

Uno sguardo sull'invisibile

L'ombra del buco nero supermassiccio
al centro della Via Lattea

Elisabetta Liuzzo, Nicola Marchili
Kazi Rygl

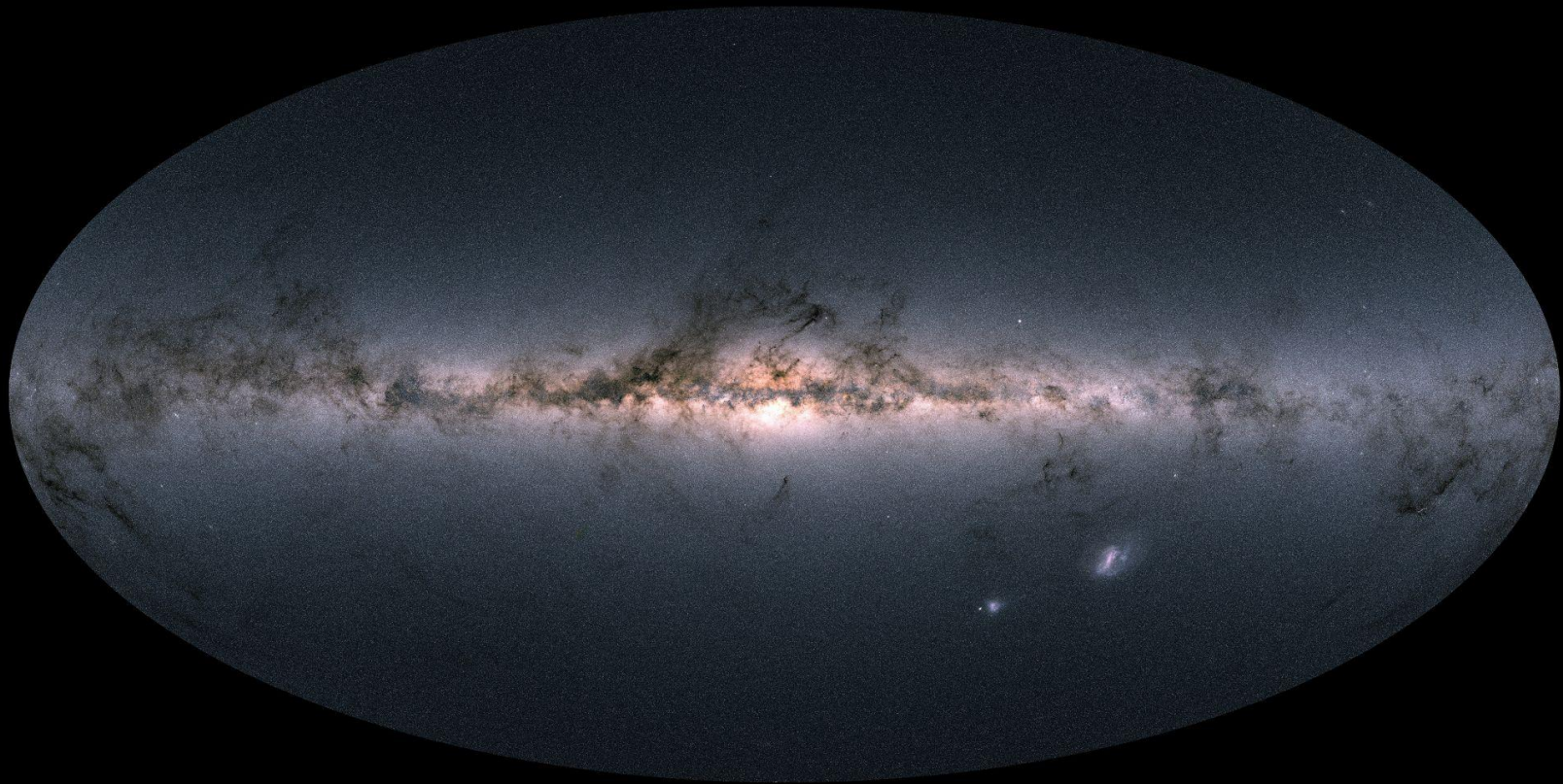
INAF - Istituto di Radioastronomia & Italian ALMA Regional Centre



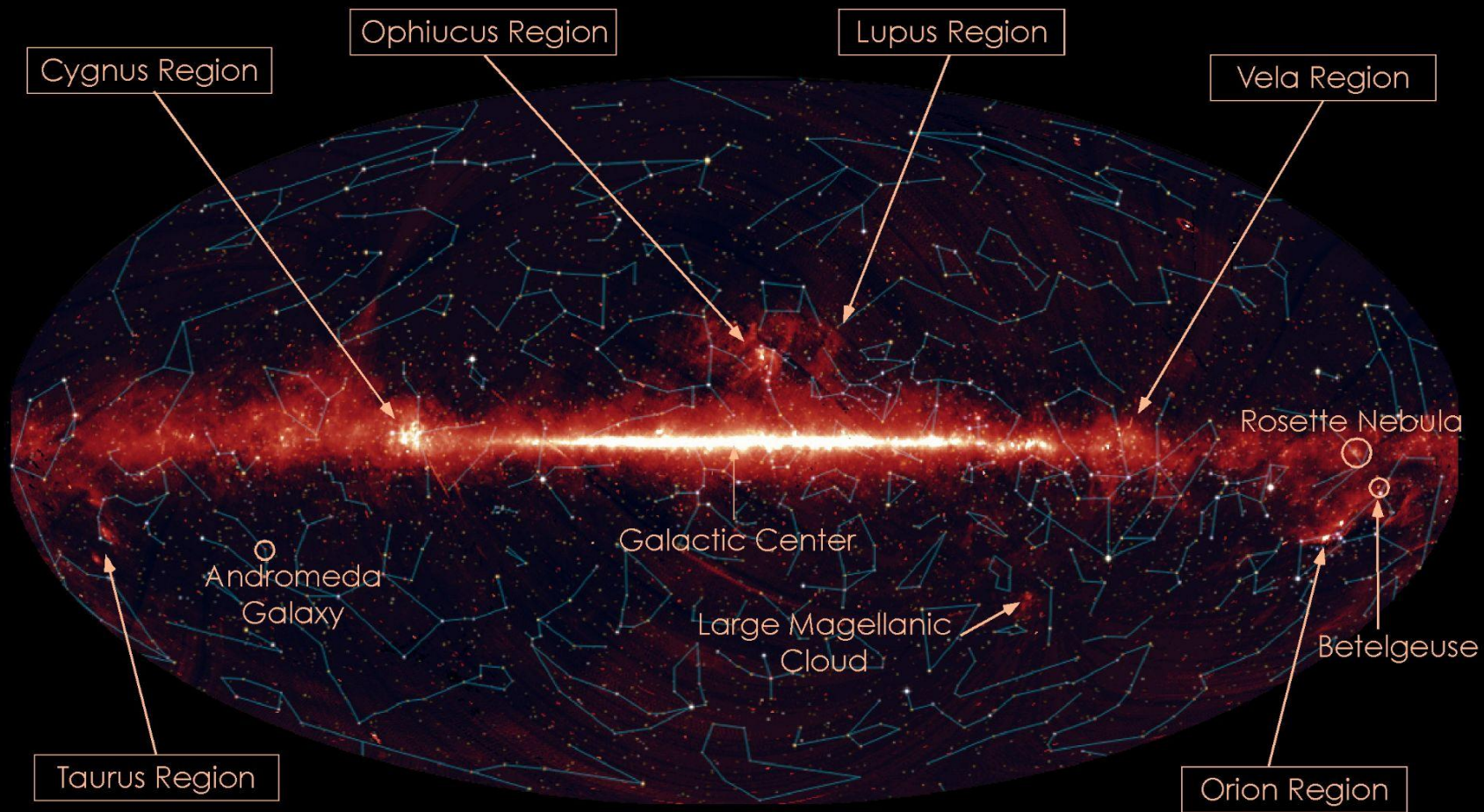
Event Horizon Telescope



EUROPEAN ARC
ALMA Regional Centre || Italian



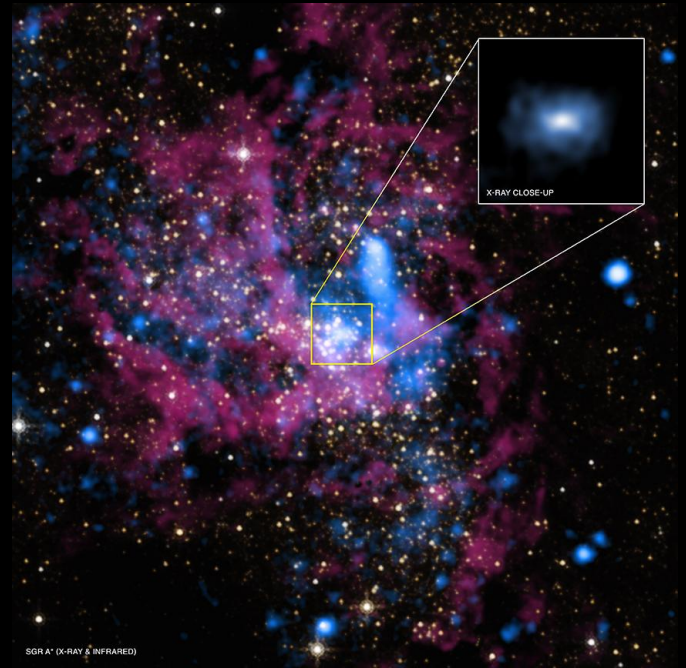
La Via Lattea: stelle e nuvole di polvere dal satellite *Gaia* (ESA/Gaia/DPAC).



La Via Lattea nell'infrarosso: polvere di nubi di formazione stellare da AKARI (JAXA).

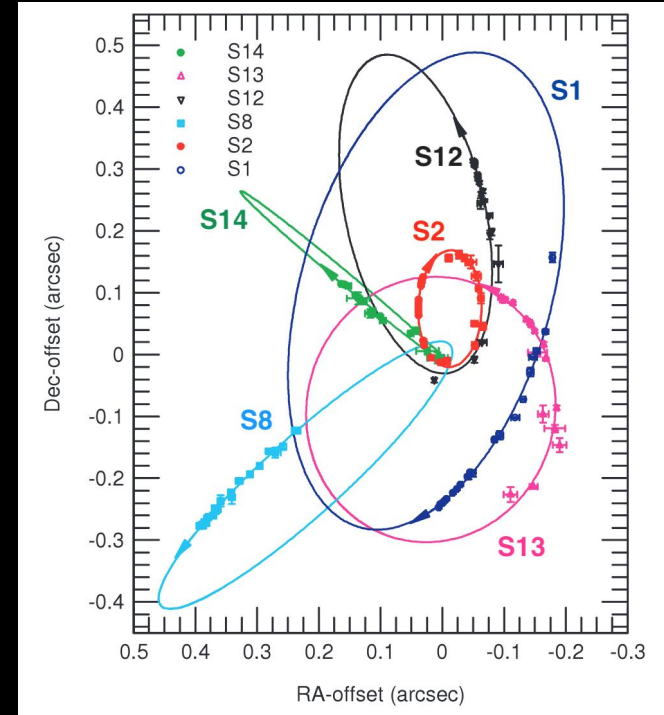
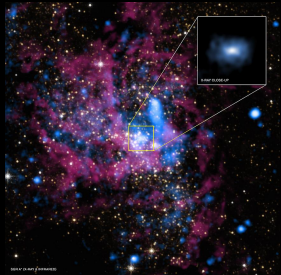
La rotta verso l'ombra del buco nero galattico: Una storia che evolve lungo diverse direttrici

→ Osservazioni multifrequenza del centro galattico



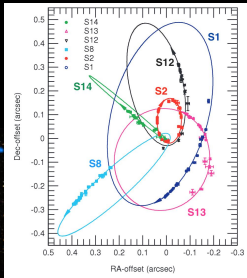
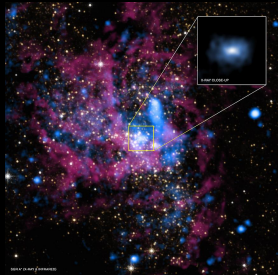
La rotta verso l'ombra del buco nero galattico: Una storia che evolve lungo diverse direttrici

- Osservazioni multifrequenza del centro galattico
- Tracciamento delle orbite delle stelle S



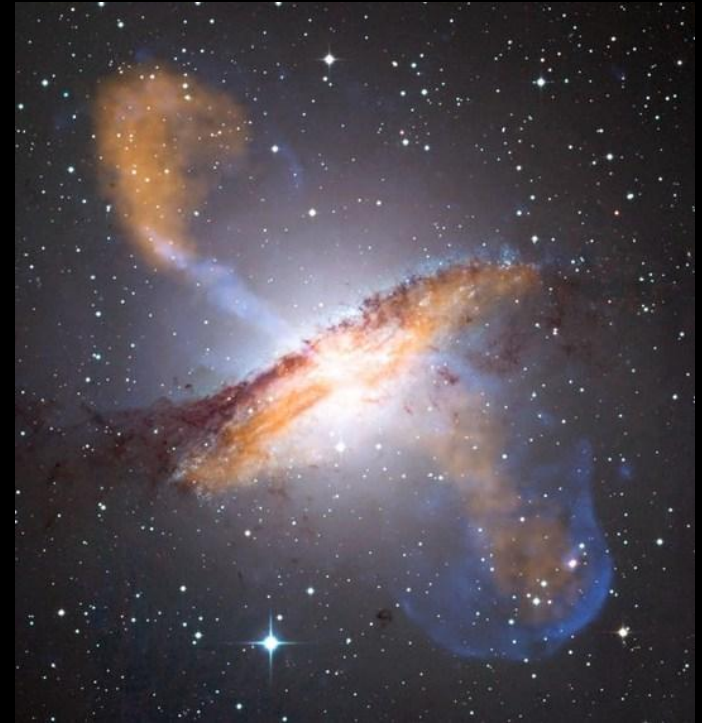
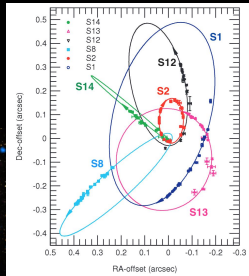
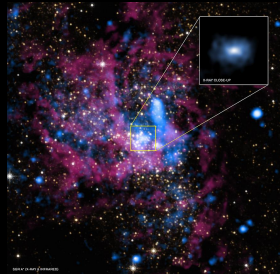
La rotta verso l'ombra del buco nero galattico: Una storia che evolve lungo diverse direttrici

- Osservazioni multifrequenza del centro galattico
- Tracciamento delle orbite delle stelle S
- Sviluppo dell'Interferometria (tecnologia)



La rotta verso l'ombra del buco nero galattico: Una storia che evolve lungo diverse direttrici

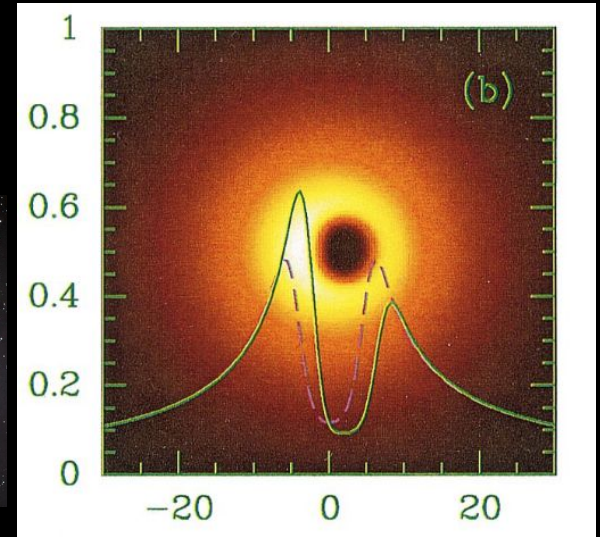
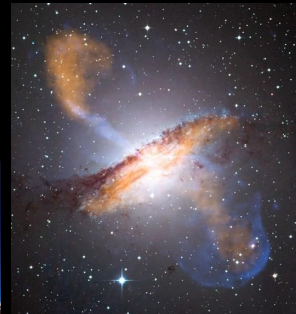
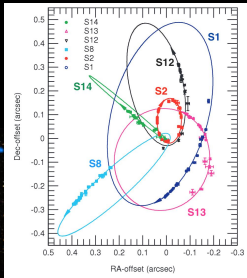
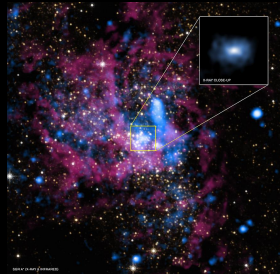
- Osservazioni multifrequenza del centro galattico
- Tracciamento delle orbite delle stelle S
- Sviluppo dell'Interferometria (tecnologia)
- Scoperta e comprensione dei Nuclei Galattici Attivi



X-ray: NASA/CXC/CfA/R.Kraft et al.; Submillimeter: MPIfR/ESO/APEX/A.Weiss et al.; Optical: ESO/WFI.

La rotta verso l'ombra del buco nero galattico: Una storia che evolve lungo diverse direttrici

- Osservazioni multifrequenza del centro galattico
- Tracciamento delle orbite delle stelle S
- Sviluppo dell'Interferometria (tecnologia)
- Scoperta e comprensione dei Nuclei Galattici Attivi
- Simulazioni della possibile ombra (computazione)



Nuclei Galattici Attivi (AGN)

1040

NATURE

March 16, 1963 VOL. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By DR. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

Доклады Академии наук СССР
1964. Том 155, № 1

АСТРОНОМИЯ

Академик Я. Б. ЗЕЛЬДОВИЧ

СУДЬБА ЗВЕЗДЫ И ВЫДЕЛЕНИЕ ГРАВИТАЦИОННОЙ
ЭНЕРГИИ ПРИ АККРЕЦИИ

ACCRETION OF INTERSTELLAR MATTER BY MASSIVE OBJECTS

E. E. SALPETER*†

Received May 7, 1964

NEWMAN LABORATORY OF NUCLEAR STUDIES AND
CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY

AND
GODDARD INSTITUTE FOR SPACE STUDIES
NEW YORK, NEW YORK

690

NATURE, VOL. 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL
Royal Greenwich Observatory,
Hartwood, Greenwich, England

Powerful emissions from the centres of nearby galaxies may represent
dead quasars.

