Max-Planck-Institut für Radioastronomie

Vniversitat de València

June 24, 2010

1st COST MC+WG Meeting

Eduardo Ros (Univ. Valencia & MPIfR)

SUPER MASSIVE BLACK HOLES (COST MP0905 WG#4)

cost

European Science Foundation

Outlook

- The Working Group (WG)
  - Composition
  - Goals
- The Science
  - Super-Massive Black Holes (SMBH)
- The WG role in the Science

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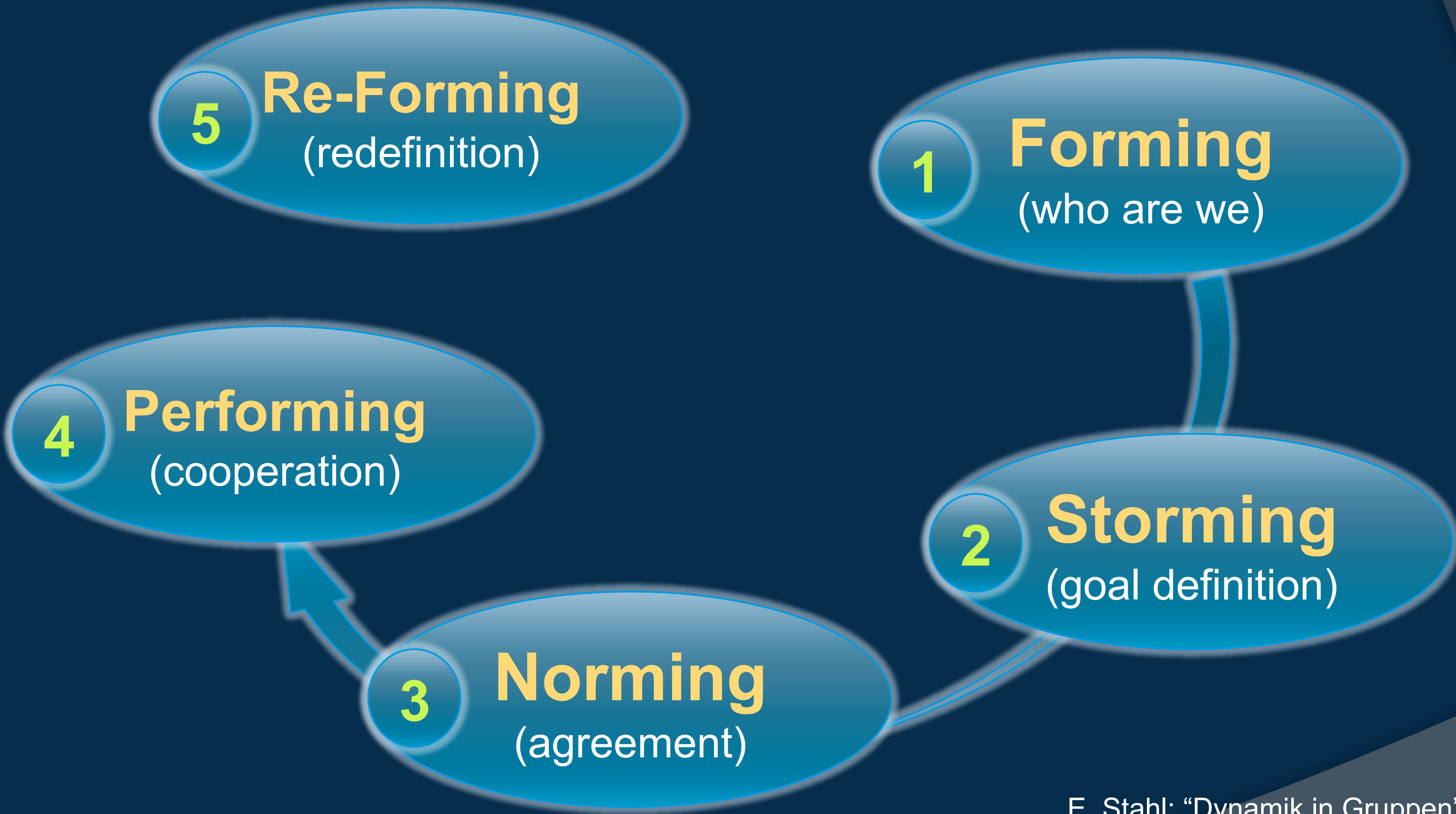
SMBH – WG#4 Objectives

Group process



E. Stahl: “Dynamik in Gruppen”: (2002)

Forming: our working group

- Who is here today?
- Who will be over the remaining 3 ½ years of the action?
- Expertise in different areas:
  - Observations at all wavelengths (with a slight bias towards high-resolution radio astronomy)
  - Theory and simulations

Storming: later today

Task force on Simulations and Observations

Summer School

Scientific Workshop

Web Contents

Text Book

Observing Program

Review of Reviews

Connections with Other WG

Norming: given by COST, our decision as well

- Agreement on the goals
- Definition of commitments and limitations
- Danger: overcommitment, dormant WG members, contradiction with expectations

Norming: goals

- What do we like to have in late 2013, when the action expires?
- Reminder: COST wants to increase intra-European cooperation in technology and basic research
  - Scientific activities of any kind
  - Sharing not only results, but also aims and methods
  - Focus on early career scientists

Performing: from today on

- We pursue the objectives of the action
- We integrate the members of the WG who could not be present here today
- Deliverables (results of our work in group) during and at the end of the action

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SMBH – The Science

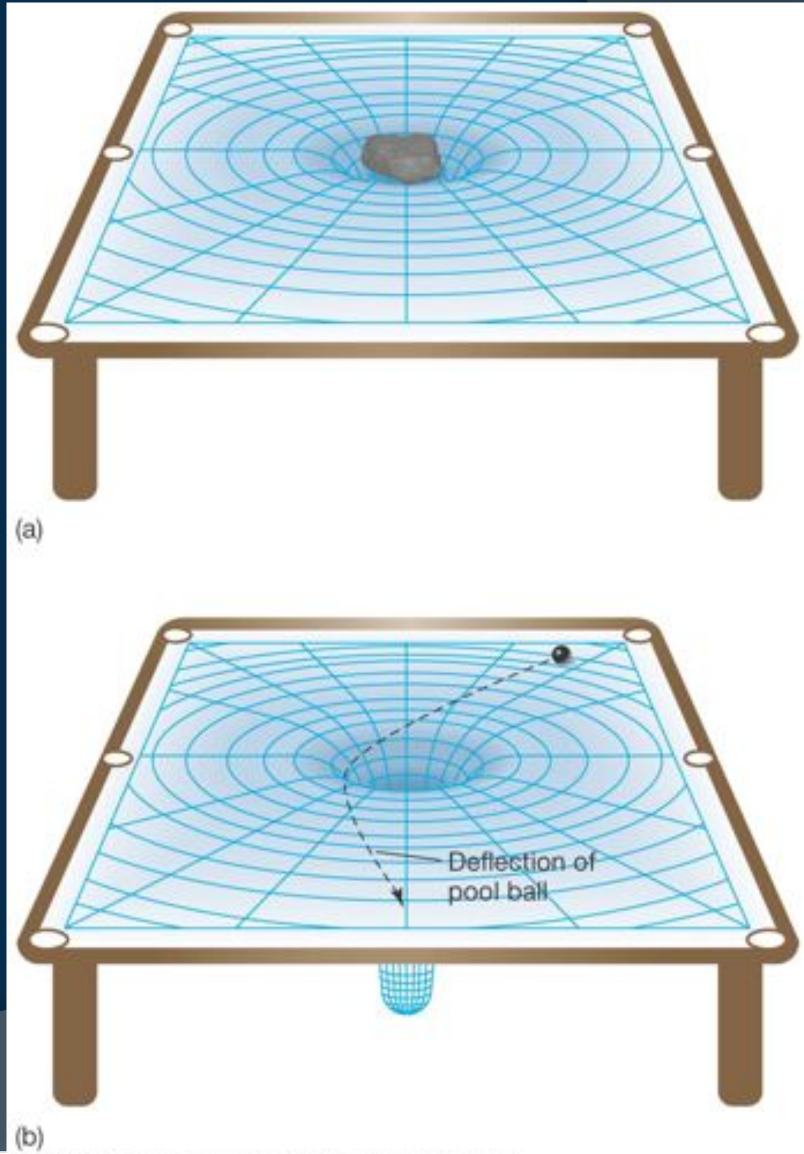
Einstein's Relativity

- Mass acts on spacetime, telling it how to curve
- Curved spacetime acts on mass, telling it how to move
- Time moves more slowly in curved spacetime

Einstein’s Relativity

- Matter tends to warp spacetime, and in doing so redefines straight lines (the path a light beam would take):

- A black hole occurs when the “indentation” caused by the mass of the hole becomes infinitely deep.



Schwarzschild Radius

- The radius at which the escape speed from the black hole equals the speed of light is called the Schwarzschild radius.
- The Earth's Schwarzschild radius is about a centimeter; the Sun's is about 3 km.
- Once the black hole has collapsed, the Schwarzschild radius takes on another meaning—it is the event horizon. Nothing within the event horizon can escape the black hole.

Schwarzschild Radius

- George Michell (1783) considered Newton's corpuscular theory of light…
- Non-rotating compact object, with the Schwarzschild metric:

$$(ds)^2 = \left(cdt\sqrt{1-2GM/rc^2}\right)^2 - \left(\frac{dr}{\sqrt{1-2GM/rc^2}}\right)^2 - (rd\theta)^2 - (r\sin\theta d\phi)^2$$

- If we consider a radius $r = R_S = 2GM/c^2$ the square roots in the metric go to zero (even $d\tau = 0$, time freezes at this radius)

BH properties

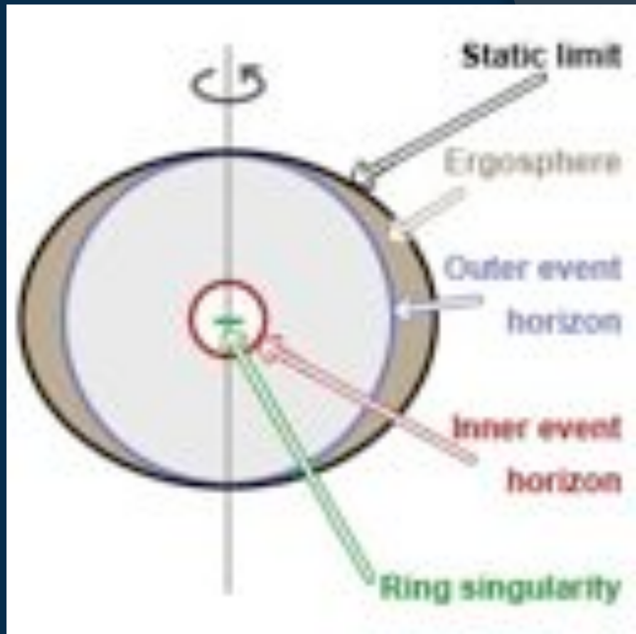
- Event horizon: surface $r = R_S$
- Singularity at the centre (non-rotating case; Schwarzschild (1916))
- For $dr = d\theta = d\Phi = 0$, for an object at rest:

$$(ds)^2 = (cdt)^2 \left(1 - \frac{R_S}{r}\right) < 0$$

- When $r < R_S$, no particle can stay at rest, all worldlines converge to singularity (even for photons)

BH properties (rotating)

- Things get more complicated with a rotating BH (Kerr)
  - Static observer becomes impossible
- Ergosphere: elliptical region in which spacetime is dragged along in the direction of rotation of the BH at a speed > c in relation with the rest of the universe.
  - Theoretically, it is possible to extract energy and mass from the ergosphere by means of the Penrose process



http://hubblesite.org

SMBH – what they are

- Compact objects with masses over $10^6\ M_\odot$
  - Upper limit of $10^{10}\ M_\odot$ (Natarajan & Treister 2010)?
- Lie at the centre of most large galaxies
- Observational evidence from optical and radio observations
  - High rotational velocities caused by a powerful gravitational field
- Neighbouring regions emitting throughout the electromagnetic spectrum, in some cases as Active Galactic Nuclei

How do we form BH?

