

Active Galaxies

The Variable Universe – Lecture 09
Fall Semester 2022

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Sauverny Observatory #265



Spiral



Elliptical



Irregular



Dwarf



Ring



Starburst



Lenticular



Ultra Diffuse

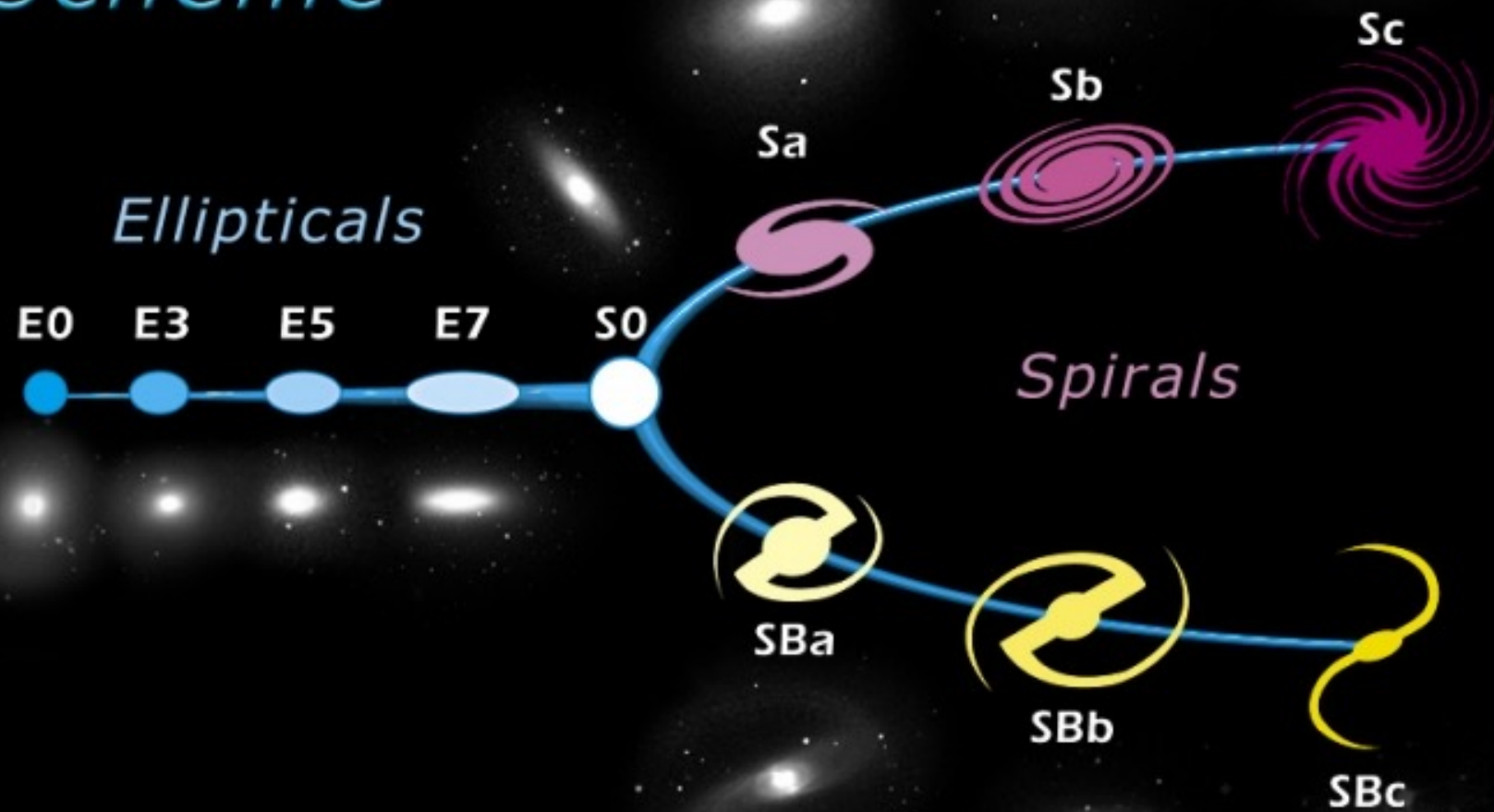


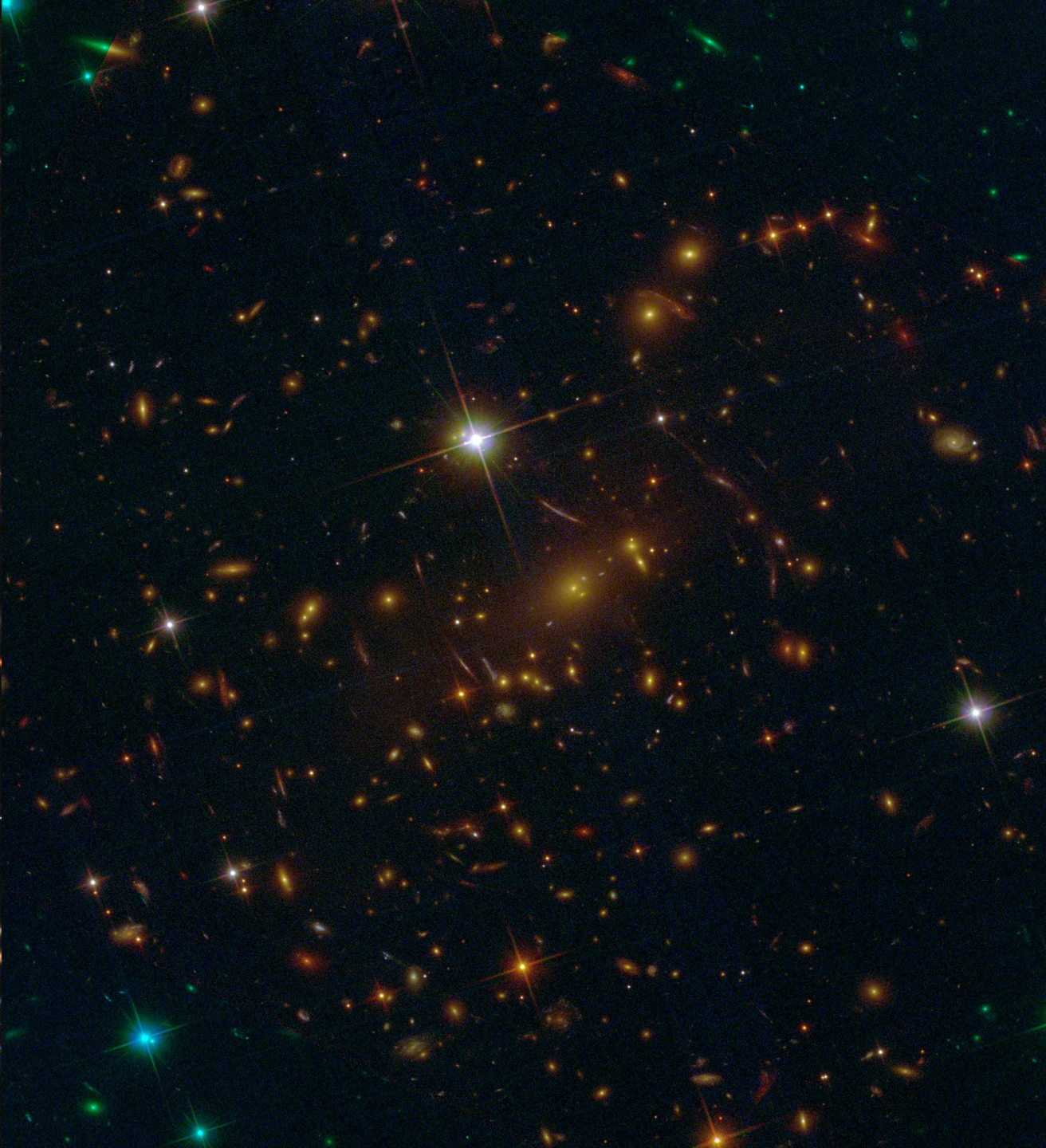
Interacting

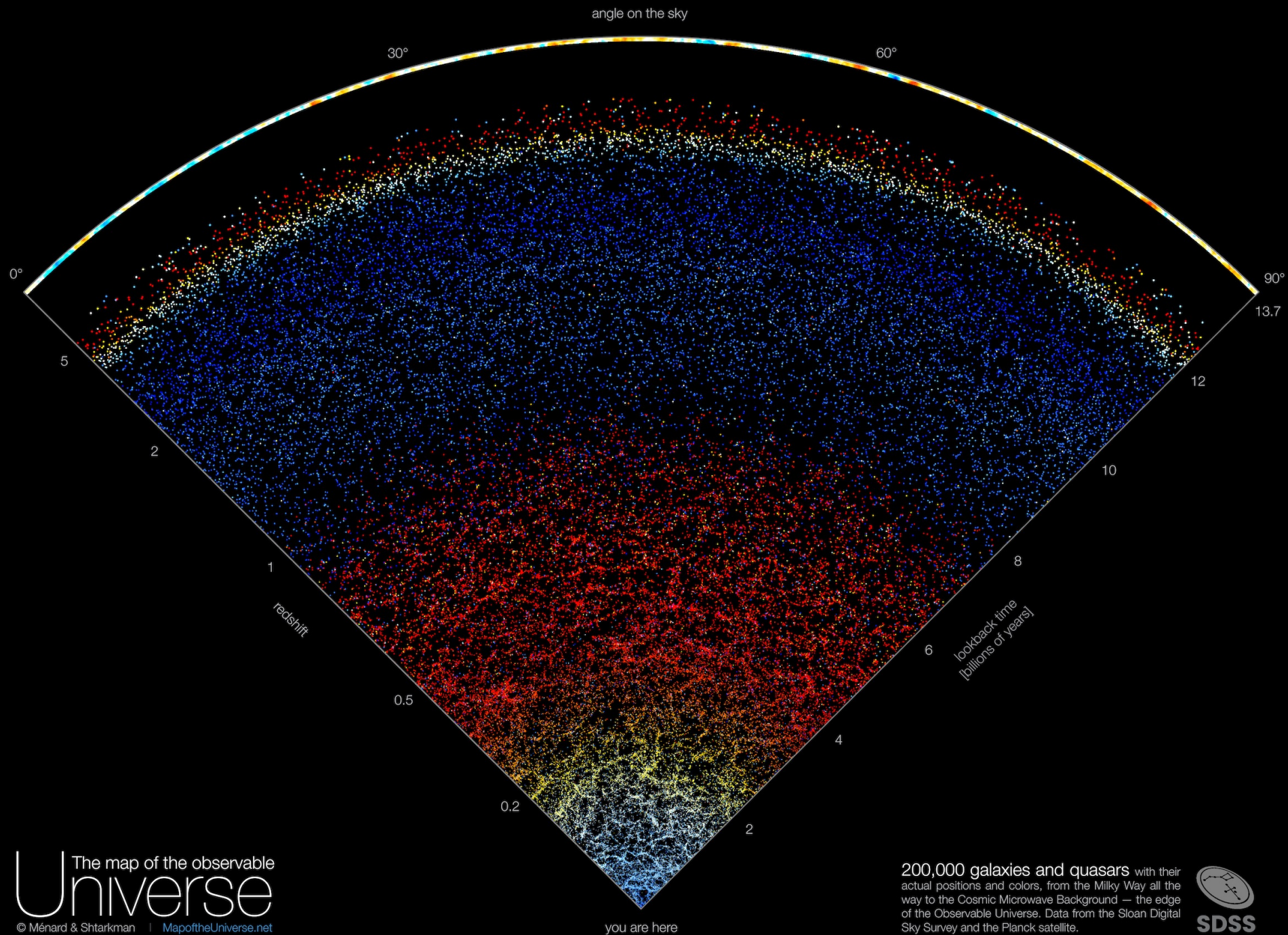


The
tuning
fork
diagram

Edwin Hubble's Classification Scheme







Not today: galaxy mergers







What are active galaxies?

What makes them active?



Seyfert galaxies, AGN & Quasars

- Seyfert 1 (type-I AGN): strong, broad permitted & semiforbidden emission lines
- Seyfert 2 (type-II AGN): heavy obscuration extincts nearly all optical-UV radiation
- Observational difference: reframe UV obscuration in spectra
- Quasars: radio loud, $z > 0.2$, luminous $L > 10^{45}$ erg/s



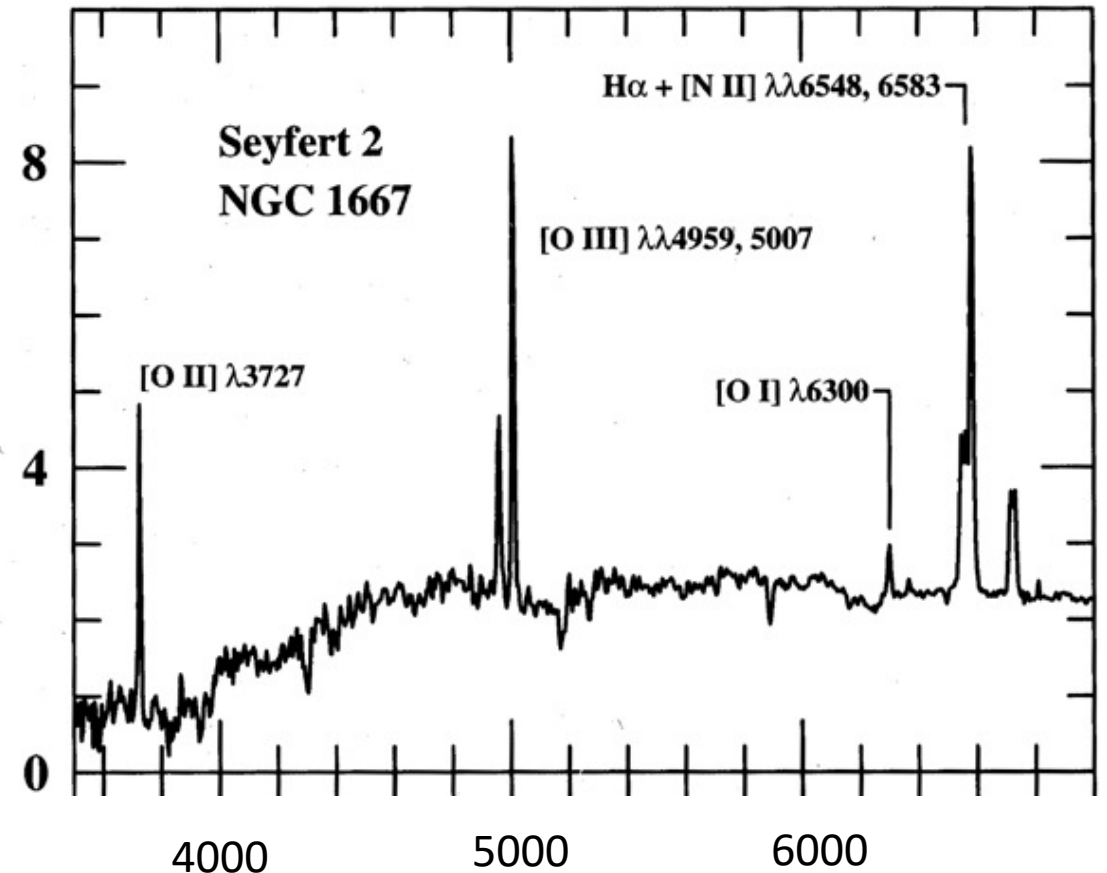
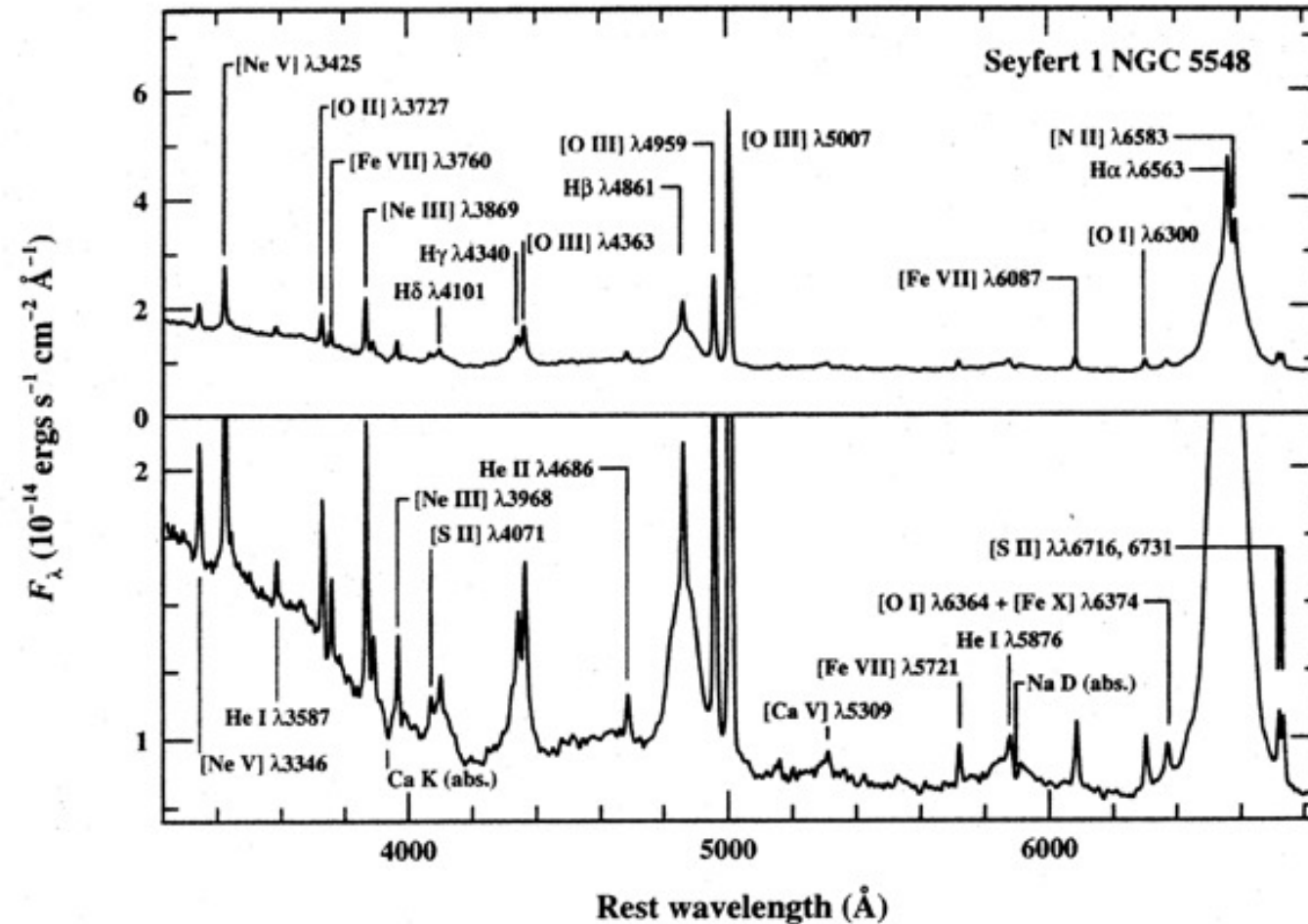
Active Galactic Nucleus Classification