SUSTENANCE OF A BLACK HOLE IN A GALACTIC NUCLEUS

G. A. SHIELDS AND J. C. WHEELER

Department of Astronomy, University of Texas at Austin

Received 1977 September 2; accepted 1977 December 5

Nuclei Galattici Attivi (AGN)

1040

NATURE

March 16, 1963 VOL. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By DR. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

Доклады Академии наук СССР
1964. Том 155, № 1

АСТРОНОМИЯ

Академик Я. Б. ЗЕЛЬДОВИЧ

СУДЬБА ЗВЕЗДЫ И ВЫДЕЛЕНИЕ ГРАВИТАЦИОННОЙ
ЭНЕРГИИ ПРИ АККРЕЦИИ

ACCRETION OF INTERSTELLAR MATTER BY MASSIVE OBJECTS

E. E. SALPETER*†

Received May 7, 1964

NEWMAN LABORATORY OF NUCLEAR STUDIES AND
CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY

AND
GODDARD INSTITUTE FOR SPACE STUDIES
NEW YORK, NEW YORK

690

NATURE, VOL. 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL
Royal Greenwich Observatory,
Hartford, Connecticut

Powerful emissions from the centres of nearby galaxies may represent dead quasars.

SUSTENANCE OF A BLACK HOLE IN A GALACTIC NUCLEUS

G. A. SHIELDS AND J. C. WHEELER

Department of Astronomy, University of Texas at Austin

Received 1977 September 2; accepted 1977 December 5

Nuclei Galattici Attivi (AGN)

1040

NATURE

March 16, 1963 VOL. 197

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By DR. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

Доклады Академии наук СССР
1964. Том 155, № 1

АСТРОНОМИЯ

Академик Я. Б. ЗЕЛЬДОВИЧ

СУДЬБА ЗВЕЗДЫ И ВЫДЕЛЕНИЕ ГРАВИТАЦИОННОЙ
ЭНЕРГИИ ПРИ АККРЕЦИИ

ACCRETION OF INTERSTELLAR MATTER BY MASSIVE OBJECTS

E. E. SALPETER*†

Received May 7, 1964

NEWMAN LABORATORY OF NUCLEAR STUDIES AND
CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY

AND
GODDARD INSTITUTE FOR SPACE STUDIES
NEW YORK, NEW YORK

690

NATURE, VOL. 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL
Royal Greenwich Observatory,
High Elms, Greenwich, S.E. 10, London

Powerful emissions from the centres of nearby galaxies may represent dead quasars.

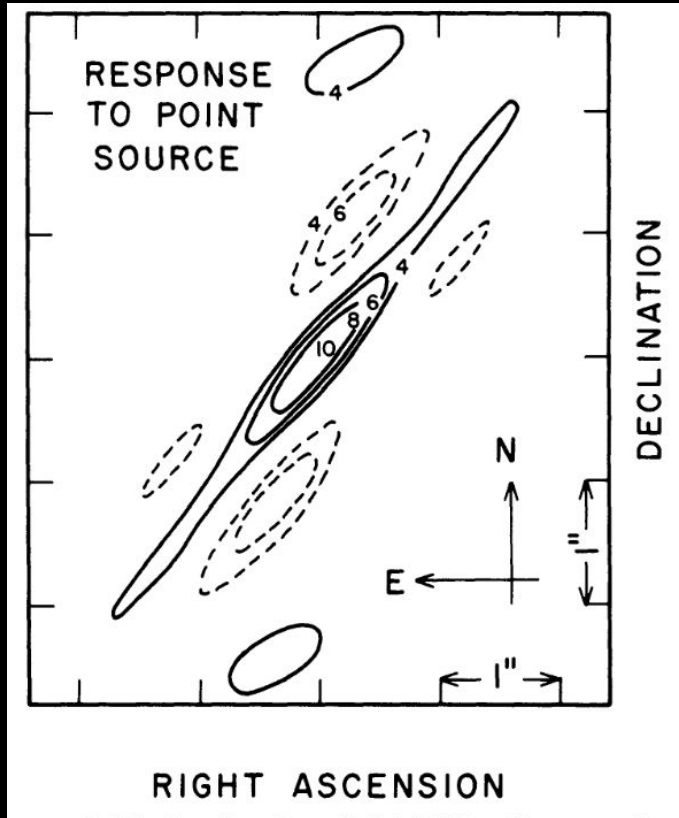
SUSTENANCE OF A BLACK HOLE IN A GALACTIC NUCLEUS

G. A. SHIELDS AND J. C. WHEELER

Department of Astronomy, University of Texas at Austin

Received 1977 September 2; accepted 1977 December 5

Scoperta di una sorgente radio compatta nel 1974



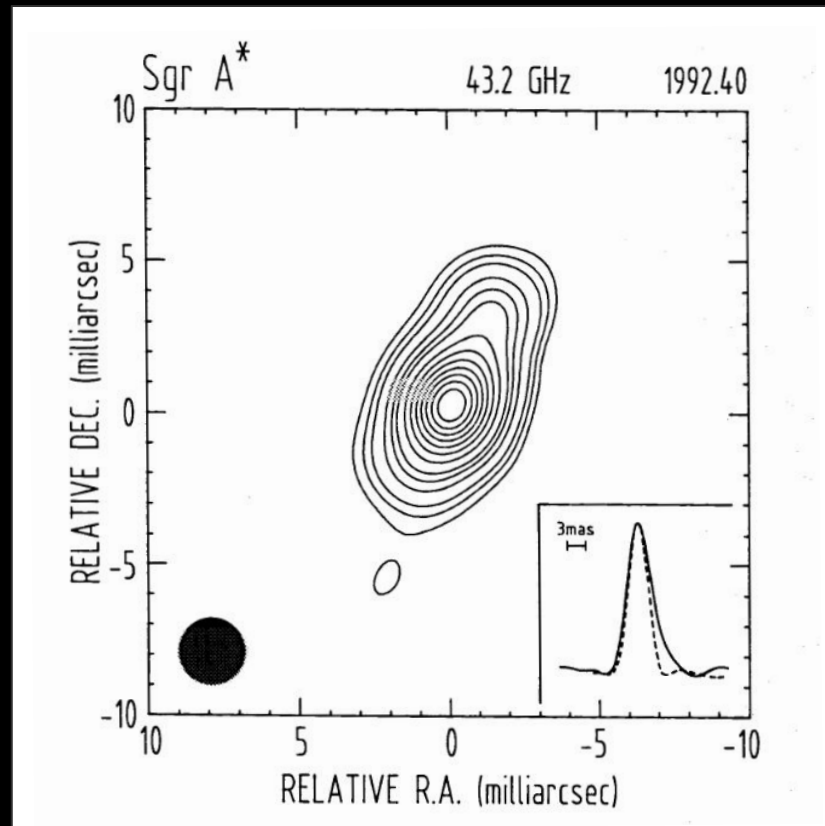
*Potrebbe essere il nostro
nucleo Galattico?*

NRAO [Interferometer](#), 4 antenne,
Balick & Brown 1974

Prima immagine a λ 7mm nel 1993

*Similarità con nuclei attivi
noti, ma su scala ridotta*

Very Long Baseline Array, 4 antenne,
Krichbaum *et al.* 1993

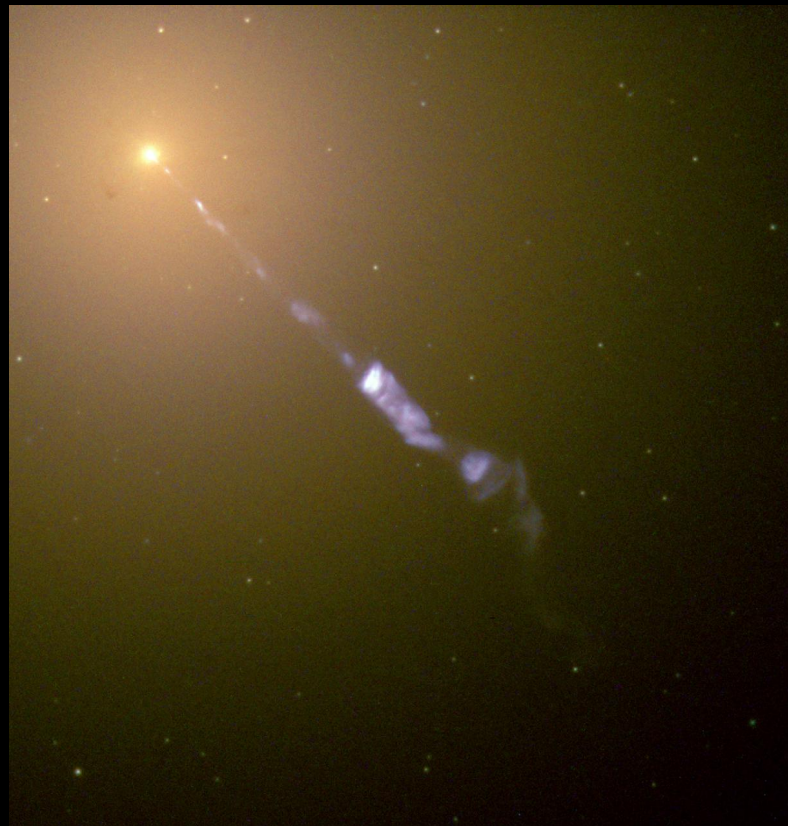


Analogie e differenze

Posizione
Compattezza
Emissione radio

Luminosità
Getto?

Il getto di M87



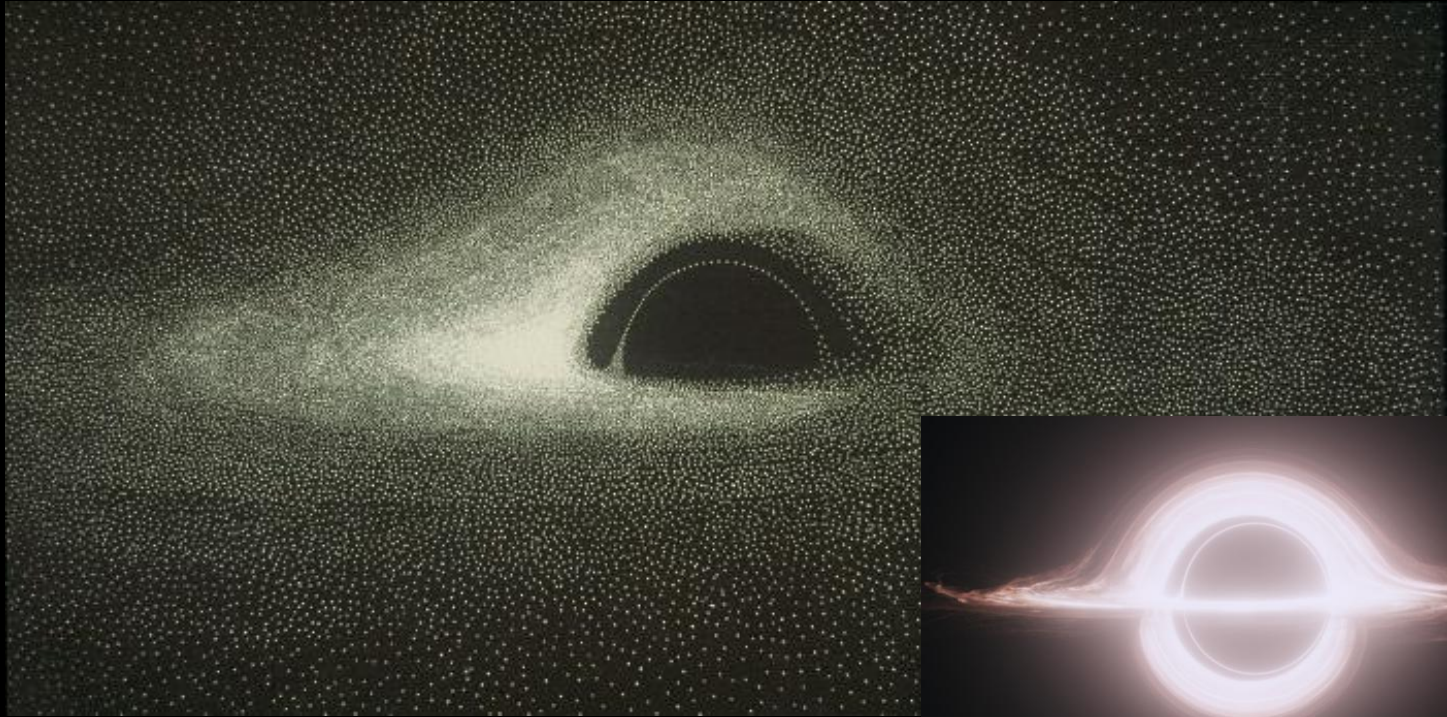
NASA and The Hubble Heritage Team (STScI/AURA)

Prima “simulazione” dell’ombra di un buco nero



Luminet 1979

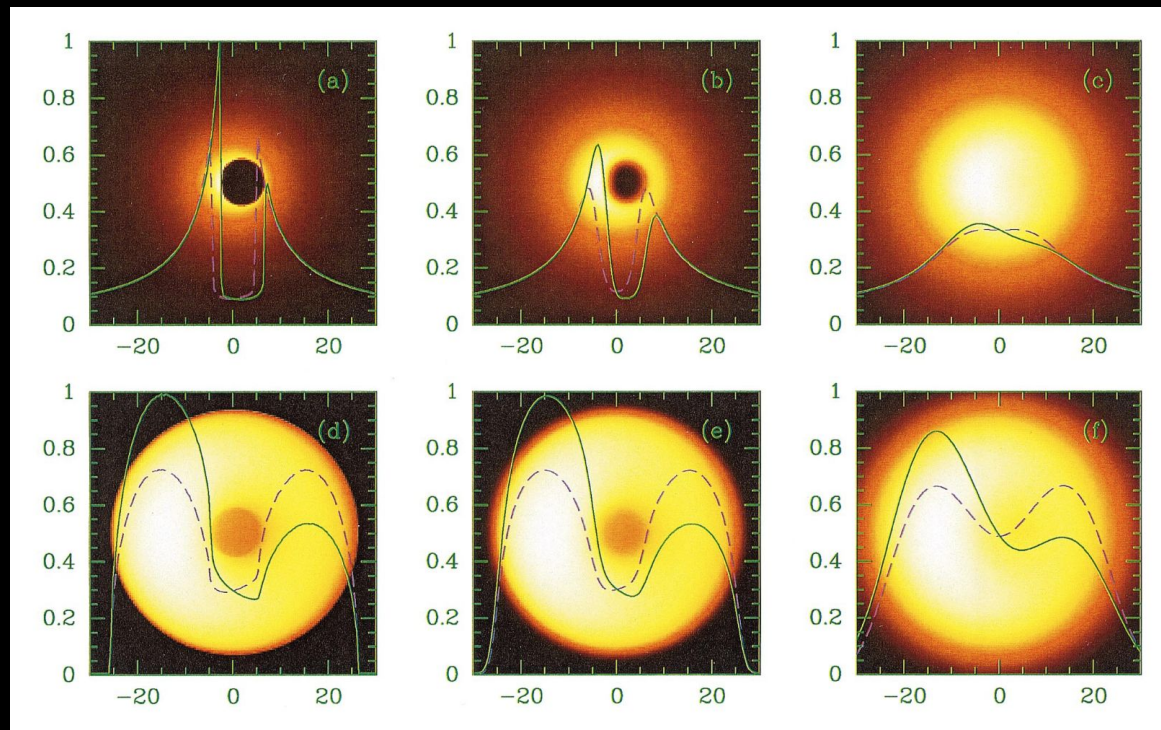
Prima “simulazione” dell’ombra di un buco nero

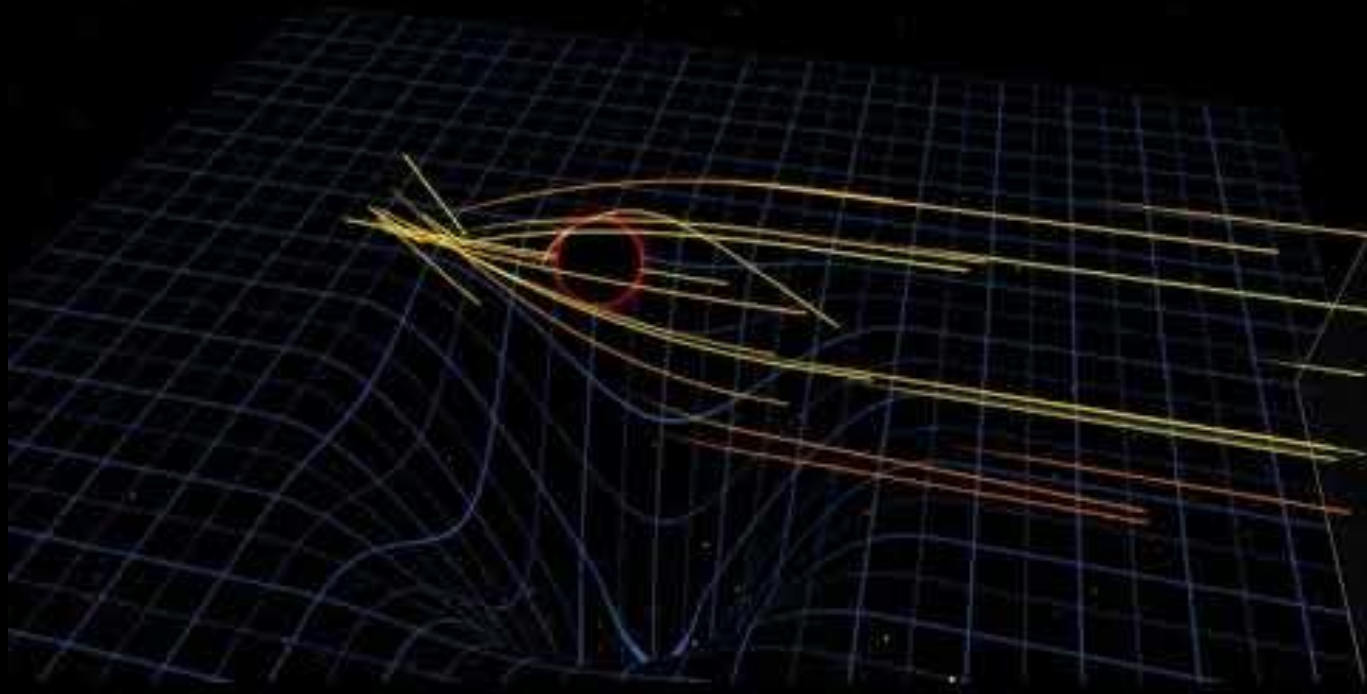


Luminet 1979

Credits: <https://cerncourier.com>
DNEG/Warner Bros. Entertainment Inc.

