How many petabytes does it take to

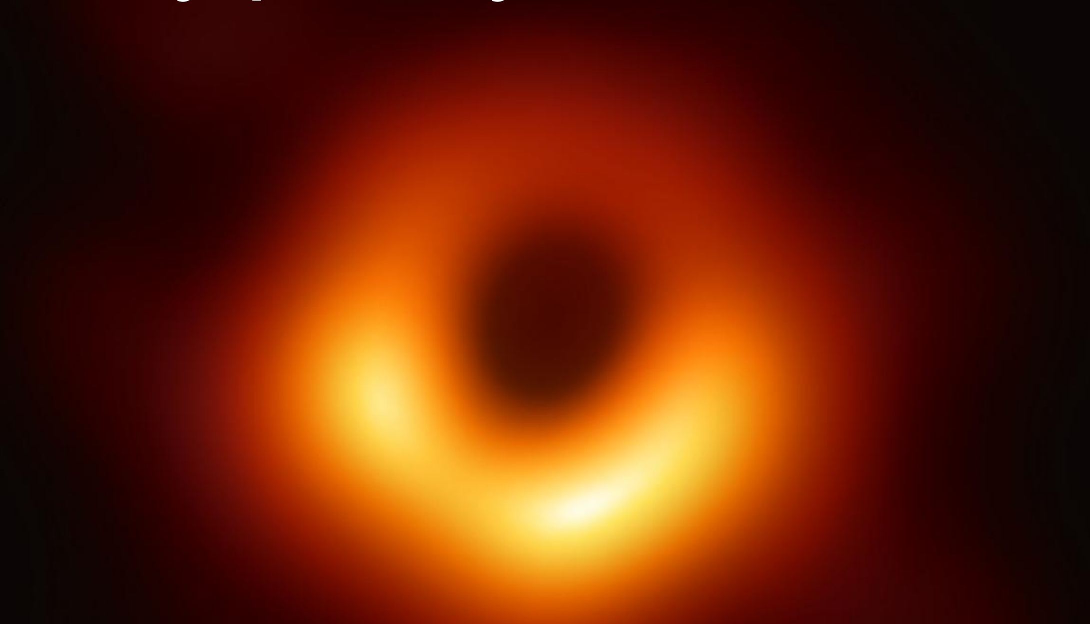

image a Black Hole?

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BLACK HOLE CAM

European Research Council

EUROPEAN ARC
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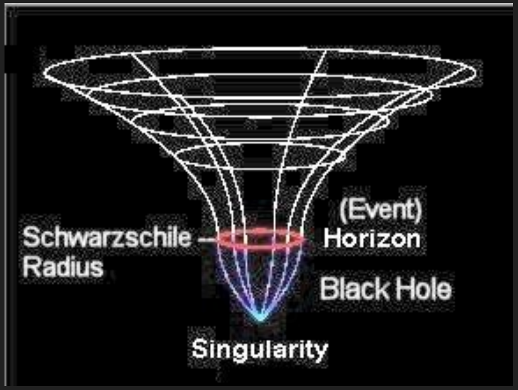
20 ANNI DI RICERCA SCIENTIFICA DI ECCELLENZA

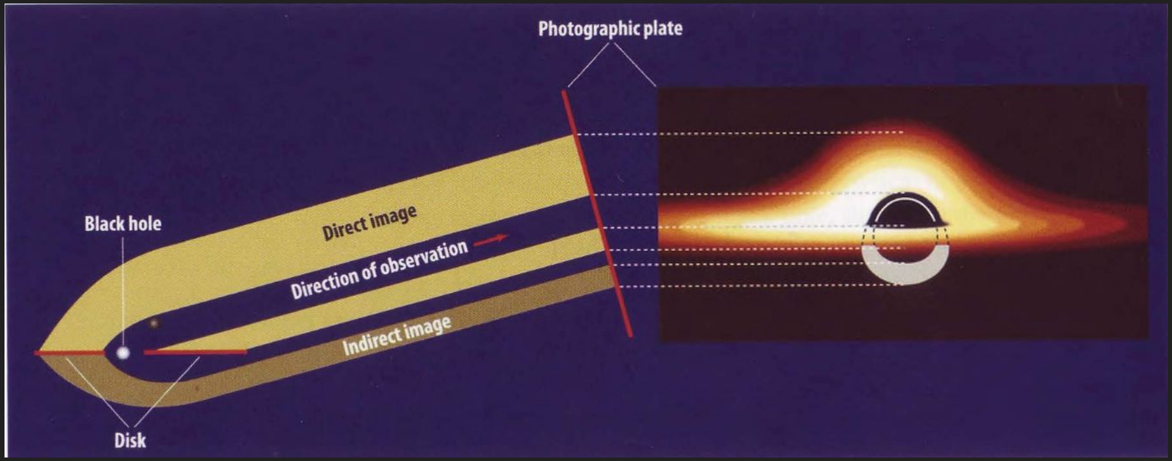
GARR - Connecting the Future, June 4, 2019