- At least one of the following points fulfilled:
 - Object contains compact nuclear region emitting significantly beyond what is expected from stellar processes typical of its galaxy type
 - Object shows clear signature of nonstellar continuum emitting process in its center
 - Object's spectrum contains strong emission lines with line ratios typical of excitation by nonstellar radiation field
 - Object exhibits line and/or continuum variations
- Terminology contentious
- AGN is a transient phenomenon! Starbursts can potentially trigger AGN activity, which can also decay

Type I vs type II AGN spectra

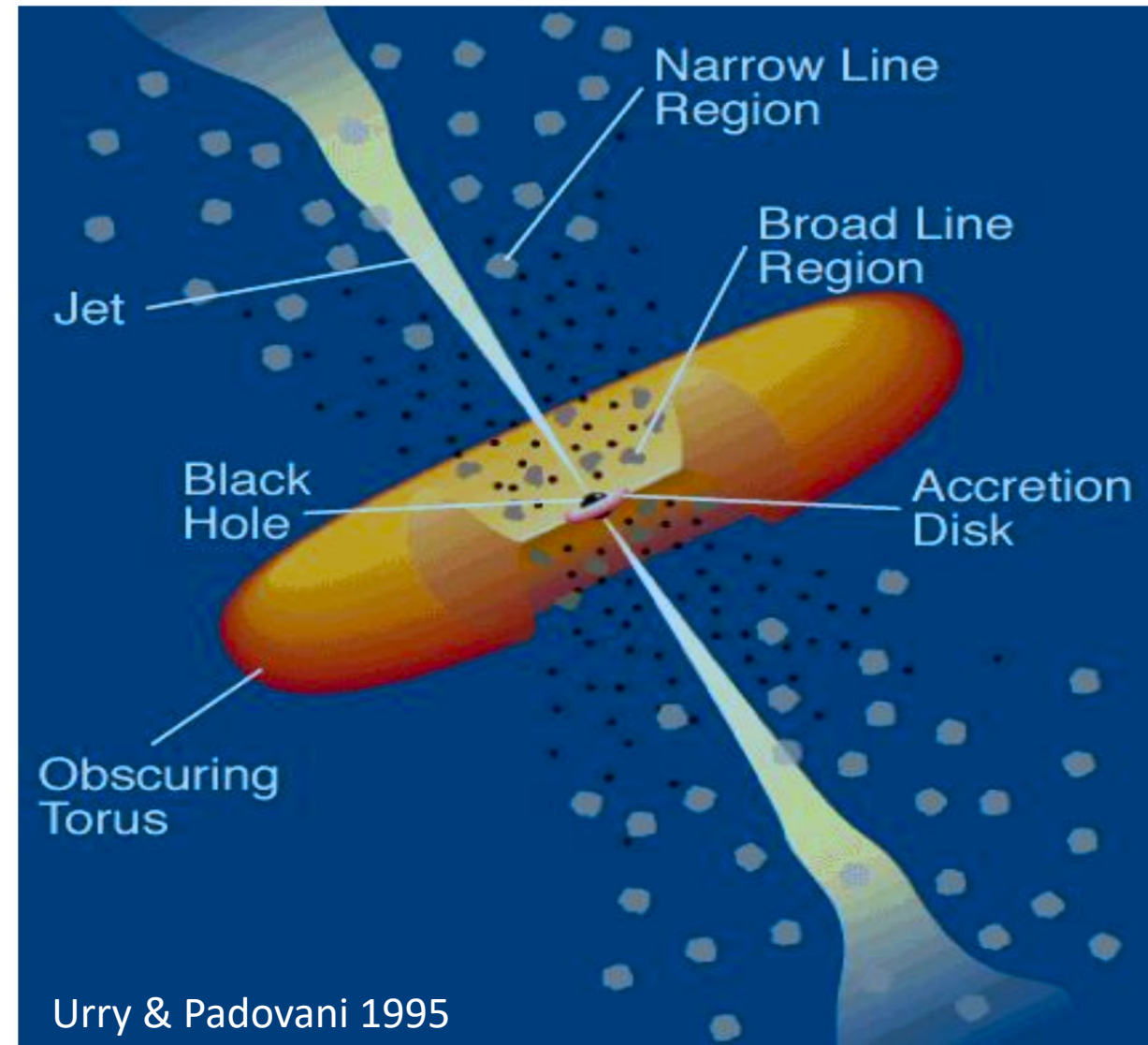
SEDs are usually power laws, at least over some intervals (different for different types & wavelength ranges)

$$L_\nu \propto \nu^{-\alpha}$$

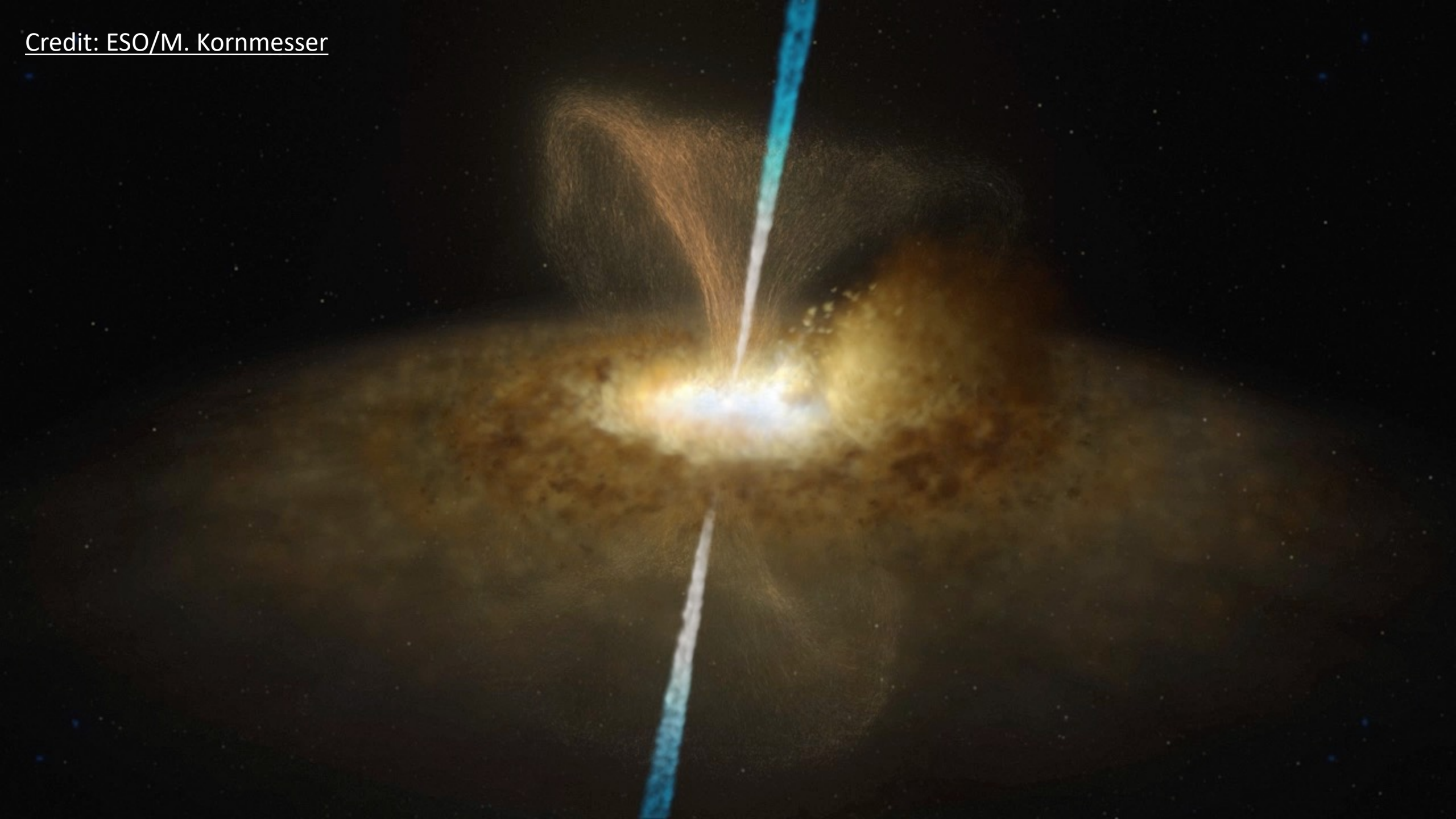


Unified AGN Model

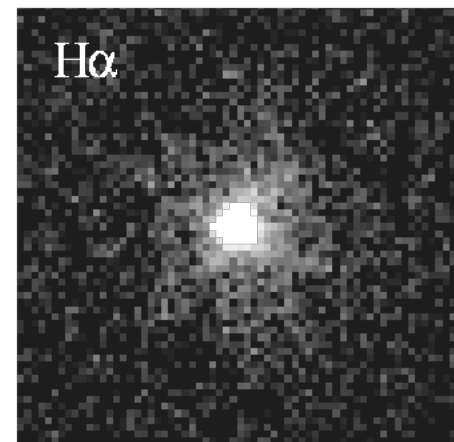
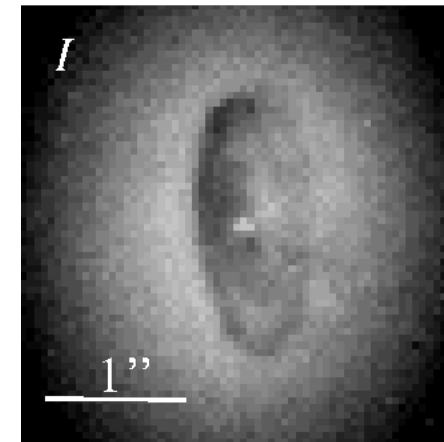
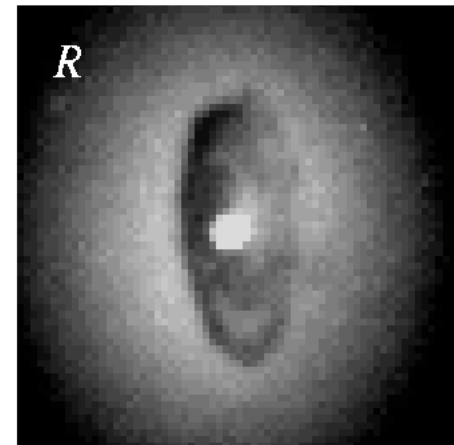
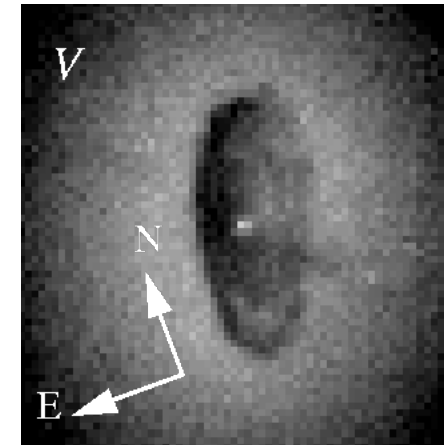
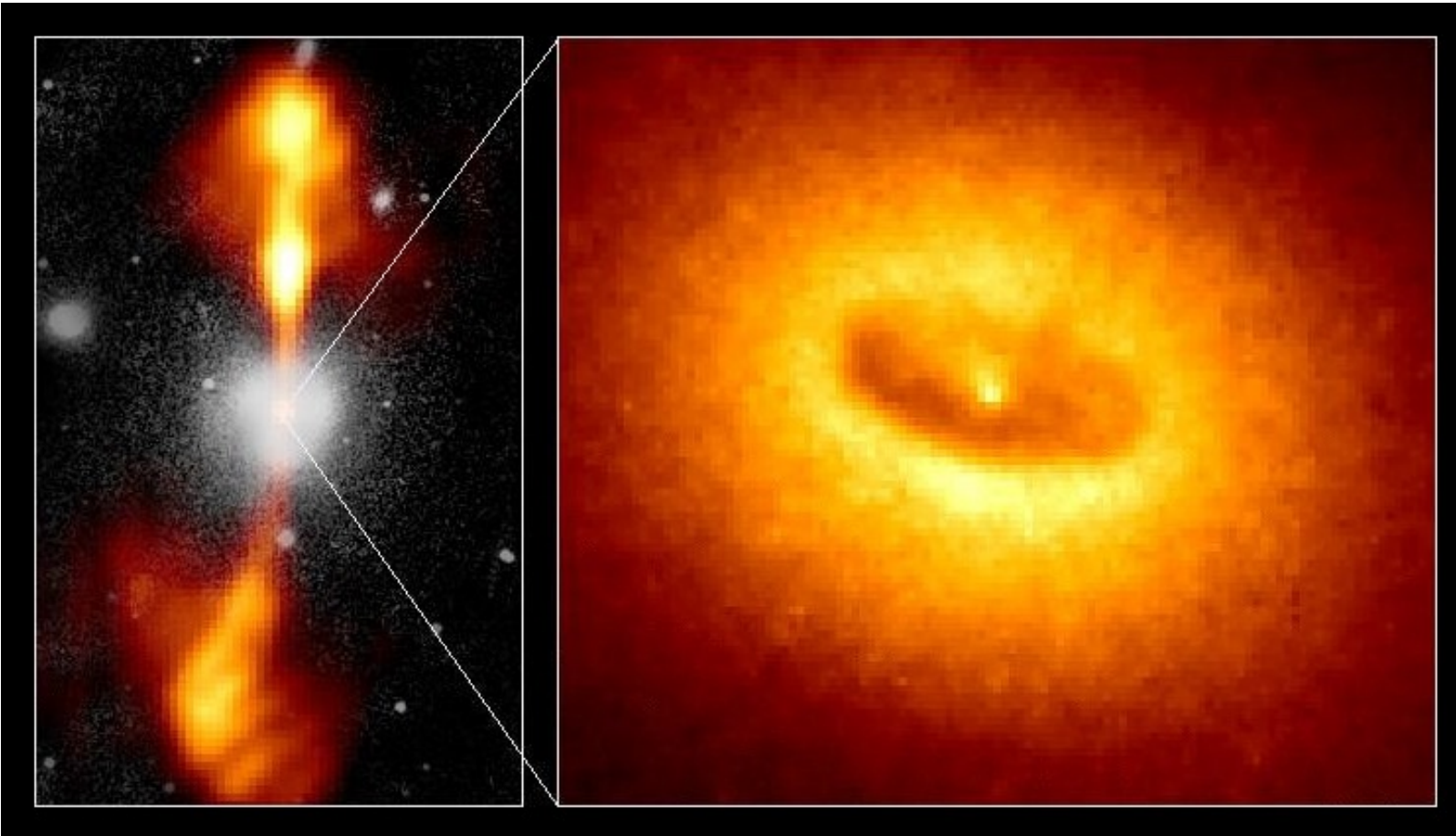
- SMBH with accretion disk & relativistic jet
 - Typically 10^6 - 10^{10} M_{sol}
 - Size: a few light days (Solar system)
 - Jets can extend from AU to 1 Mpc scales!
- Broad Line Region (BLR)
 - 100 light days across
 - Very broad emission lines (2000-10000 km/s)
 - Inner spherical zone highly ionized & dense
 - Outer zone more flattened & low ionization
- Molecular torus
 - Dusty doughnut, 100ly across
 - Optically thick: viewing angle relevant
- Narrow Line Region (NLR)
 - Lower density than BLR
 - Emission lines less broadened (<1200 km/s)