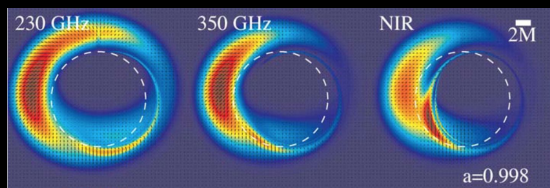
Diversi modelli di ombra del buco nero





Credits: Crazybridge Studios, Center for Astrophysics | Harvard & Smithsonian, US National Science Foundation

Sulle tracce del buco nero



2002 - Orbita della stella **S2** ($M \sim 3.7 \cdot 10^6 M_{\odot}$)
(Schödel et al.)

2006 - Studio di osservabilità in prossimità di un buco nero (Broderick & Loeb)

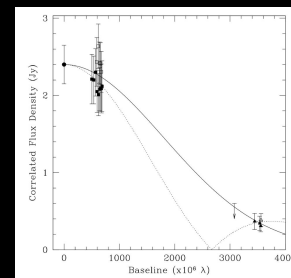
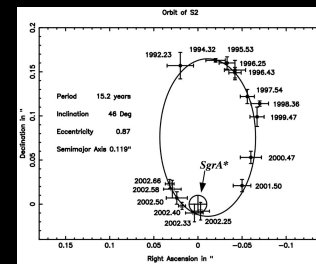
2008 - Scoperta di una struttura di dimensioni compatibili con un'ombra (Doeleman et al.)

2009 - *Imaging an Event Horizon* (white paper)
(Doeleman et al.)

2014 - Aggiornamento di **ALMA** per partecipare ad osservazioni EHT



2020 - Premi Nobel a **Reinhard Genzel** e **Andrea Ghez** per studio orbite stelle S



Dimensione dell'ombra

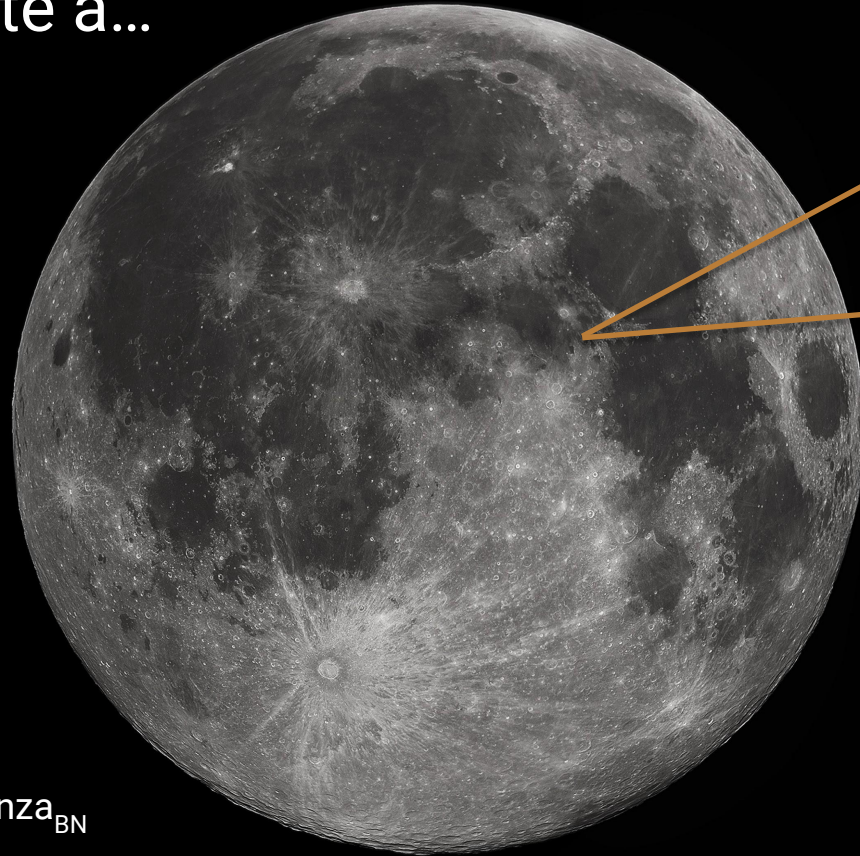
Raggio di Schwarzschild: $r_s = 2 GM/c^2$
(e definisce l'orizzonte degli eventi)

Diametro dell'ombra $d_{sh} = 10 GM/c^2$

Se i calcoli sono corretti, il diametro dell'ombra di Sgr A* corrisponderebbe, all'incirca, all'orbita di Mercurio...



... corrispondente a...



Raggio angolare: $d_{sh} / \text{Distanza}_{BN}$

EHT è un telescopio rivoluzionario

Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

2017 OBSERVATIONS

ALMA Atacama Large Millimeter/submillimeter Array
CHAJNANTOR PLATEAU, CHILE

APEX Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE

30-M IRAM 30-M Telescope
PICO VELETA, SPAIN

JCMT James Clerk Maxwell Telescope
MAUNAKEA, HAWAII

LMT Large Millimeter Telescope
SIERRA NEGRA, MEXICO

SMA Submillimeter Array
MAUNAKEA, HAWAII

SMT Submillimeter Telescope
MOUNT GRAHAM, ARIZONA

SPT South Pole Telescope
SOUTH POLE STATION

JCMT SMA

SMT

LMT

ALMA APEX

30-M

SPT

EHT NRAO

La collaborazione EHT > 300 membri



Il contributo italiano in EHT



Mariafelicia De Laurentis

- Deputy Project Scientist
- Theories of gravitation
- Leader SgrA* paper VI



Ciriaco Goddi

- Osservazioni
- Calibration & Errors
- Segretario EHT (fino 2020)



Rocco Lico

- Imaging
- Co-lead parameter survey & gains team
- ICT Officer & Segretario EHT



Elisabetta Liuzzo

- EHT Board guest
- Calibration & Errors



Nicola Marchili

- 2° author Official Sgr A* paper
- Variability

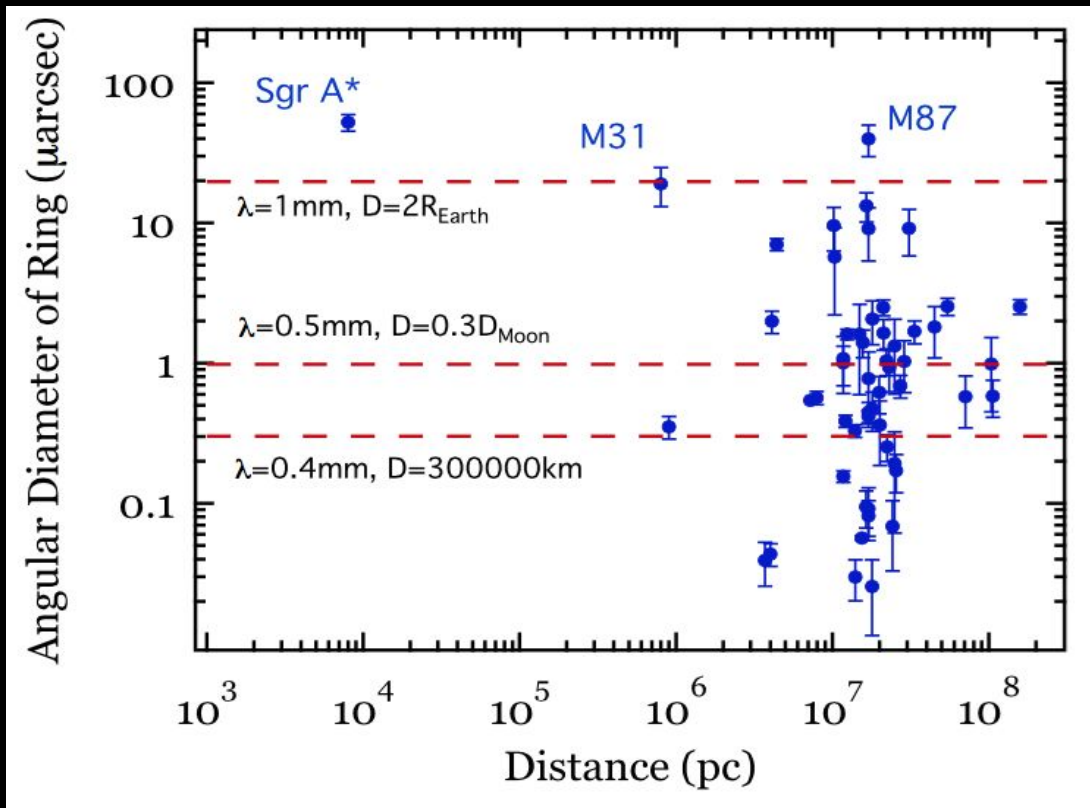


Kazi Rygl

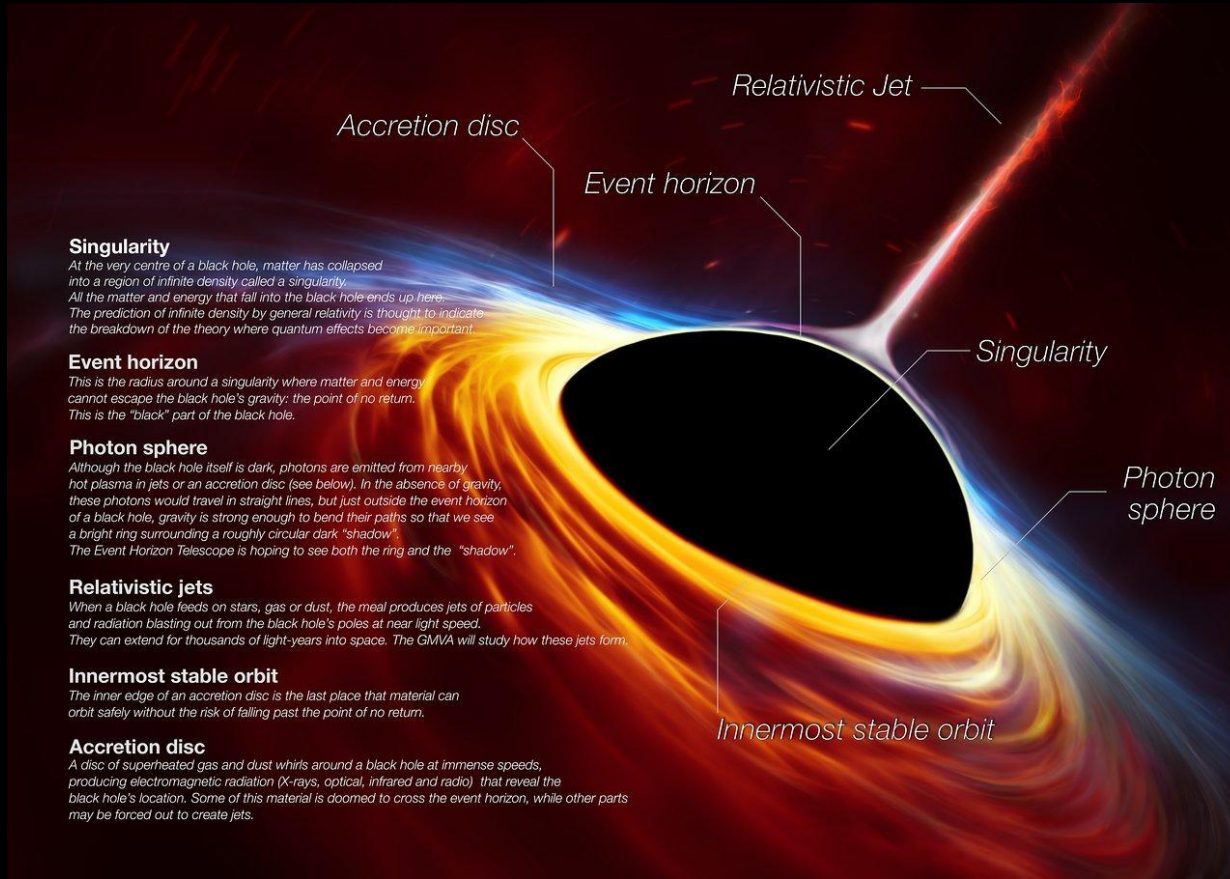
- Publication committee
- Calibration and Errors

Quali ombre di buchi neri sono osservabili?

Johanssen+, arXiv:1201.0758



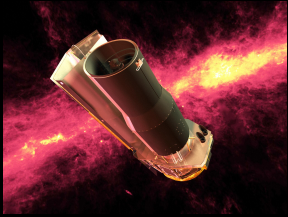
..non solo ombra del buco nero



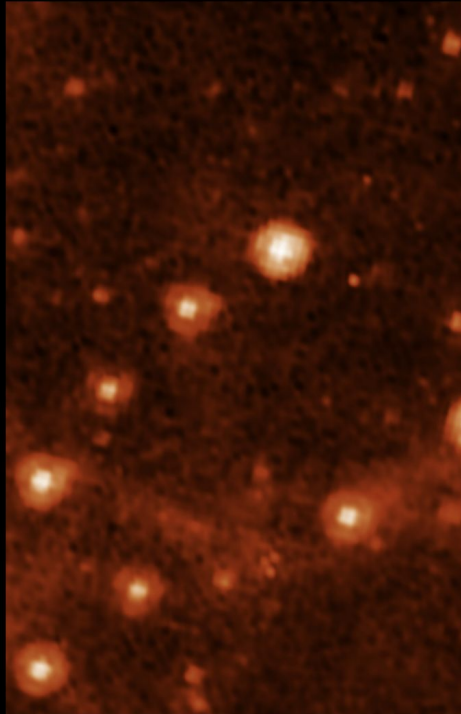
Il potere risolutivo di un telescopio
aumenta all'aumentare del diametro



$$\theta \sim \lambda / D$$



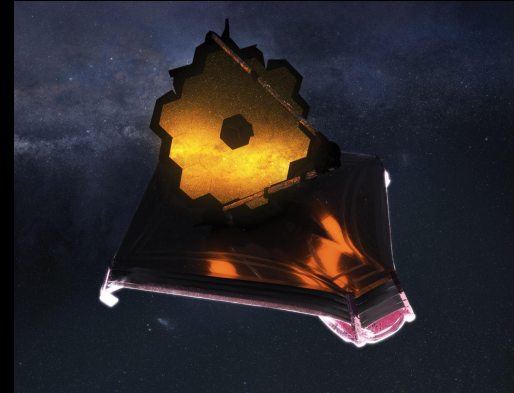
85 cm



SPITZER IRAC 8.0 μ

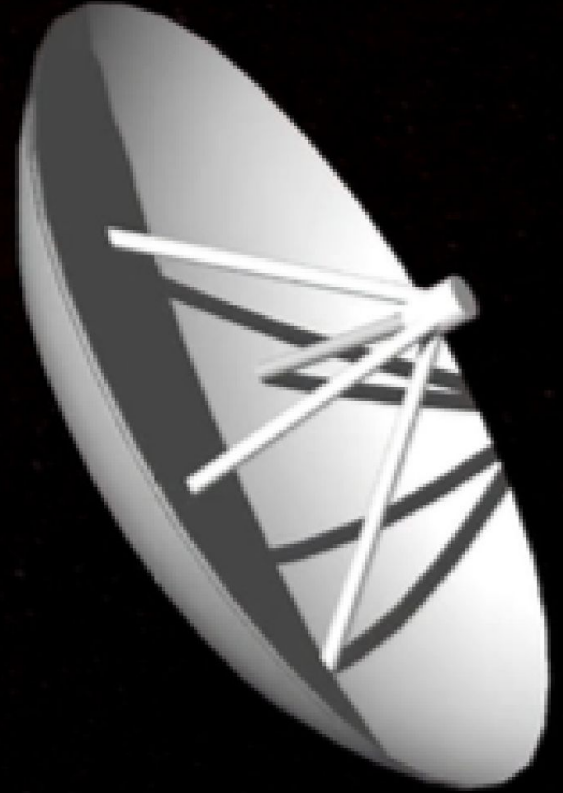


WEBB MIRI 7.7 μ



6.5 m

Ci serve un telescopio ...



