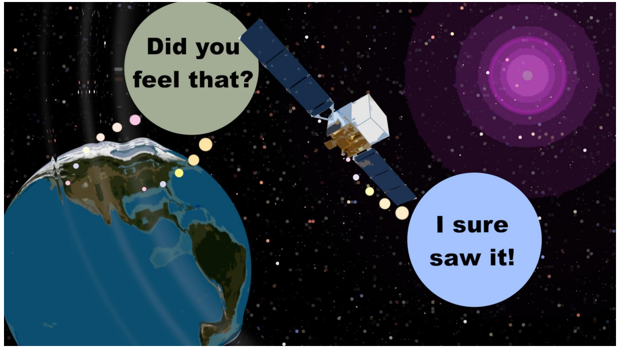
Johnson, Lupsasca et al 2019



Credit: ESO/N. Bartmann/A. Broderick/C.K. Chan/D. Psaltis/F. Ozel

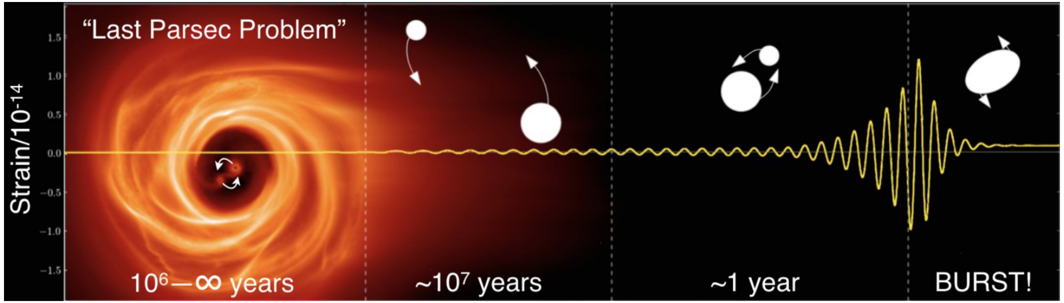
BH Mergers: Multi-Messenger Signatures





- On September 14, 2015, LIGO sensed the undulations in spacetime caused by gravitational waves generated by two colliding black holes

Binary SMBH Systems

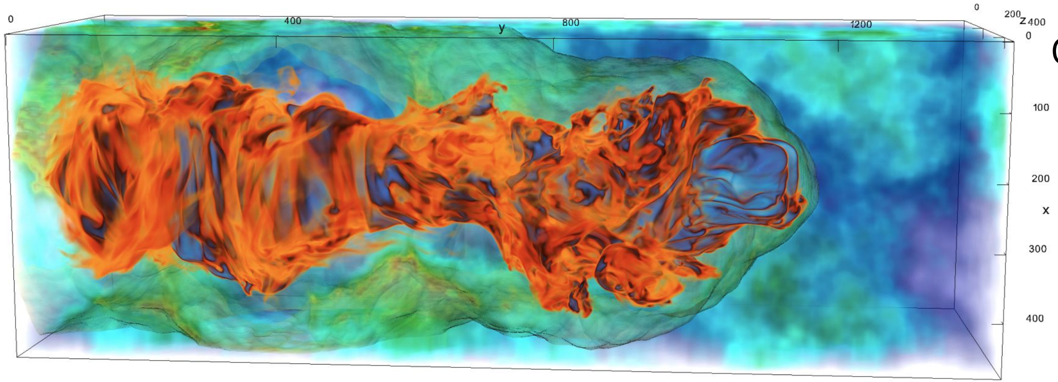


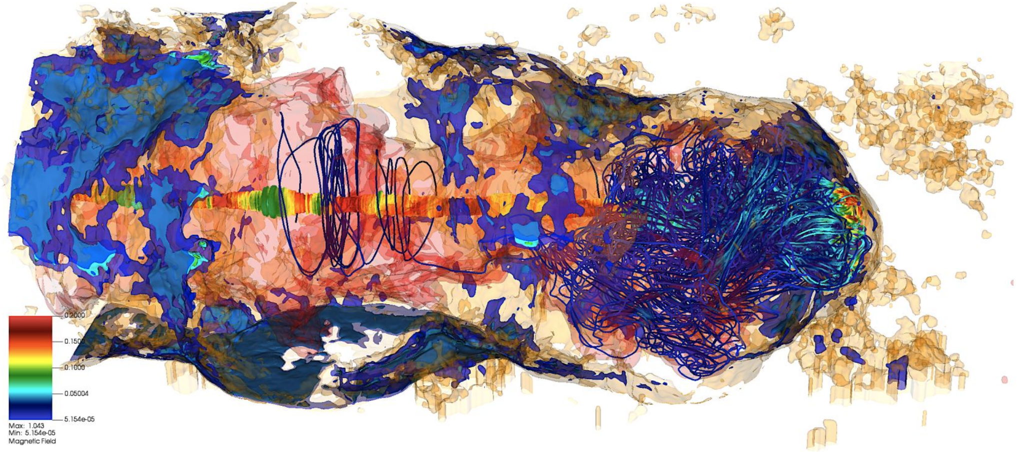
Credits: Chiara Mingarelli

- ❖ The binary quickly ejects all stars on orbits that intersect the orbit of the SMBH binary (loss cone is depleted).
- ❖ In a spherical, isotropic galaxy in equilibrium the loss cone can only be refilled by two-body relaxation.
  - ➢ Timescale of loss cone refilling is longer than Hubble time
  - ➢ The supply of stars to the binary is cutoff and binary's further evolution stalls.
- ❖ The stalling happens at ~1 parsec (Milosavljevi´c & Merritt 2003b).

	GW only	EM only	GW + EM
T1: Identification and MBHB properties	Detection of GWs from individual MBHBs provides measurement of a subset of binary parameters.	EM signatures provide MBHB candidates but may not conclusively confirm the binary nature.	Allow a measurement of additional MBHB parameters (e.g., Eddington ratio and radiative efficiency) and improved constraints of others.
T2: MBHB evolution	Spectrum of the GW background (PTAs) and MBHB coalescence rate (space-based detectors) can constrain MBHB/ environment interactions.	Direct imaging of kpc-scale dual AGNs. Multiwavelength studies of time-variable emission from MBHBs at smaller separations.	Provide a complete sequence of evolution from kpc scales to inspiral and coalescence.
T3: MBH-host co-evolution	Measurements of the MBHB mass and mass ratio free of biases inherent to the EM methods.	Constrains of the host galaxy properties (bulge mass, stellar velocity dispersion, Sersic index, etc.).	Direct measurements of MBH masses and host galaxy properties allow to calibrate scaling relationships.
T4: Cosmology and fundamental physics	Measurement of the luminosity distance and time of arrival for gravitons.	Provides redshift of the host galaxy/associated AGN and time of arrival for photons.	Can be used to constrain cosmological parameters and to test the equivalence principle and Lorentz invariance.