Seeing the invisible

Black holes (BHs) are the most extreme objects predicted by General Relativity (GR).
They are characterised by their Event Horizon.



70s: first ideas of how to observe the lensed photon ring predicted to surround the black hole shadow - emission will be faint and on tiny angular scales



Last 20 years: building a sensitive and sharp enough instrument that could detected the plasma emission in lensed photon ring of the nearest and most massive supermassive BHs

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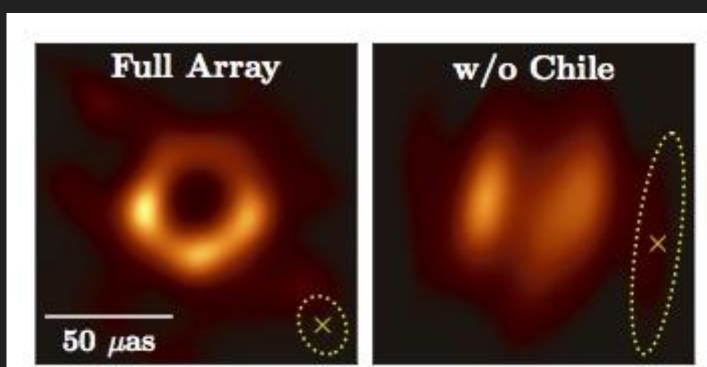
Event Horizon Telescope

mm-VLBI array of 8 radio telescopes in 2017 (now 11) observing at 1.3 mm wavelength with 4 GHz bandwidth having a resolving power of:

$$\frac{\lambda}{D} = \frac{1.3\,\mathrm{mm}}{10,700\,\mathrm{km}} = 25\mu\mathrm{asec}$$

Data recording rate of 32 Gbps (2-bit sampling) onto Mark 6 VLBI recorders (Whitney+ 2013)
Current capacity: 64 Gbps, factor 10 larger than other radio VLBI arrays



Most sensitive component: the Atacama Millimetre/submillimetre Array (ALMA) in Chile

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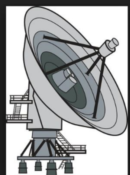
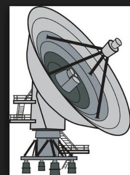
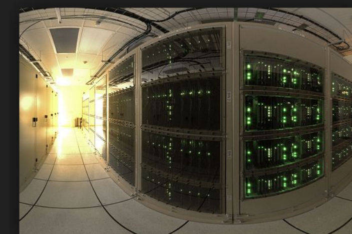
EHT data flow and volume





Antennas observe simultaneously and record data on hard disks
8 antennas - 4 Pb in total for 5 observing nights

Hard disks are shipped to **correlator site** where the data of each antenna pair are correlated by DiFX software correlator (Deller+ 2011) and averaged in frequency and time
Output datasets: 10-100Gb per source per day



Calibration of the data to remove atmospheric and instrumental effects, second averaging in time and frequency
Output datasets: ~1Gb per source per day

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Imaging of the data through a number of mathematical operations involving inverse Fourier Transform

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EHT pipeline development

EHT is a new instrument operating at unprecedented sensitivity and angular resolution, required development of new software tools for calibration and imaging