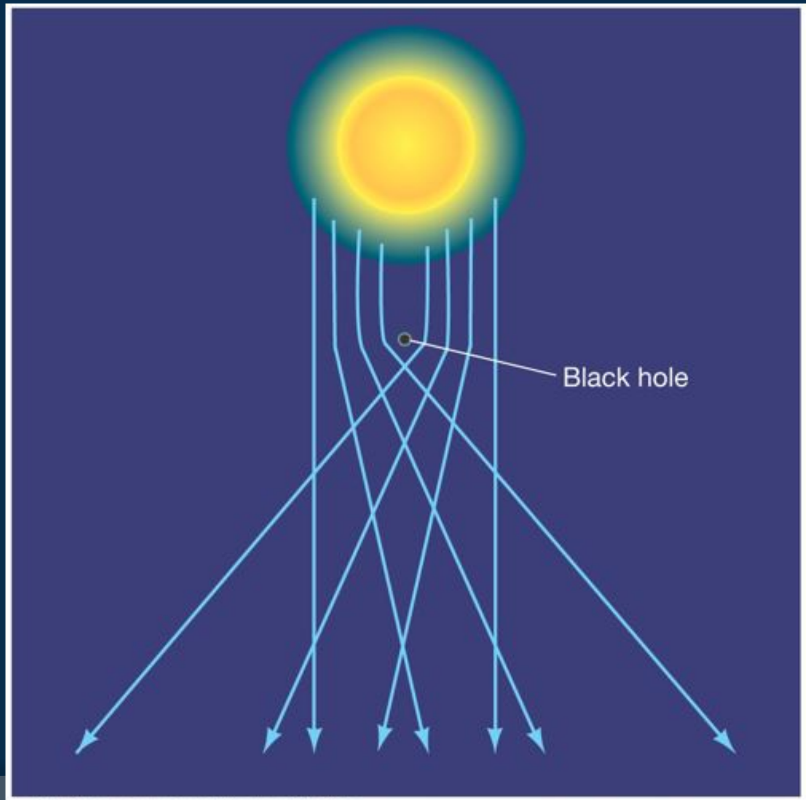
- Collapse of a massive supergiant star: neutron star whose self-gravity exceeds degeneracy pressure turns into BH at the Tolmann-Oppenheimer-Volkoff limit (WG#2)
- Formation by a high density of matter in the early universe, with values of 10^{-5} g to 10^{5} $M_{\odot}$: primordial black holes (WG#1)
- SMBH case – various theories (later)

Stellar Black Holes

- The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.
- Eventually, the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.

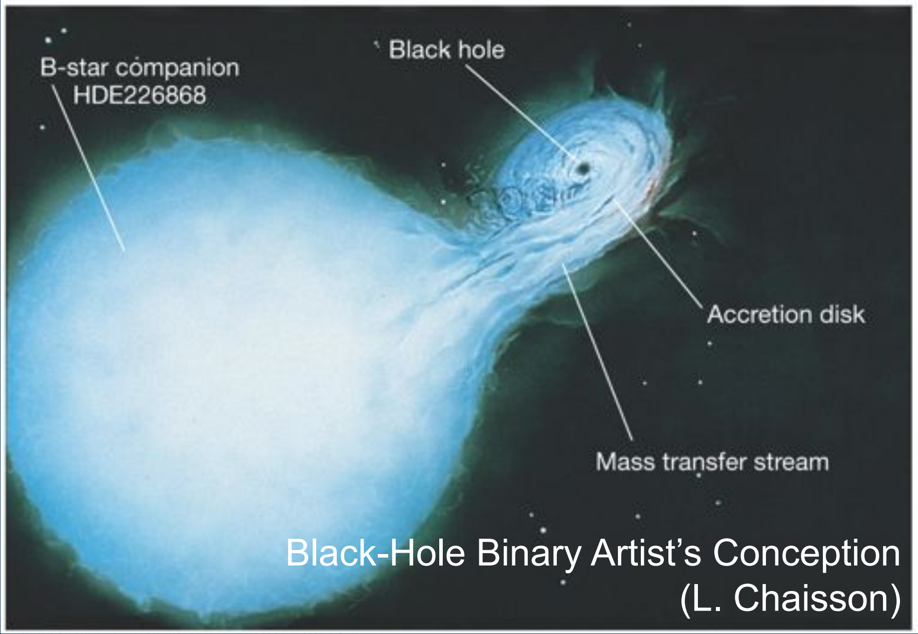
Observational Evidence for BH

- Black holes cannot be observed directly, as their gravitational fields will cause light to bend around them.

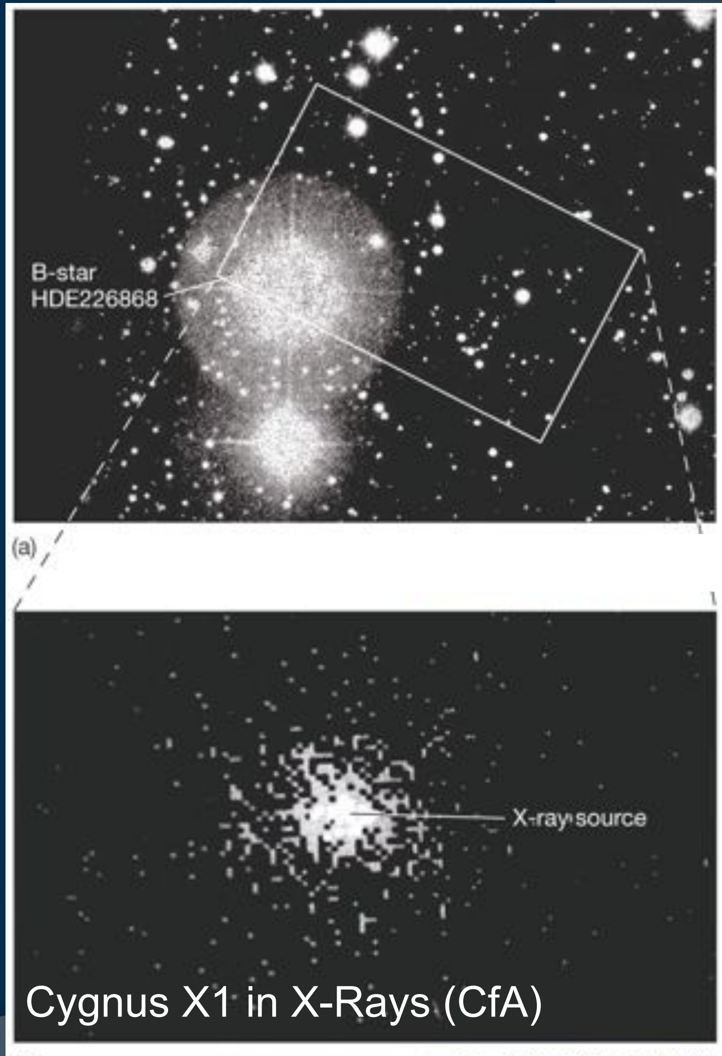


Observational Evidence for Stellar BH (WG#2)

- The existence of black-hole binary partners for ordinary stars can be inferred by the effect the holes have on the star's orbit, or by radiation from infalling matter



Black-Hole Binary Artist's Conception (L. Chaisson)



Cygnus X1 in X-Rays (CfA)

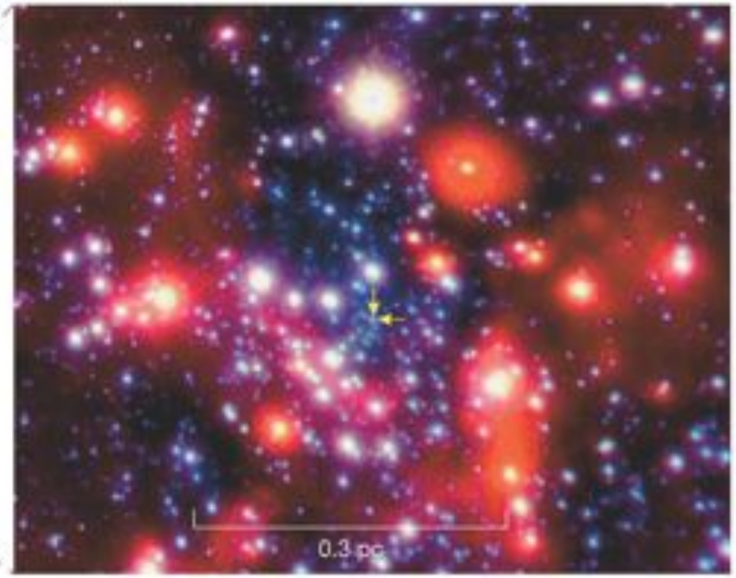
Observational Evidence for Stellar BH (WG#2)

- Cygnus X-1 is a very strong black-hole candidate:
  - Its visible partner is about 25 solar masses.
  - The system's total mass is about 35 solar masses, so the X-ray source must be about 10 solar masses.
  - Hot gas appears to be flowing from the visible star to an unseen companion.
  - Short time-scale variations indicate that the source must be very small.

Observational Evidence: The Galactic Center (WG#3)

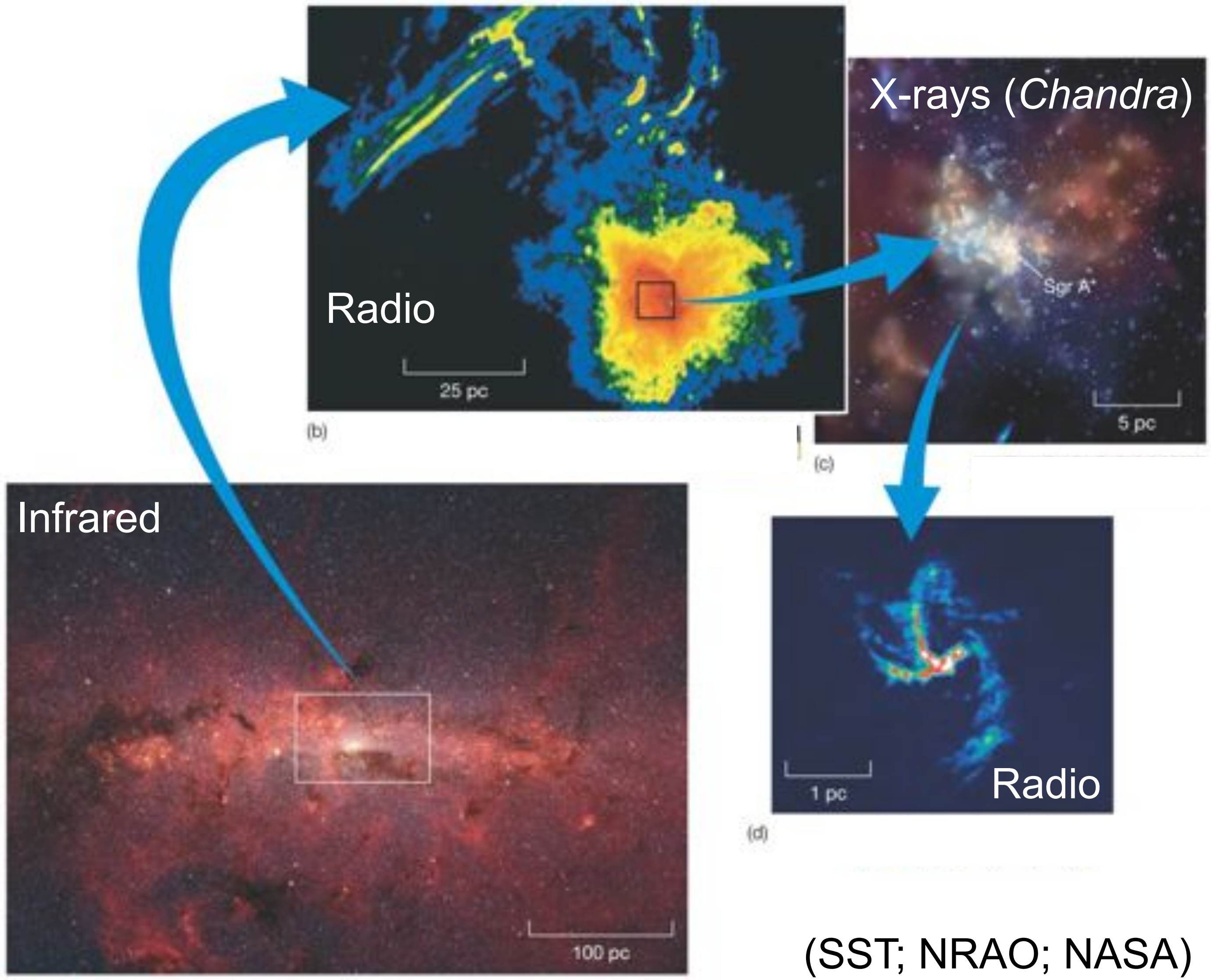
(AURA; ESO)