The AGN phenomenon: Relativistic Jets - Rs scale





Credit: López-Miralles+2022

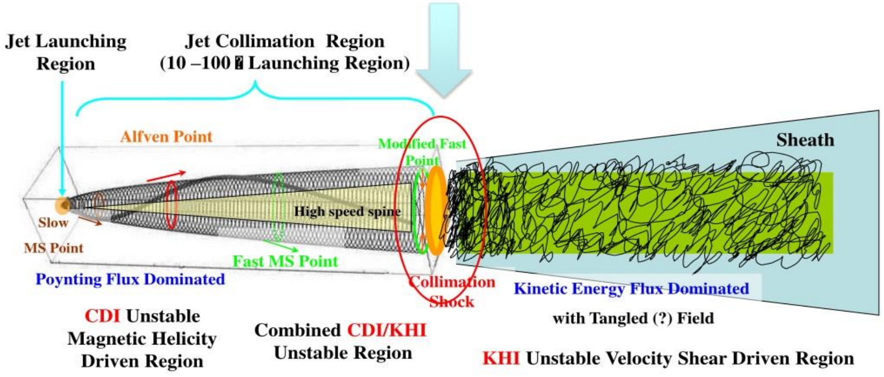
Open questions:

- ❖ What is the energy that actually powering the jets?
  - ➢ The rotational energy of the black hole (“Blandford-Znajek” mechanism)?
  - ➢ Accretion disc (“Blandford-Payne” mechanism)?
  - ➢ Radically different process (magnetic reconnection, annihilation of neutrinos from the accretion disc, etc)?
- ❖ Magnetic fields topology close to the central engine?

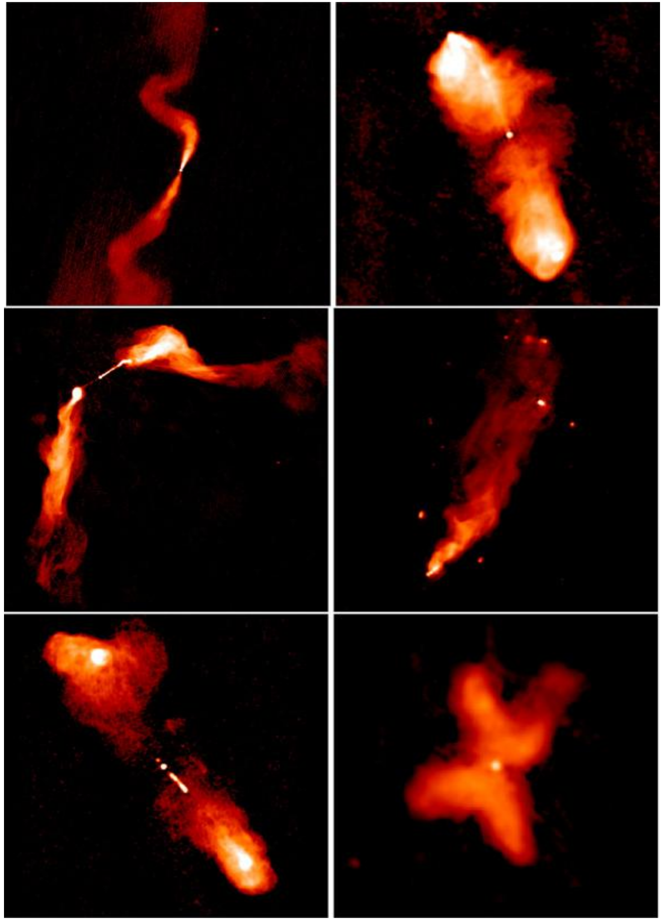
The AGN phenomenon: Relativistic Jets - pc/sub-pc scale

Open questions:

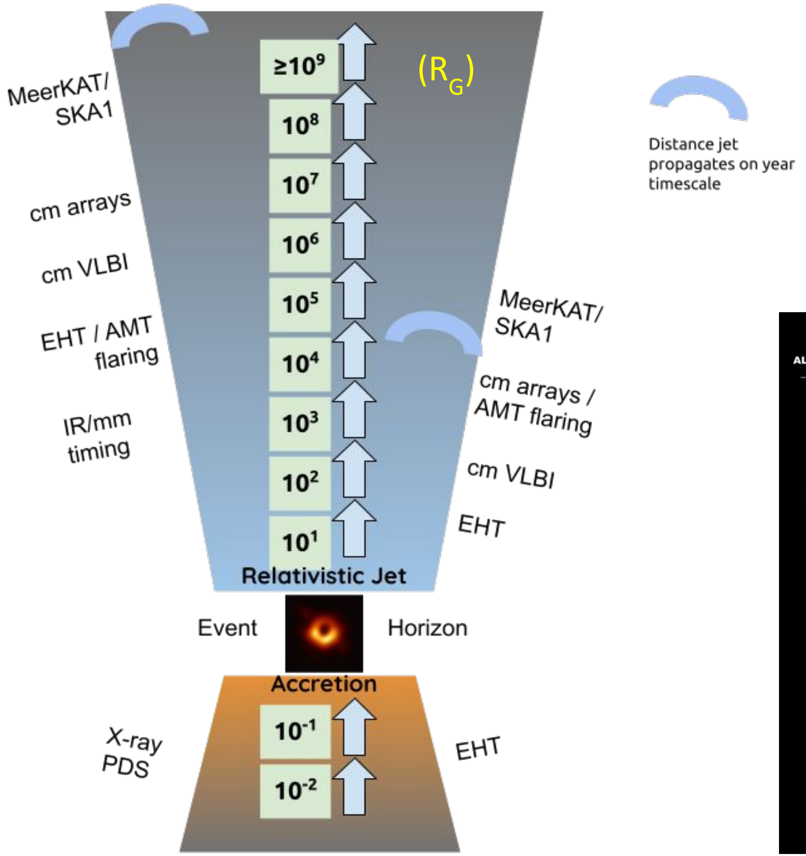
- What accelerates relativistic jets?
- Jets confinement and collimation?
- Origin of high energy emission?
- Plasma leptonic/hadronic etc?
- Nature of moving and standing features in AGN jets?