delle dimensioni della **Terra**

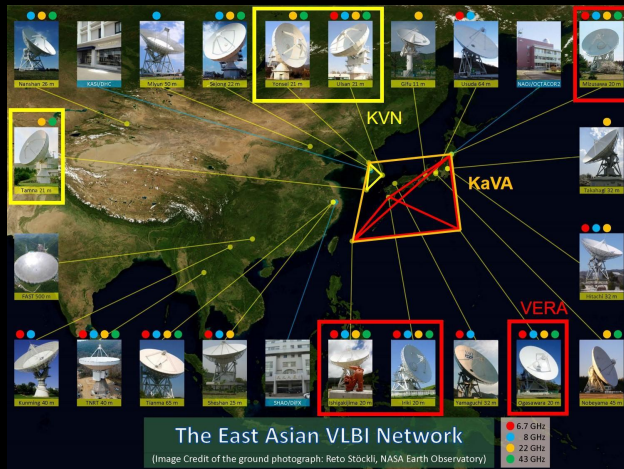
Serve la tecnica Very Long Baseline Interferometry (VLBI)

Per un INTERFEROMETRO:

risoluzione angolare $\sim \lambda / B$

dove B è la distanza massima tra le
coppie di antenne

Esempio di un array VLBI
B > interferometro



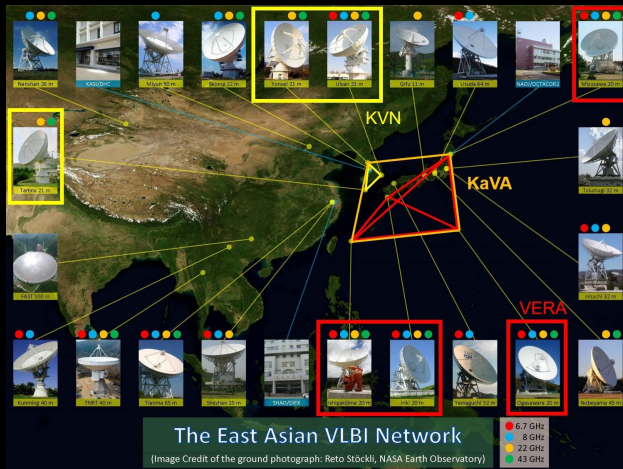
Serve la tecnica Very Long Baseline Interferometry (VLBI)

Per un INTERFEROMETRO:

risoluzione angolare $\sim \lambda / B$

dove B è la distanza massima tra i
coppie di antenne

Esempio di un array VLBI
B > interferometro



VLBI globale
B- Diametro terrestre



image credit
European VLBI Network
<https://www.evlbi.org/>

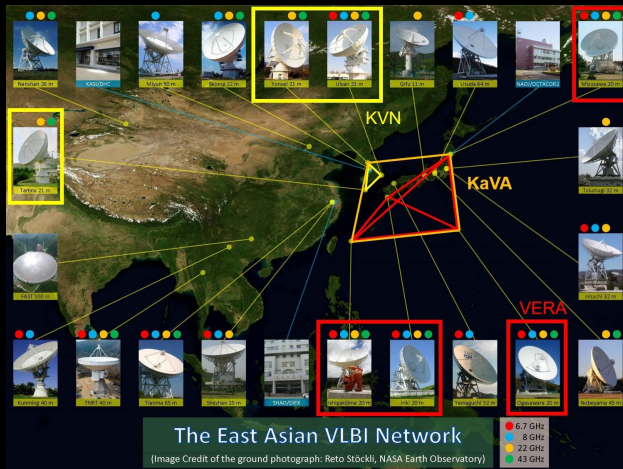
Serve la tecnica Very Long Baseline Interferometry (VLBI)

Per un INTERFEROMETRO:

risoluzione angolare $\sim \lambda / B$

dove B è la distanza massima tra i
coppie di antenne

Esempio di un array VLBI
B > interferometro



VLBI globale
B- Diametro terrestre



image credit
European VLBI Network
<https://www.evlbi.org/>

VLBI spaziale
B > Diametro terrestre

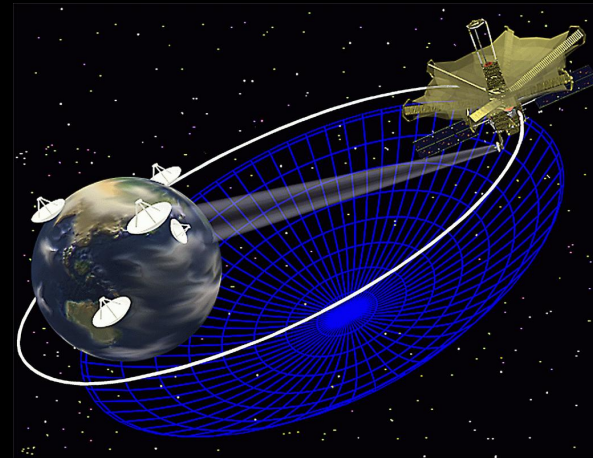
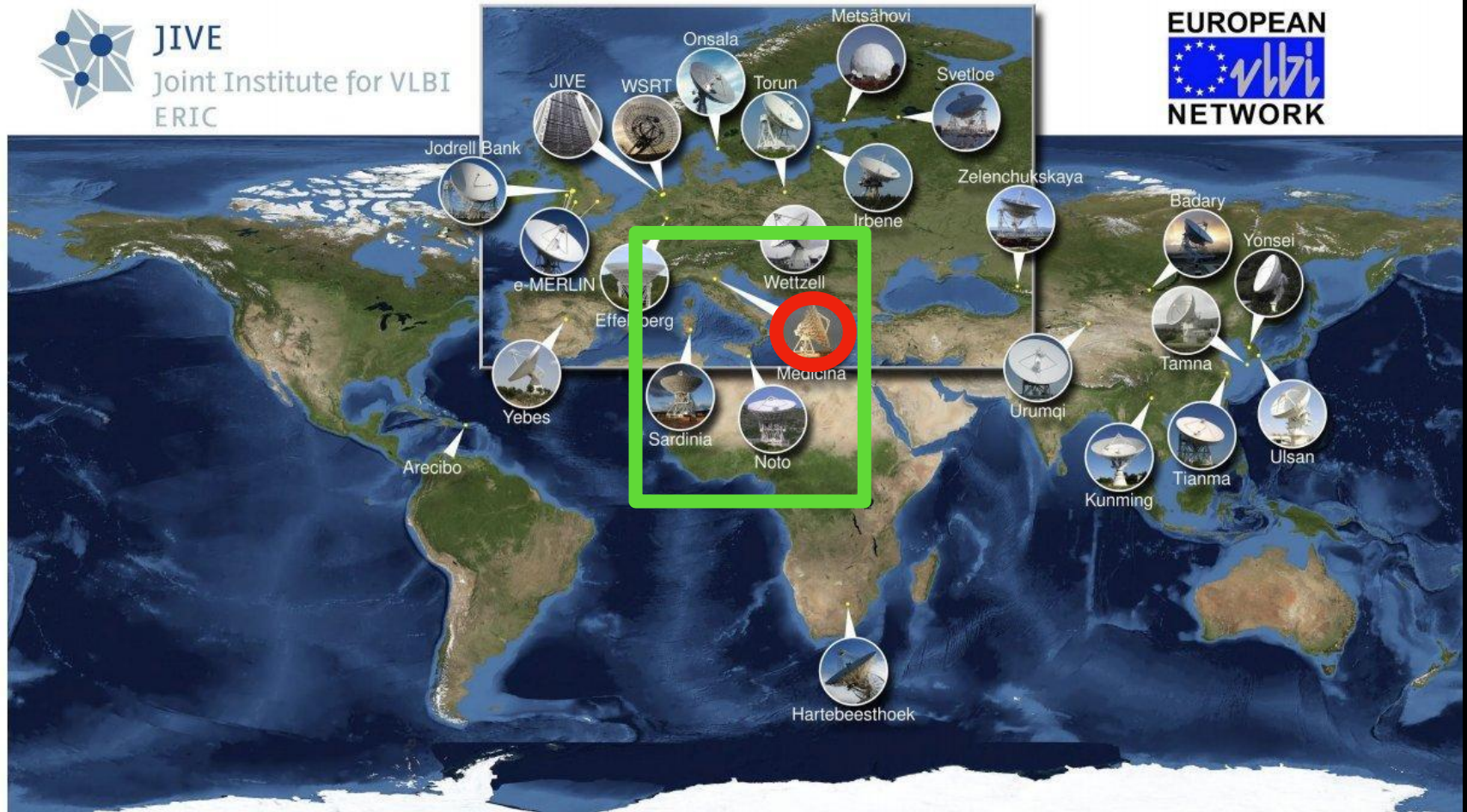


image credit
<https://www.jpl.nasa.gov/missions/spac-e-very-long-baseline-interferometry-space-vlbi>

Il VLBI è nato nella banda centimetrica



JIVE
Joint Institute for VLBI
ERIC

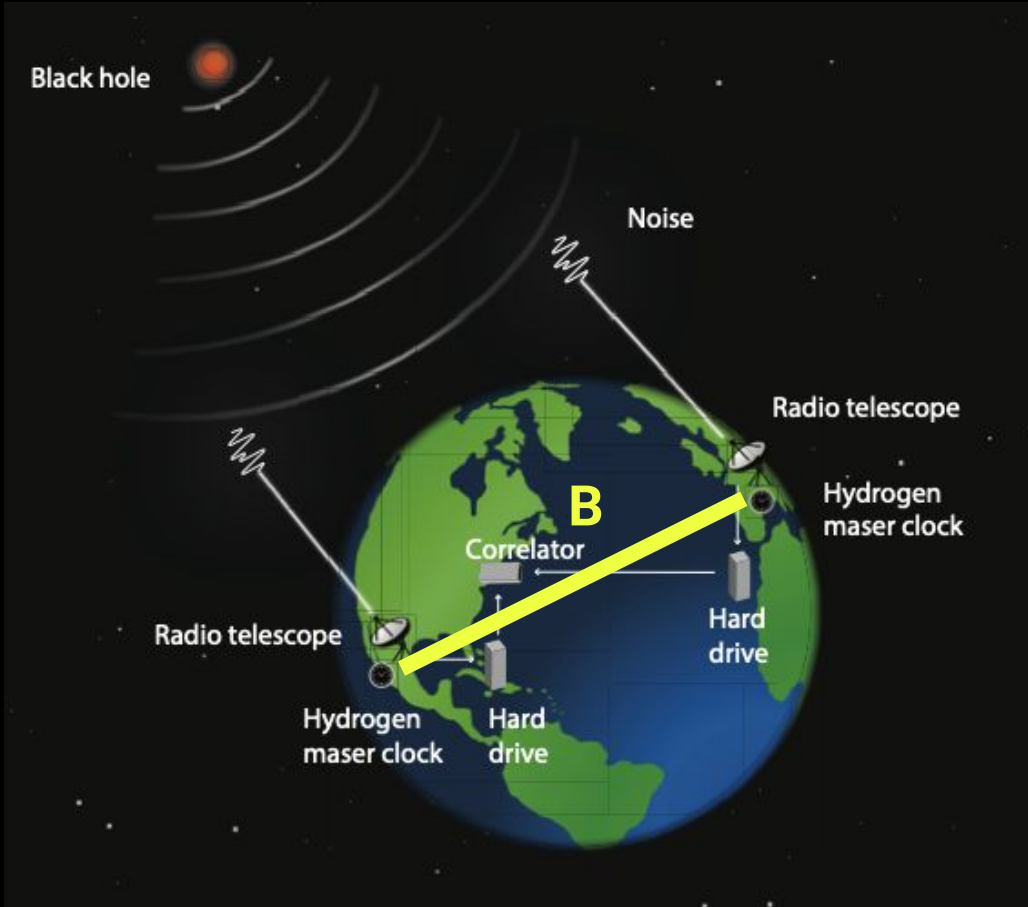


Bologna partecipa all'European VLBI Network (EVN)



Stazione radioastronomica di Medicina (Bologna)
INAF - Istituto di Radioastronomia di Bologna

EHT è il più esteso esperimento VLBI a 1 mm di sempre!!



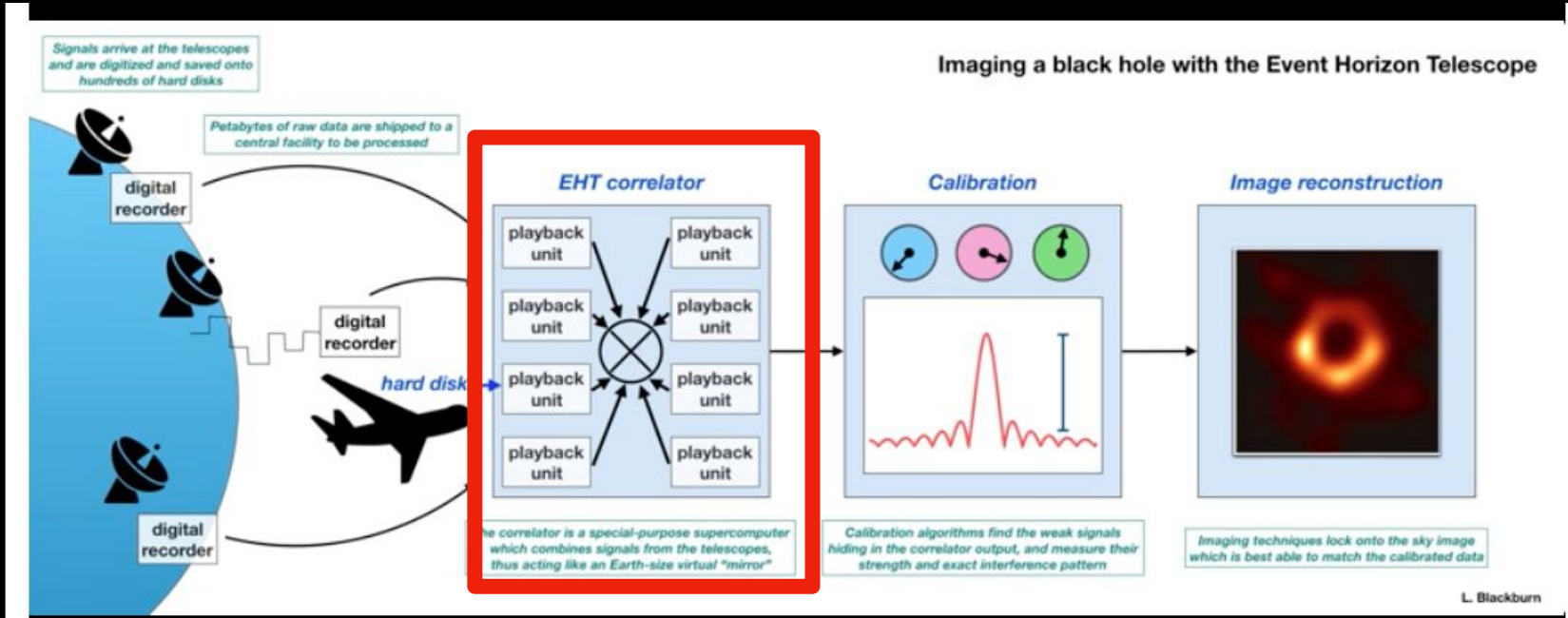
Nel VLBI, la risoluzione angolare è

$$\theta \sim \lambda / B$$

Per EHT:

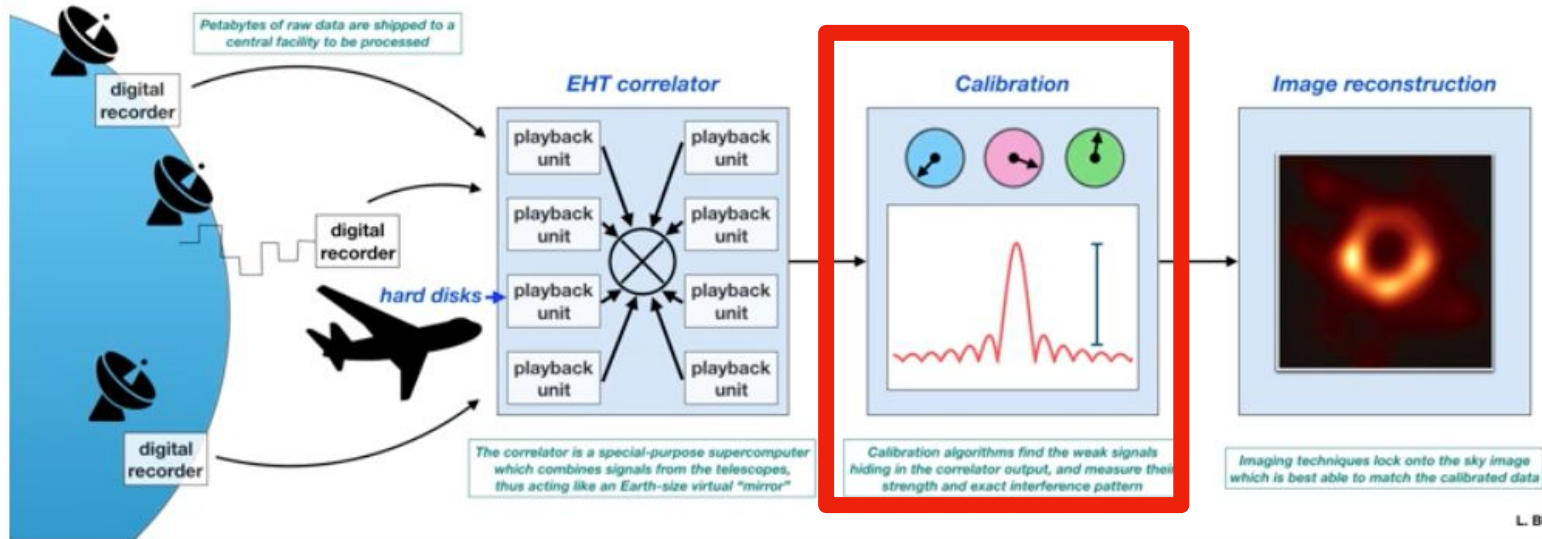
- $B \sim 10\,700$ km
- $\theta \sim 25$ microarcsec

Come funziona la tecnica VLBI



Come funziona la tecnica VLBI

Signals arrive at the telescopes and are digitized and saved onto hundreds of hard disks



Imaging a black hole with the Event Horizon Telescope

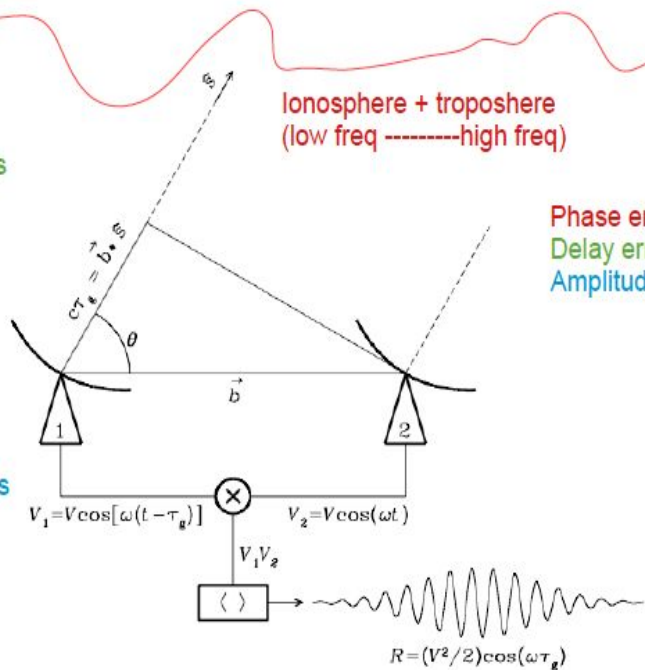
Perché la calibrazione dei dati VLBI è importante?