GC in the visible
(obscured by dust)



Adaptive-optics IR view of the
dense stellar cluster around the GC

The Galactic Center



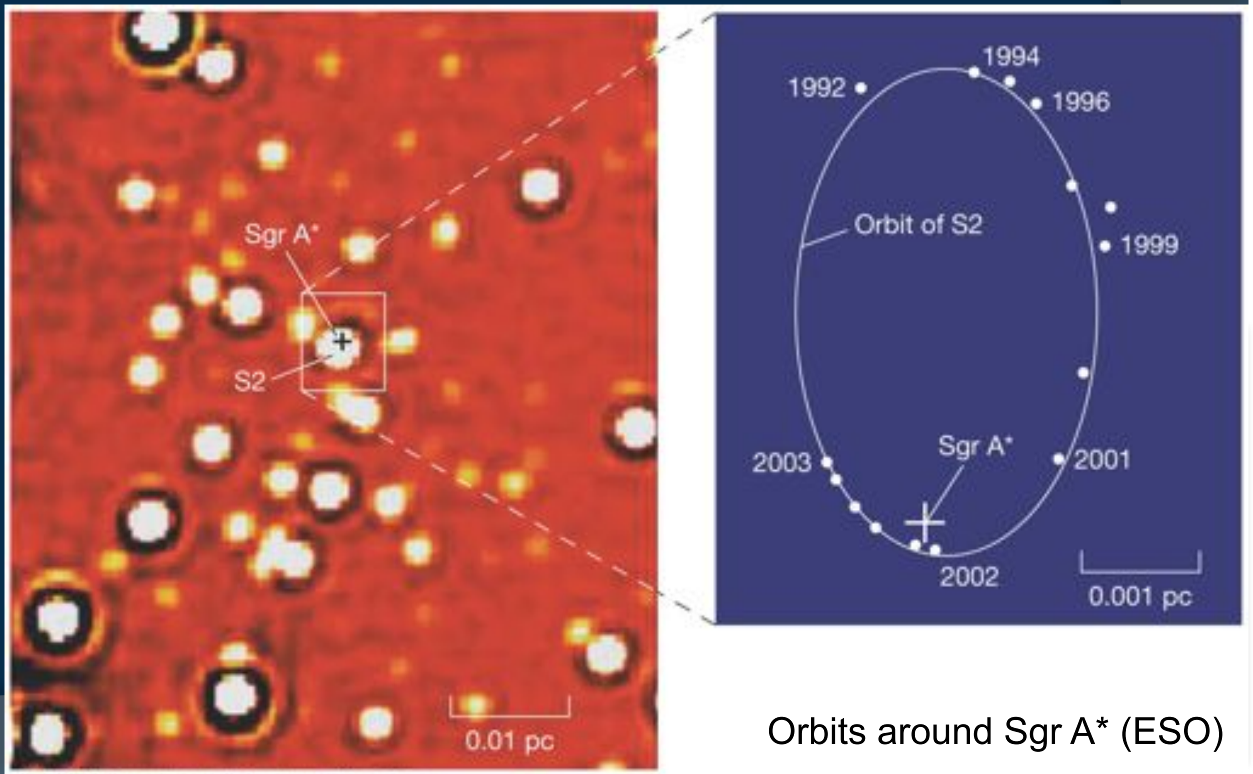
(SST; NRAO; NASA)

The Galactic Center: Ingredients

- A stellar density a million times higher than near Earth.
- A ring of molecular gas 400 pc across
- Strong magnetic fields
- A rotating ring or disk of matter a few parsecs across
- A strong X-ray source at the center

The BH at the Galactic Center

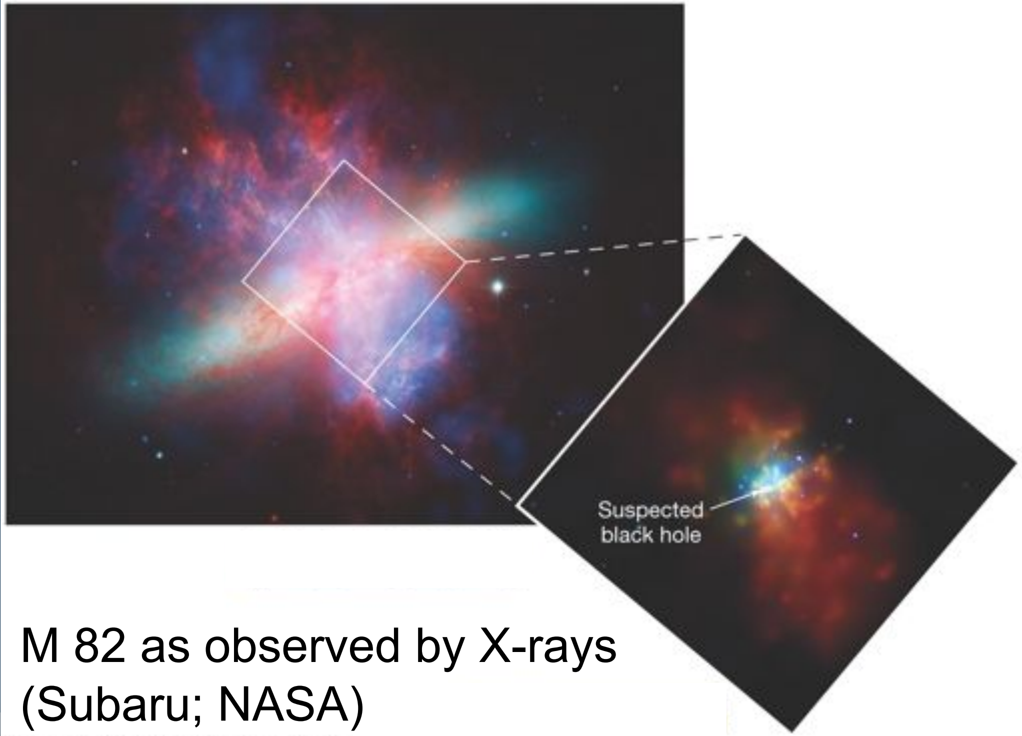
- Possible emission of an accretion disk
- Orbits of stars near the GC, yielding a central mass of $3.7\times10^6\ M_\odot$ ➔ BH



Orbits around Sgr A* (ESO)

Observational Evidence for BH: Intermediate Mass

- Evidence for intermediate-mass black holes has been found; these are about 100 to 1000 solar masses. Their origin is not well understood.



M 82 as observed by X-rays
(Subaru; NASA)

Observing SMBH - limitations

- Optical methods: radius of influence R_i on the surrounding gas by a BH of mass $M_\bullet$, defined as $R_i = GM_\bullet / V_G^2$ (V_G is the inner rotation velocity of the Galaxy)
- At a distance D, the size of this is:

$$\alpha_i = 1'' \times \left(\frac{M_\bullet}{10^8 M_{Sun}} \right) \times \left(\frac{V_G}{100 \text{ km s}^{-1}} \right)^{-2} \times \left(\frac{D}{10 \text{ Mpc}} \right)^{-1}$$

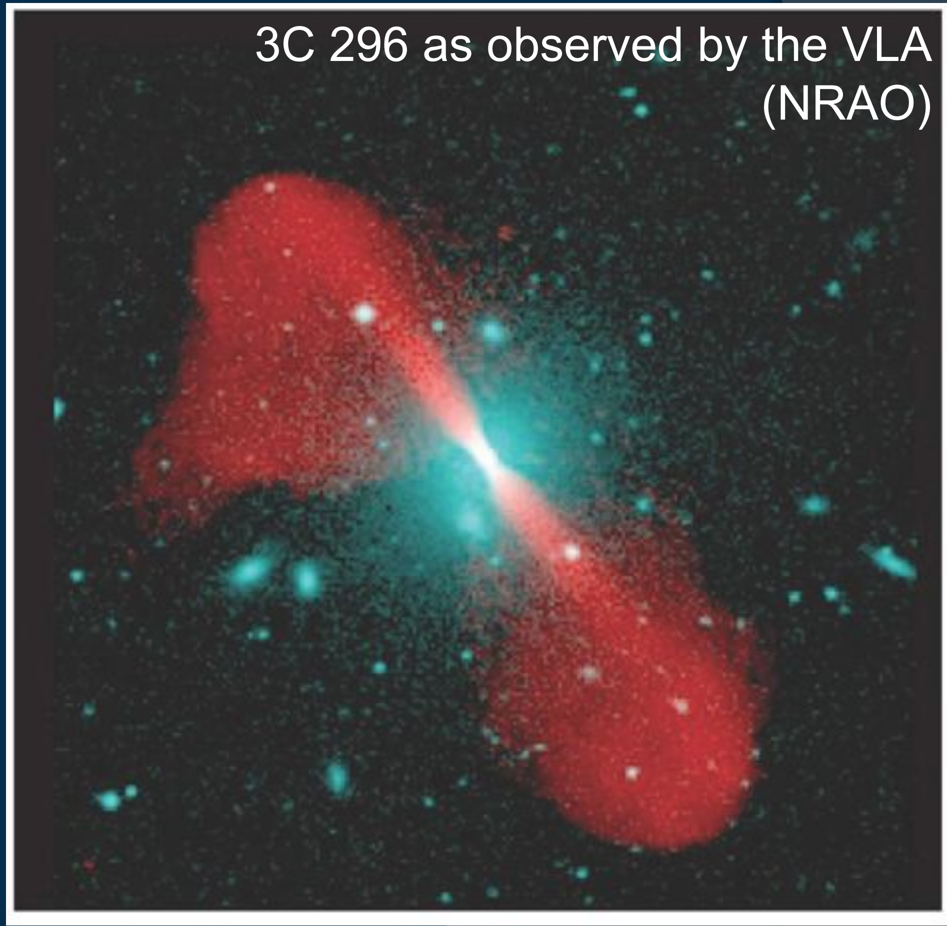
- This makes 40'' for the Milky Way, 2'' in M 31, or 0.5'' for an elliptical galaxy in the Virgo Cluster of $10^8 M_\odot$

Observational Evidence

- *Hubble Space Telescope* imaging of galaxies (e.g., M 87 mass of 3×10^9 $M_\odot$)
- Very-Long-Baseline Interferometry (VLBI) measurements of H_2O megamasers in NGC 4258, enclosing a mass of 3.6×10^7 $M_\odot$
- *ASCA* Fe Kα measurements of MCG −6−30−15 with a profile indicating a big mass
- Further methods to probe galactic centres:
  - Reverberation mapping (10^6–10^8 $M_\odot$)
  - Gas & Stellar Dynamics in nearby galaxies 10^7–10^9 $M_\odot$

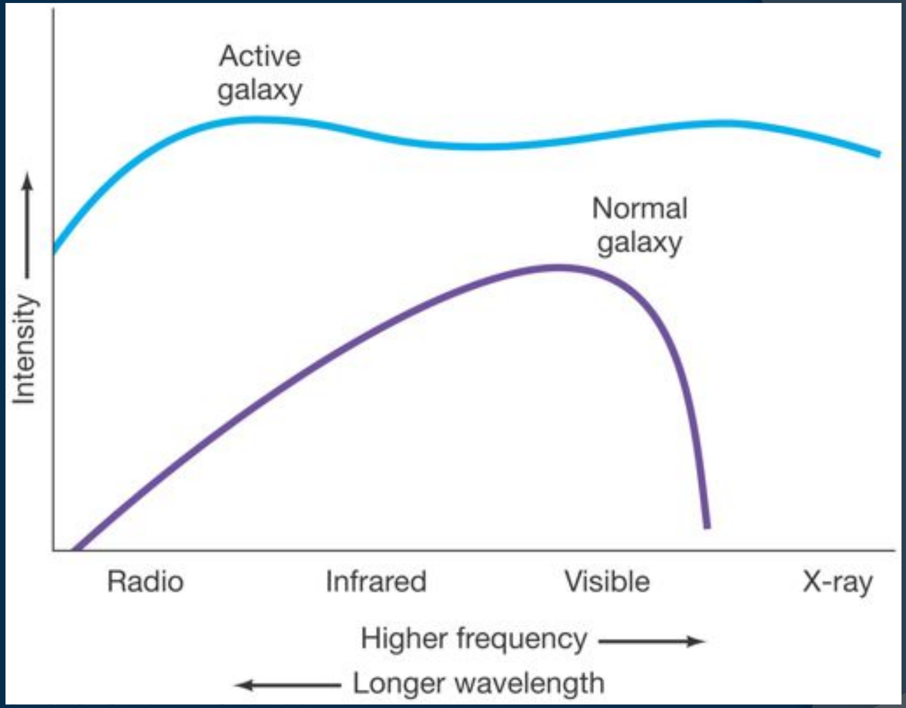
Observational Evidence for SMBH

- Jets nearby SMBH in active galaxies are one of the best proofs
- 3C 296, with huge jets of emission up to 500,000 lt-yr across