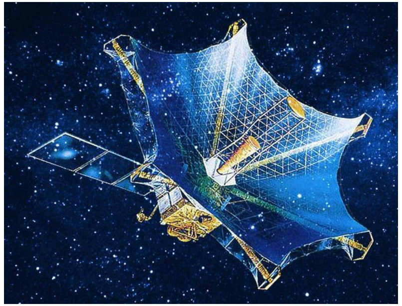
Credit: David Meier

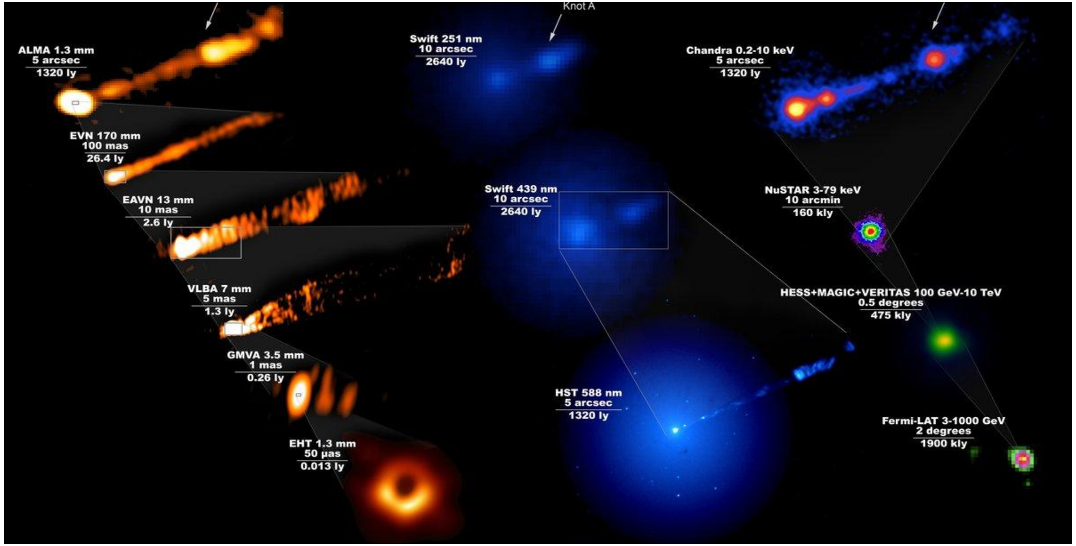


High Resolution & Sensitivity: The holy grails of AGN physics



Credit: Daryl Haggard, Rob Fender

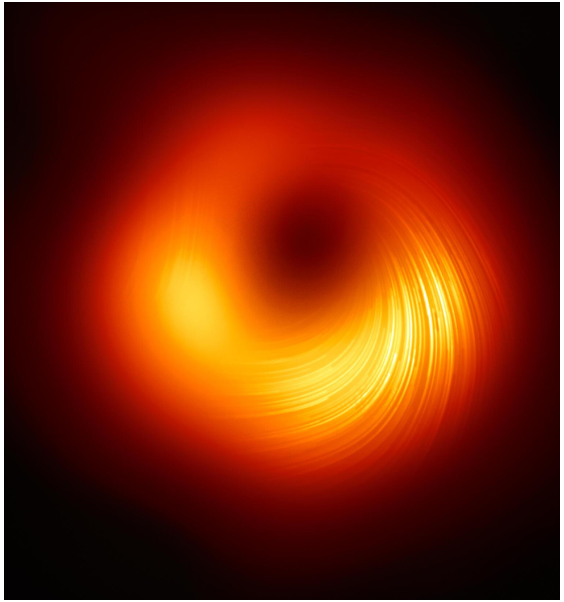


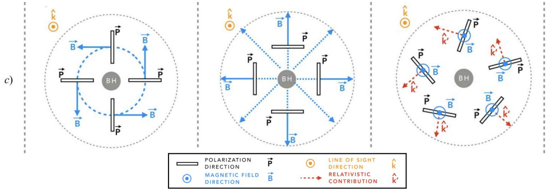


Credit: MWL WG, EHTC

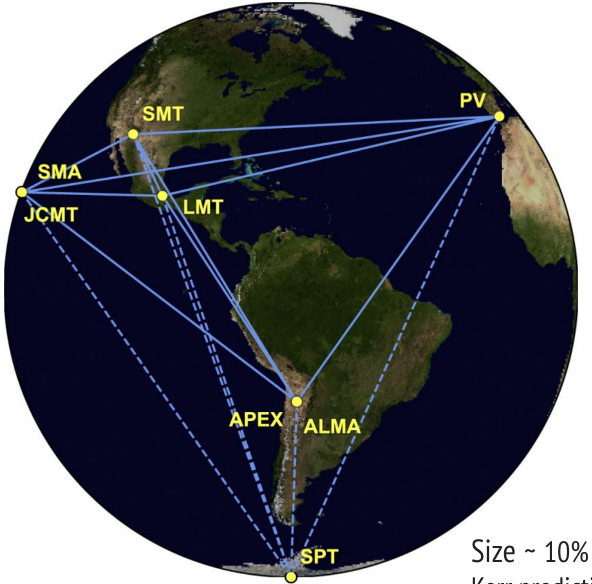
Physics of μas structures of AGN: Recent Achievements