Credit: ESO/M. Kornmesser



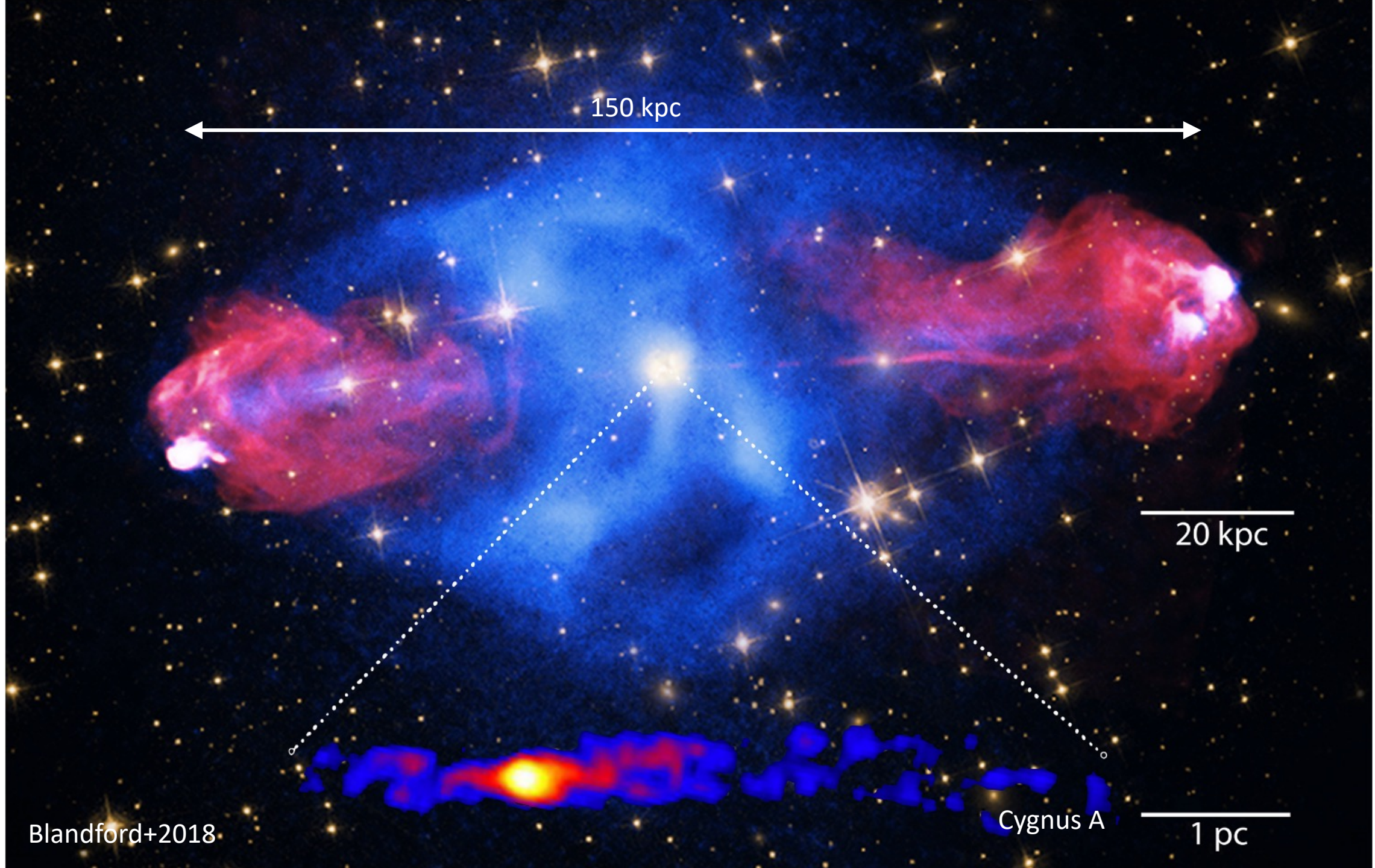
Gas & dust disk of NGC4261 seen by Hubble



Credit: HST/NASA/ESA

[Ferrarese et al. 1996](#)

Jets in Cygnus A



Megamasers orbiting SMBHs

M106 = NGC4258

One of 22 nearby mega-
maser hosting galaxies.
Yet uniquely important



Credit: X-ray: NASA/CXC/Caltech/P.Ogle et al; Optical: NASA/STScI &
R.Gendler; IR: NASA/JPL-Caltech; Radio: NSF/NRAO/VLA

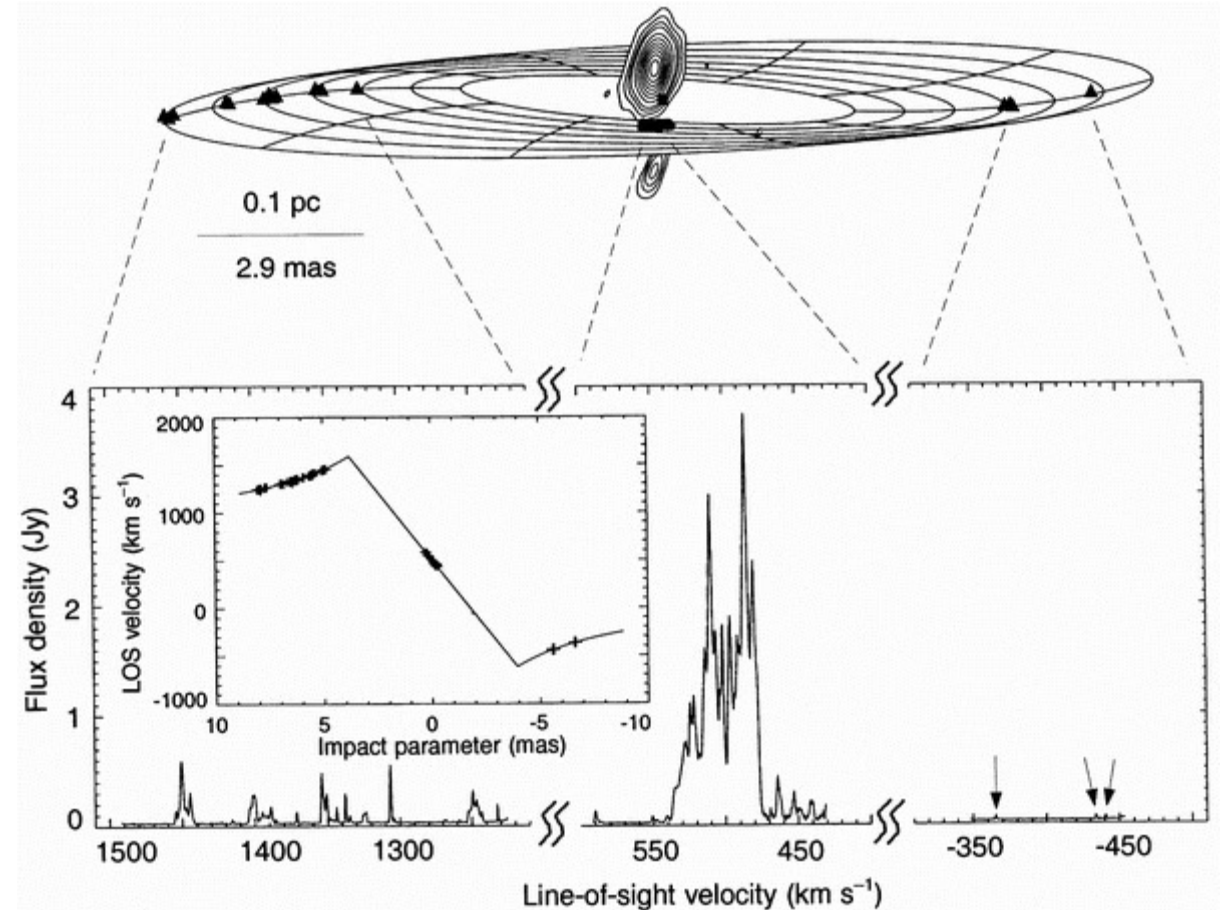
Megamasers

- MASER: Microwave/Molecular amplification by stimulated emission of radiation
- Water (H_2O) at $\lambda = 1.35\text{cm}$, Methanol, SiO Molecular Cloud masers
- Megamasers: extremely high power compared to other astrophysical masers (e.g. in Mira stars or Molecular clouds)
- Extremely useful due to high L and narrow lines (monochromatic)
- AGN megamasers: localized regions @ 0.1pc from central BH
- Megamasers like it dense ($10^8 - 10^{10} \text{ cm}^{-3}$) and warm (300-800 K): dusty torus!
- Amplification varies exponentially with path length
- Emission seen from regions where velocity coherence is large
- Disks show 3 points: in front of continuum source ($v=0$) and tangent points
- Concentric rings should show multiple masers at each of these three

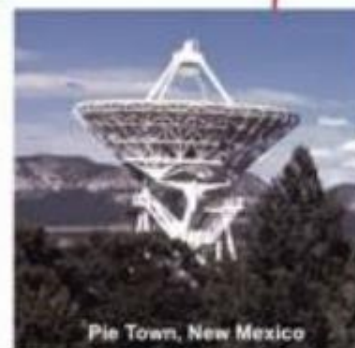
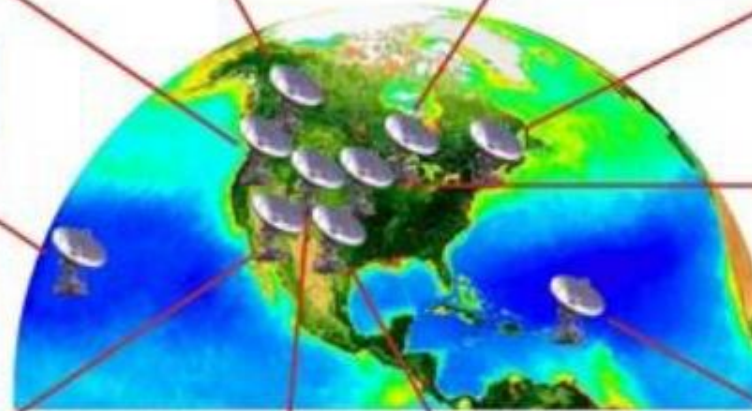
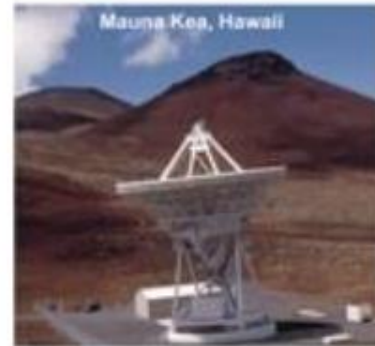
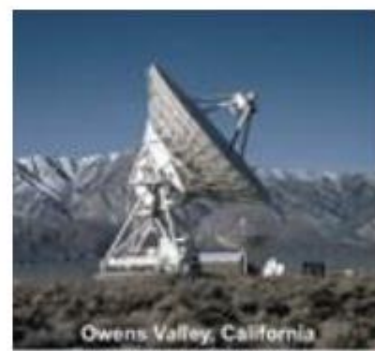
NGC4258: measuring orbital motion at 7.6 ± 0.2 Mpc

[Herrnstein et al. \(1999\)](#) [Reid et al. \(2019\)](#)

- Masers trace motions by 30 discrete clumps of gas
- Clumps fairly stable: 70% persisted 1994-1997
- Very Long Baseline Array (VLBA) observations
- Now based on 18 VLBI epochs



VLBA



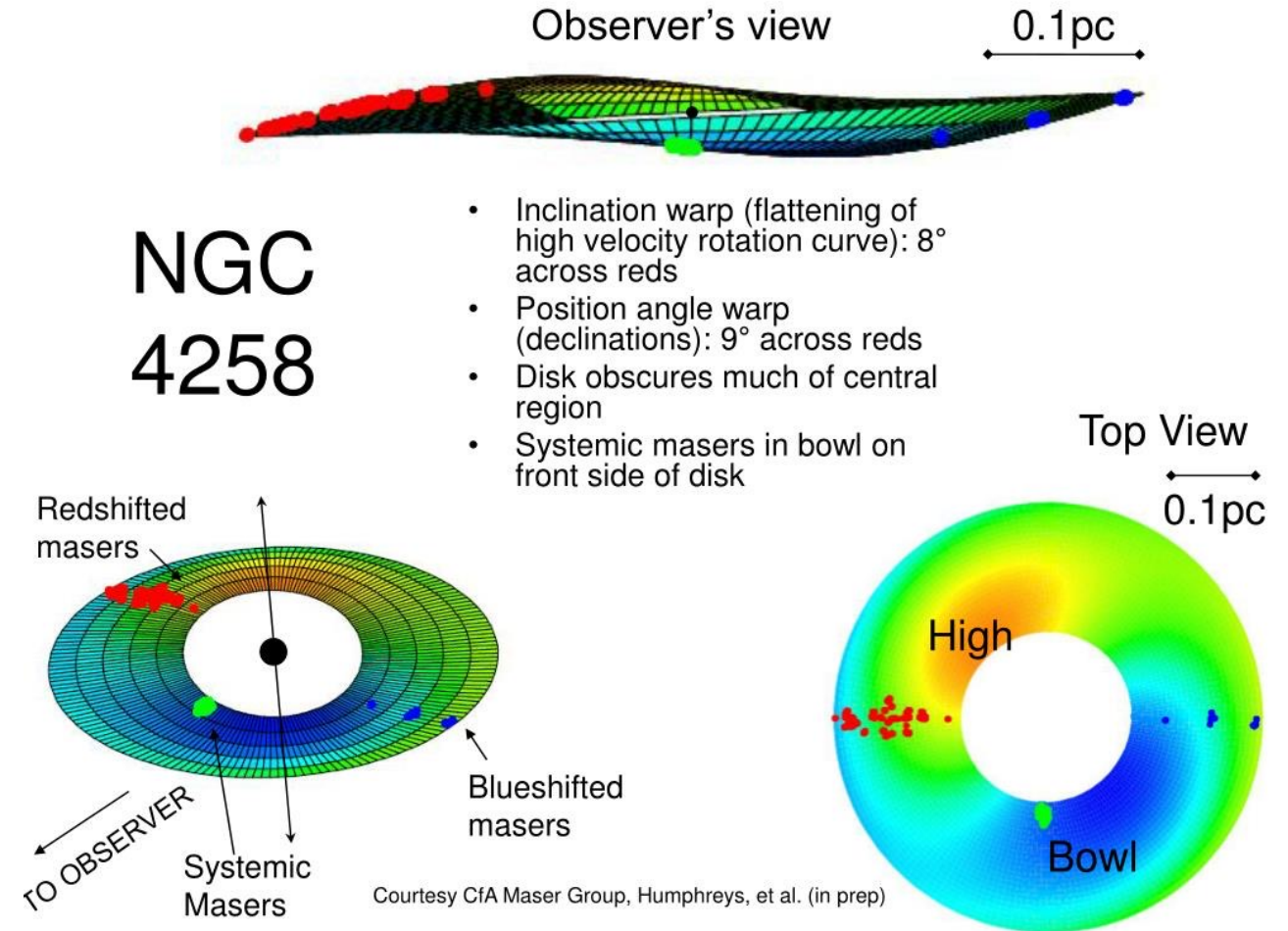
Angular resolution = $200 \mu\text{as}$ (0.006 pc at 7.2 Mpc)

Spectral resolution $< 1 \text{ km s}^{-1}$

NGC4258: measuring orbital motion at 7.6 ± 0.2 Mpc

[Humphreys et al. \(2013\)](#) [Reid et al. \(2019\)](#)

- Maser distances 0.13 – 0.26pc from BH
- BH mass 3.9×10^7 Msol
- Rotation axis of disk nearly perfectly aligned with jets
- Velocity centroid = average velocity of M106
- >100 megamasers known, 12 BH masses

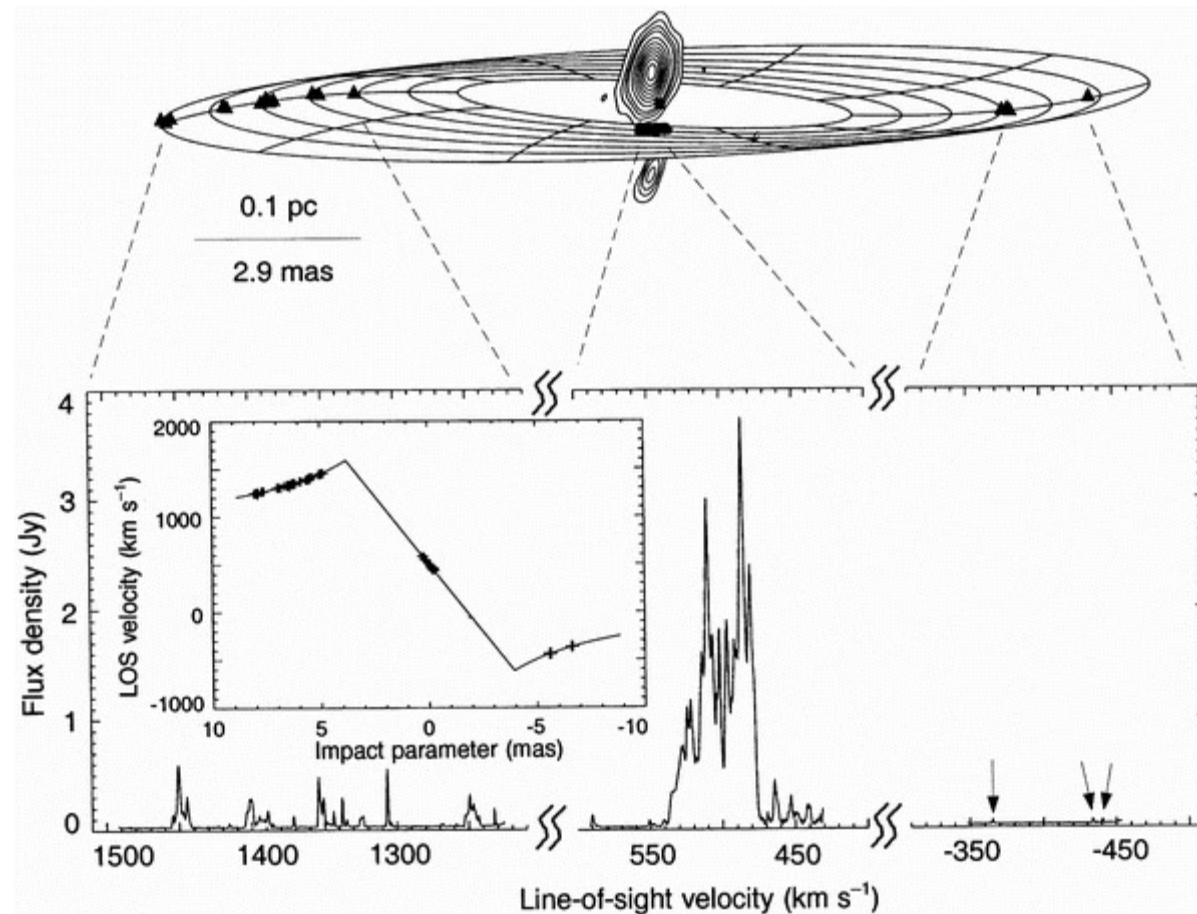


NGC4258: measuring orbital motion at 7.6 ± 0.2 Mpc

[Humphreys et al. \(2013\)](#) [Reid et al. \(2019\)](#)

- Assuming circular Keplerian disk

$$v_{los} = v_r \sin i_r \sin \phi + v_\gamma \sin i_r \cos \phi + v_0$$
- $v_r = [GM_{BH}/(rD(1 + e \cos \gamma))]^{\frac{1}{2}} e \sin \gamma$: radial velocity
- $v_\gamma = [GM_{BH}(1 + e \cos \gamma)/(rD)]^{\frac{1}{2}}$: tangential velocity
- $\gamma = \phi - \omega_r$: argument of periastron
- Rotation curve constrains $\sqrt{\frac{M_{BH}}{D}} \sin i_r$
- $a_{los} = -\frac{GM_{BH}}{(rD)^2} \sin i_r \sin \phi$: acceleration
- $X = r(\sin \Omega_r \cos \phi - \cos \Omega_r \cos i \sin \phi) + X_0$
- $Y = r(\cos \Omega_r \cos \phi - \sin \Omega_r \cos i \sin \phi) + Y_0$