Active Galactic Nuclei

- About 20–25% of galaxies don't fit well into the Hubble scheme—they are far too luminous.
- Such galaxies are called active galaxies. They differ from normal galaxies in both the luminosity and type of radiation they emit:



Picture: E. Chaisson, Astronomy Today

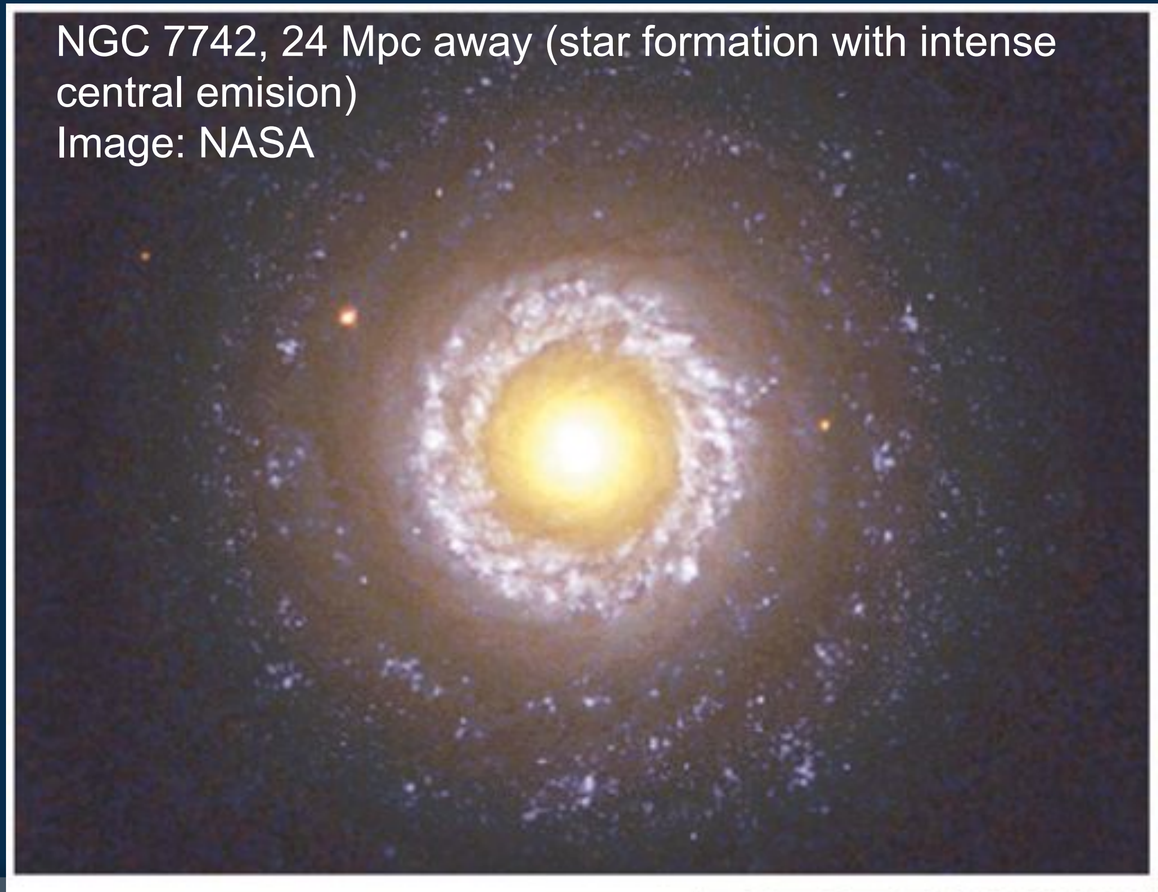
Active Galactic Nuclei

- Radiation in those galaxies is non-stellar
- Galaxies with most activity near occurring at their galactic center

- Avoid confusion with starburst galaxies (hosting an outburst of star formation mainly due to interactions with a neighbour)

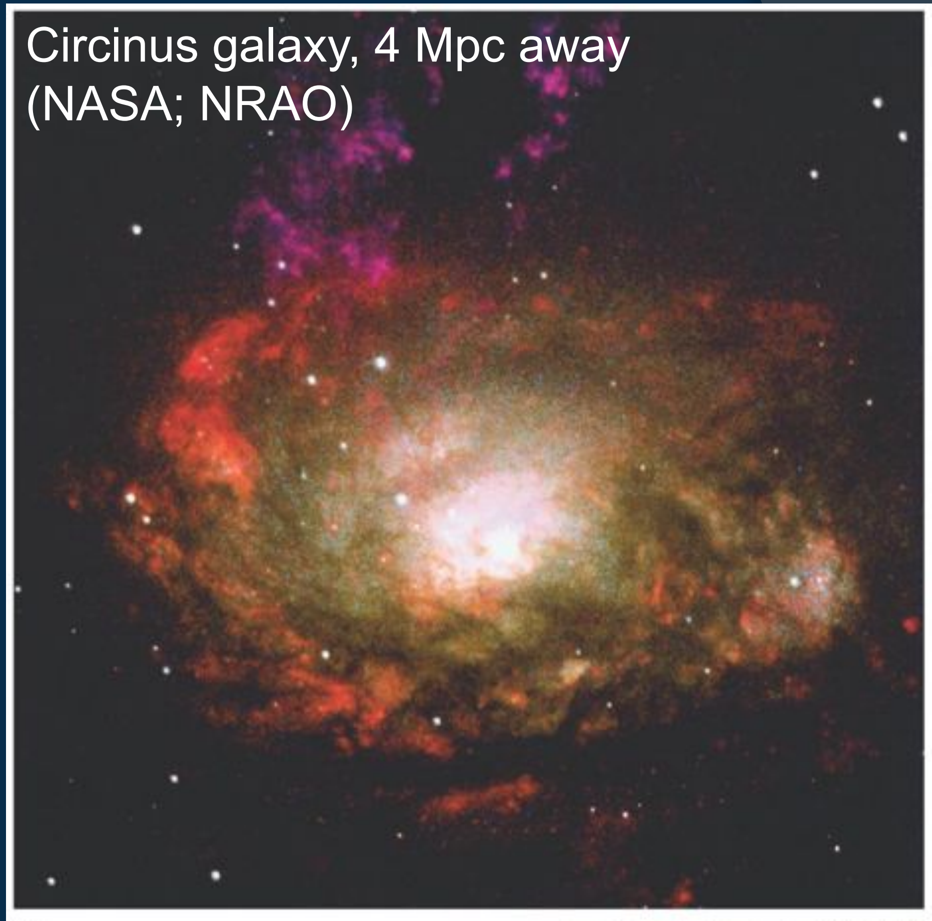
Active Galactic Nuclei

- Active galaxy with star-formation rings surrounded by an active central core



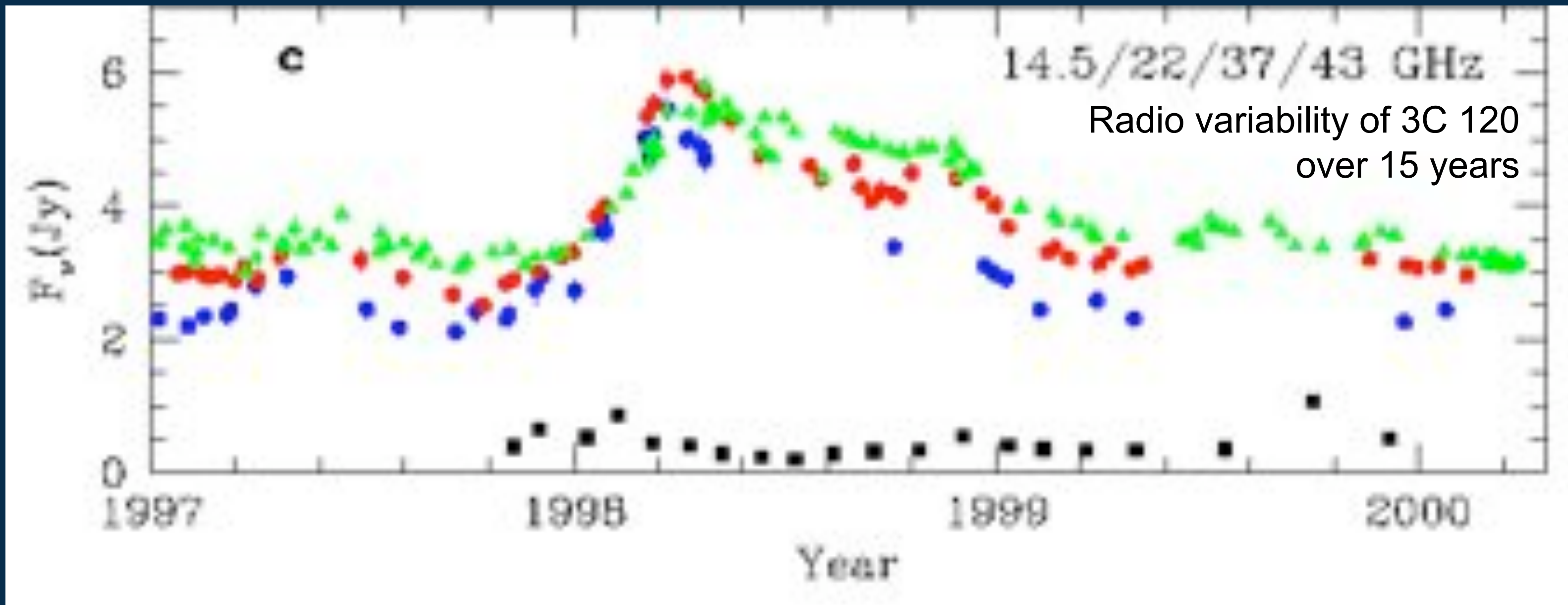
AGN classes

- Seyfert Galaxies
  - Resemble normal spiral galaxies, 1000× brighter
  - Circinus (right)
- Radio Galaxies
- Quasars



AGN Variability

- Rapid variations indicate that the core is very compact



Boston University, Univ. Michigan & Metsähovi Obs.

Radio Galaxies

- Radio galaxies emit very strongly in the radio portion of the spectrum. They may have enormous lobes, invisible to optical telescopes, perpendicular to the plane of the galaxy.