M87: Black Hole Shadow + Magnetic Fields



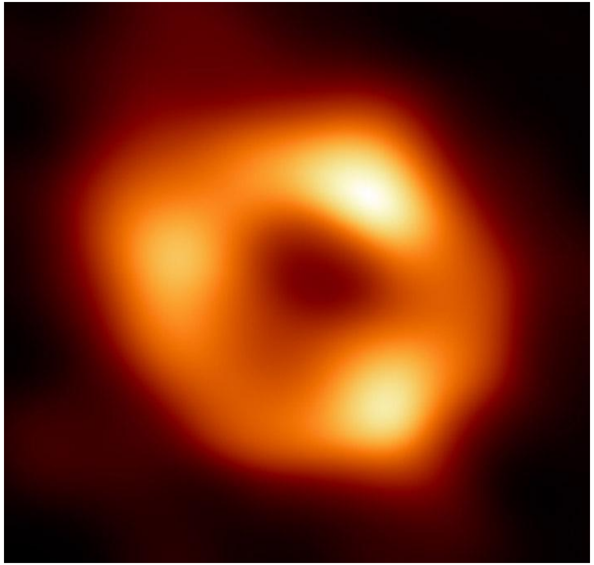


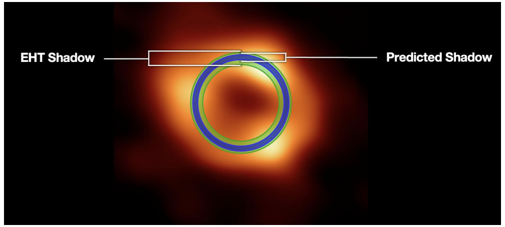
Event Horizon Telescope



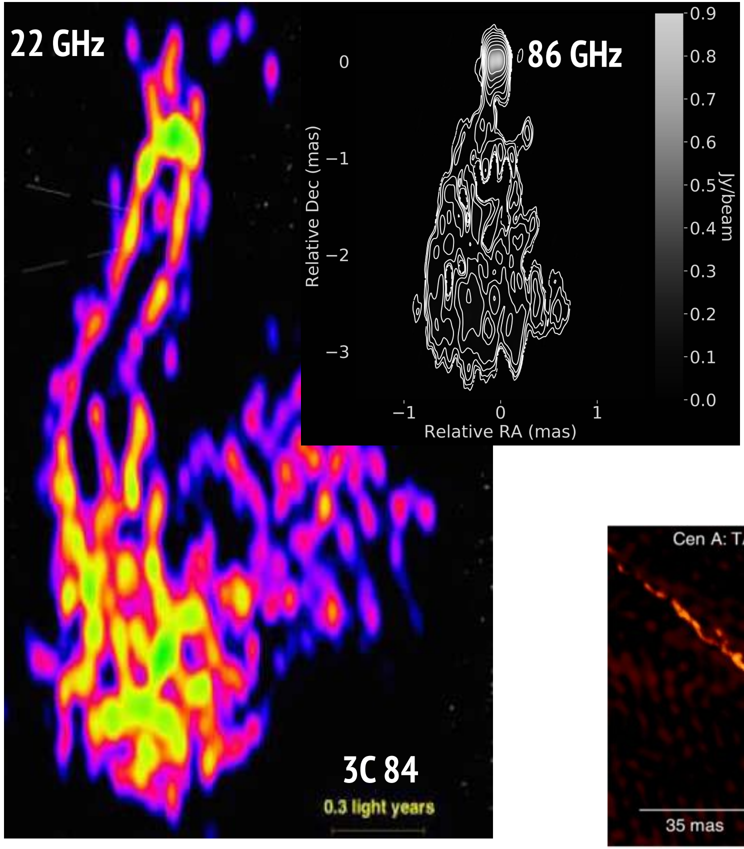
Size ~ 10% of the Kerr predictions

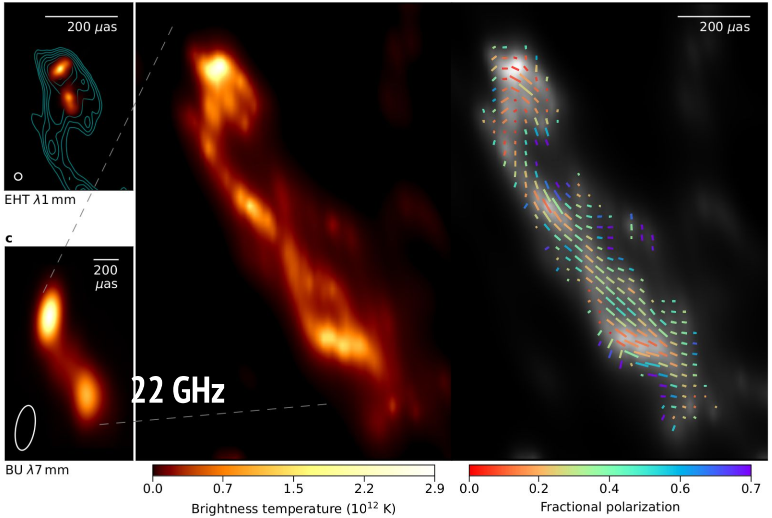
SgA*: Black Hole Shadow



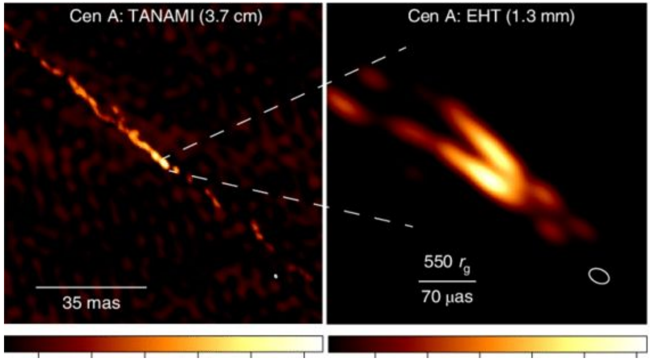


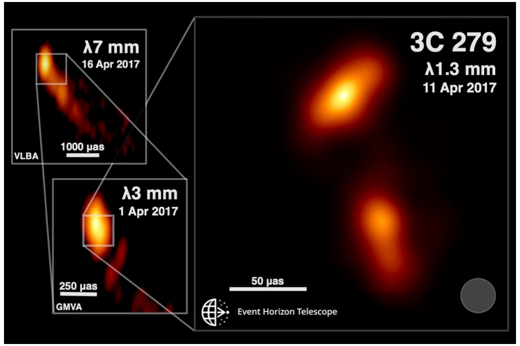
Physics of μas structures of AGN: Recent Achievements





Fuentes A., Nat. As., 2022



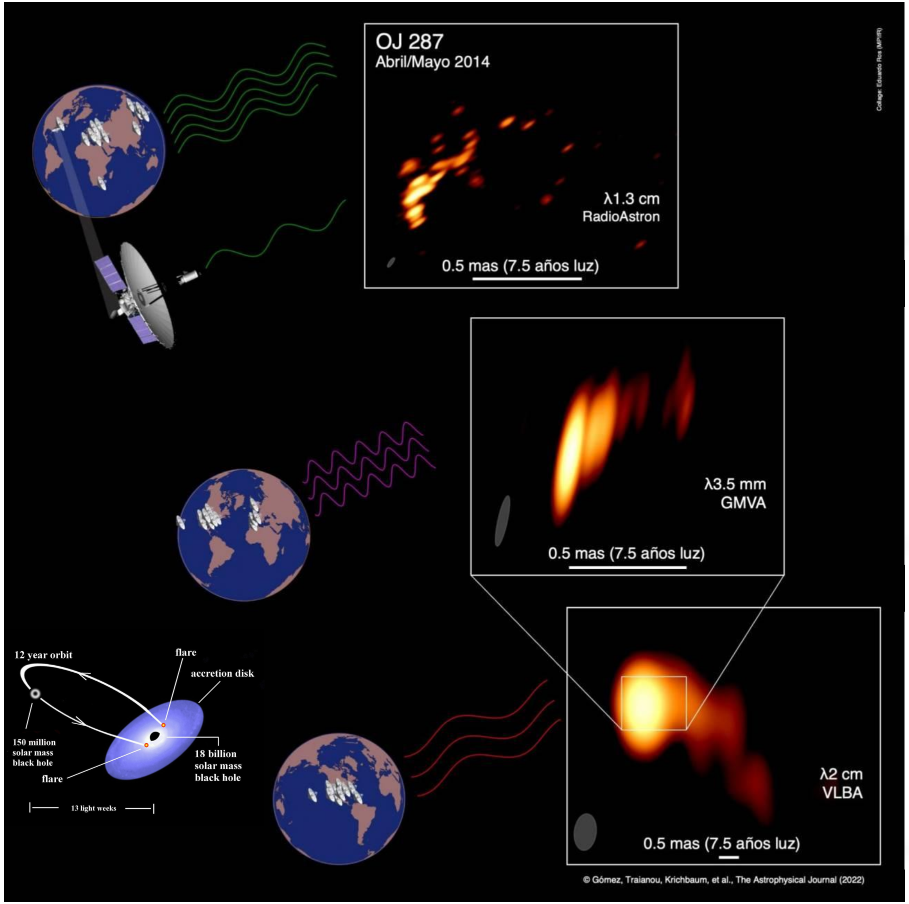


Giovanini G., Nat. As., 2018| Paraschos G., A&A, 2021

Janssen M.., Nat. As.,2021

Kim JY., A&A., 2020

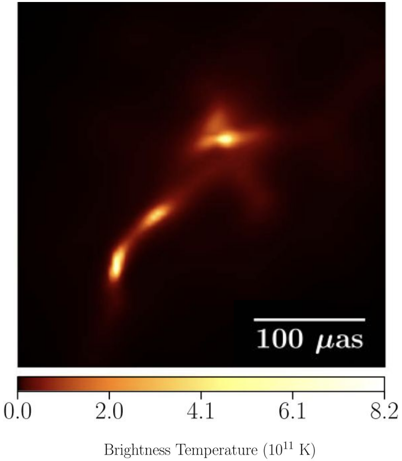
Physics of µas structures of AGN: Recent Achievements