Bad positions & width bandwidths

Ionosphere + troposphere
(low freq -----high freq)

Phase error
Delay error ($\delta\phi/\delta v$)
Amplitude error

Non identical electronics/gains



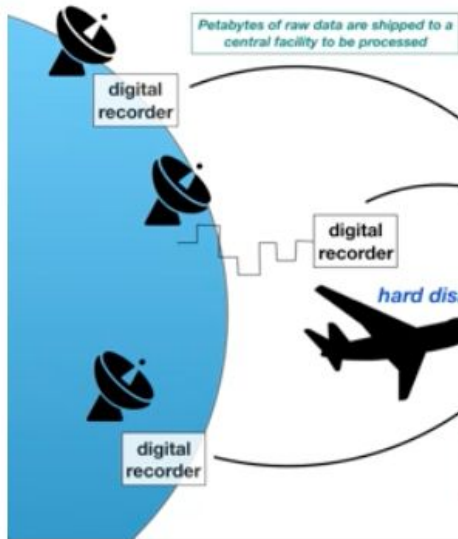
Prima

2 anni

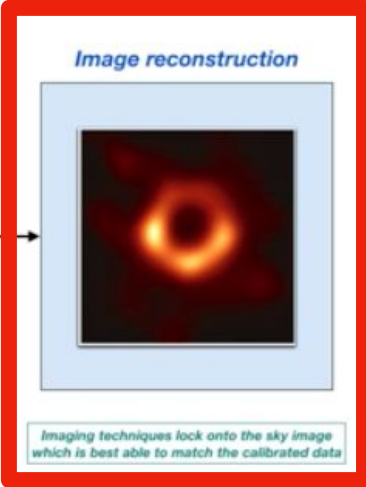
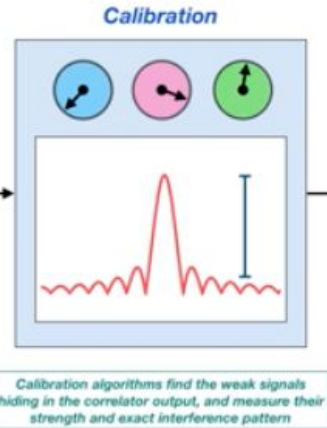
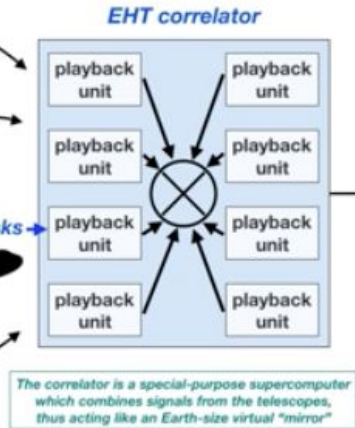
Dopo

Come funziona la tecnica VLBI

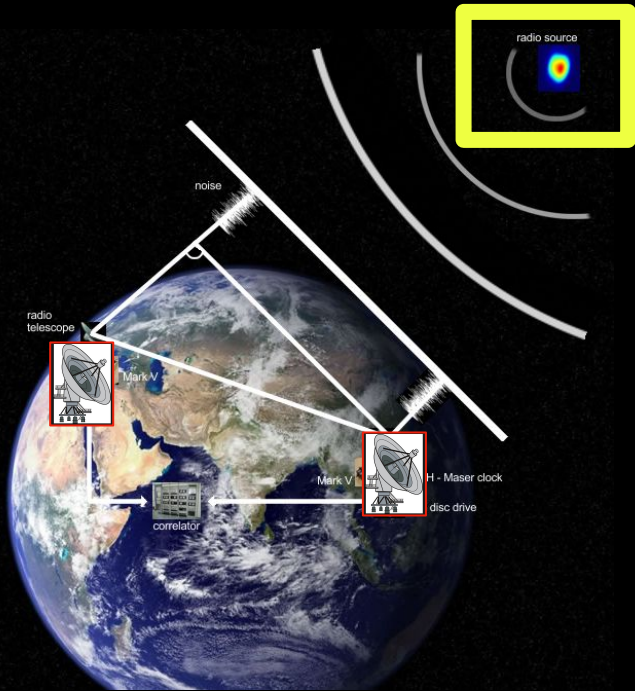
Signals arrive at the telescopes and are digitized and saved onto hundreds of hard disks



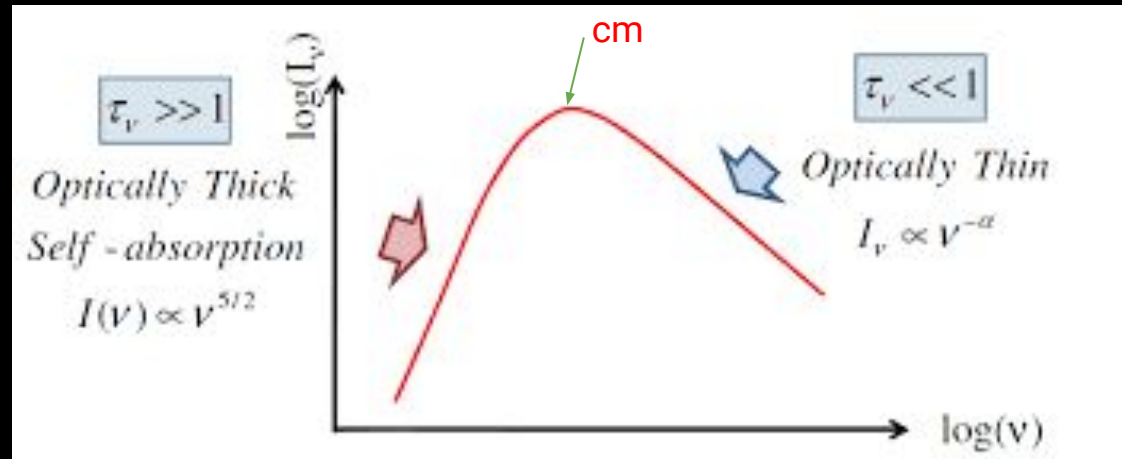
Imaging a black hole with the Event Horizon Telescope



Il VLBI nel millimetrico pone svariate sfide

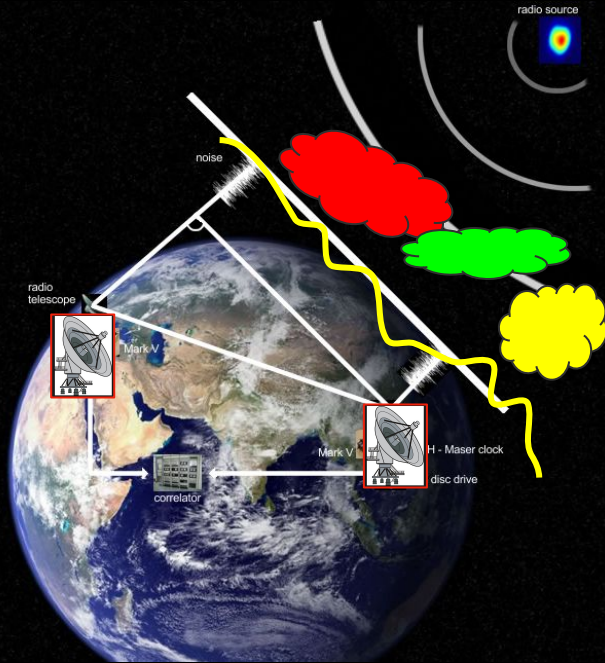


- Sorgenti deboli



Spettro di sincrotrone

Il VLBI nel millimetrico pone svariate sfide



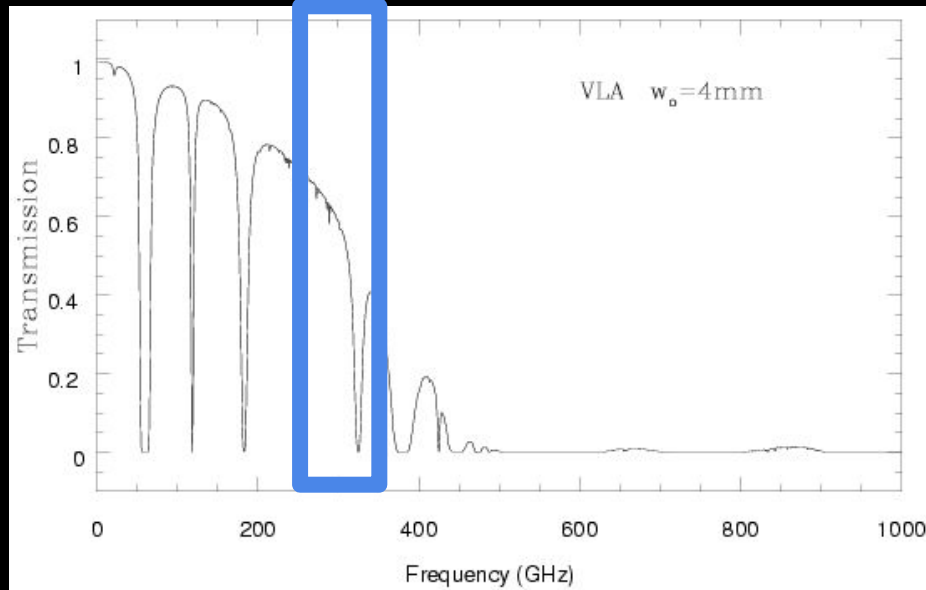
Effetti distorsivi della troposfera:

- forte dipendenza della qualità delle osservazioni dal meteo all'aumentare della frequenza osservativa → climi secchi

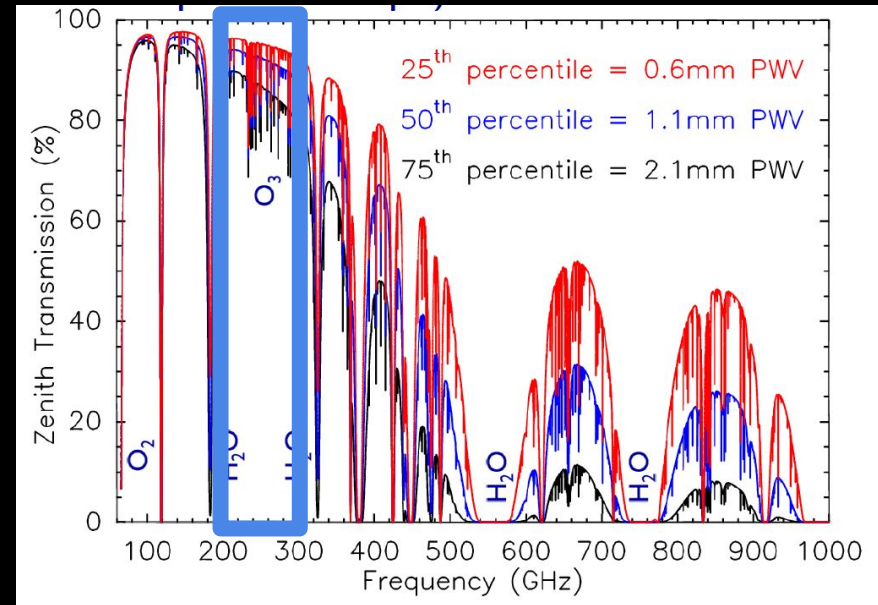
Il VLBI nel millimetrico pone svariate sfide

- Effetti distorsivi della troposfera

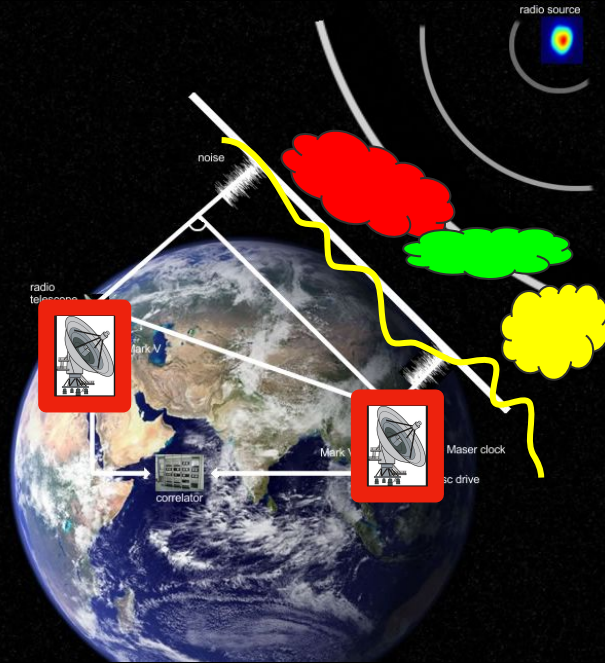
VLA (cm) - New Mexico (USA)- 2000 metri



ALMA (mm) -CHILE - 5000 m



Il VLBI nel millimetrico pone svariate sfide



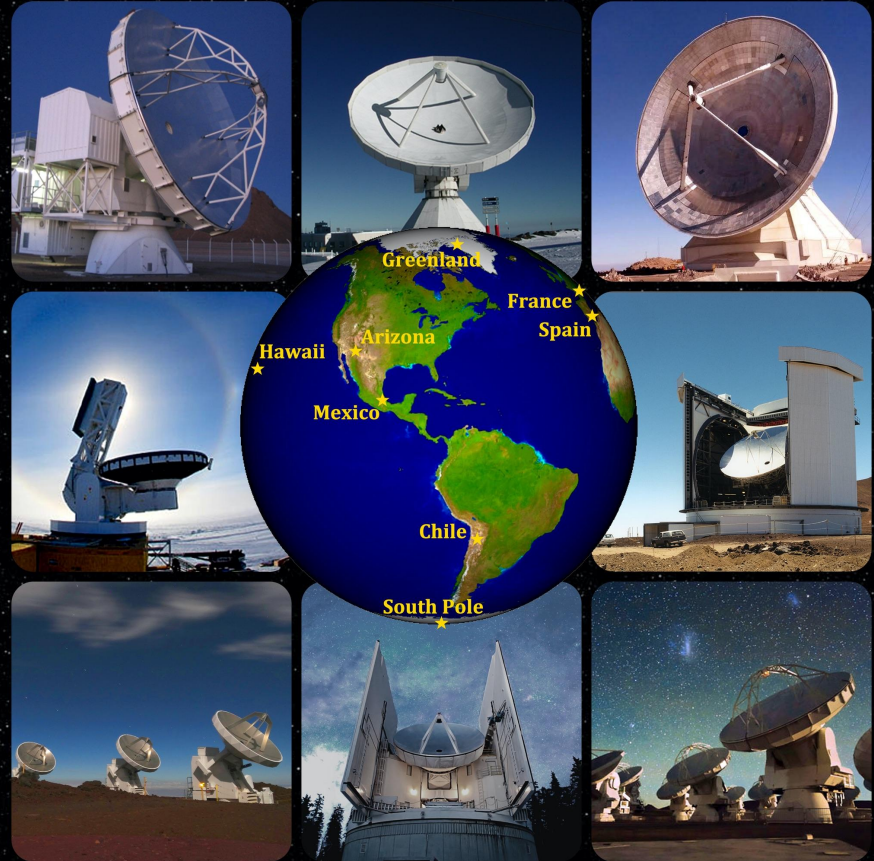
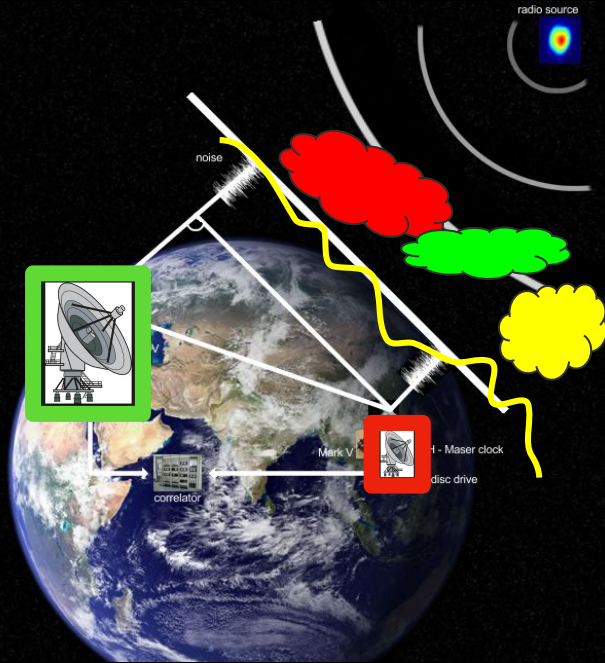
Bassa sensibilità:

- peggiore performance dei ricevitori
- diametri telescopi piccoli (10-15m)
- ridotto numero di antenne nell'array

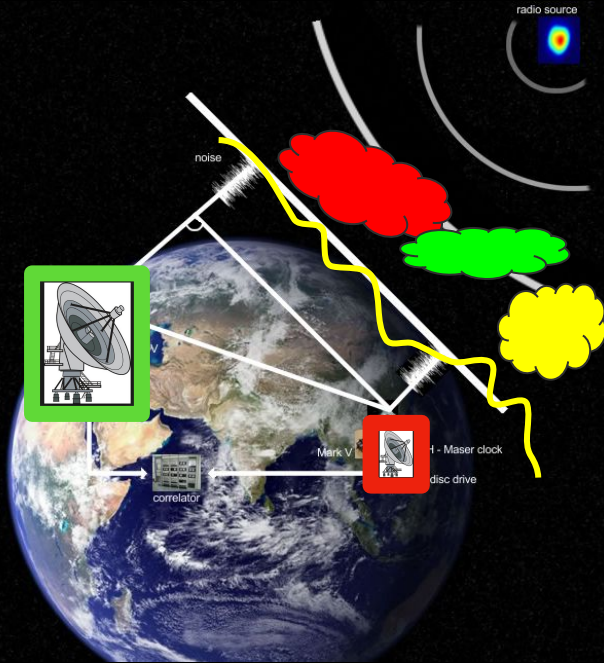
For an interferometer :

$$\sigma_S \approx \frac{2kT_{\text{sys}}}{A_{\text{eff}} \sqrt{n(n-1)} \times \Delta\nu \times \eta_{\text{pol}} \times t_{\text{int}}} \text{ [Jy]}$$

Il VLBI nel millimetrico pone svariate sfide



Il VLBI nel millimetrico pone svariate sfide



Le antenne non sono omogenee:

- Dimensione disco
- Proprietà dei siti
- Caratteristiche costruttive

→ *processi di calibrazione ed imaging ad hoc*

Un'enorme quantità di dati

Dati del South Pole Telescope



Dati di un'intera
campagna EHT



~ 4 Petabyte

~ 1 milione di



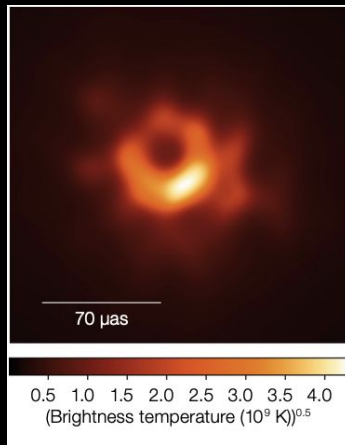
da 1 Gb!!

ALMA è cruciale

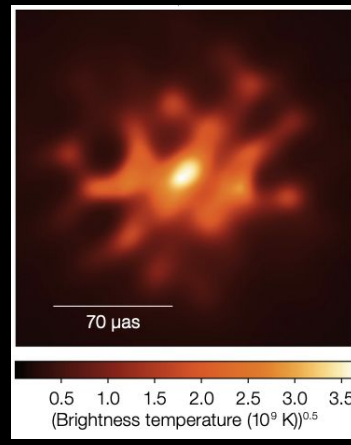
Interferometro di 66 antenne a 5000 metri in Chile



Con ALMA



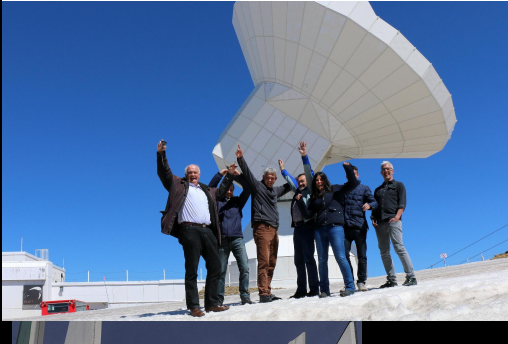
senza ALMA



osservazioni simulate di M87

Campagna osservativa del 2017!!!

IRAM/Spagna



ALMA+APEX/Chile



LMT/Mexico



SMT/Arizona

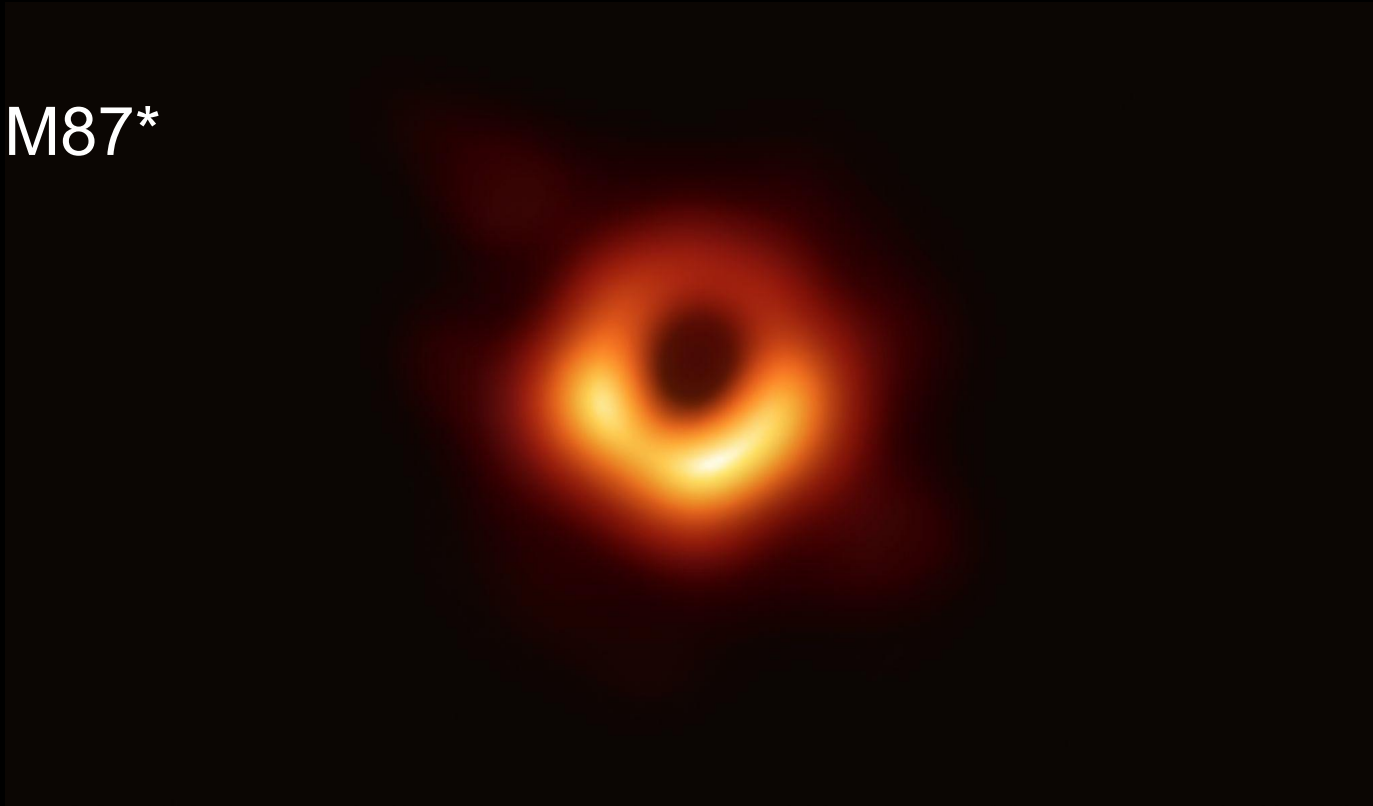


SMA + JCMT/Hawaii



SPT/Polo Sud

2019: M87*



Credit: Event Horizon Telescope

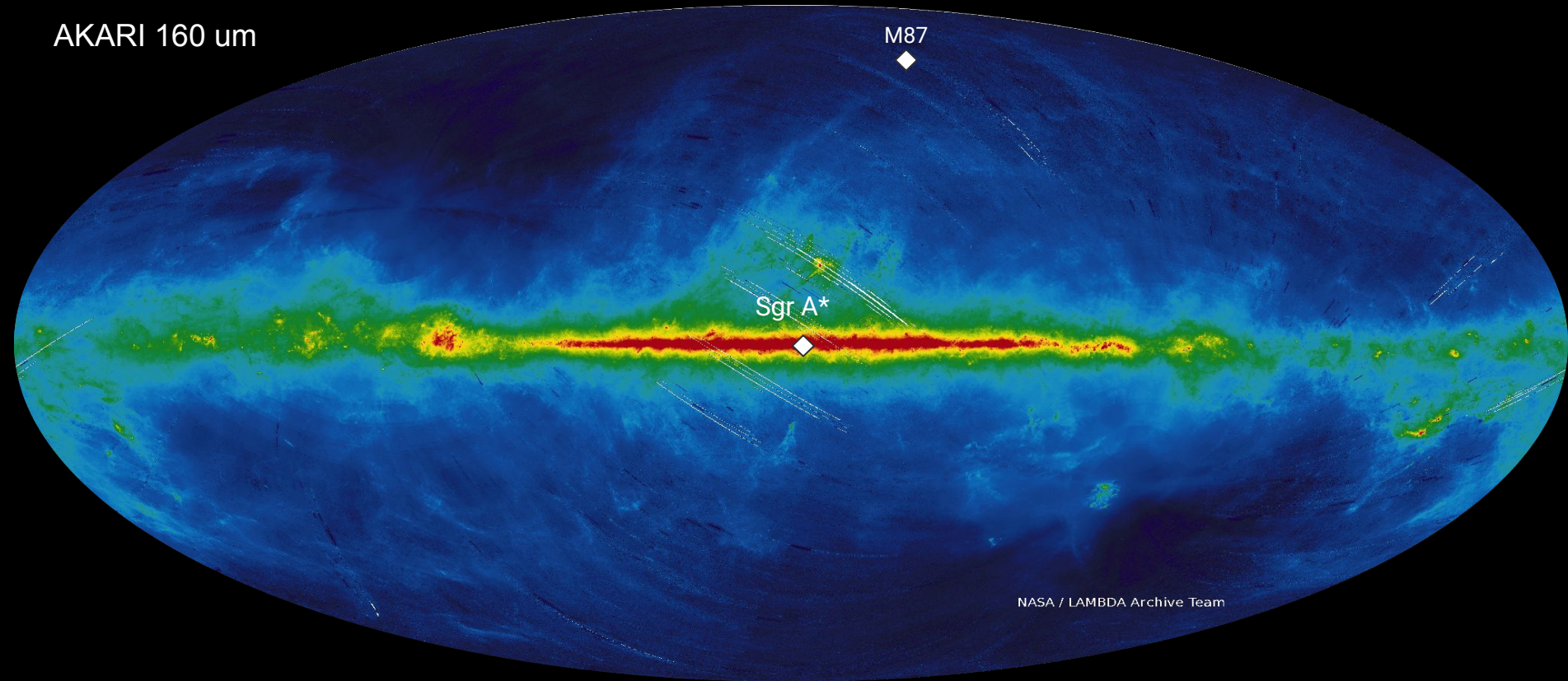
Credits: H.Falcke, A.Schut, R.Fraga-Encinas/Radboud University/Fiks Films



Perché è così difficile fotografare Sgr A*?

1. Il Mezzo InterStellare

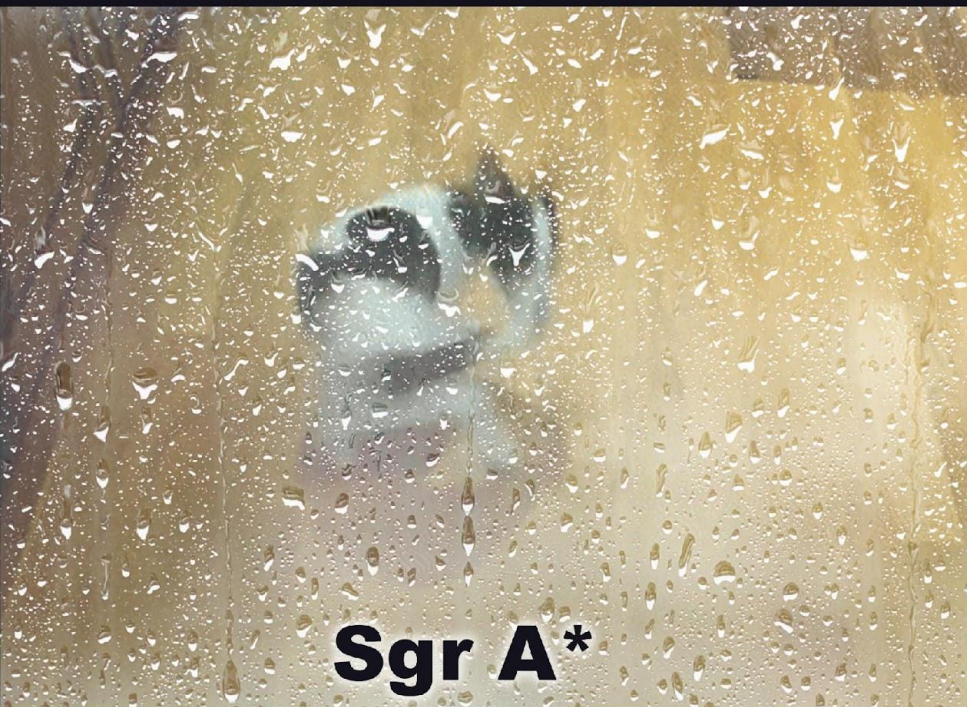
AKARI 160 μm



2. La Variabilità

Credit: Iván Martí Vidal (University of Valencia)