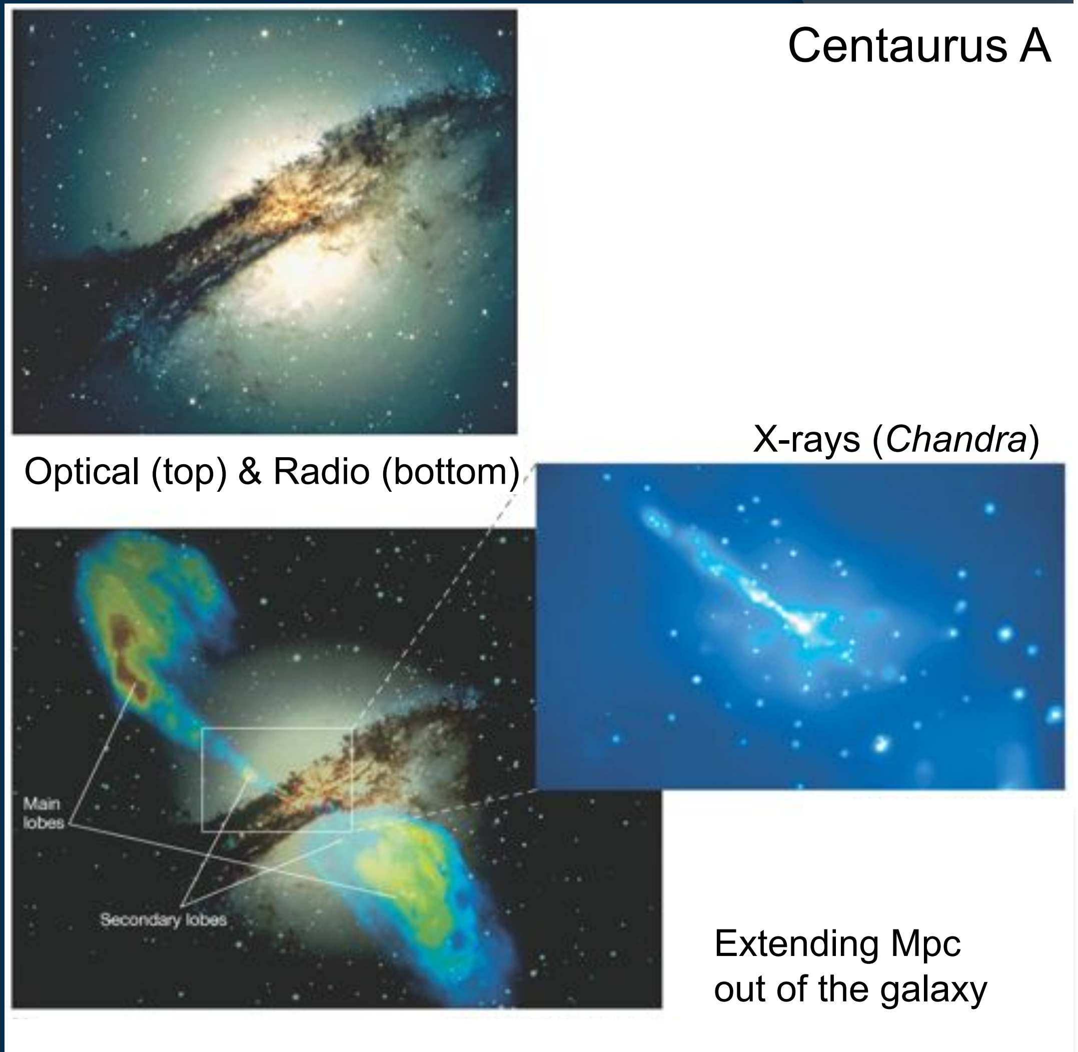
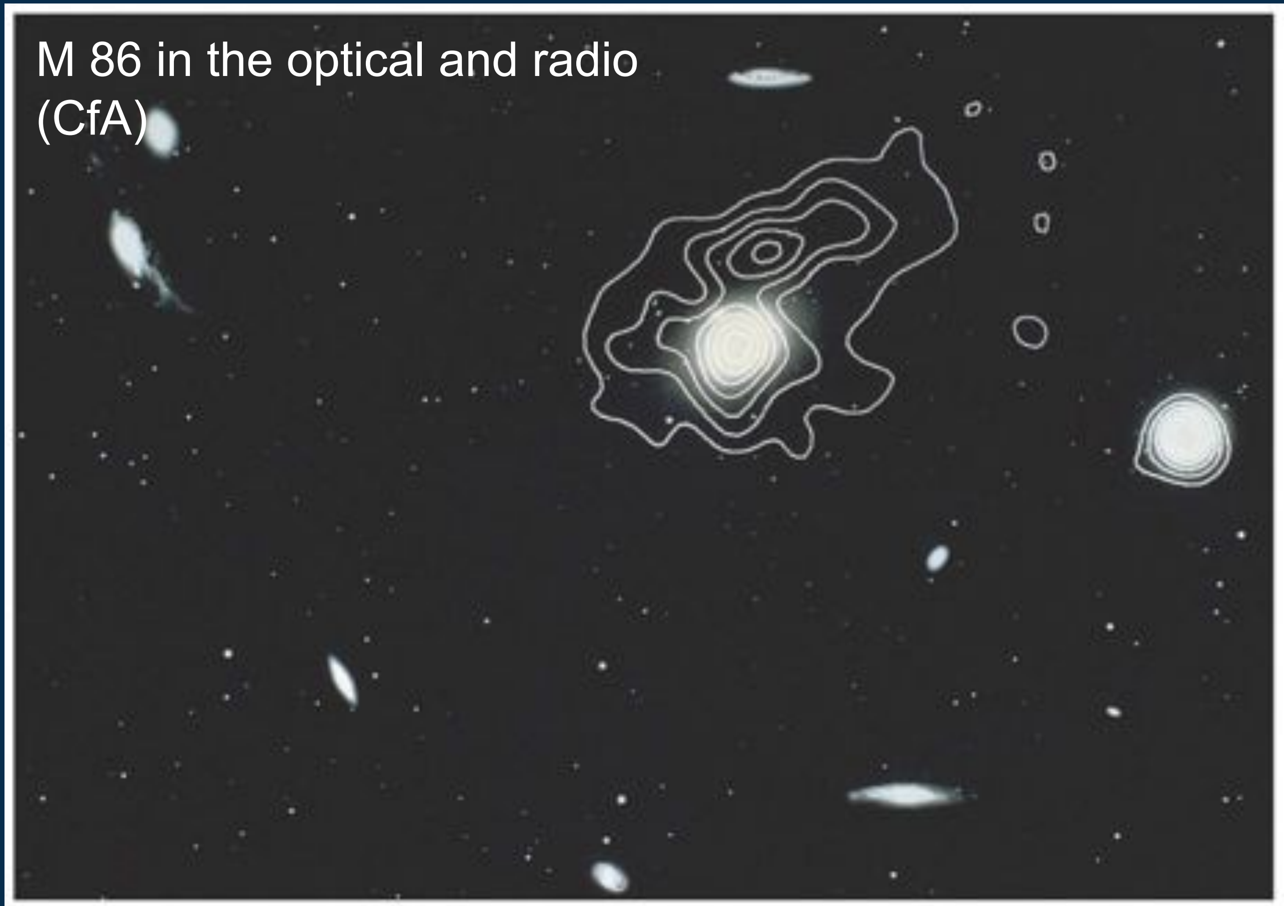


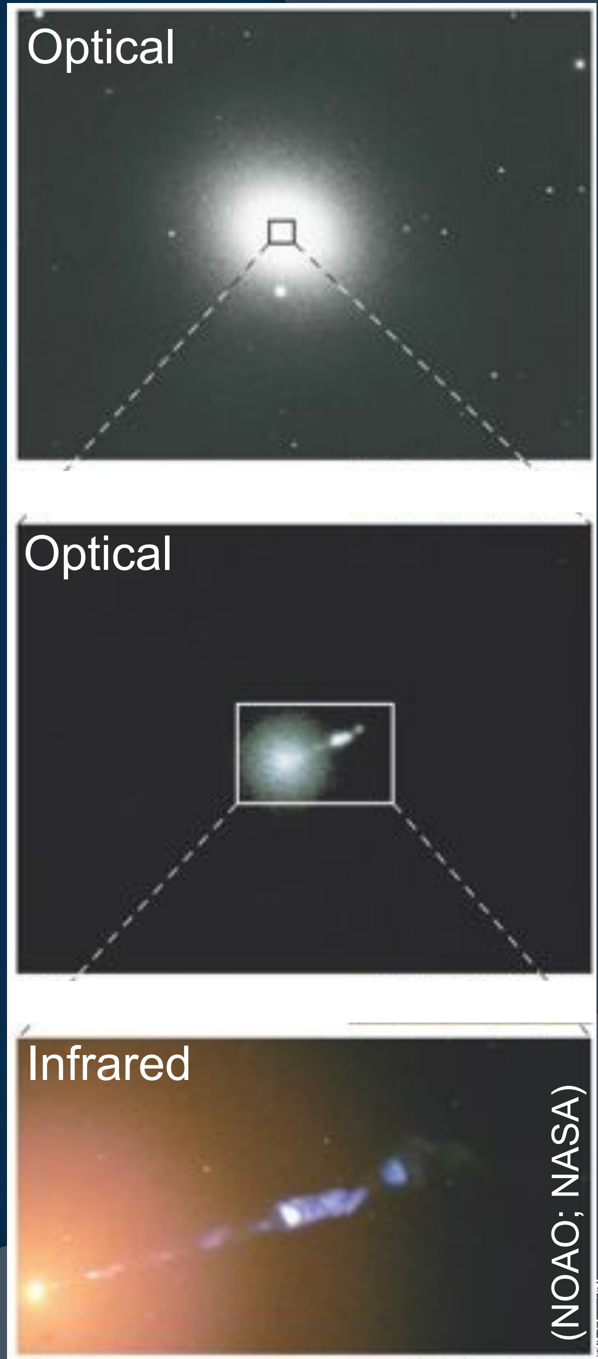
Image: ESO; NRAO; SAO

Core-dominated radio galaxy



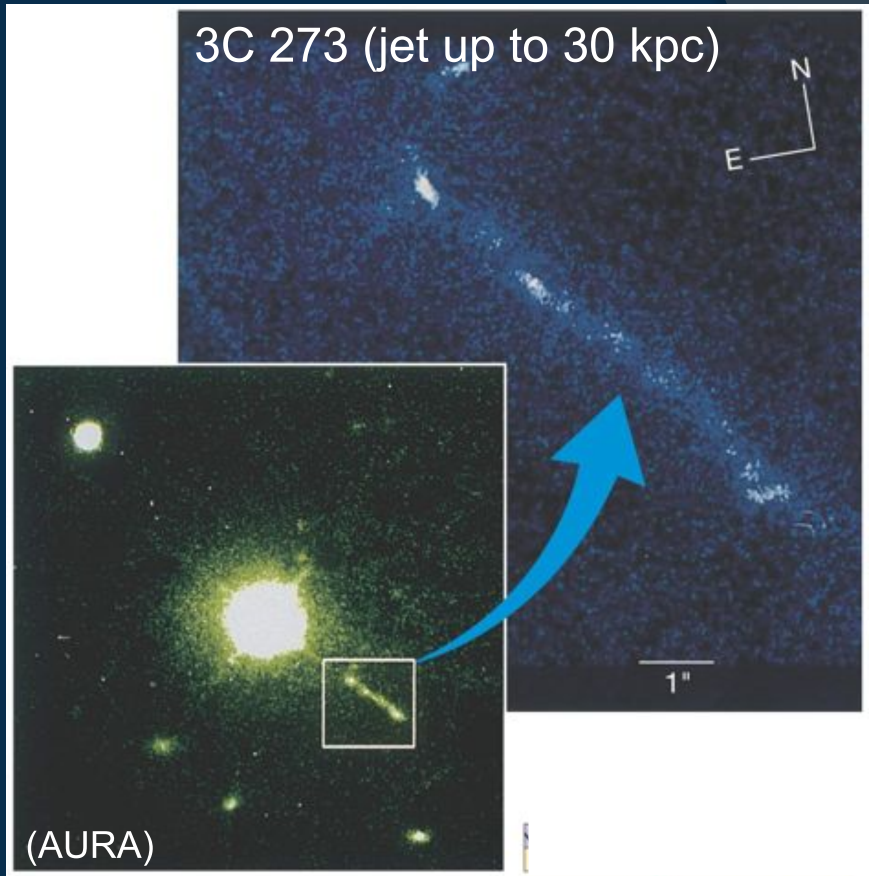
M 87 and its jet

- Many galaxies hosting a SMBH have jets
  - M 87 one-sided jet (discovered in 1919) is one of the best examples
- Most of these galaxies show signs of interaction with other galaxies