Lico R.+2022 in prep: K band, ground array + RA (5 ED), 2017

Traianou T.+2022 in prep: K band, ground array + RA, 2016

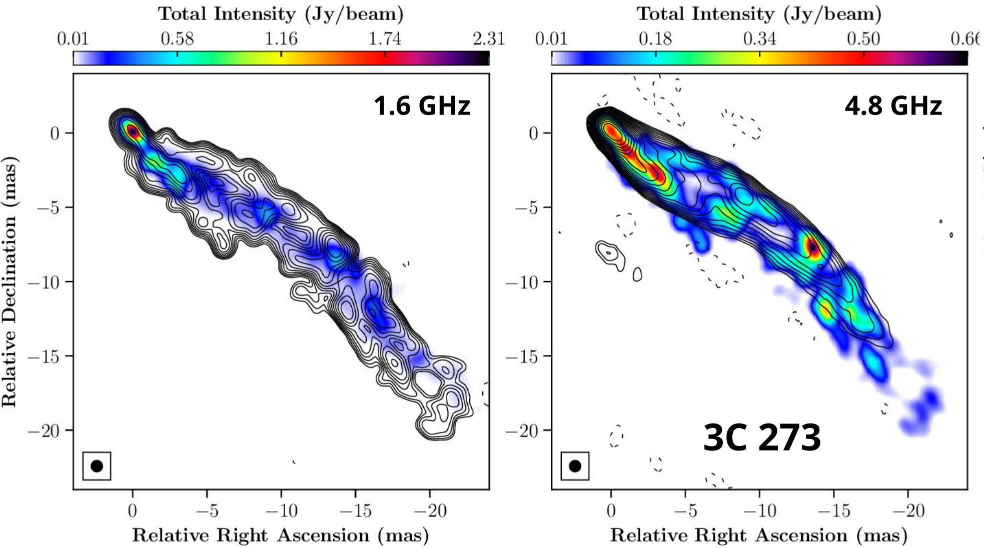
Cho I.+2022 in prep: L band, ground array + RA, 2016



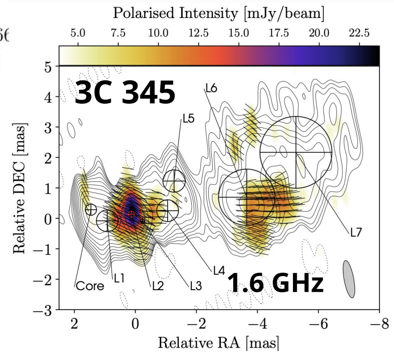
Zhao GY+2022, ApJ, GMVA+ALMA

Gomez JL+2022 in prep: EHT,2017

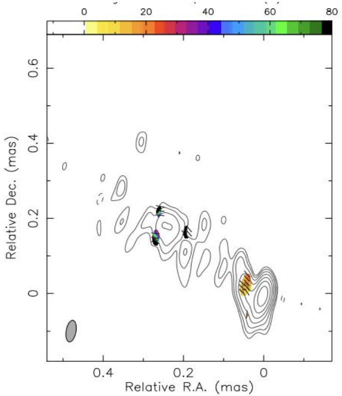
Physics of µas structures of AGN: Recent Achievements