How to Get a Distance? Measure accelerations & proper motions

Acceleration Distance

$$v_{\text{los}}^2 \propto M/D\theta_{\text{hi}} \longrightarrow M/D$$

$$dv_{\text{los}}/d\theta \propto [M/D\theta_{\text{sys}}^3]^{1/2} \longrightarrow \theta_{\text{sys}}$$

$$a_{\text{los}} \propto v^2/D\theta_{\text{sys}} \longrightarrow D \longrightarrow M$$

or

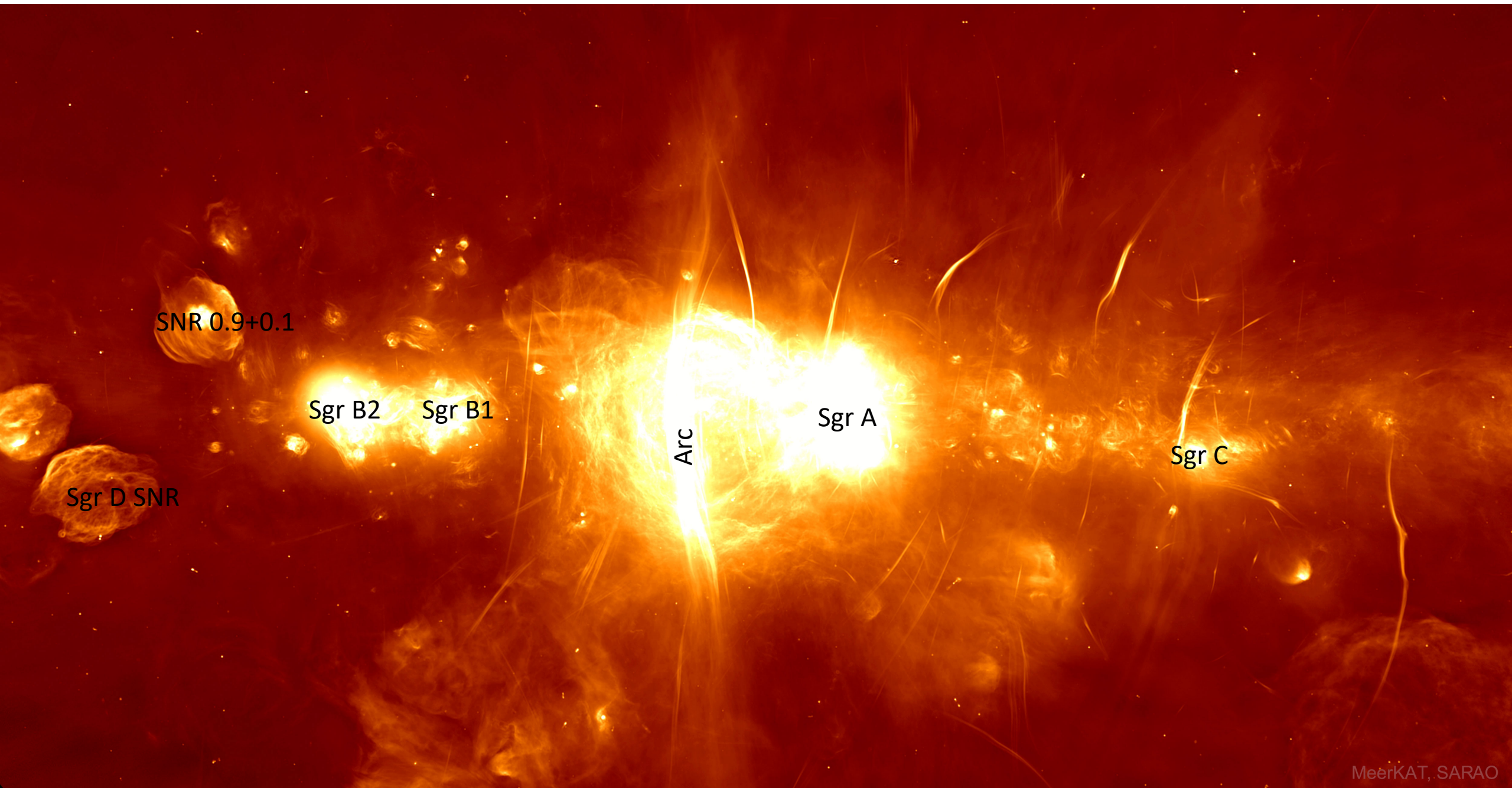
Proper Motion Distance

$$\dot{\theta} \sim v_t/D \propto (M/D)^{1/2}/D\theta_{\text{sys}}^{1/2} \longrightarrow D \longrightarrow M$$

NGC4258:
 7.6 ± 0.2 Mpc

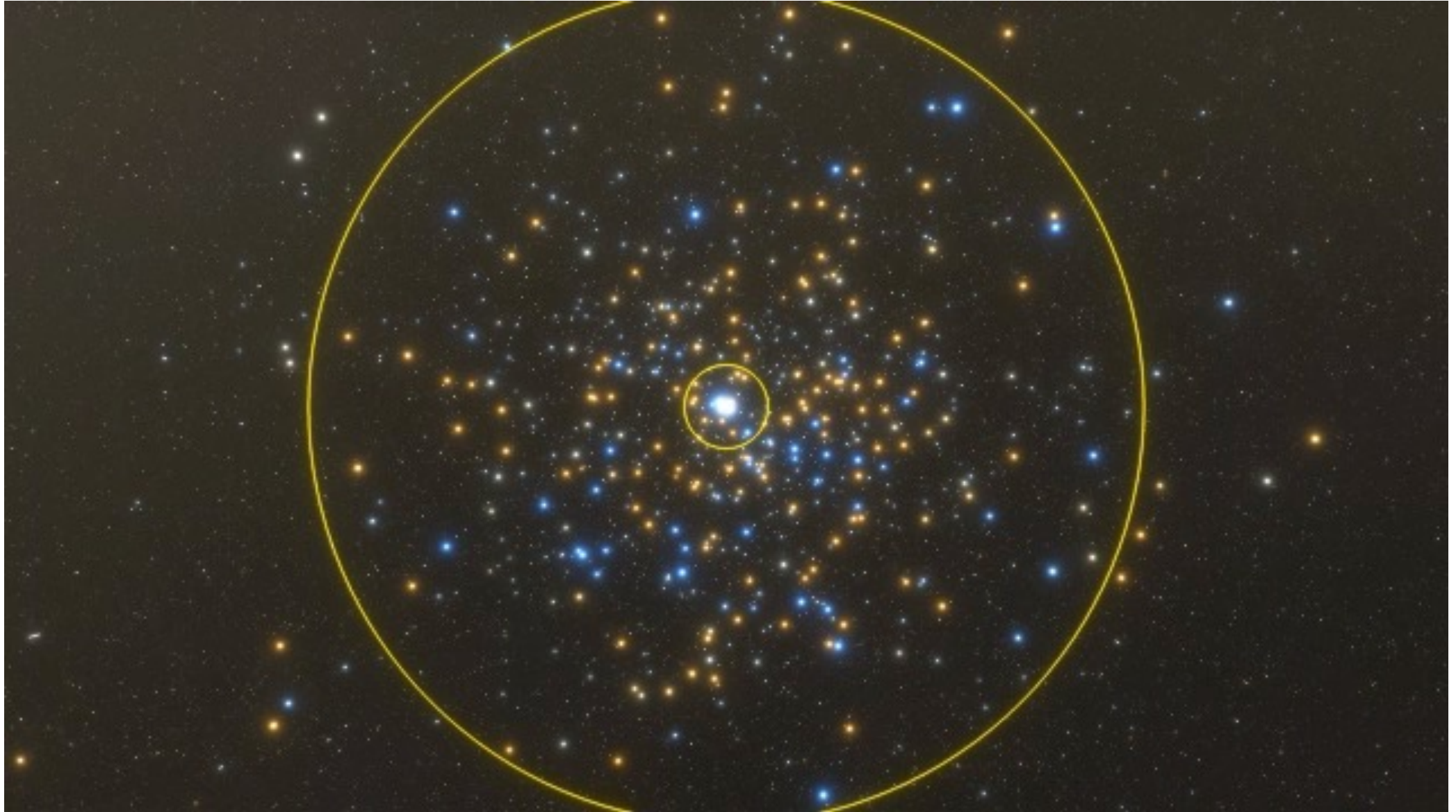


Sagittarius A* - the MW's SMBH



MeerKAT, SARAO

GRAVITY/VLTI weighs MW's SMBH

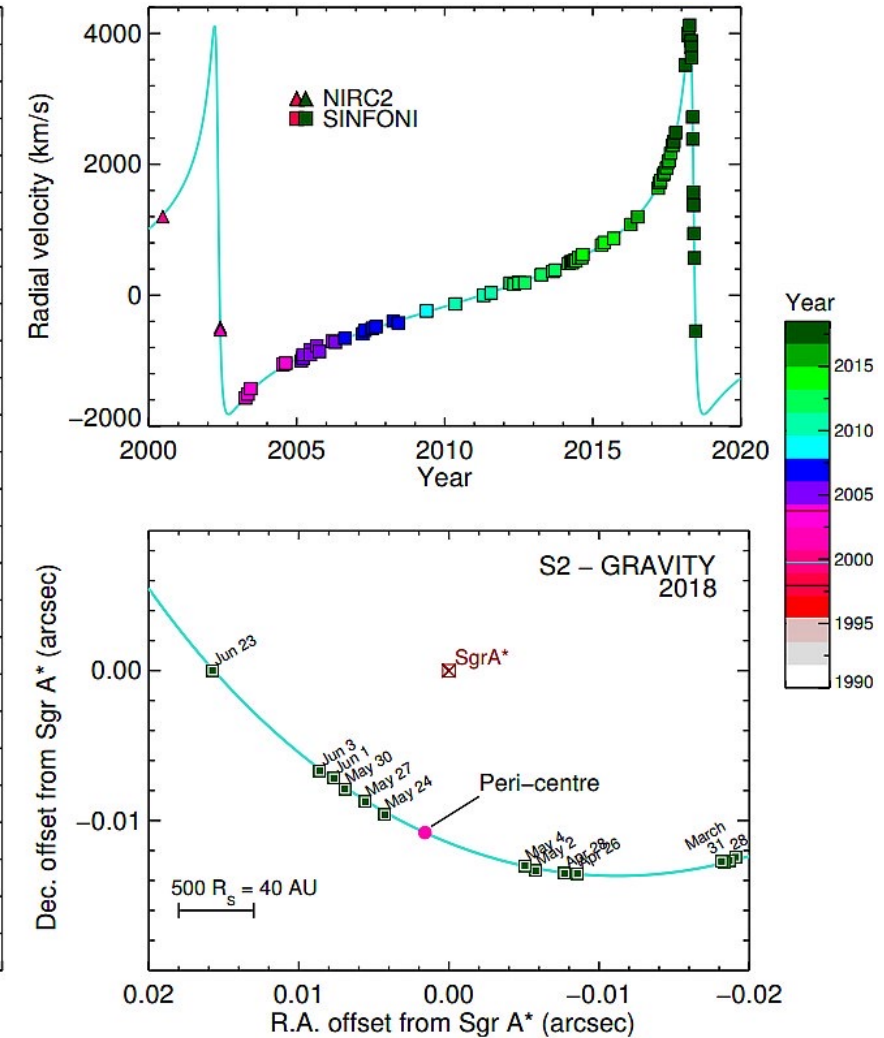
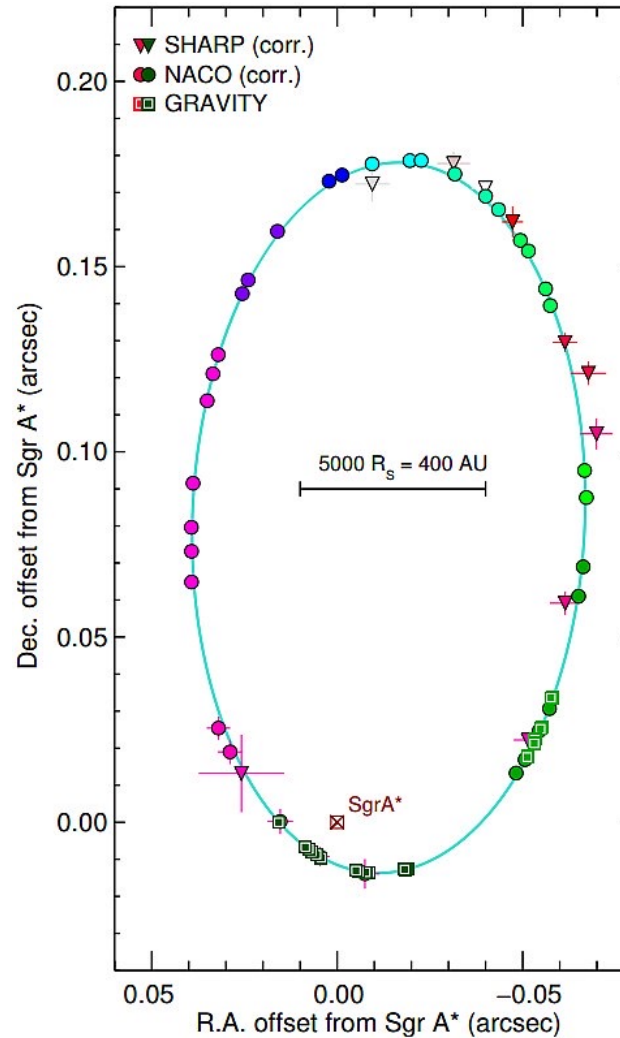
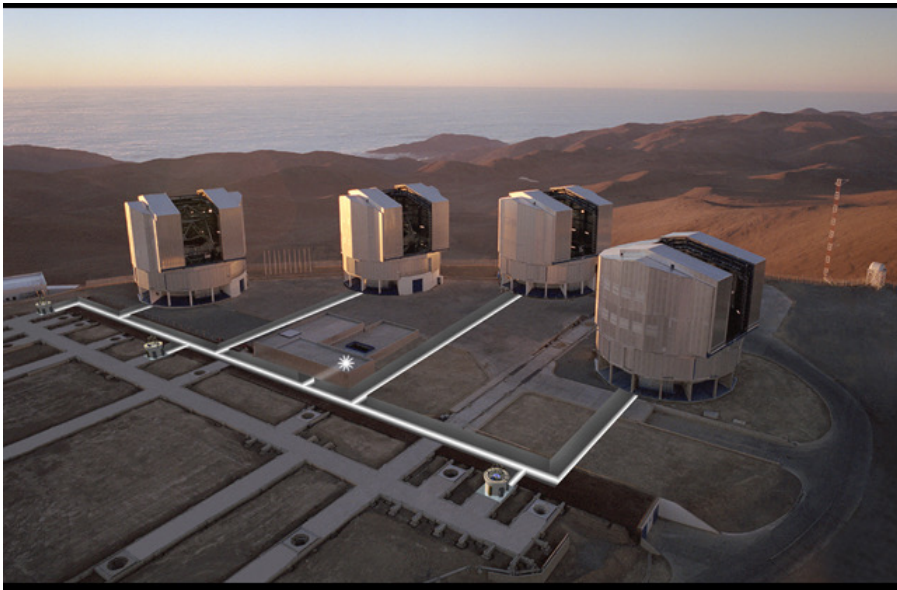




The orbit of S2 around Sgr A*

[GRAVITY collaboration \(2018\)](#)

- RVs of S2 + astrometry: full orbital solution
- $M_{SgrA^*} = 4.3 \pm 0.4 \times 10^6 M_{\odot}$
- $R_0 = 8178 \pm 13 \pm 22 \text{ pc}$
- $\Delta d/d \approx 0.3\%$ to MW Center!!