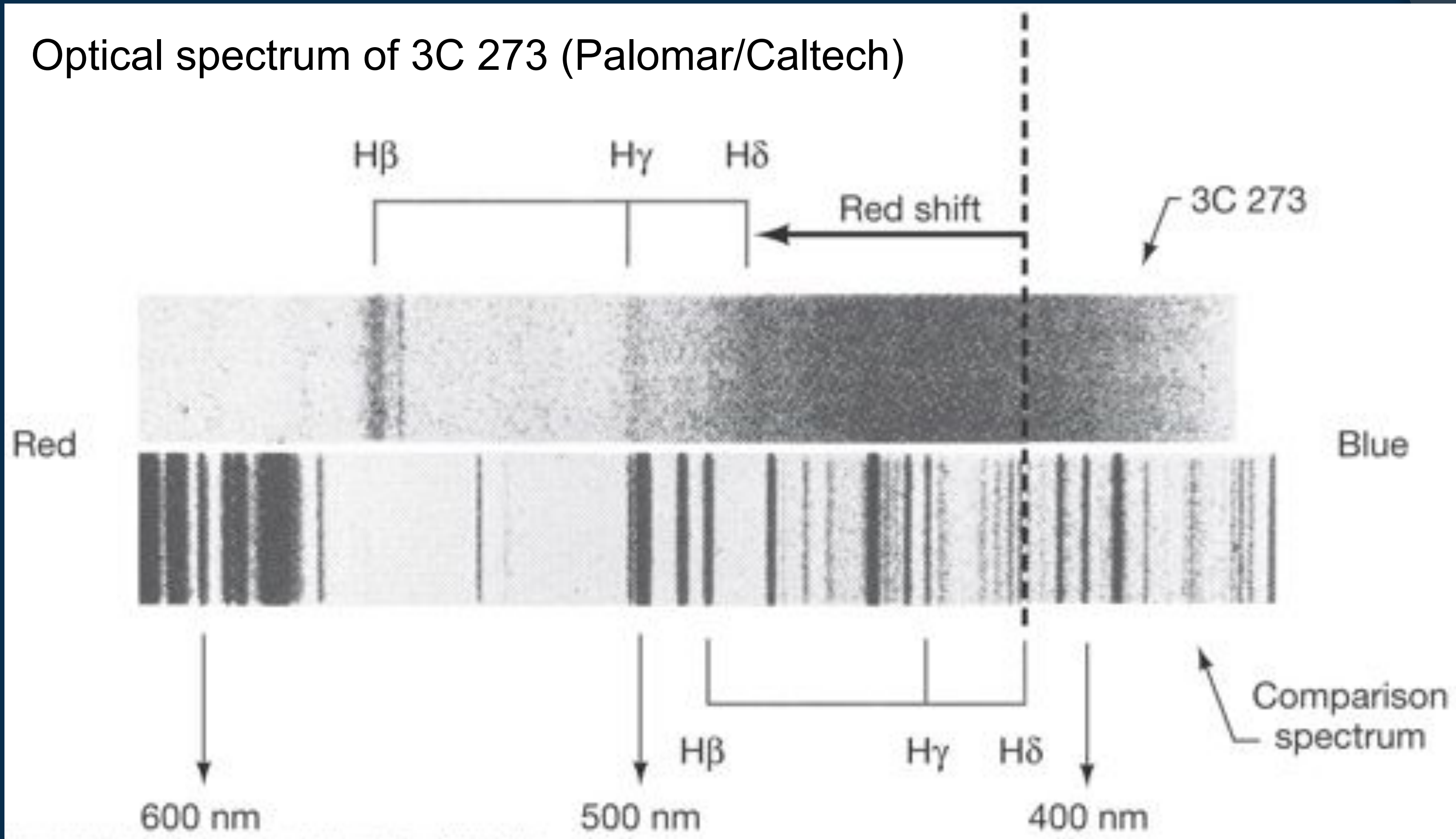


Quasars

- QSO 3C 273 with a luminous jet of matter and a starlike core
- Unusal spectral lines

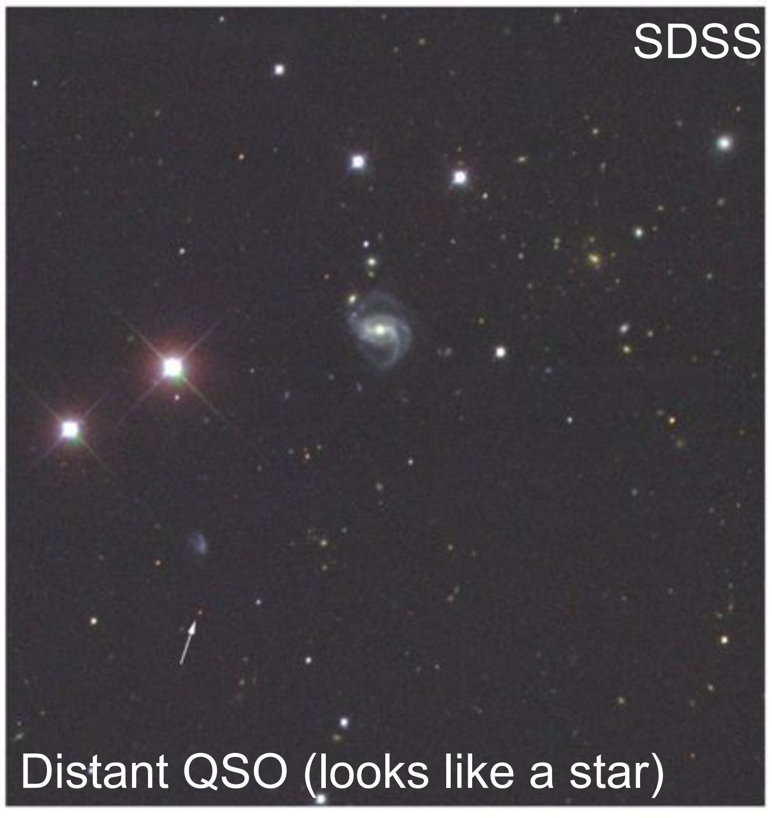


3C 273 optical spectrum



Active Galactic Nuclei

- Being so far away, quasars have to be the most luminous objects in the Universe

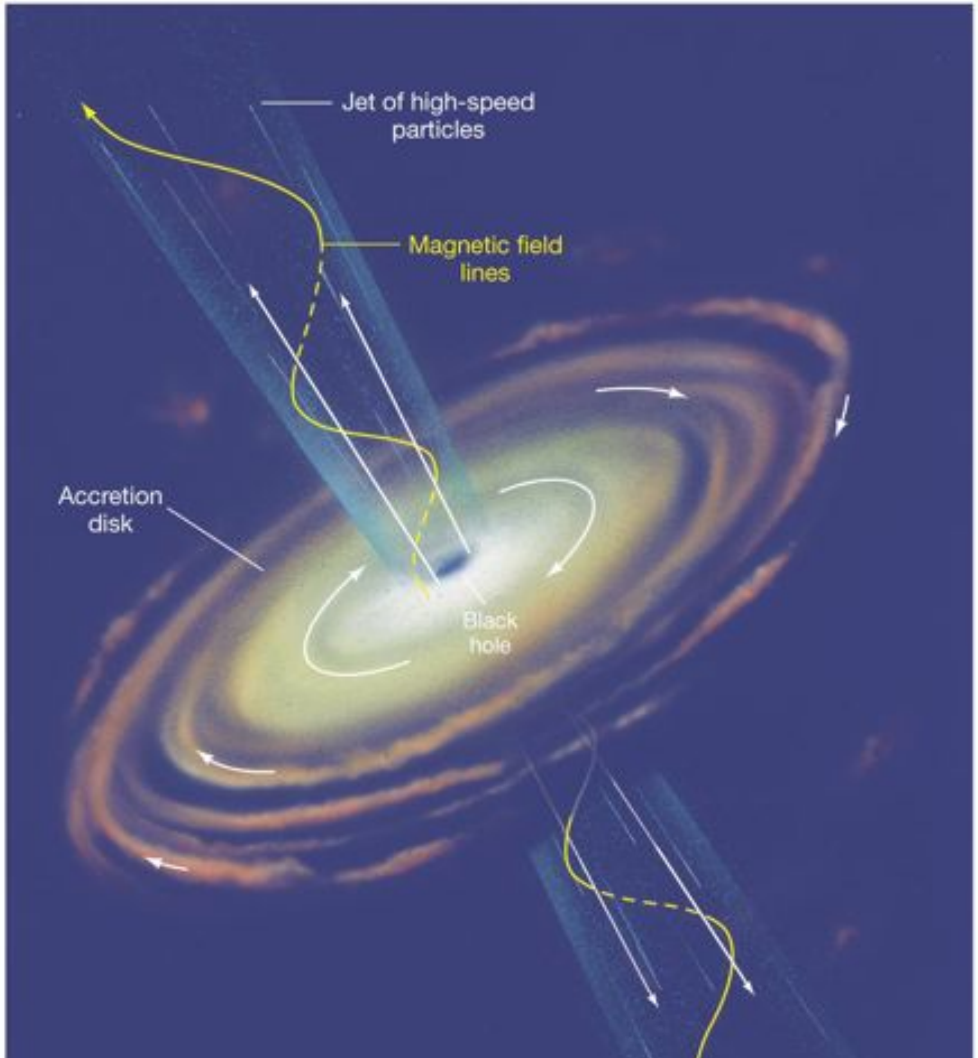


AGN Properties

- High luminosity
- Non-stellar energy emission
- Variable energy output, indicating small nucleus
- Jets and other signs of explosive activity
- Broad emission lines, indicating rapid rotation

Central Engine of an Active Galaxy

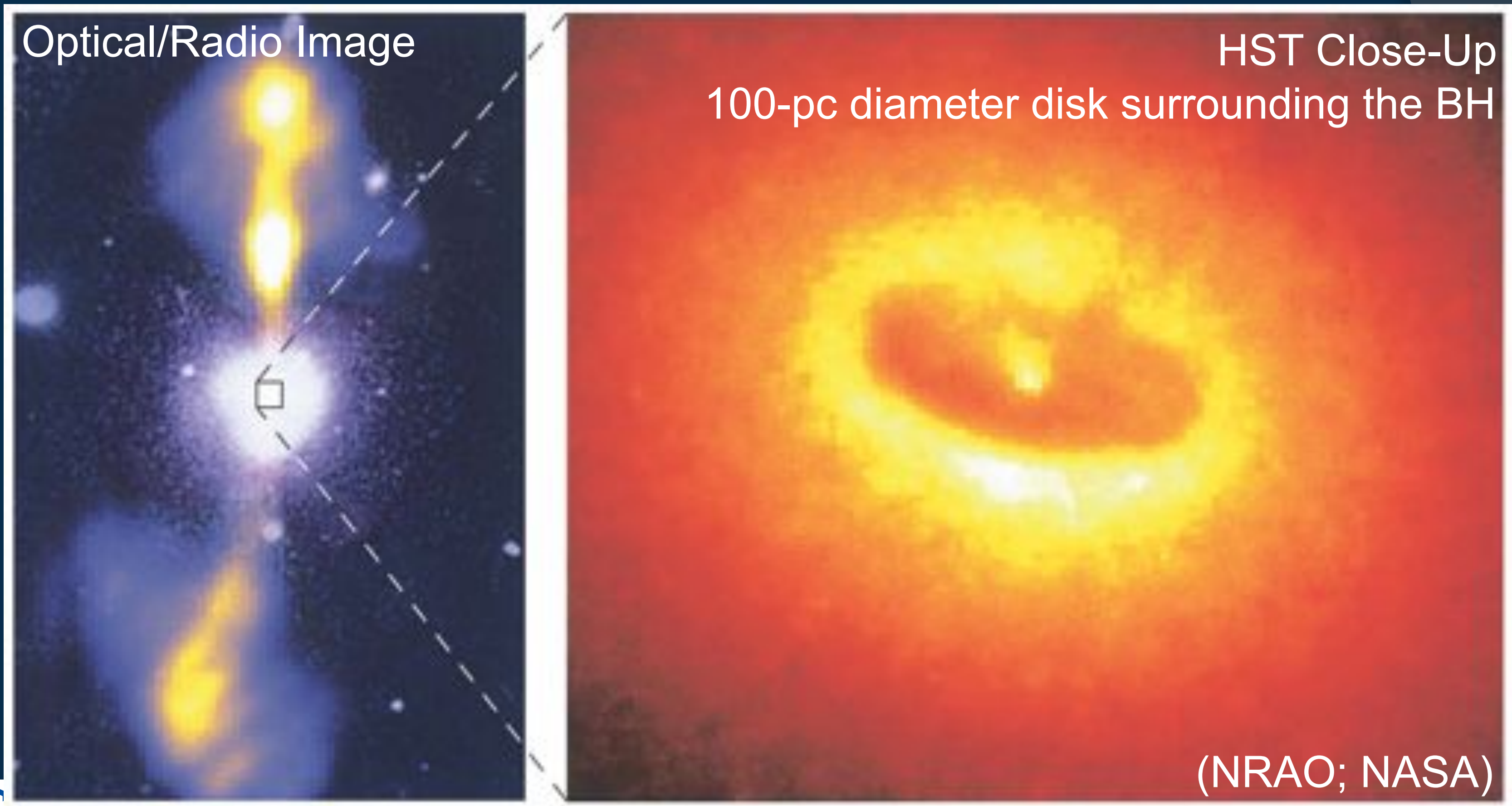
- Black hole, surrounded by an accretion disk. The strong magnetic field lines around the black hole channel particles into jets perpendicular to the magnetic axis.
- Central BH mass of billions of $M_\odot$
- The accretion disk may radiate away as much as 10–20% of their mass before disappearing