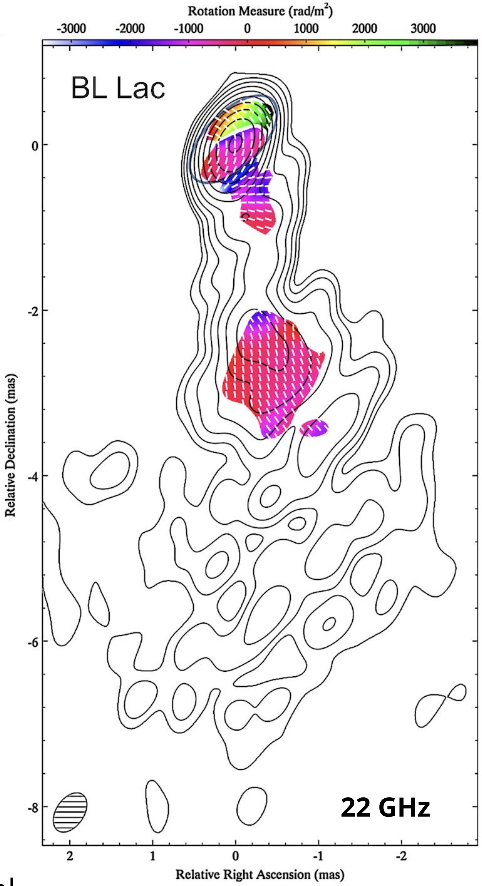
Bruni+2021,A&A



Poetzl+2021,A&A



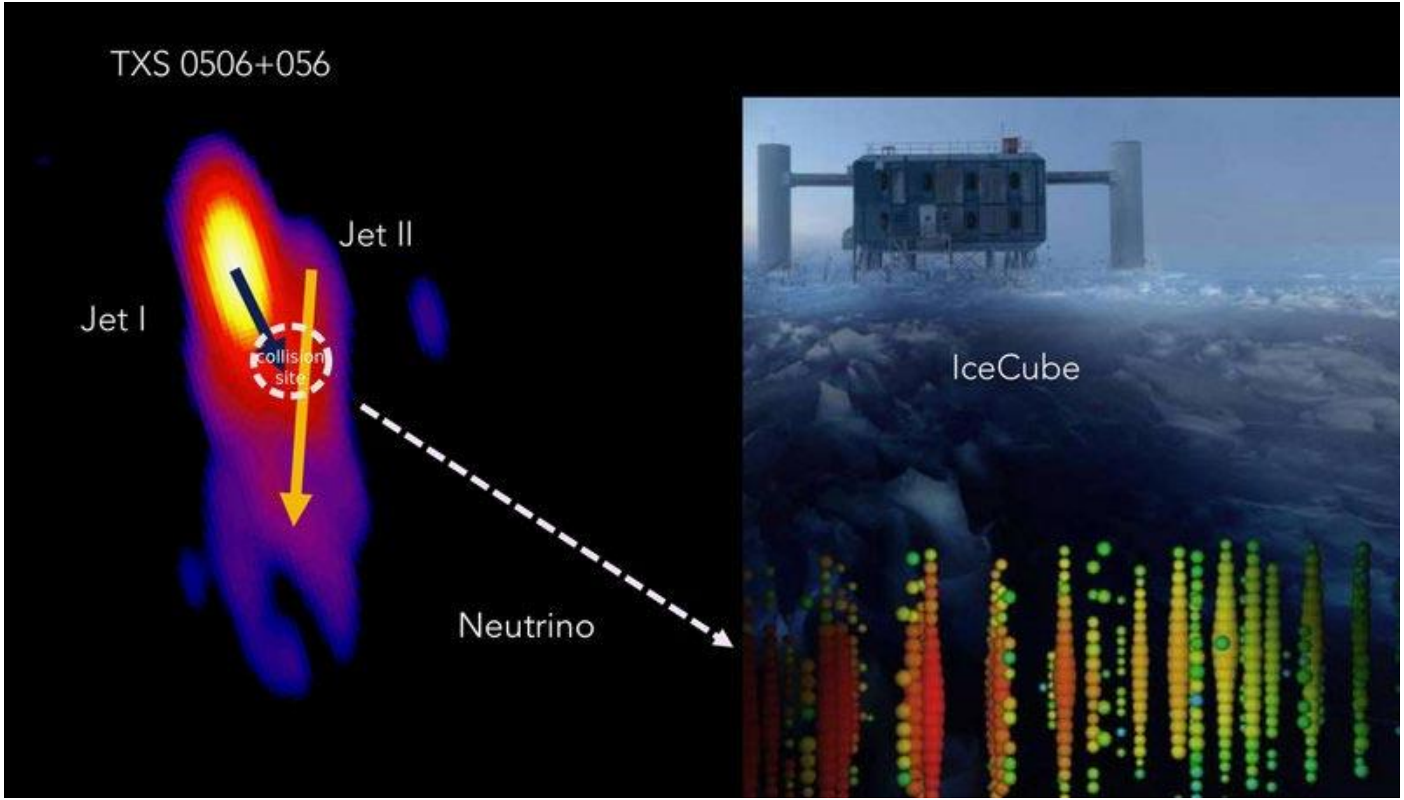
Kravchenko+2020,ApJ



Gomez+2015,ApJ

- RadioAstron revealed spectacular jet images, allowing such outflows to be studied in great detail, including the inner regions in the proximity of the jet base.
- Limb-brightening.
- High Brightness Temperature.

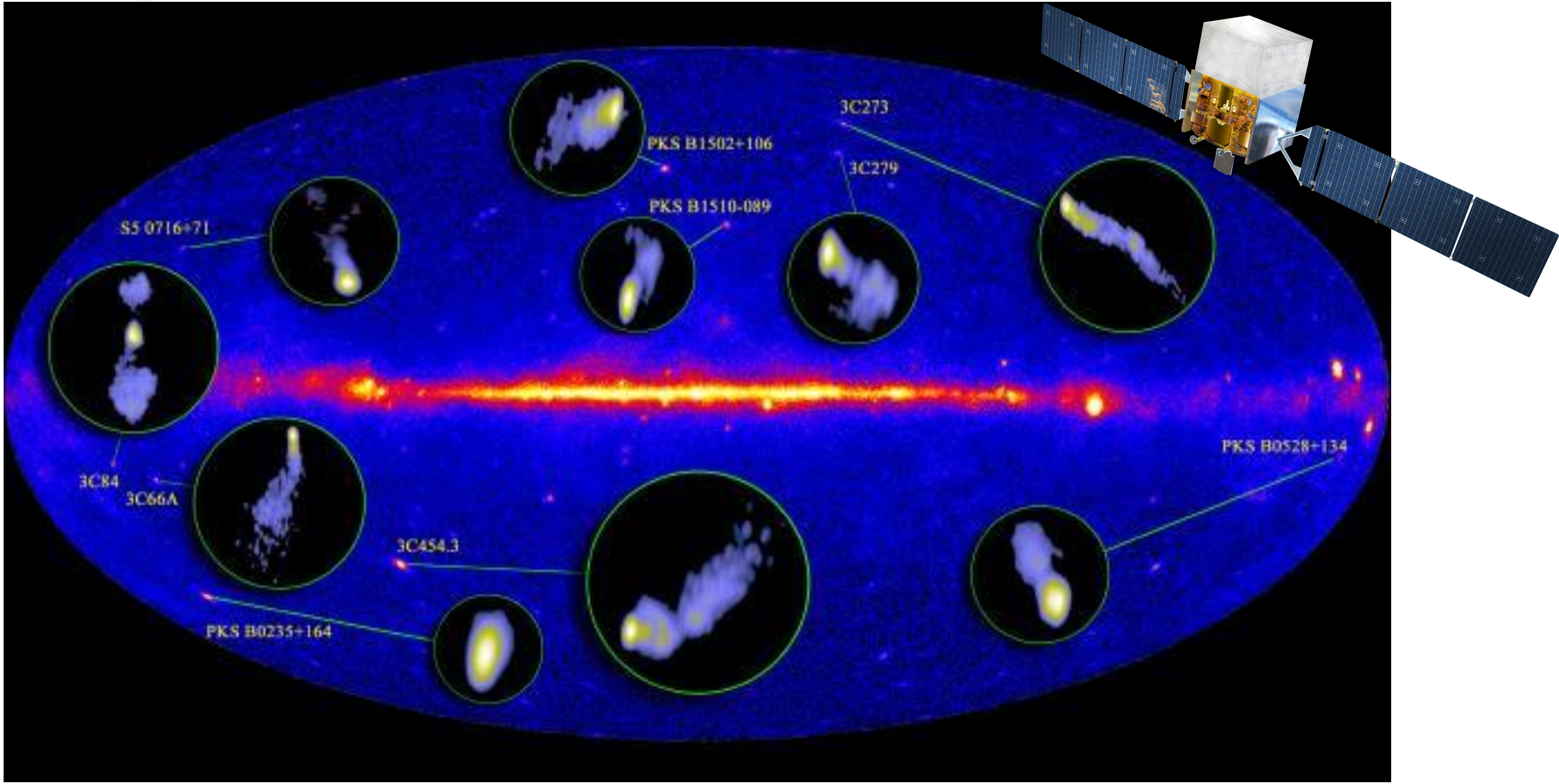
Physics of μas structures of AGN: Recent Achievements



- First time ever confirmation of at least part of the jet material has to be hadronic