Nobel prize 2020: Black Holes

Roger Penrose (1/2), Reinhard Genzel (1/4), Andrea Ghez (1/4)

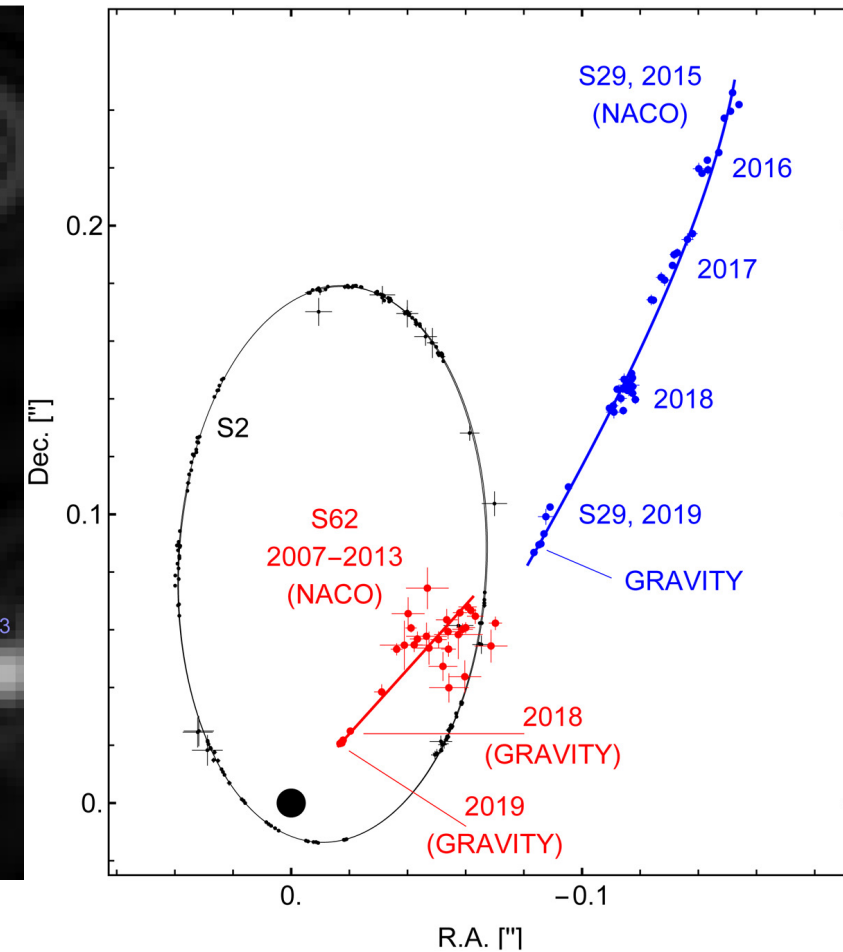
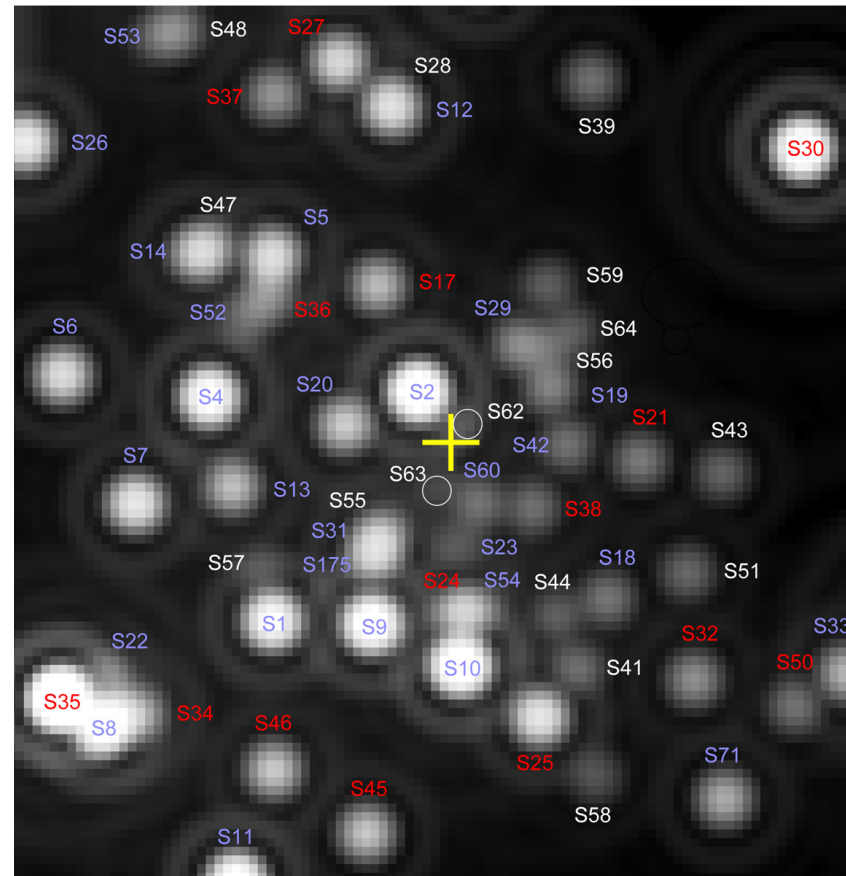
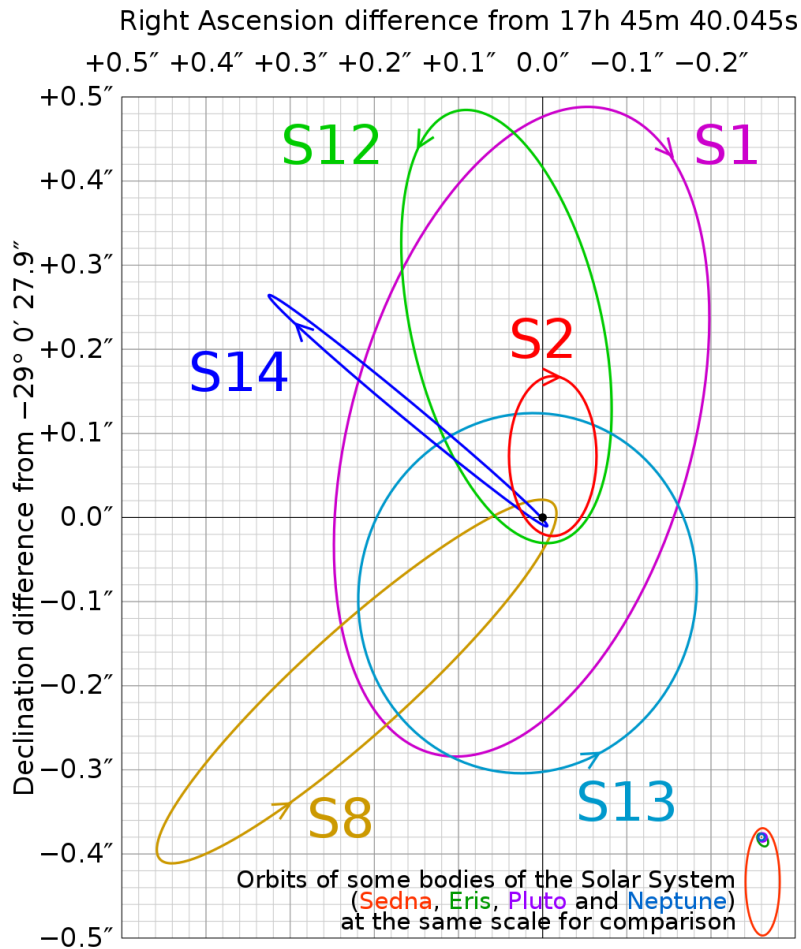
- Penrose: for the discovery that black hole formation is a robust prediction of the general theory of relativity
- Genzel & Ghez: for the discovery of a supermassive compact object at the center of our Galaxy



S2 is not alone!

[Gravity Collaboration \(2021\)](#)

Orbits in extreme gravitational well
allow for tests of GR, cf. lecture 13



Is Sgr A* an AGN?

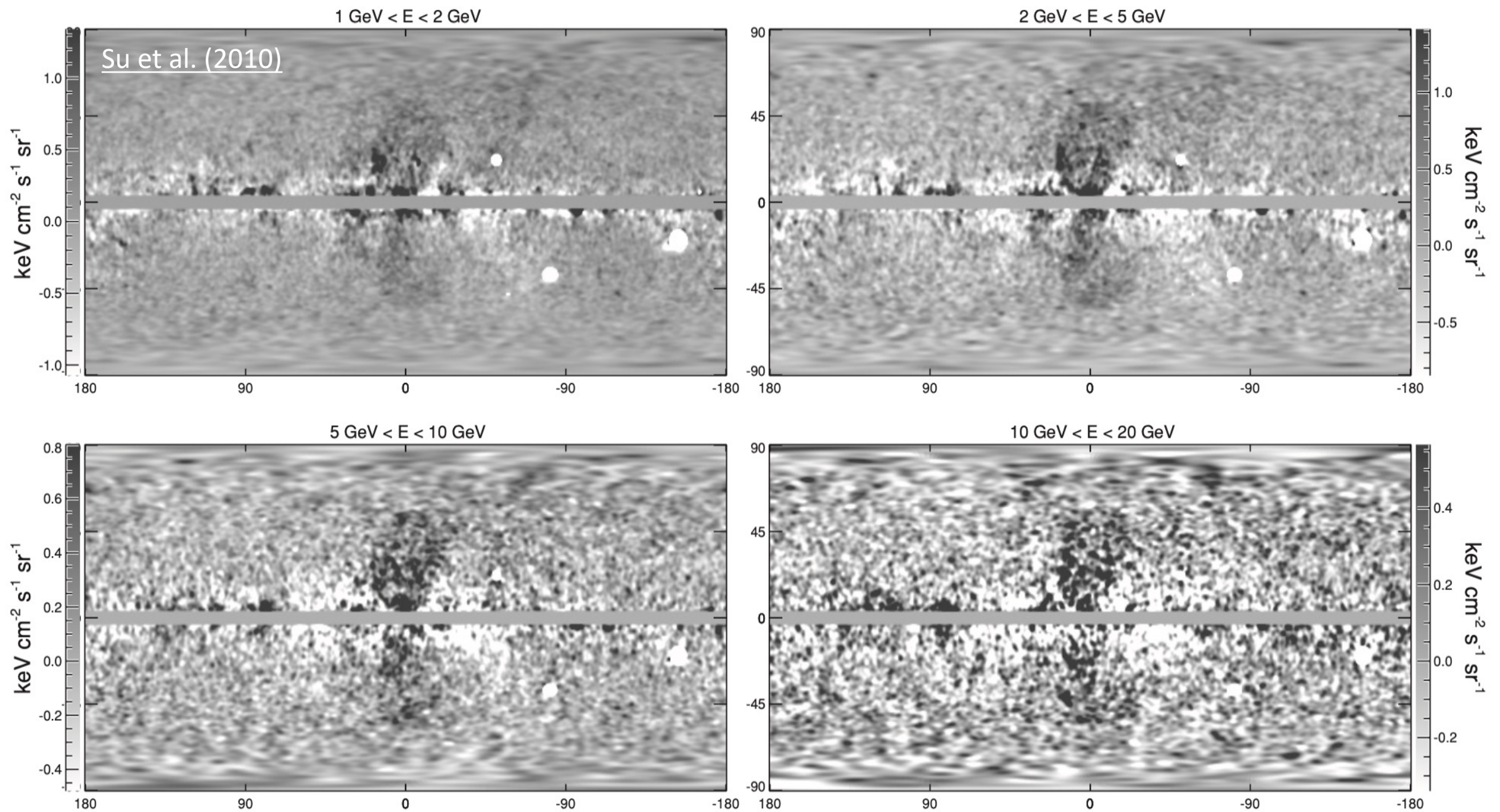
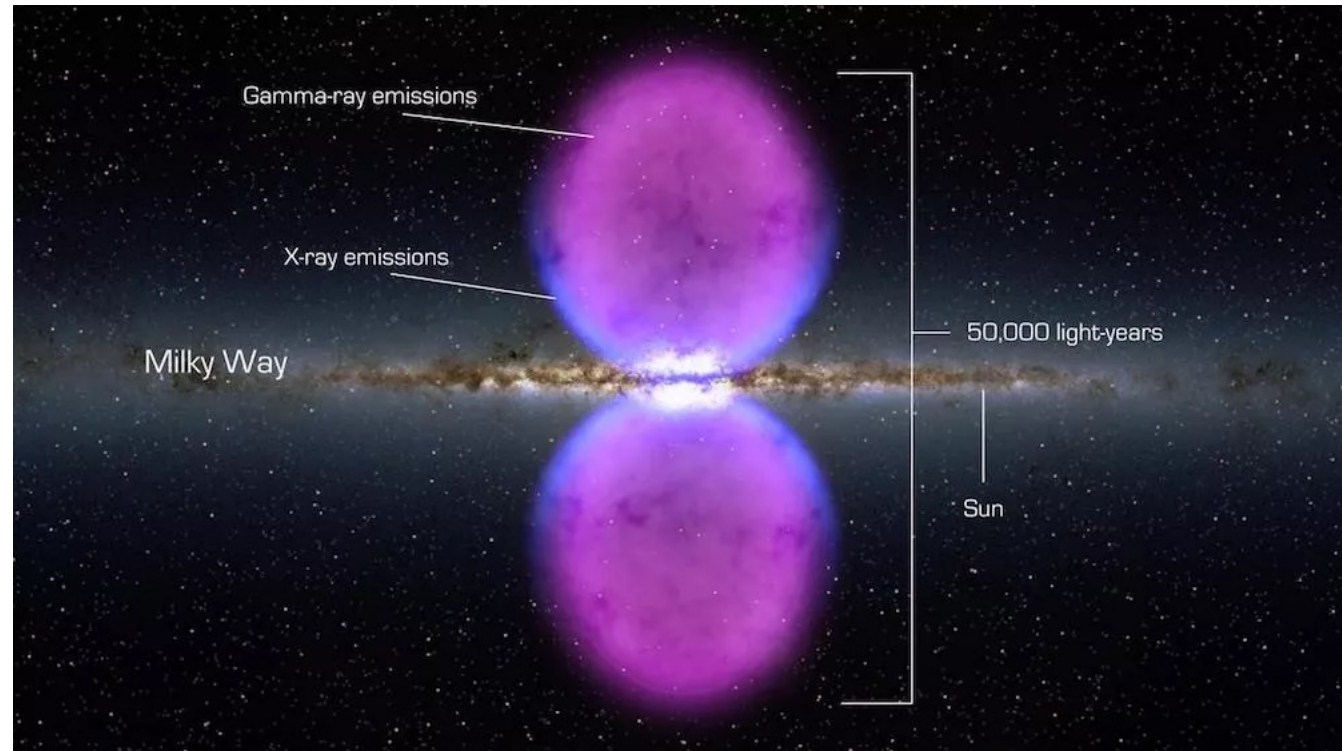
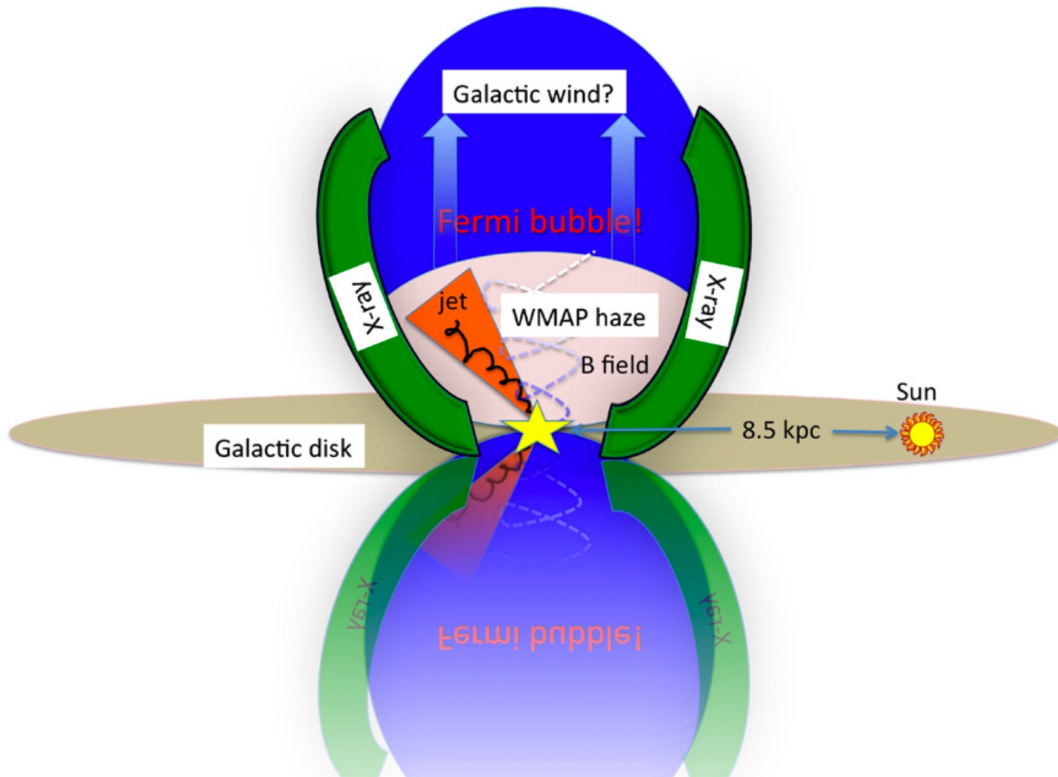


Figure 2. All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in four energy bins (see Section 3.1.1). Two bubble structures extending to $b \pm 50^\circ$ appear above and below the GC, symmetric about the Galactic plane.

The “Fermi Bubbles”

[Su et al. \(2010\)](#)

- Evidence of the Milky Way’s past as an AGN?
- Signs of dark matter annihilation?



Our Galaxy a long long time ago?