Picture: E. Chaisson (2008)

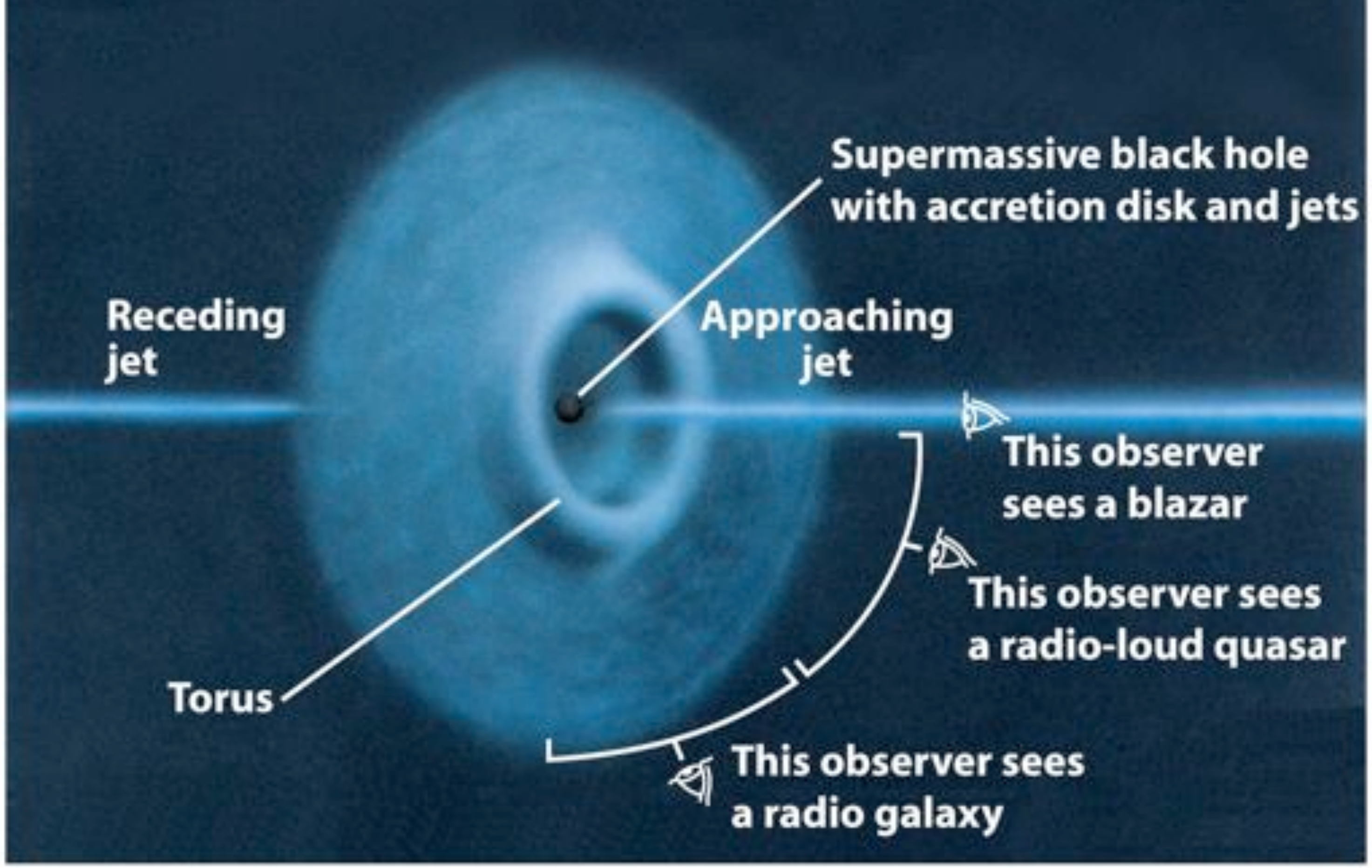
The Central Engine

- NGC 4261 and its black hole



AGN – different viewing angles

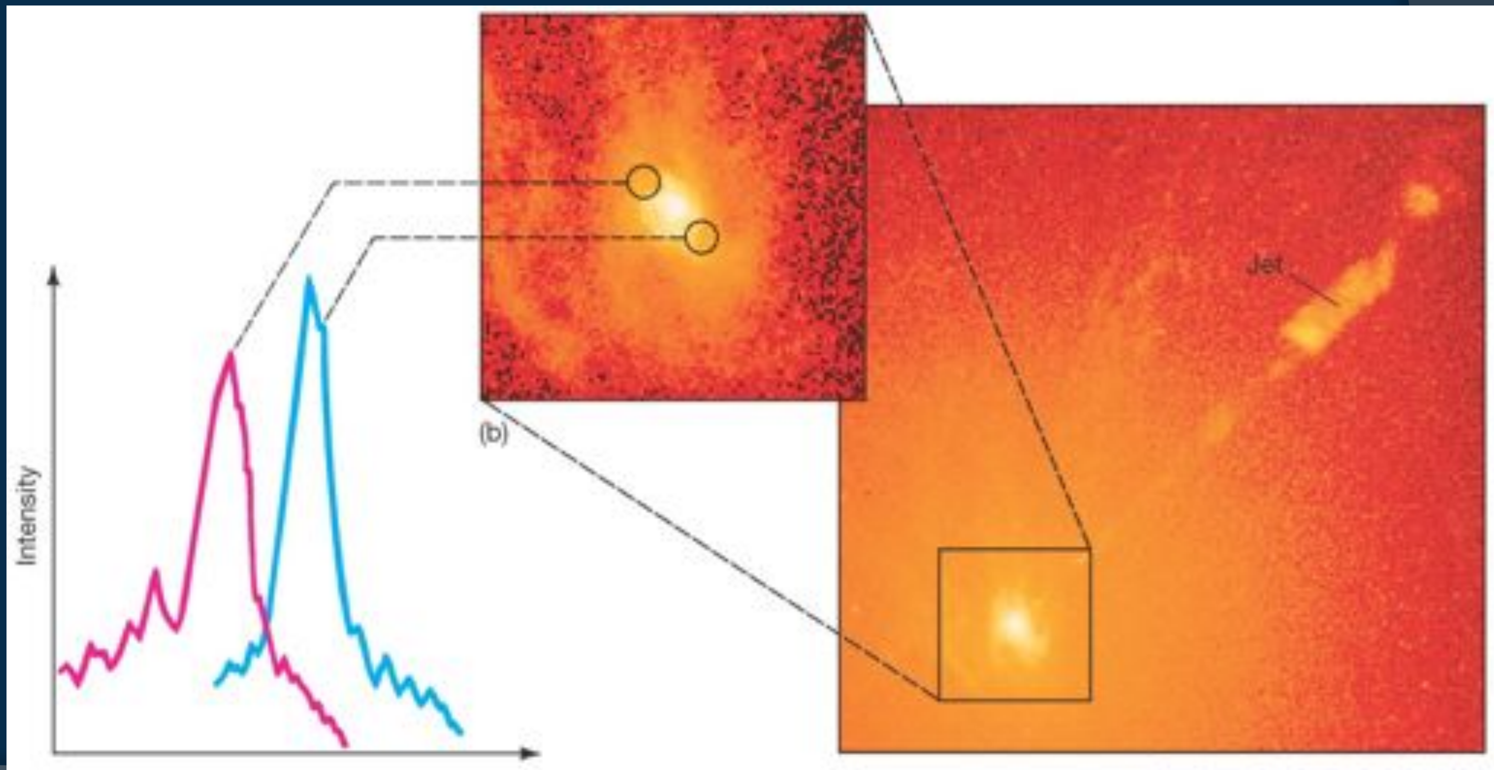
Picture: S. Antonucci (UCSD)



M 87 central region

- Rapid motions and jets characteristic of the presence of a SMBH

(NASA)



Triggering a jet

- Not a proof of the existence of BH, but directly associated with them: relativistic plasma outflows, aka jets
- Non-thermal emission, observed throughout the spectrum, at highest resolution with VLBI
- Engine for magnetic fields: dynamo effect in the accretion disk?

Open Questions in SMBH Research

- The SMBH itself
- Accretion disks
- Merging of BH
- Jet issues

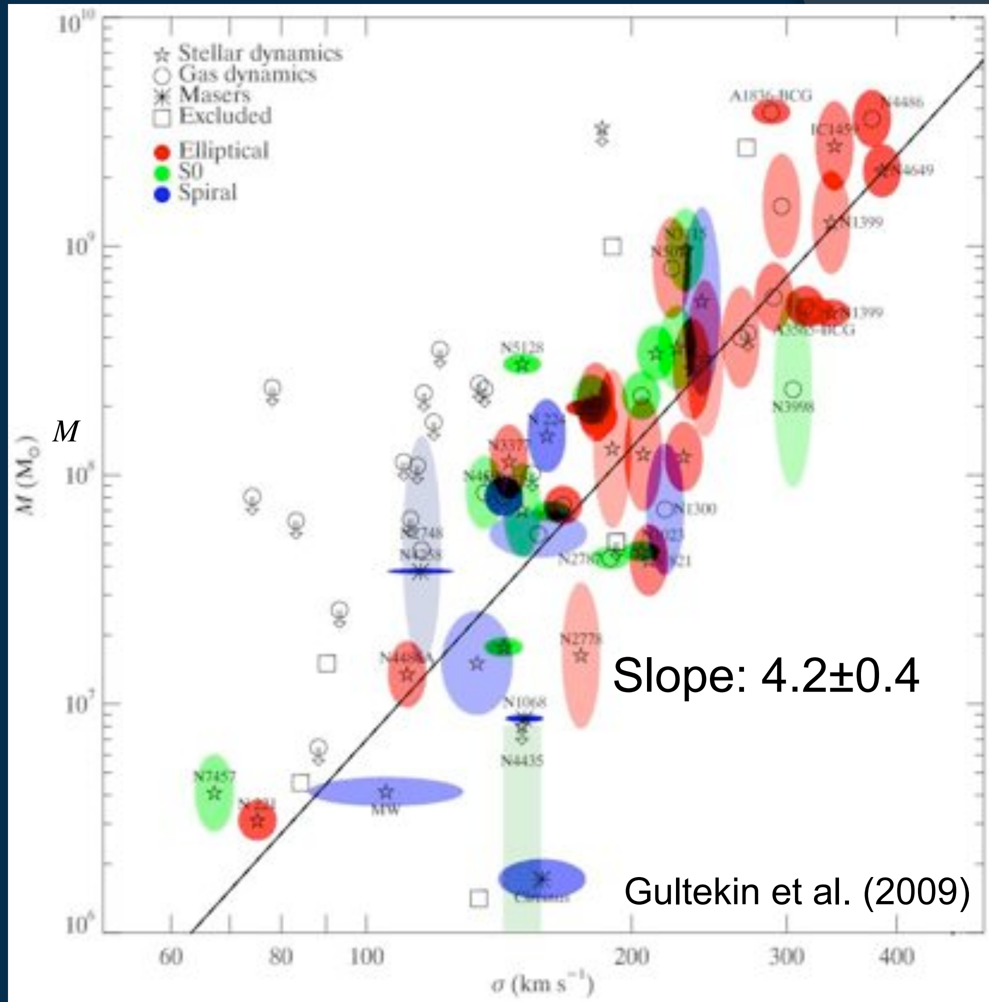
- Add your one, let's have a look to it

Formation of SMBH

- Slow accretion onto a stellar size BH
- Gas cloud collapsing onto a relativistic star without SN phase (Begelman et al. 2006)
- Core-collapse of a dense stellar cluster with inner part reaching relativistic speeds (Spitzer 1987)
- Note: connection between the galaxy and the SMBH formation given by the M_{BH}–σ relationship
- Your theory?