Sgr A* vs M87*

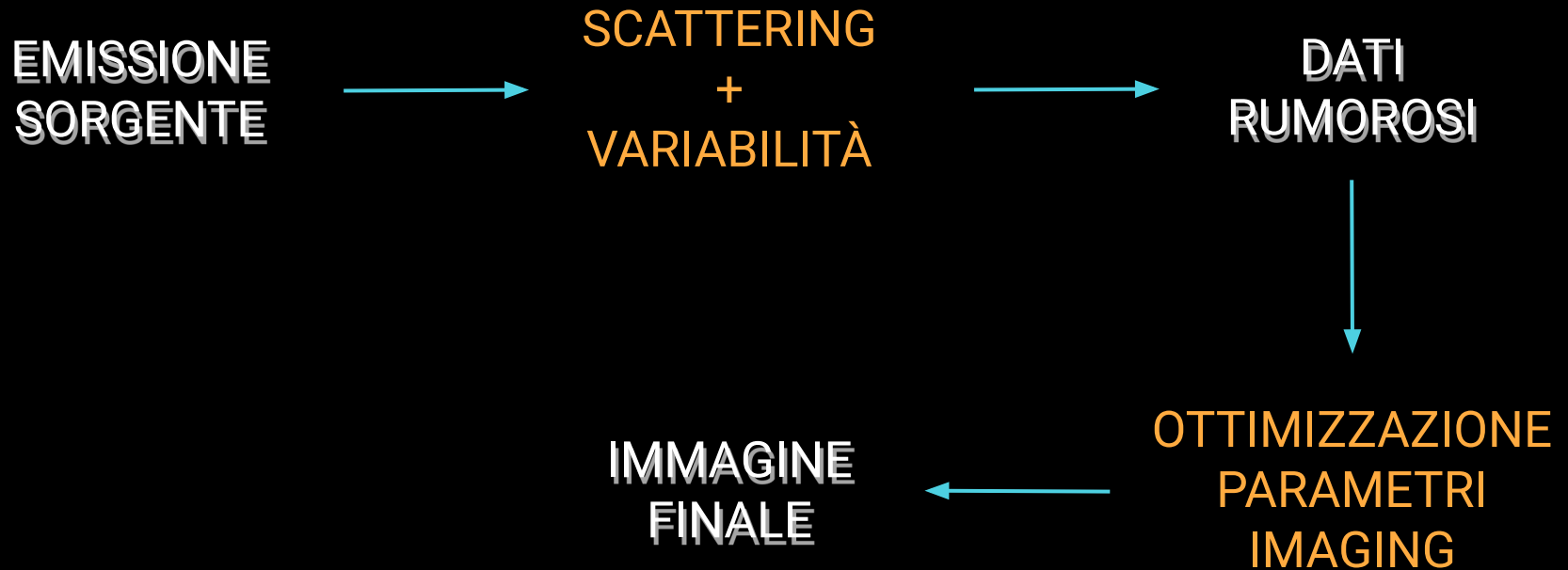


Sgr A*

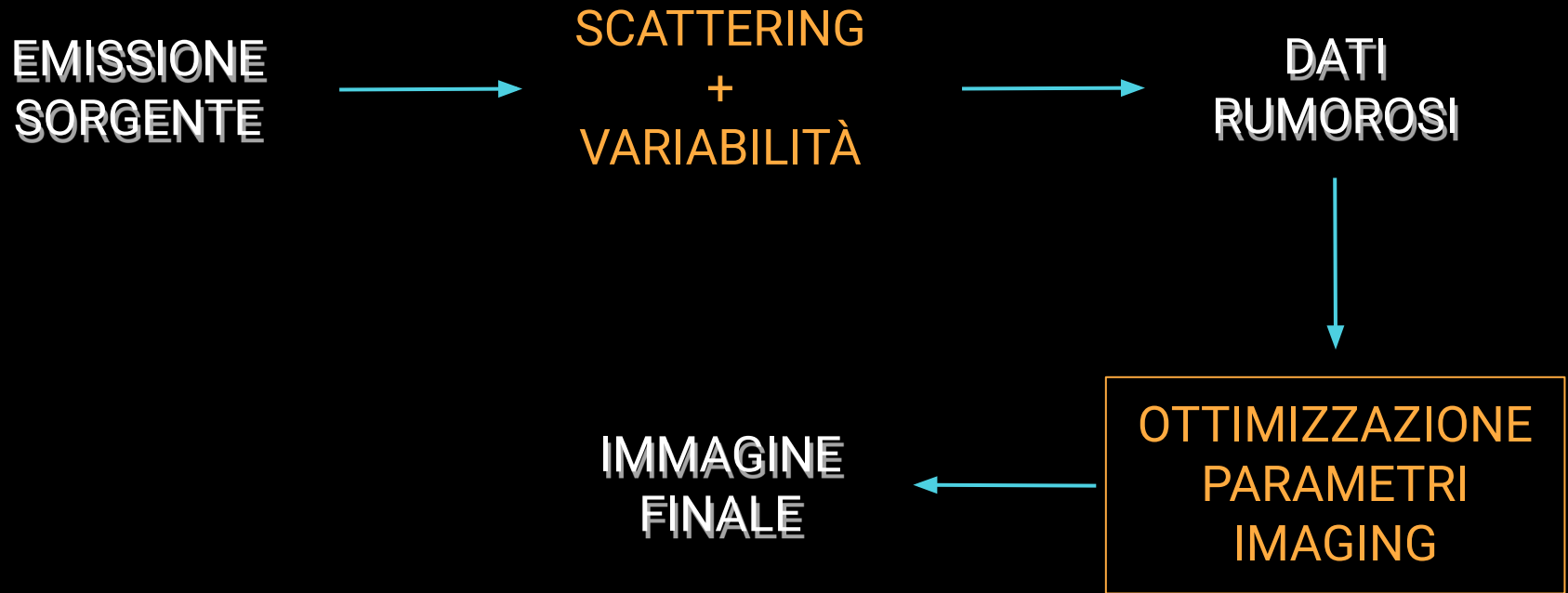


M87

Dai dati all'immagine



Dai dati all'immagine

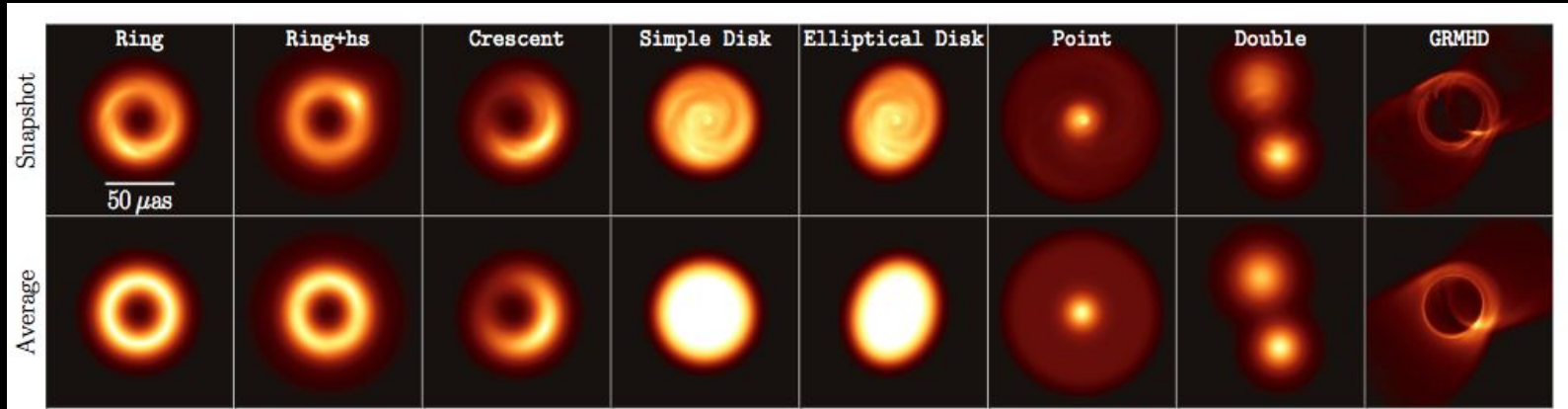


Dai dati all'immagine

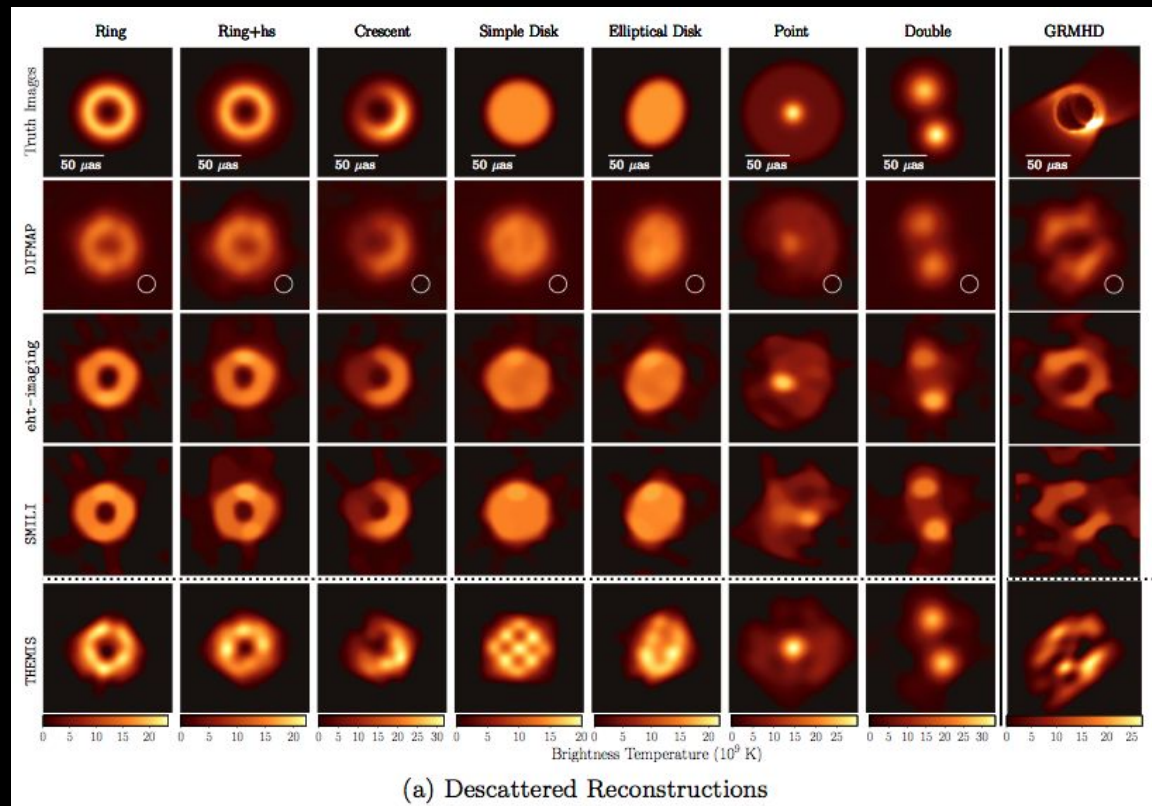
NON POSSIAMO RIMUOVERE
SCATTERING E VARIABILITÀ DAI DATI,
MA SIAMO IN GRADO DI
QUANTIFICARNE L'EFFETTO

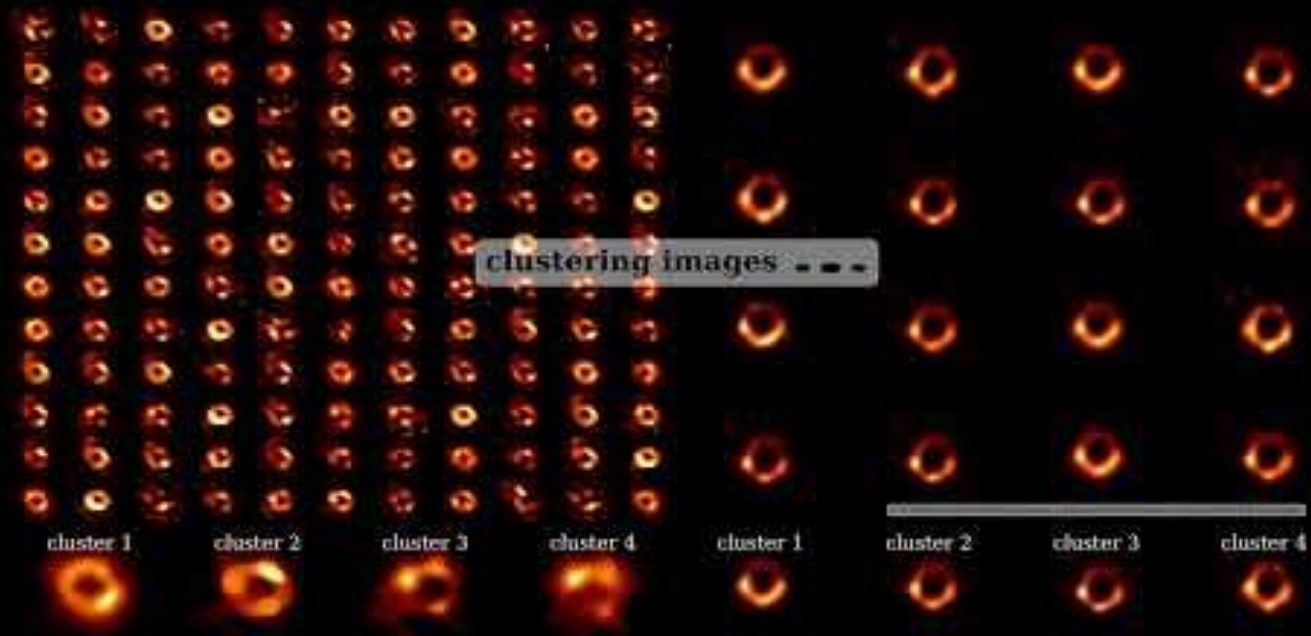
OTTIMIZZAZIONE
PARAMETRI
IMAGING

Ottimizzazione dei parametri per l'elaborazione dell'immagine: i modelli...

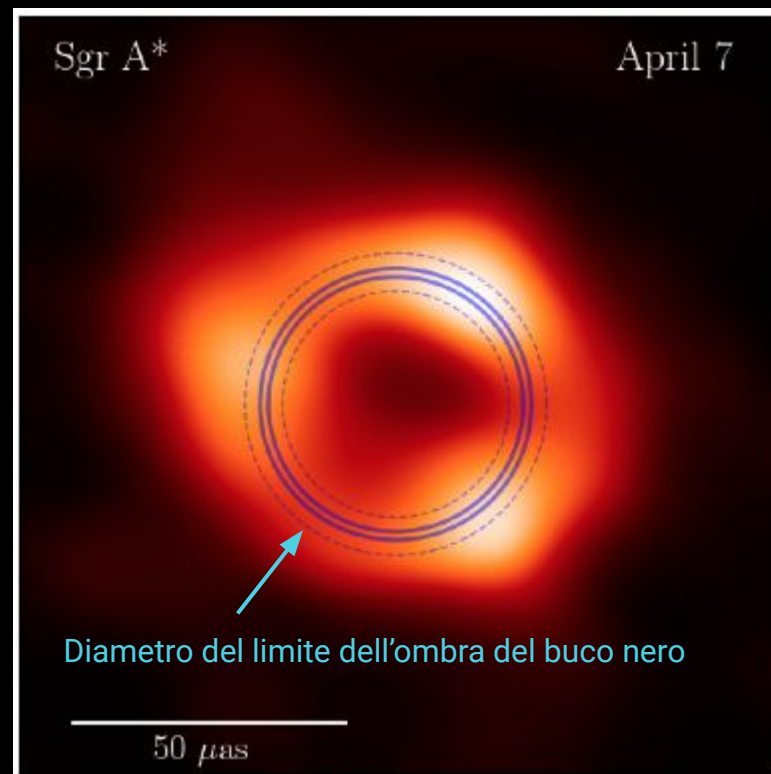


... e la loro ricostruzione





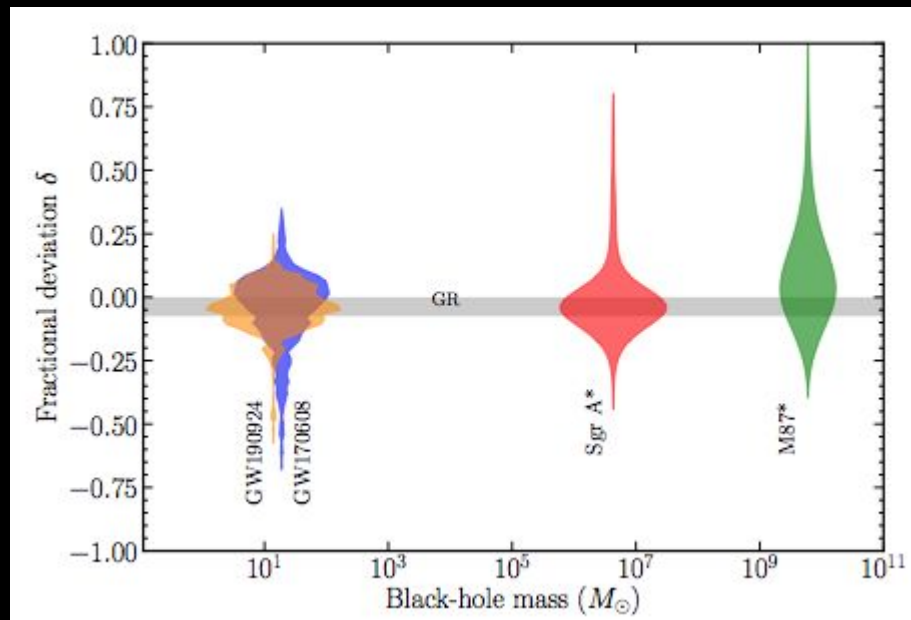
Interpretazione dei risultati: *La Relatività Generale*



Interpretazione dei risultati:

La Relatività Generale

1. Le caratteristiche dell'oggetto supermassiccio al centro della Via Lattea sono in **eccellente accordo** con le predizioni relative ad **un buco nero**.
2. Tale accordo, messo in relazione con analoghi studi relativi ad M87 e GW, **conferma la teoria della Relatività Generale su scale di massa molto diverse**
3. Le informazioni fornite dall'immagine, unite ad altre conseguite tramite l'analisi dei dati, rendono **modelli alternativi** ad un buco nero **estremamente improbabili**



Deviazione dalle predizioni di Schwarzschild

Interpretazione dei risultati:

Parametri fisici

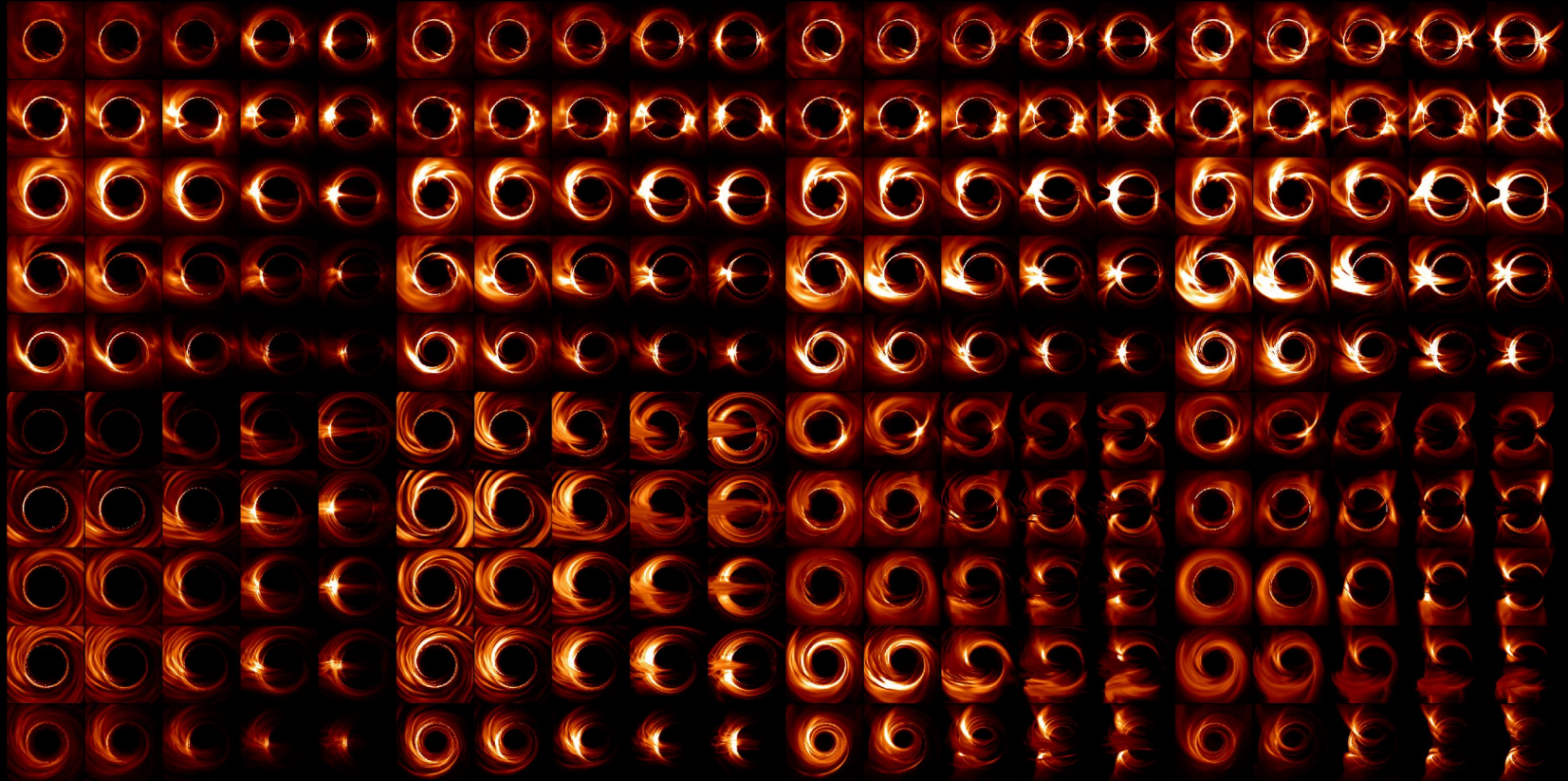
Vincoli osservativi

1. L'immagine
2. Flussi multi-frequenza (non-EHT)
3. Variabilità

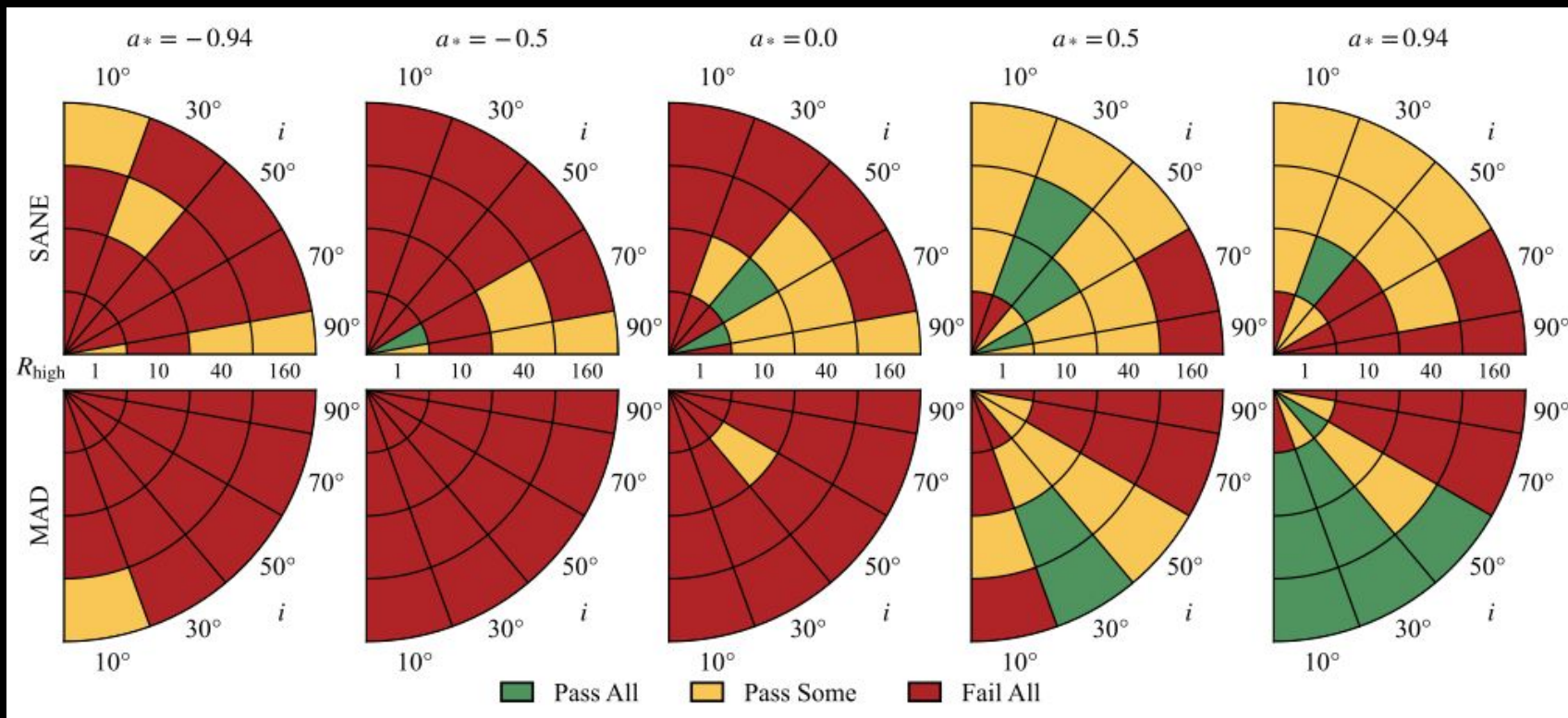
Parametri testati

1. Modello di accrescimento del disco
2. Rapporto temperature ioni-elettroni
3. Velocità di rotazione del buco nero
4. Orientazione dell'asse di rotazione

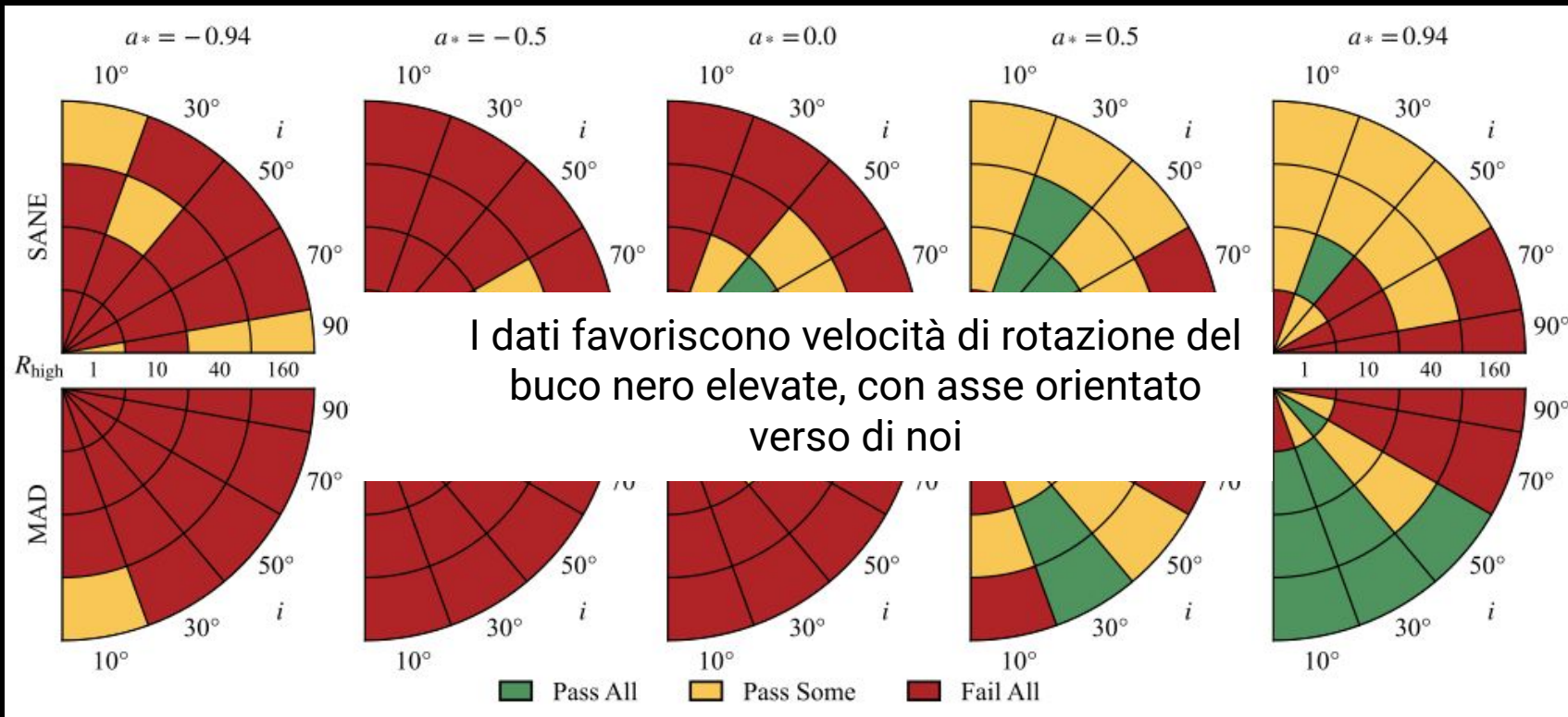
La Libreria EHT: migliaia di modelli teorici



Compatibilità dei modelli con i vincoli osservativi



Compatibilità dei modelli con i vincoli osservativi



Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes



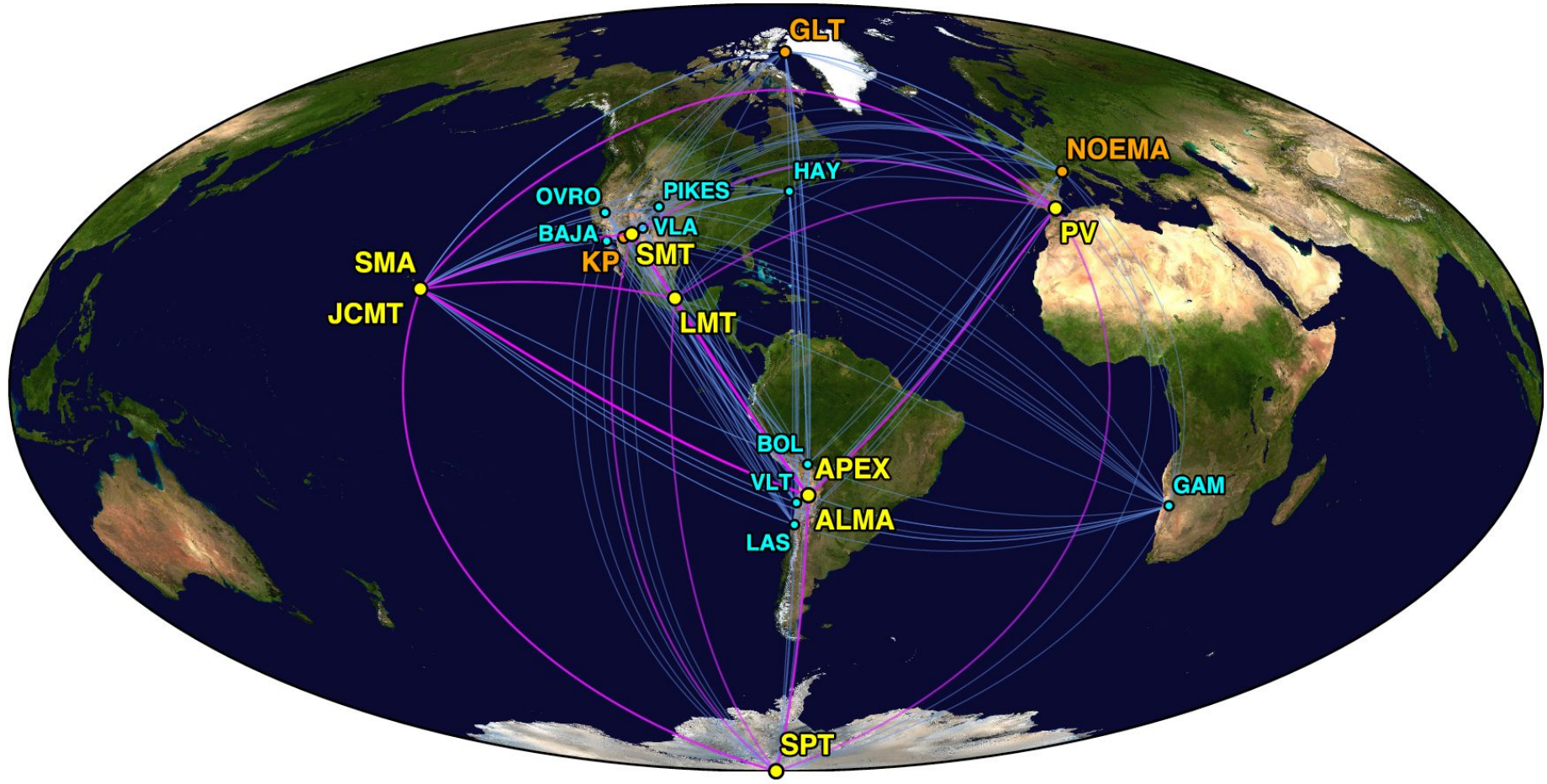
2018 Observations

- ALMA**  Atacama Large Millimeter/submillimeter Array
CHAJNANTOR PLATEAU, CHILE
- APEX**  Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE
- 30-M**  IRAM 30-M Telescope
PICO VELETA, SPAIN
- JCMT**  James Clerk Maxwell Telescope
MAUNAKEA, HAWAII
- LMT**  Large Millimeter Telescope
SIERRA NEGRA, MEXICO
- SMA**  Submillimeter Array
MAUNAKEA, HAWAII
- SMT**  Submillimeter Telescope
MOUNT GRAHAM, ARIZONA
- SPT**  South Pole Telescope
SOUTH POLE STATION
- GLT**  The Greenland Telescope
THULE AIR BASE, GREENLAND, DENMARK
- Kitt Peak**  Kitt Peak 12-meter Telescope
KITT PEAK, ARIZONA, USA
- NOEMA**  NOEMA Observatory
PLATEAU DE BURE, FRANCE

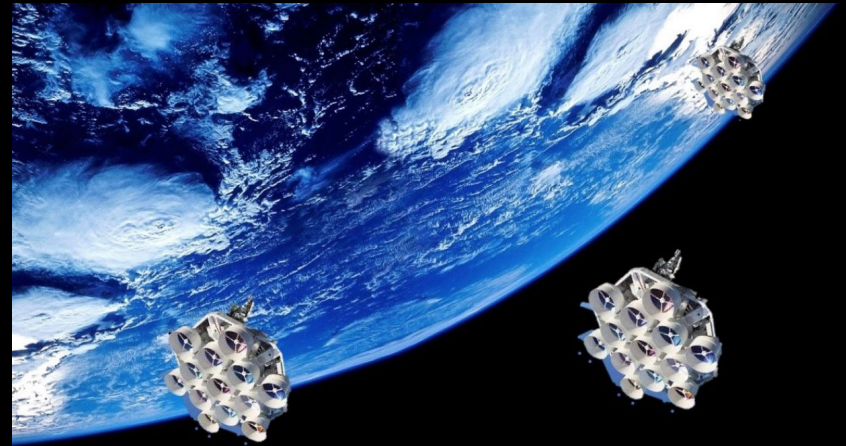
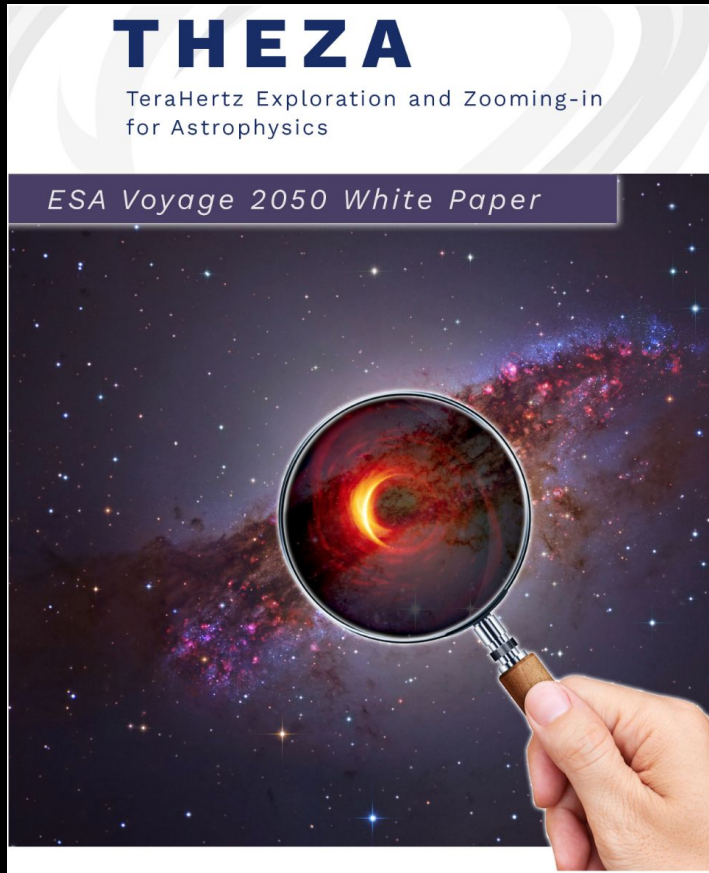
Observed in 2021 and 2022



Ancora più telescopi in vista



Il Futuro è nello Spazio

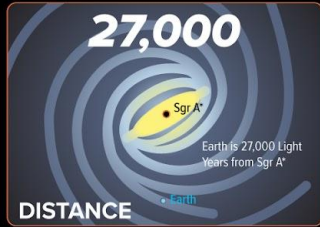


*Gurvits et al. 2021, Experimental
Astronomy*

Sagittarius A*

Sgr A* /sadge-ay-star/

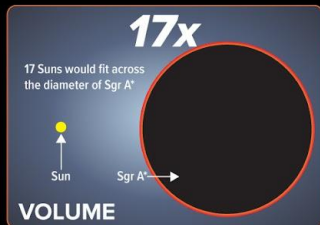
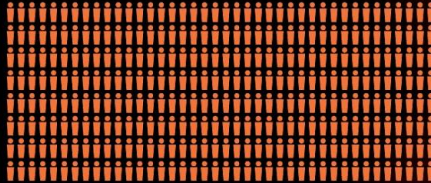
This is the first image of our neighborhood black hole in the center of the Milky Way galaxy. The ring around the black hole is captured light bent by the powerful gravity of the black hole.



This result is made possible by a global human effort of more than 300 researchers from 80 institutions.



300+ RESEARCHERS



National Radio Astronomy Observatory