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

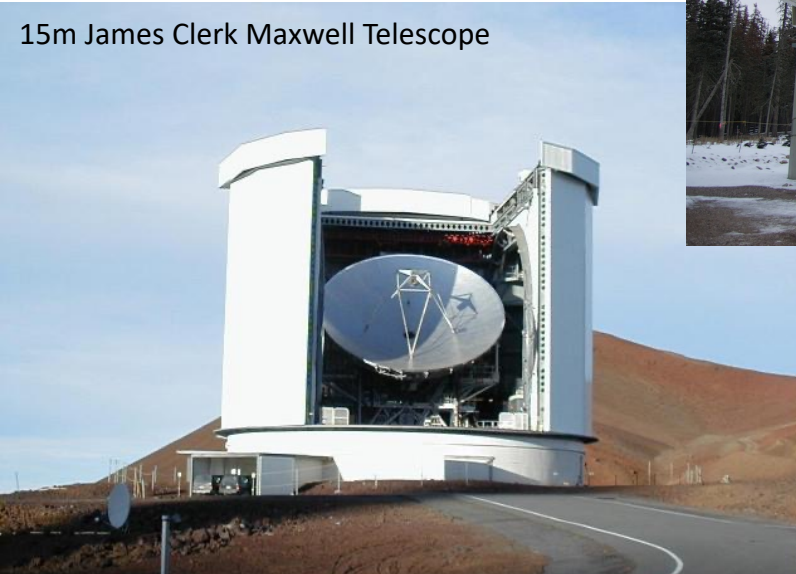
Imaging M87's Supermassive BH

10m Heinrich Hertz Sub-mm Telescope,
Mt Graham, AZ, USA



50m Large Millimeter Telescope,
Sierra Negra, Puebla, Mexico

15m James Clerk Maxwell Telescope



ALMA, Chile, Atacama Desert
52x12m, 12x7m dishes



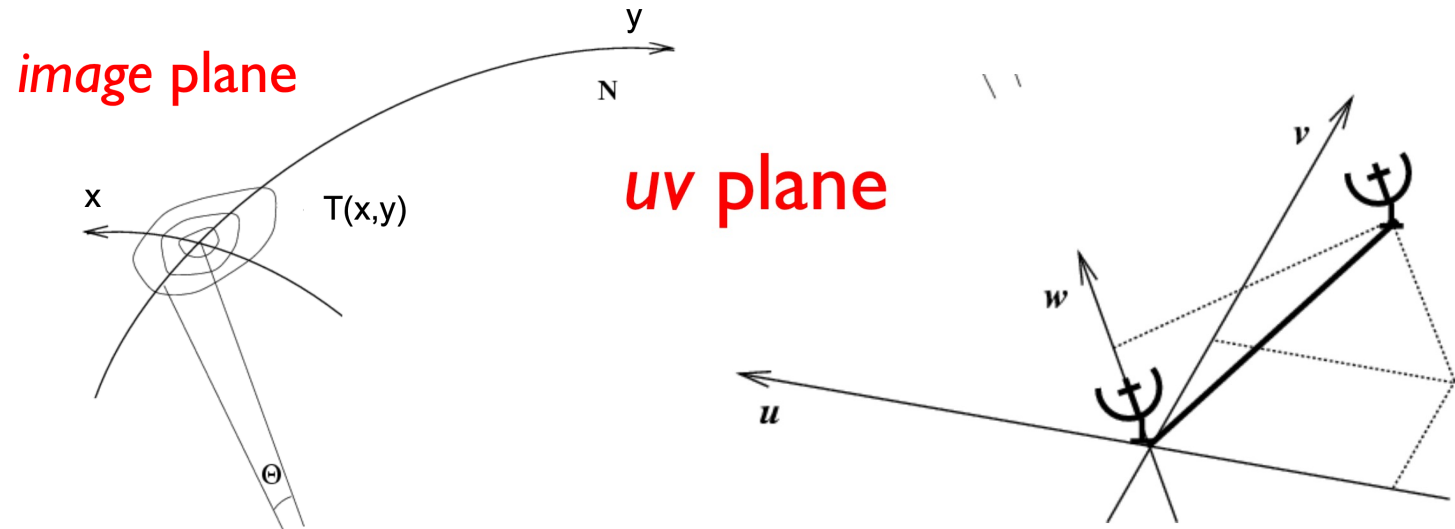
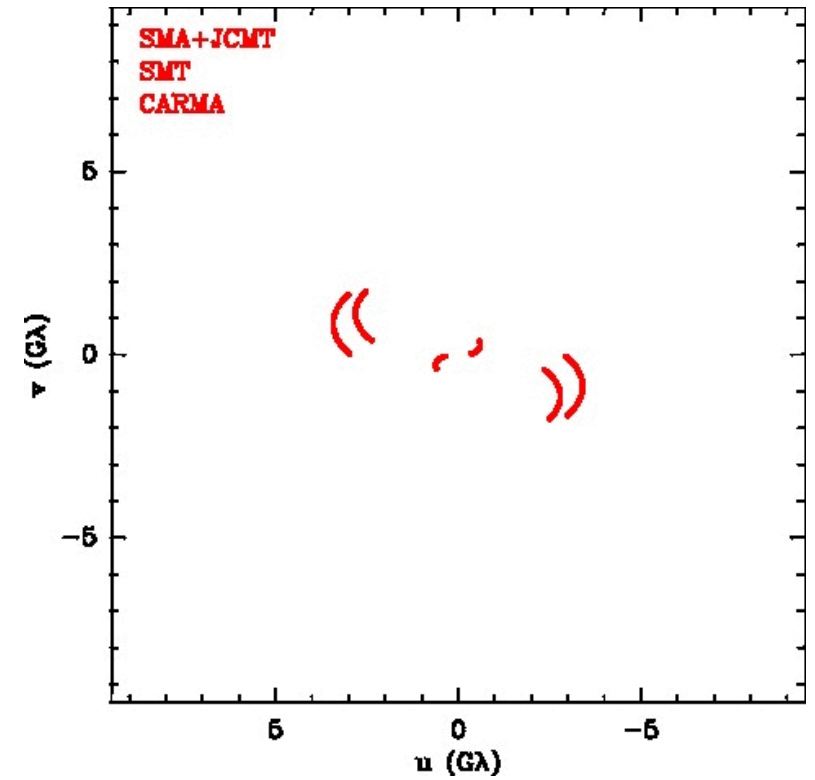
30m IRAM, Spain, Sierra Nevada

10m South Pole Telescope



Filling the (u,v) plane

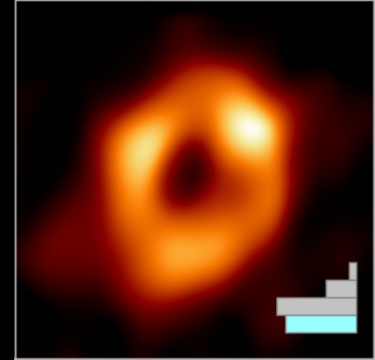
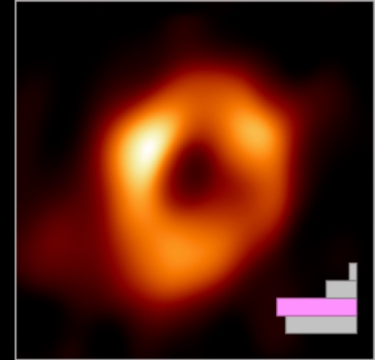
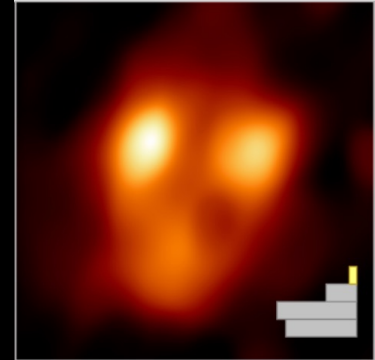
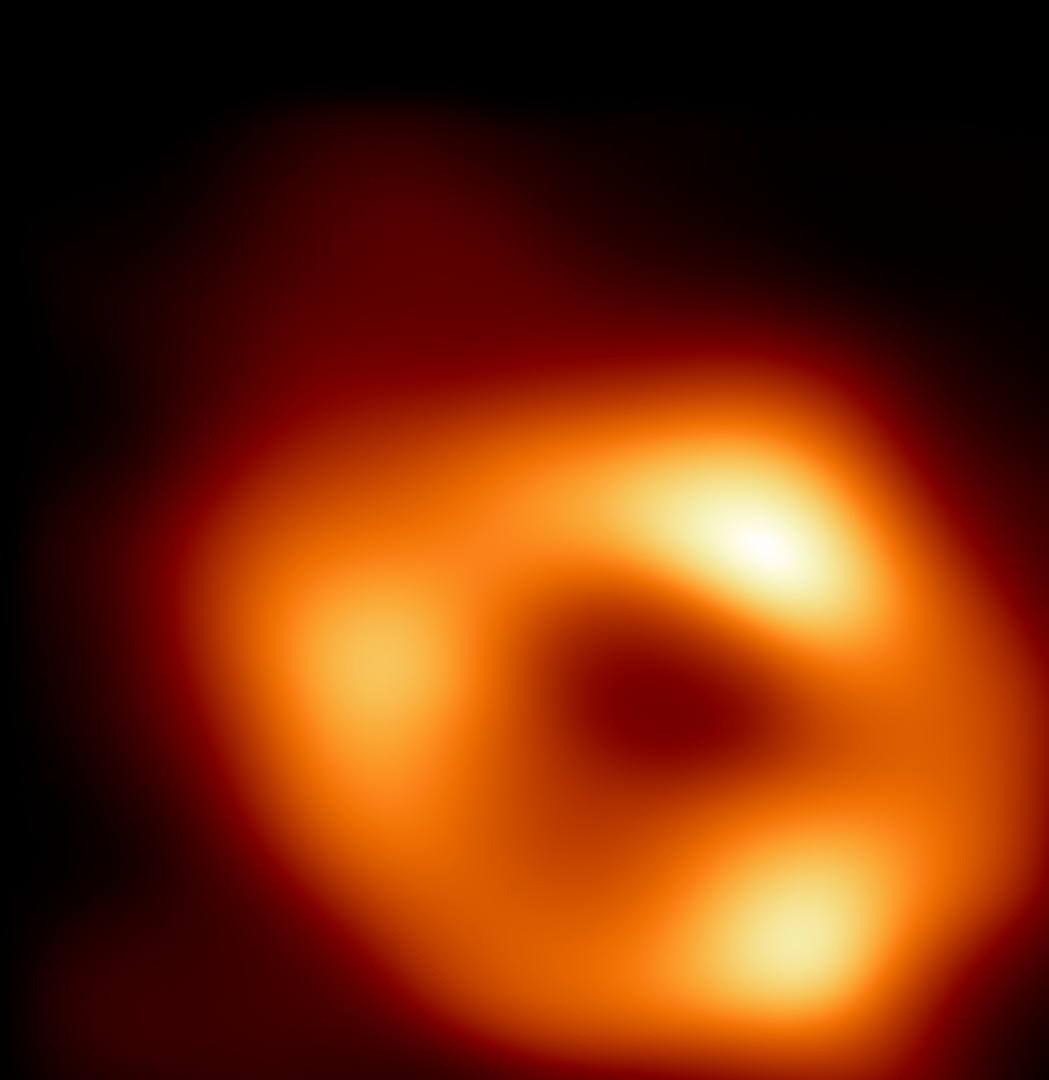
- Interferometers measure interference patterns observed by aperture pairs
- 2D Fourier transform of on-sky brightness $T(x,y)$ is the complex visibility $V(u,v)$ [van Cittert-Zernike theorem]
- $V(u,v) = \iint T(x,y) e^{2\pi i(ux+vy)} dx dy$
- (u,v) sampling crucial for image quality
- Time (Earth's rotation) increases (u,v) coverage



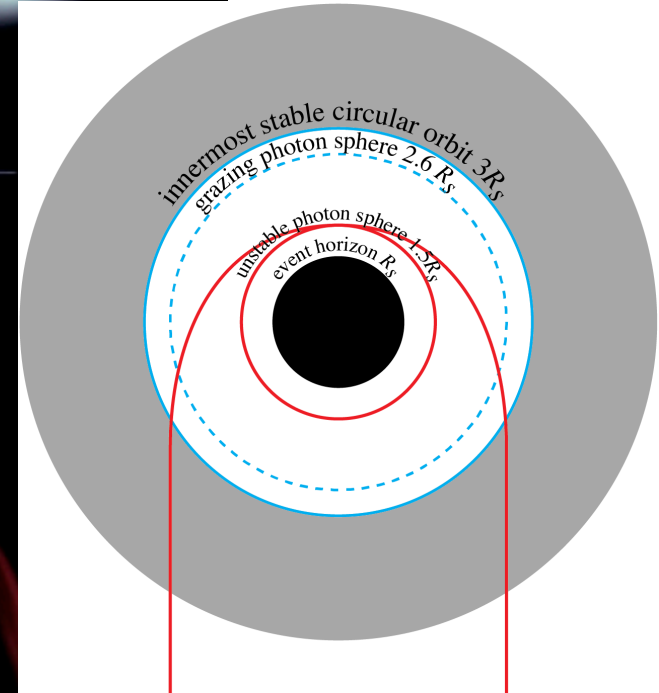
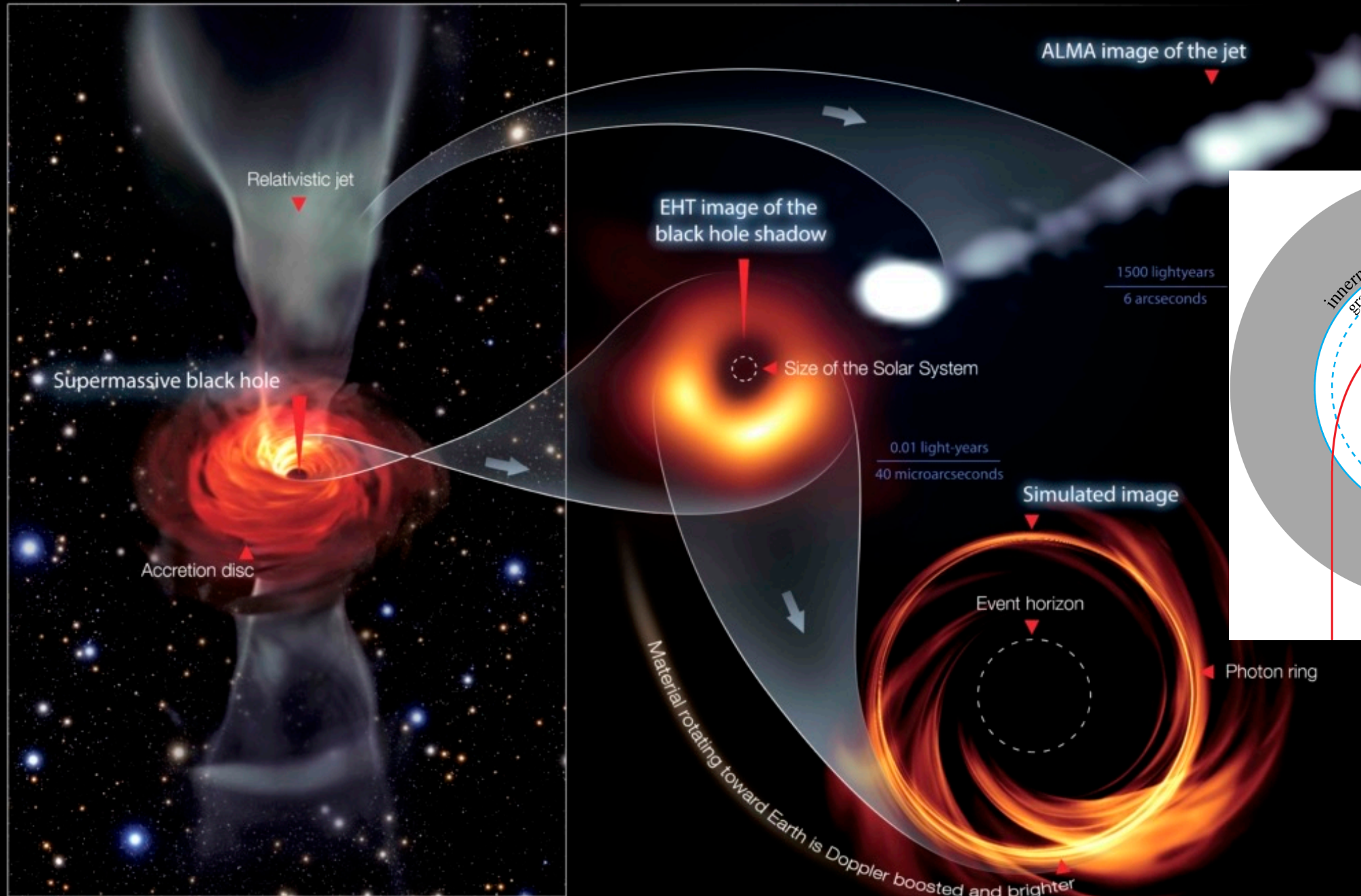


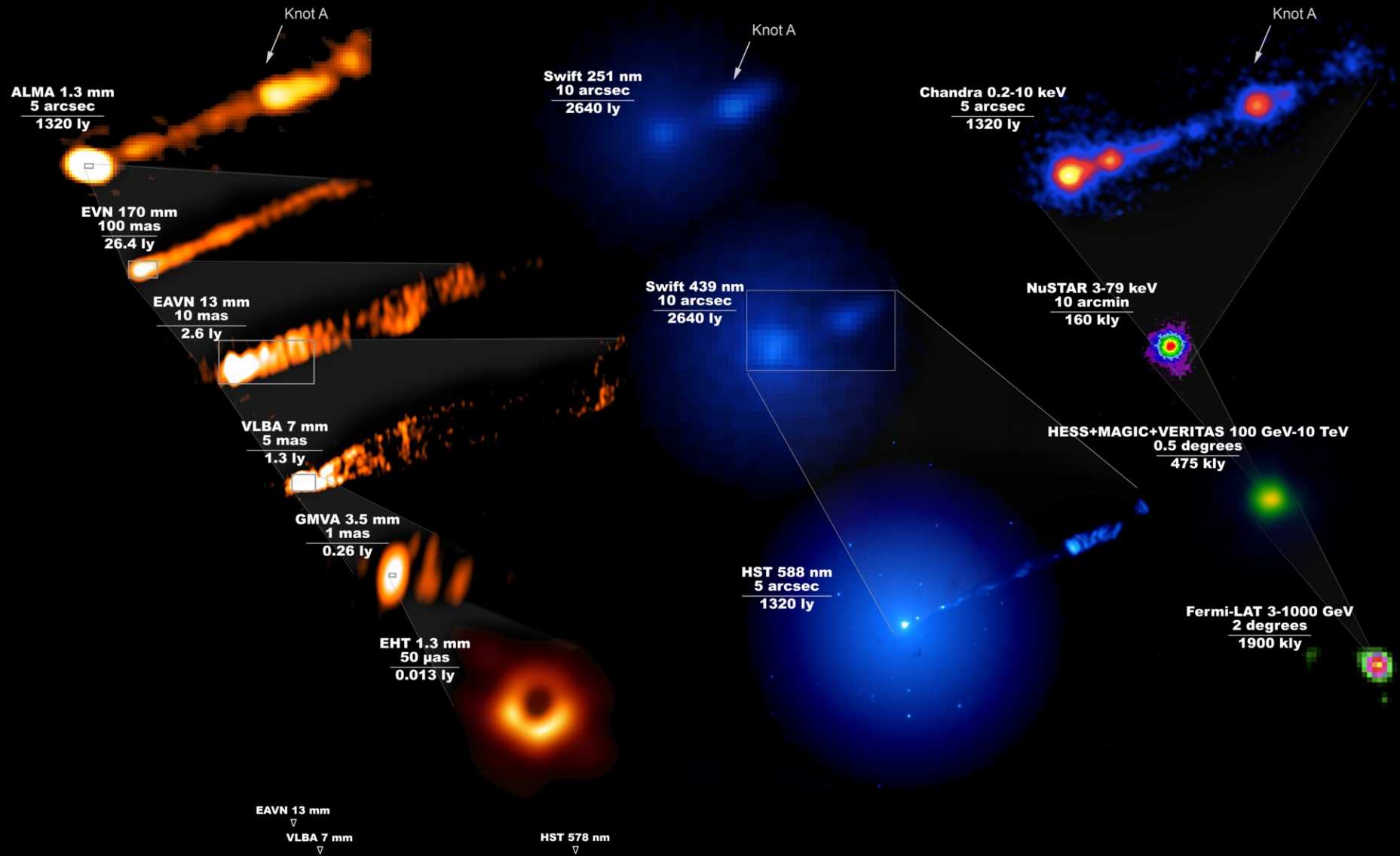
Imaging Magnetic Fields at 16.4 Mpc using Polarization