Credit: IceCube/NASA, MOJAVE, S. Britzen, & M. Zajaček| Ros E.+2020, A&A

Physics of μas structures of AGN: Recent Achievements

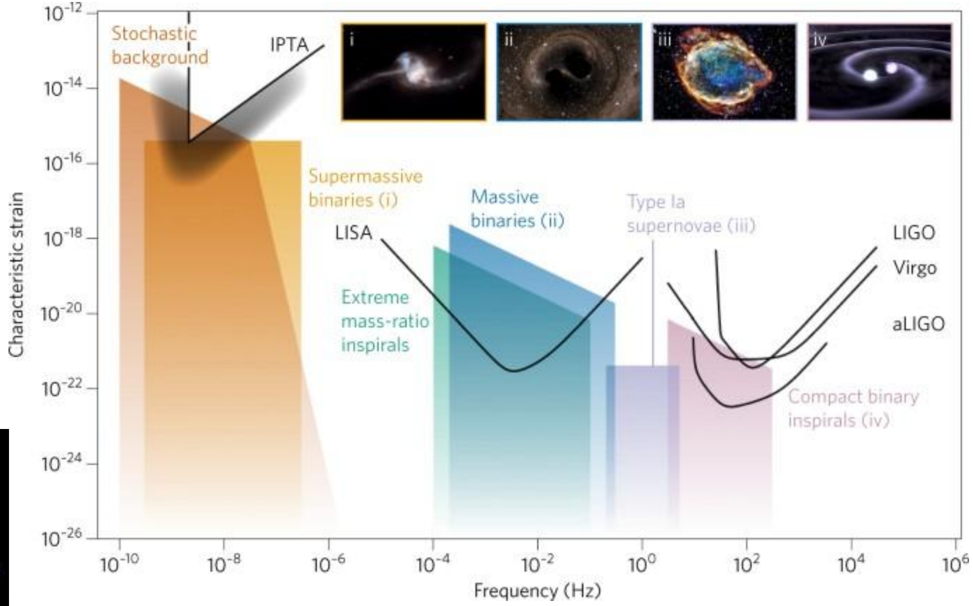


Credit: M. Kadler & MOJAVE

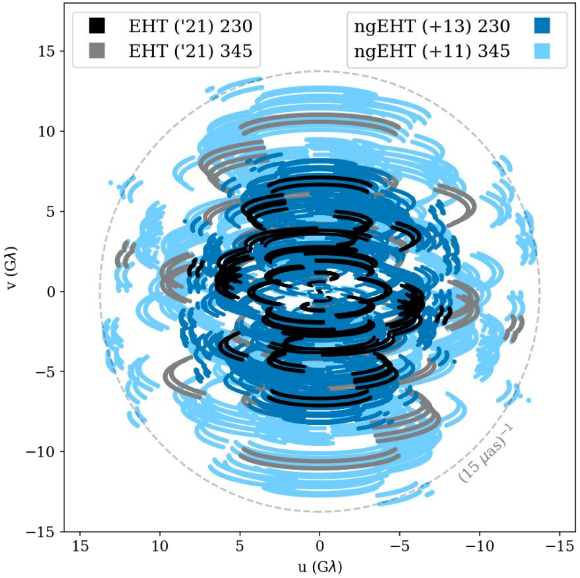
Synergies & Future Perspectives

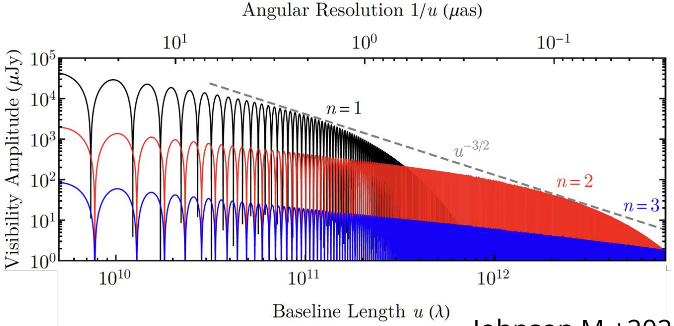
- 1.2 GHz (21 cm) to 116 GHz (2.6 mm)

ngEHT SWG “BHs and their cosmic context”



Synergies & Future Perspectives





Johnson M.+2020

BH Growth

- Black hole-galaxy coevolution
- How do SMBHs form and grow? The role of accretion vs. mergers
- Demographic study of masses and spins in ~10 sources

Binary BHs

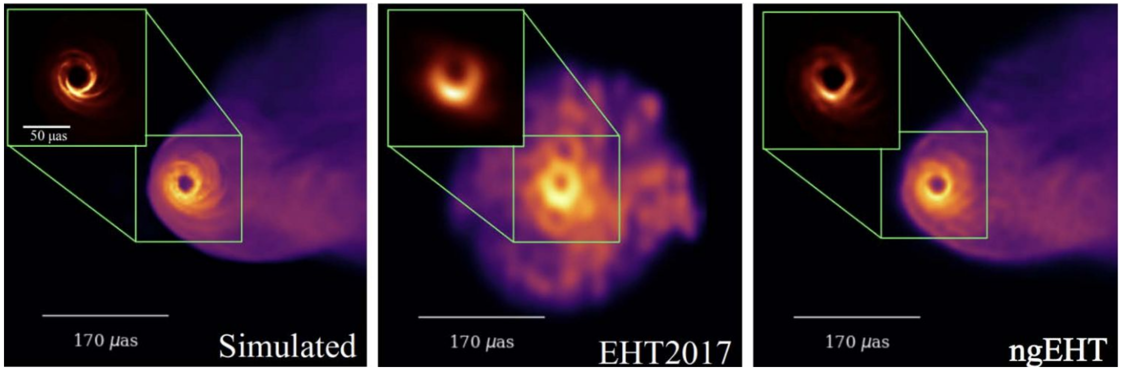
- Final-parsec problem
- Survey of binary candidates
- Cosmological distance ladder
- EM counterparts in other wavelengths: X-ray, optical & IR

MWL studies of BH and jets

- Disk-Jet connection
- GeV & VHE γ-ray & neutrino events
- BH spin and AGN radio-loudness
- Nature of the VLBI core
- Polarization and magnetic field studies

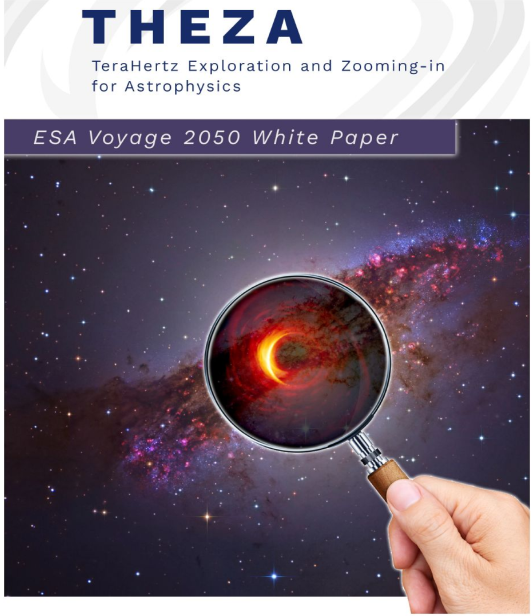
❖ **Time Lapse Movies of Jet Launching**