Calibration: three dedicated calibration pipelines HOPS, CASA and AIPS

Haystack Observatory post-processing system

Common Astronomy Software Applications

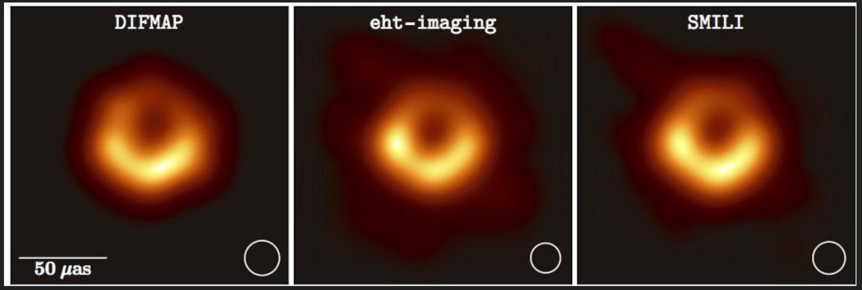
Astronomical Image Processing system

Typical used working stations at Italian ARC for EHT calibration:

RAM 64Gb, CUP Intel Xeon E3-1275 v6, cores 4/8, clocks 3800, Data net 10GbE, work disk 22Tb, scratch disk 57Gb

CASA (McMullin+ 2007) pipeline rPicard (Janssen+ 2019), modular python-based pipeline using the *fringefit* algorithm (van Bemmel+ 2019)

Imaging: three dedicated image pipelines DIFMAP, eht-imaging, SMILI



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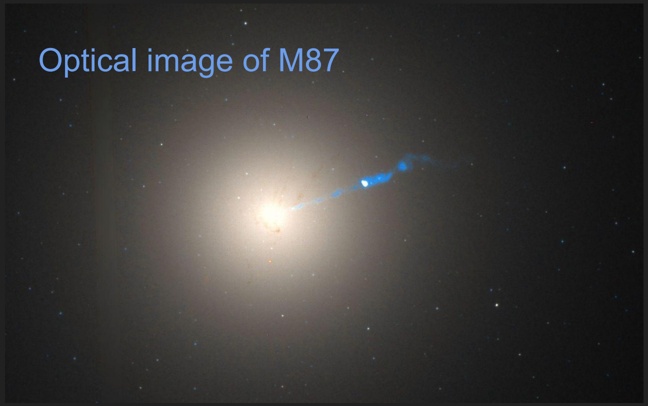
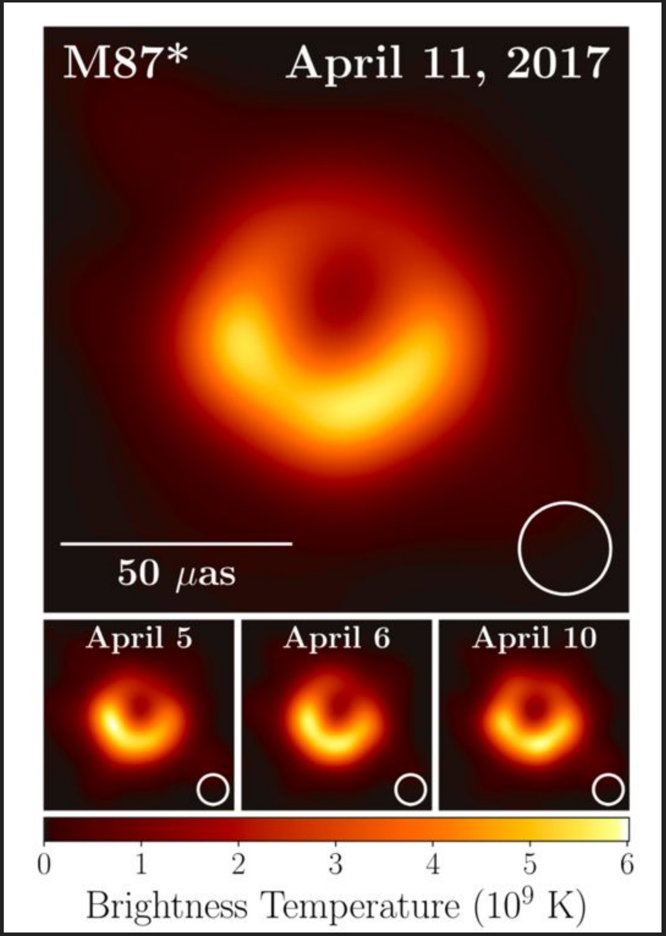
Supermassive Black Hole in the center of M87

Ring diameter: 42 ± 3 μas
→ **confirms GR and yields the BH mass**

Axial ratio of the ring: < 4:3
→ indication of **rotating (Kerr) BH**

Brightest peak position angle: ~175 degree
→ **doppler boosting** effect on rotating hot plasma and constraints BH rotation vector





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