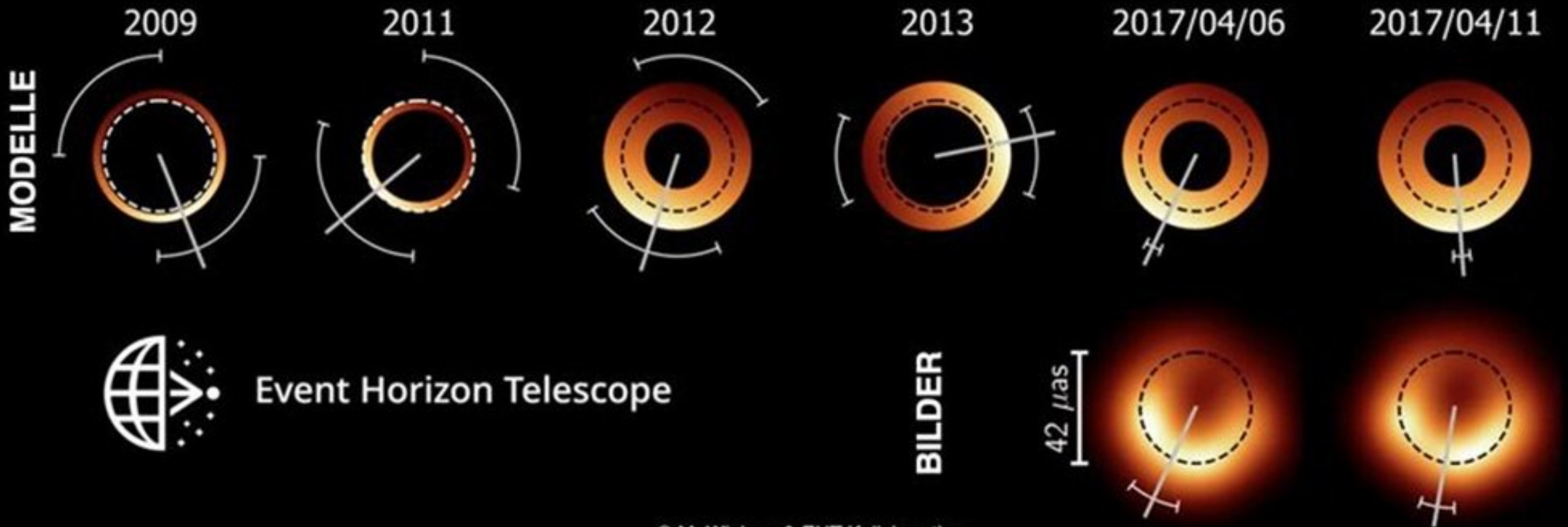
M87 Black Hole – Event Horizon Telescope





“A curious straight ray lies in a gap in the nebulosity in p.a. 20° , apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is $11''$ from the nucleus.” – Heber D. Curtis description of a 5 min exposure of NGC4486 (M87), 1918.

M87's variable morphology

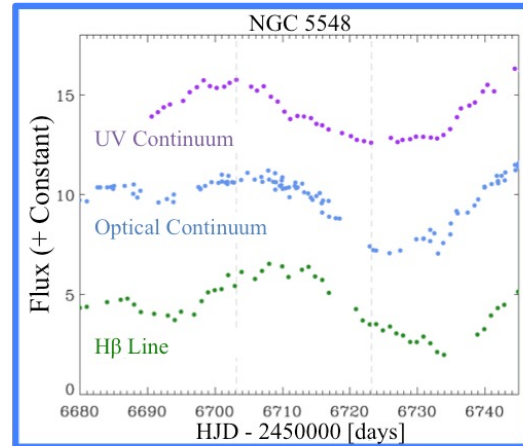


© M. Wielgus & EHT-Kollaboration

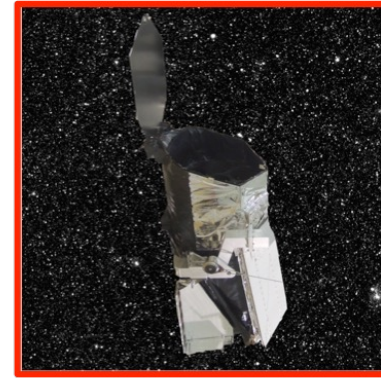
Reverberation Mapping

X-ray and optical variations are offset in time, allow to probe the size of BLR

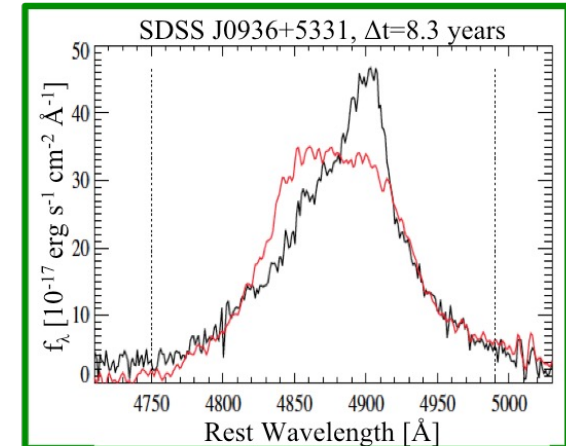
SDSSV – Black Hole Mapper & Reverberation mapping



Reverberation Mapping
Measuring BLR sizes and BH masses



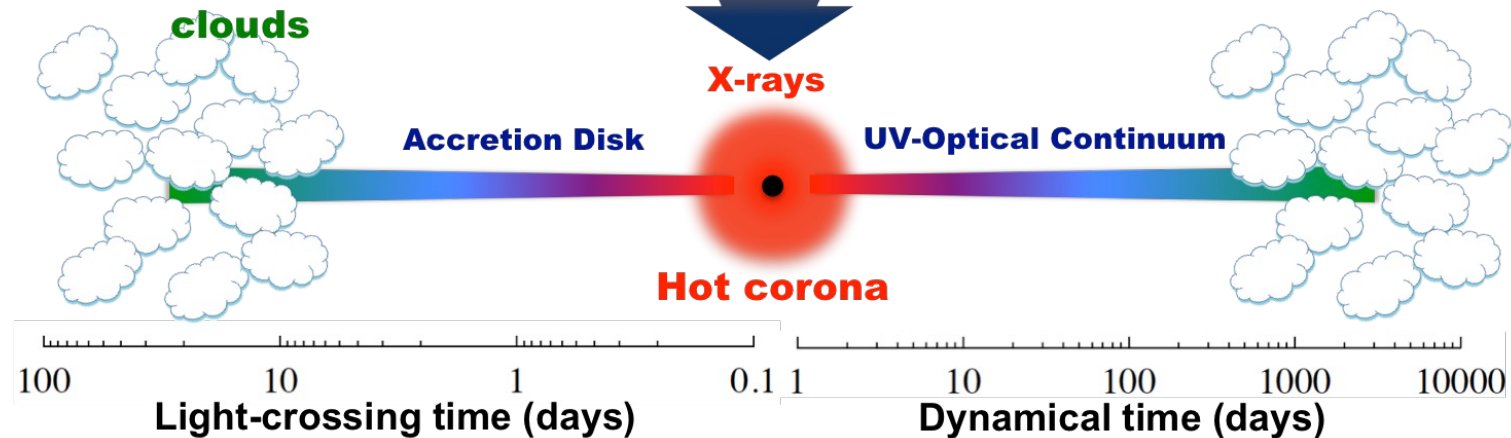
eROSITA Follow-up
Probing hot X-ray coronae

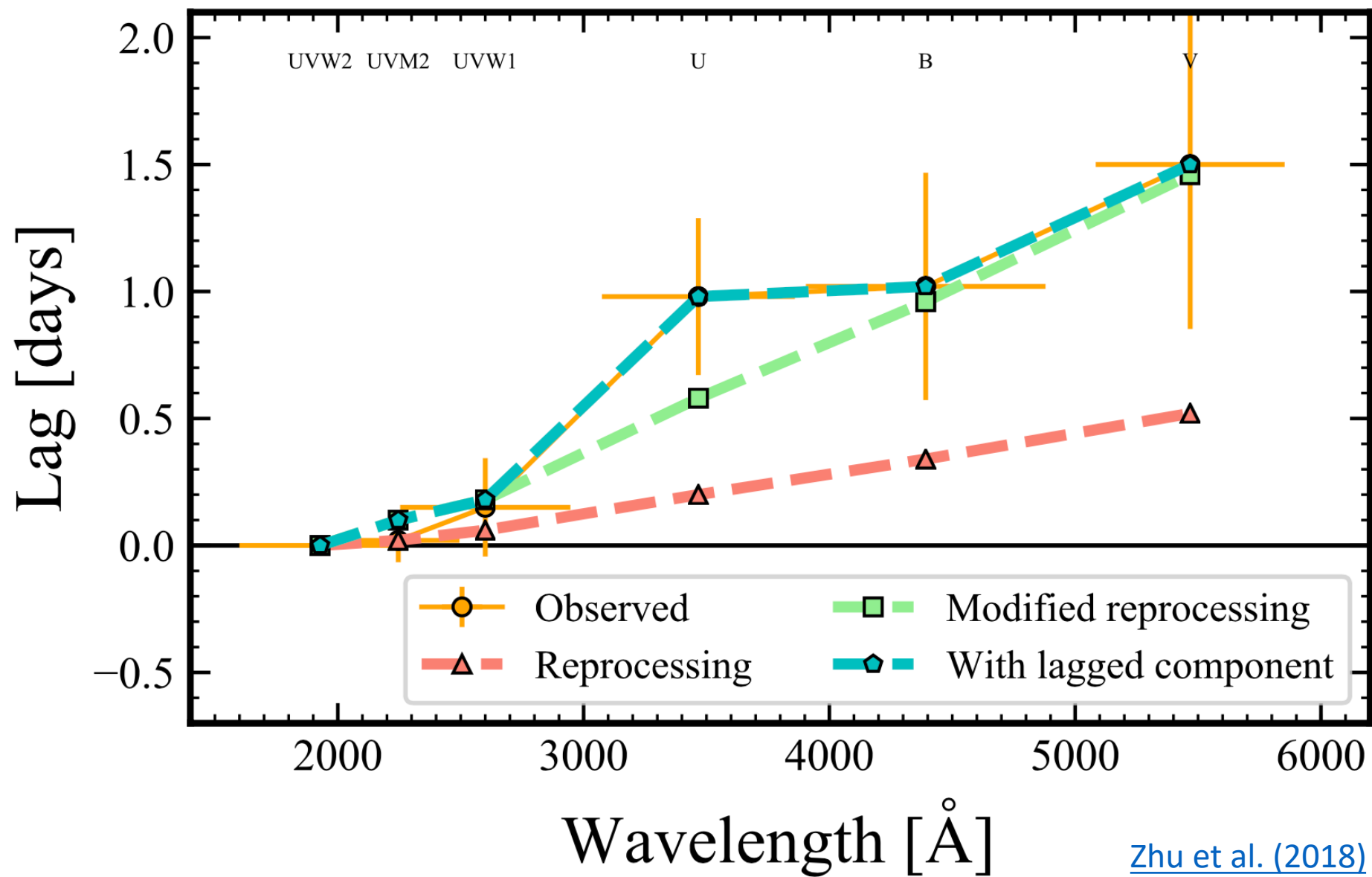


Multi-epoch Spectroscopy
Probing dynamical changes in the BLR

Broad-line region (BLR) clouds

Broad emission lines



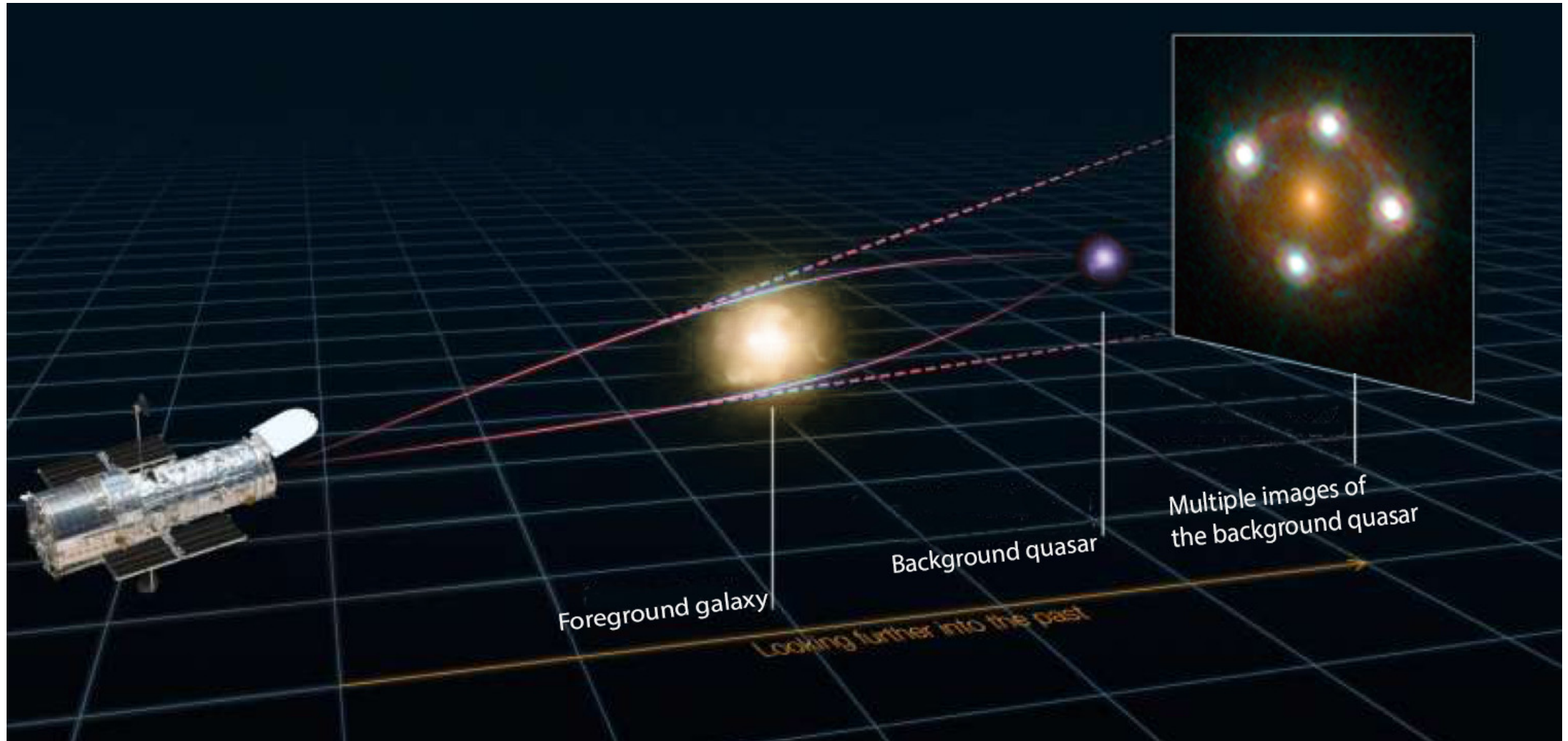


Time Delay Cosmography

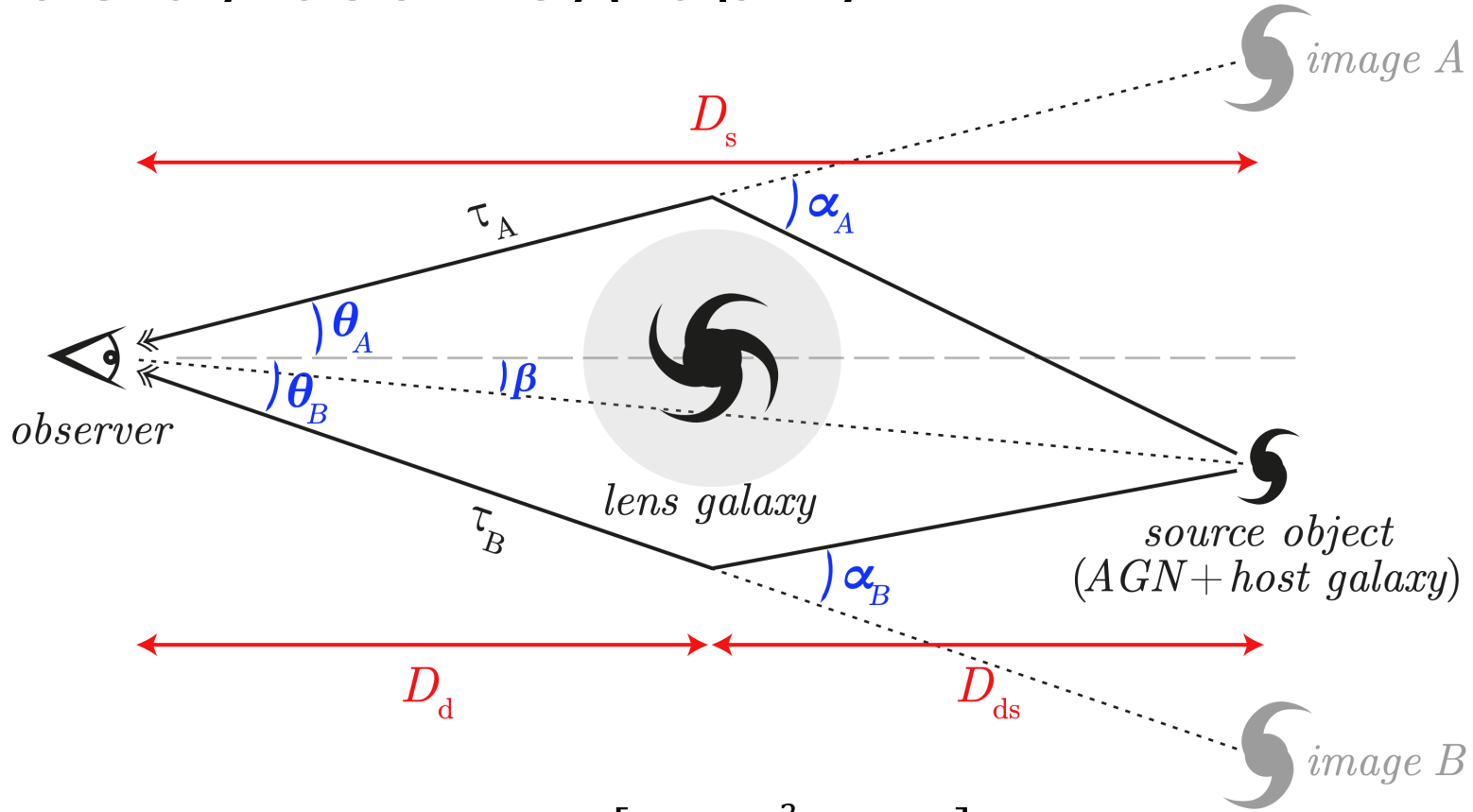




Strong gravitational lensing



Time-delay cosmography



Arrival time :