Blackburn et al. 2019 astro2020 white paper (GRRMHD simulation: Chael + 2019



THz Exploration and Zooming-in for Astrophysics

- ❖ THEZA – one of the ESA's Voyage 2050 White Papers
- ❖ Builds up on strong SVLBI and mm/sub-mm heritage
- ❖ Extends parameters in the <u>inevitable</u> direction, μas @ THz
- ❖ "Sister" Voyage 2050 concepts:
  - ➢ *Origins Space Telescope (Wiedner+2021, ExpA 51:595)*
    - ■ *single-dish spectrometry*
  - ➢ *Far infrared spaceborne interferometer (Linz+2021, ExpA 51:661)*
    - ■ *interferometric imaging*



Gurvits+2021, ExpA 51:559

- ❖ *"Boundary" demo parameters of spaceborne THEZA telescope*
- ❖ *Frequency coverage 220–1200 GHz*

ν (GHz)	230	230	690	690
D (m)	4.4	25	4.4	25
T_{sys} (K)	150	150	150	150
η_{ap}	0.58	0.58	0.58	0.58
η_{cor}	0.97	0.97	0.97	0.97
η_{clock}	0.87	0.87	0.87	0.87
$\Delta\nu$ (GHz)	5	5	5	5
$t_{int,center}$ (s)	453	453	453	453
$t_{int,edge}$ (s)	94	94	32	32
SEFD (Jy)	5.6×10^4	1.7×10^3	5.6×10^4	1.7×10^3
σ_{center} (Jy)	0.030	0.00092	0.030	0.00092
σ_{edge} (Jy)	0.065	0.0020	0.11	0.0035

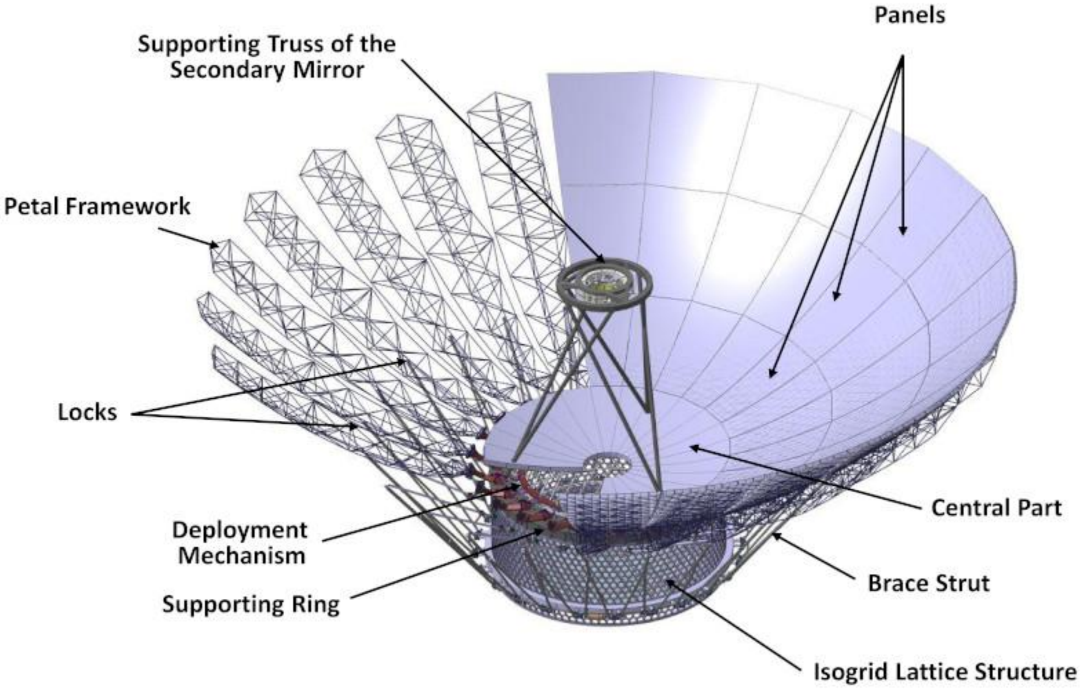
Roelofs+2019, AA 625, A124

Credit: Gurvits L.

Synergies & Future Perspectives

Millimetron Space Observatory

- Primary mirror with 10-meter aperture angular resolution can reach 3.7x10-2 μas.
- Operates in 84 up to 373 GHz.
- Study the structure of space-time in the vicinity of the event horizon of a black hole
- Investigate the properties of plasma in strong gravitational field.
- Identify areas corresponding to shadow around the supermassive black holes and certain frequency parts of the spectrum.
- Search for wormholes can be performed.



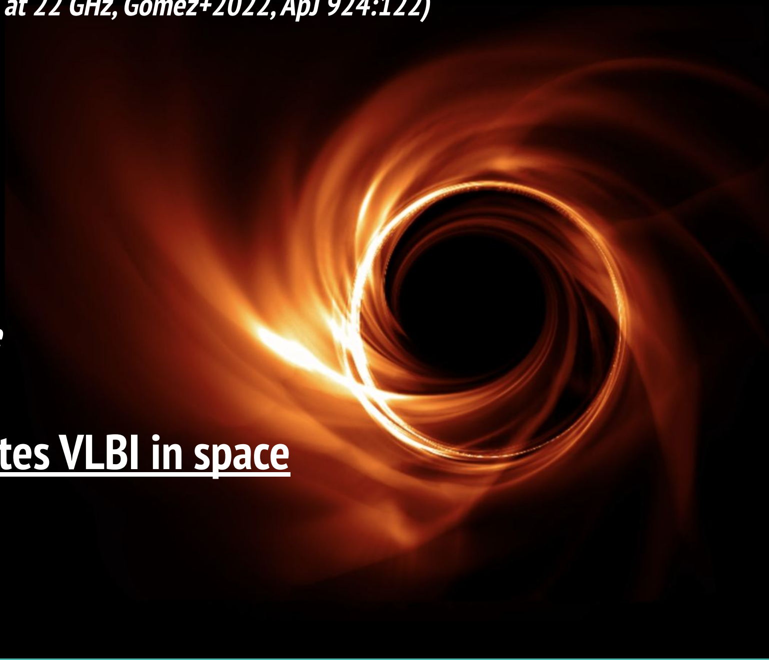
Physics of µas structures of AGN: Summary

- ❖ Expanding parameter space of astronomical tools – the main driver of discoveries

- ❖ Major innovative parameter of SVLBI and EHT – angular resolution,
  - ➢ EHT: ~20 μas, limited by $D_{\oplus}$ at the high end of atmosphere transparency
  - ➢ SVLBI (RadioAstron): ~10 μas, at ~30 $D_{\oplus}$, λ=1.3 cm (*~50 μas* for *OJ287 at 22 GHz, Gomez+2022, ApJ 924:122)*

- ❖ Future goals to even higher angular resolution:
  - ➢ Increase baseline beyond 10^4 km go in space
  - ➢ Shorten wavelength below ~1 mm go in space
    - ■ *Additional bonus: μas-level astrometry in the absence of atmosphere*

- ❖ <u>Angular resolution exceeding Earth-imposed limits necessitates VLBI in space</u>
  - ➢ … and it is science-driven
  - ➢ … basically, a combination of EHT and Space VLBI



Credit: Gurvits L.