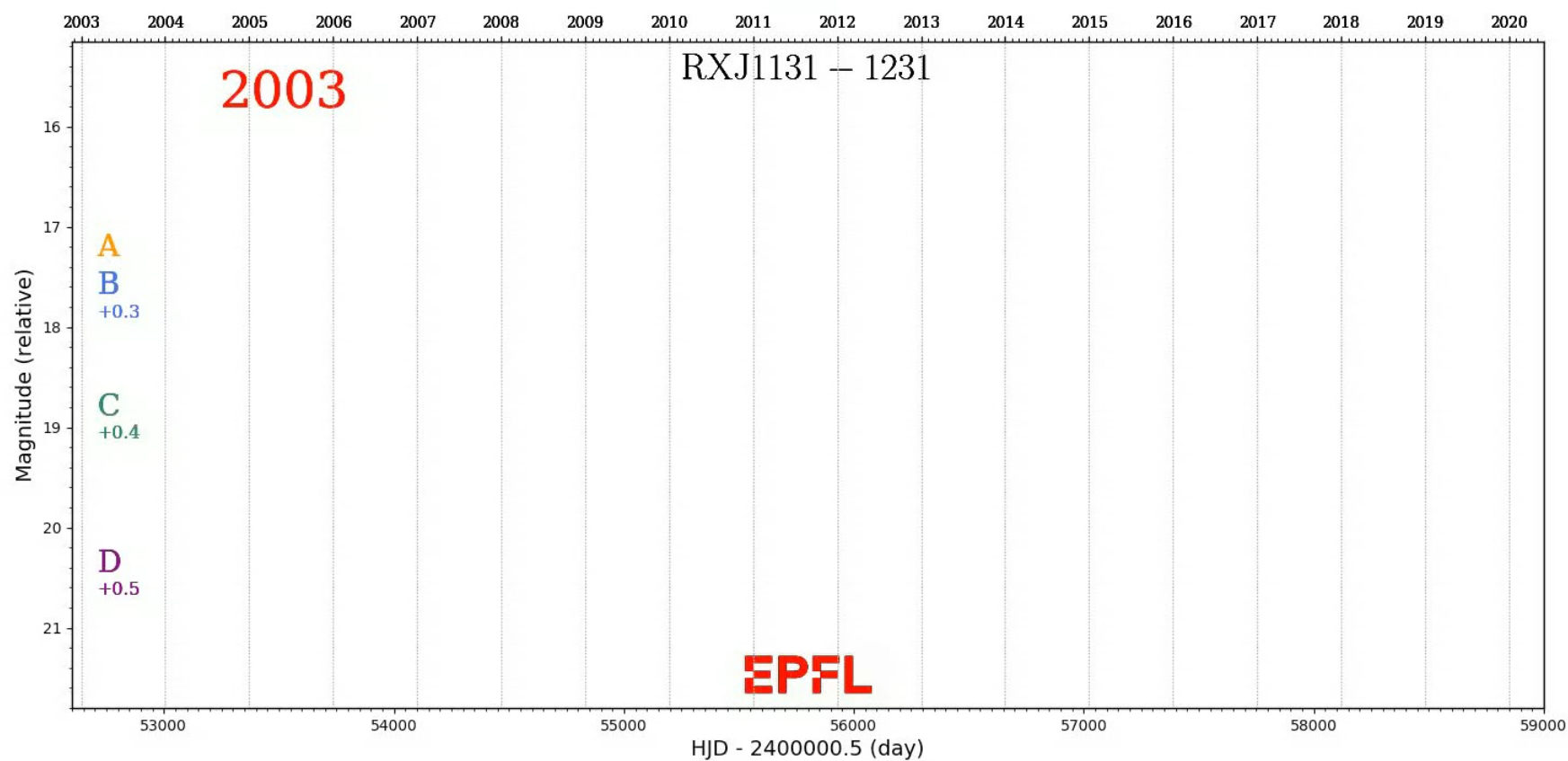
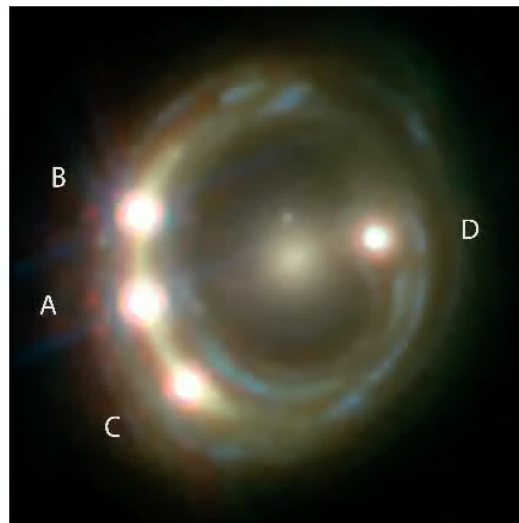
$$\tau(\vec{\theta}, \vec{\beta}) = \frac{D_{\Delta t}}{c} \left[\frac{(\vec{\theta} - \vec{\beta})^2}{2} - \psi(\vec{\theta}) \right]$$

Delays:

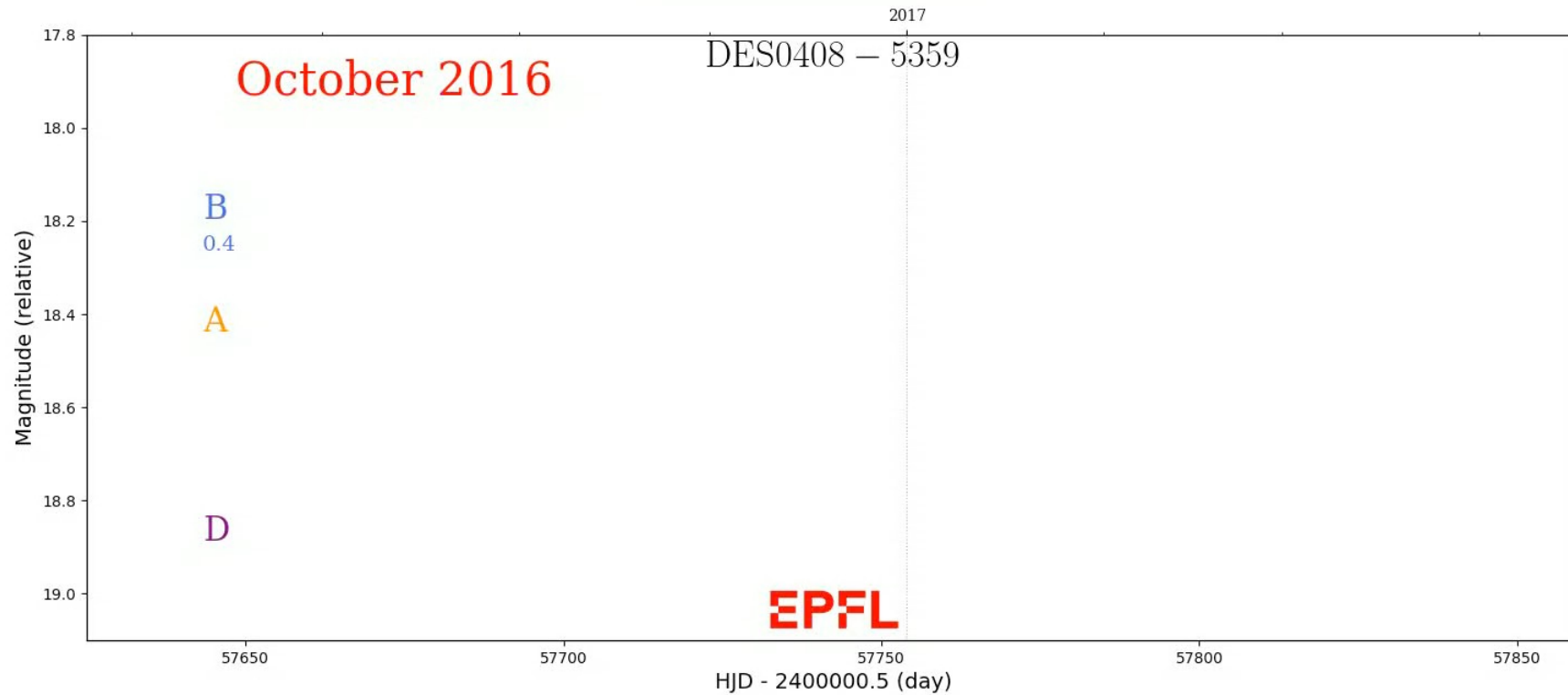
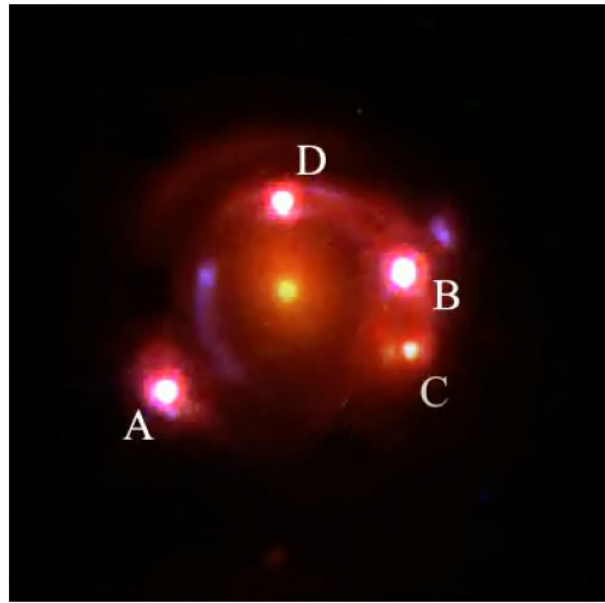
$$\Delta t_{ij} = \frac{D_{\Delta t}}{c} \left[\frac{(\vec{\theta}_i - \vec{\beta})^2}{2} - \psi(\vec{\theta}_i) - \frac{(\vec{\theta}_j - \vec{\beta})^2}{2} + \psi(\vec{\theta}_j) \right]$$

$$D_{\Delta t} = (1 + z_d) \frac{D_d D_s}{D_{ds}} = \frac{c \Delta t_{ij}}{\Delta \phi_{ij}} \propto H_0^{-1}$$

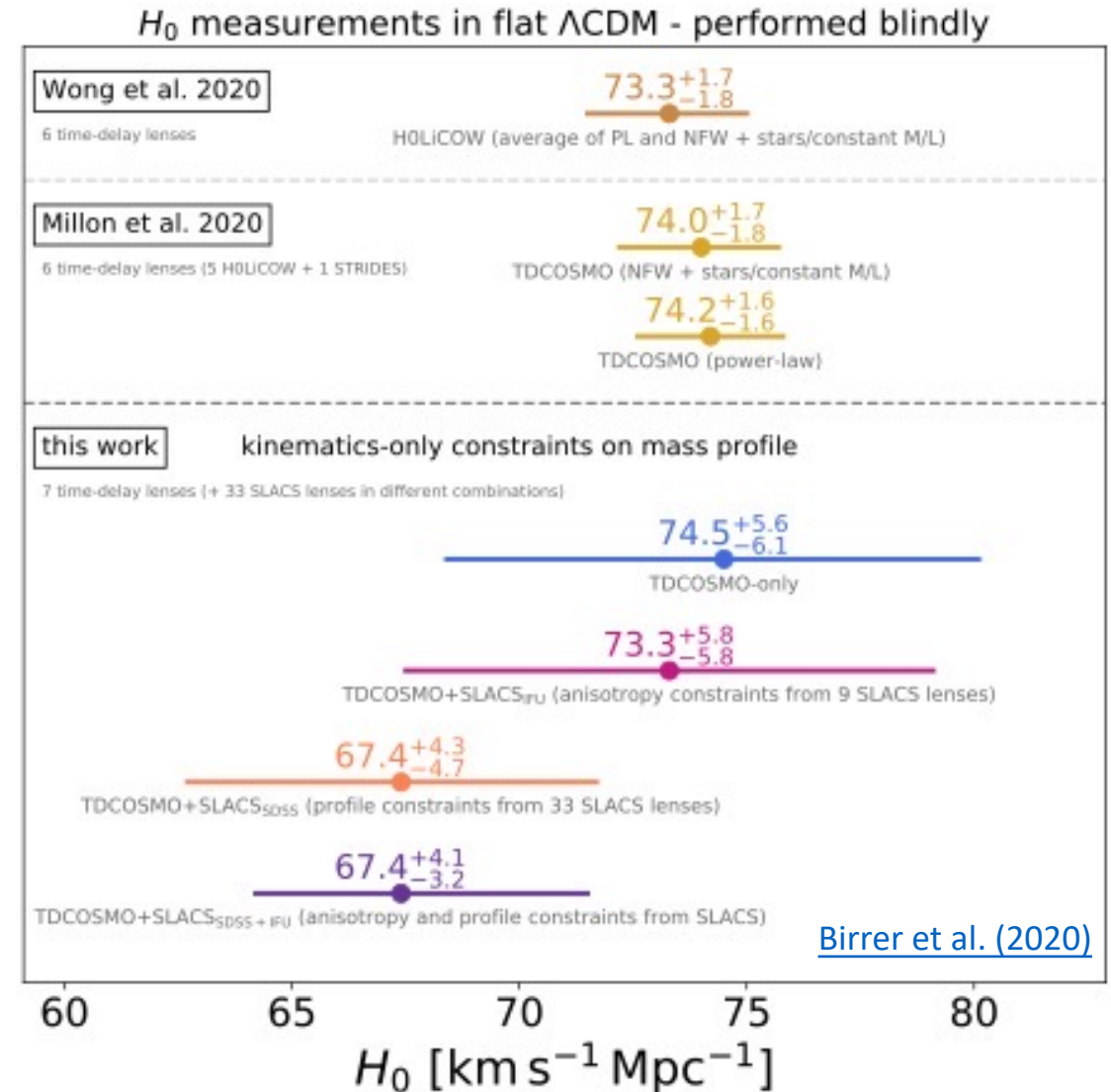
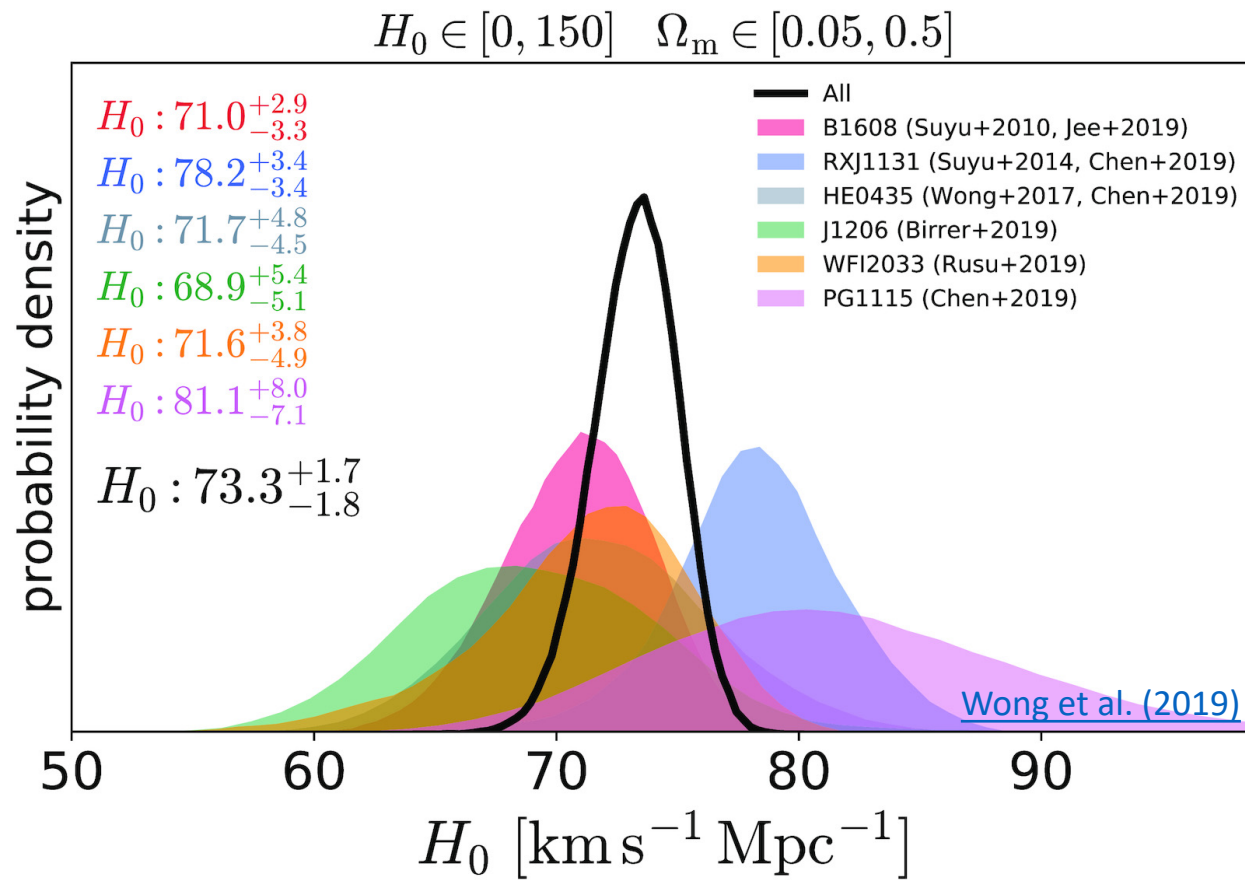
17 years of time delays



Rapid time delay tracking



Hubble's constant from time delays



Questions?