The M_{BH}–σ relationship

- Empirical correlation between the stellar velocity dispersion σ at a galaxy bulge and the mass of a the black hole M_{BH} at its centre
- Deep relationship between galaxy and its BH
- Silk & Rees (1998) predict a value of M_{BH} prop. to σ^5



Binary black holes (BBH)

- Begelman, Blandford & Rees suggested the presence of BBH in galactic mergers
- After merging, rapid sinking due to dynamical friction, and forming a 1-lt-yr separated BH binary system
- Those BBH would explain, e.g., observed twists in jets, recurrent outbursts (periodicity)
- Coalescence of a SMBBH Could be detected by gravitational waves (scientific case for LISA)

What can be done: observations – ideal case

- Infinite spectral coverage (λ)
  - From the VHE gamma-rays to the longest radio wavelengths, broadband studies, and all unaffected by atmosphere
- Infinite spectral resolution (dλ)
  - Get the last details of spectral lines
- Infinite resolution (dθ)
  - Get the ultimate details of all objects and get their large scale structure at low brightness temperatures as well
- All four Stokes parameters (I,Q,U,V)
  - Get the polarisation properties and infer the magnetic fields
- Infinite temporal coverage and resolution (t, dt)
  - Get long term and very short-term lightcurves to analyze the radiation
- Last but not least: infinite resources and computing power and personnel to analyze data (€)

Observations: the real world

- Limited regions in the parameter space
- Every new instrument opens a new window to the Universe (explores a new region in the parameter space (λ,θ,t))
  - 1970s: Effelsberg, VLBI, VLA, early X-Ray Satellites
  - 1980s: IRAM
  - 1990s: *HST*, *CGRO*/EGRET, VLBA
  - 2000s: VLT, *Chandra*, *XMM-Newton*, *Fermi*/LAT, *Spitzer*
  - 2010s: ALMA
  - 2020s: eELT, SKA, LISA, new X-Ray satellites
- Every new instrument is more expensive than the previous ones

Covering the spectrum
(all-purpose telescopes)

	Radio-cm	mm/FIR	IR	Optical	UV	X-rays	γ-rays	Very-High-Energy γ-rays
Present	VLBI	mm-VLBI	*Spitzer*	Keck, GTC, VLT, LBT, etc.	*HST*	*XMM-Newton, Chandra, Suzaku*	*INTEGRAL, AGILE*	HESS, MAGIC, VERITAS
	VLA, MERLIN, GMRT, LOFAR	APEX, JCMT, SMA	*HST*	*HST*	*Swift/* UVOT	*Swift*	*Fermi-GRST*	Beyond photons: Pierre Auger Telescope
	Single-dish (Effelsberg, GBT, etc.)		*Herschel,* SOFIA		*GALEX*	*RXTE, INTEGRAL*		
Future	**MeerKAT, ASKAP, ATA, eVLA, *RADIOASTRON, ASTRO-G***	**ALMA**	***JWST, SPICA***	**ELT**		***IXO (=Constellation-X & XEUS)***		**CTA**
	SKA	**CCAT**	***ATLAST***	***ATLAST***	***ATLAST***			Beyond photons: **KM3NeT**

Quasar Model

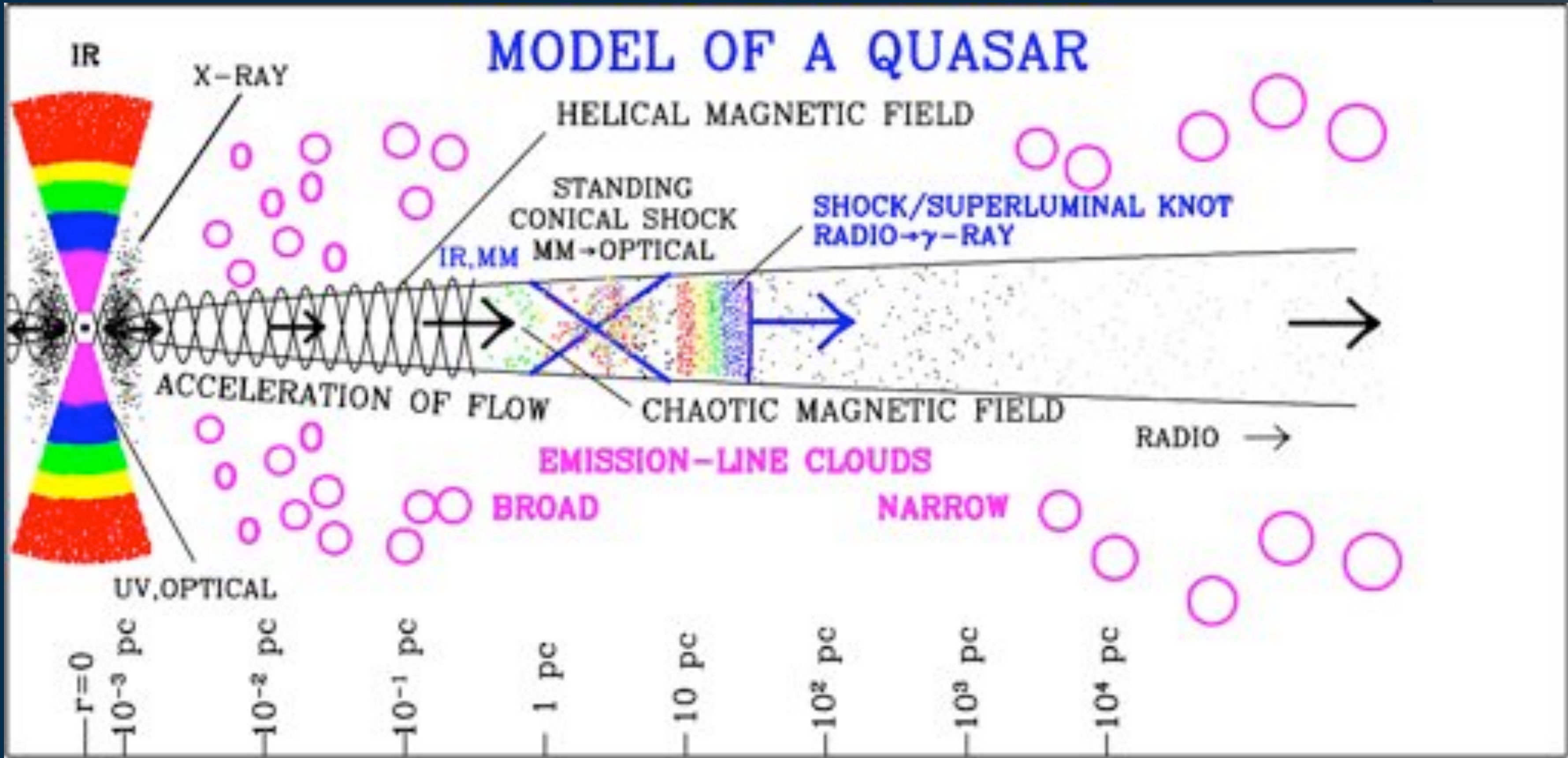
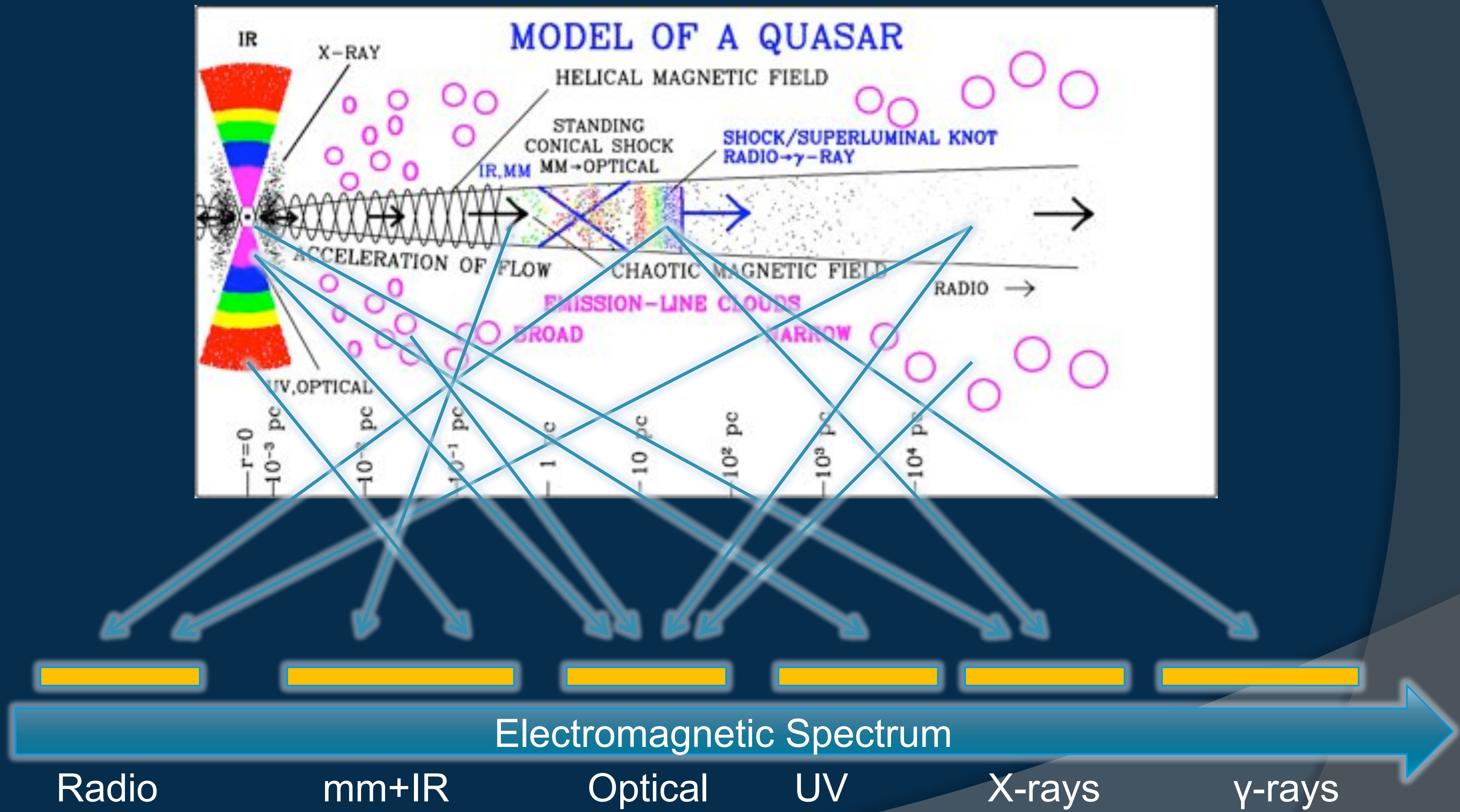


Image: A. Marscher (http://www.bu.edu/blazars/research.html)

Observing AGN



Observations

- What have we got already?
- What can we still achieve with present instruments (serendipity excluded)?
- Which new instruments do we need to learn more?

What can be done: theory (analytical approach)

- Defining the conditions in and around the BH
- Analytical solutions for the equations of the relativistic flows around the black hole
- Solutions to the equations describing the different physical scenarios
- Add your one…

What can be done: simulations

- Jet formation at the base of the outflow, and its relationship with the accretion disk (Meier & Koide, Keppens, McKinney & Blandford, …)
- Relativistic outflows further down: (Keppens, Komissarov, Martí & Perucho, Aloy & Mimica, …)
  - Challenges: HD → RHD → RMHD → GRMHD → 3D GRMHD (overflow error)

Simulations

- What have we got already ?
- What can we still achieve with present hardware and algorithms (e.g., new ideas with present equipment) ?
- Which new developments are needed to go farther (acceleration algorithms, new approaches, quantum computers, etc.) ?

The WG#4 and the Science (what can we do?)

COST – Black Holes in a Violent Universe

- COST offers us an instrument for networking, cooperating and organising ourselves
- We have to define some goals for the duration of the COST action

Instruments for Sci. Cooperation

- Scientific stays abroad (STSM in COST jargon)
- Workshops on selected topics
- Schools (oriented to junior scientists)
- Printed material (publications resulting of a collaboration; text or reviewing books)

Timeline of COST WG#4

Date	Type of Event	Location
Jun 10	WG Meeting #1	Bonn
Nov 10	WG Meeting #2	Valencia
11	WG Meeting #3	
11	WG Meeting #4	
11/12 ?	Summer/Winter School	Crete, elsewhere?
11/12 ?	Scientific Workshop	Crete, elsewhere?
12	WG Meeting #5	
12	WG Meeting #6	
13	WG Meeting #7	
13	WG Meeting #8	
13	Final Conference	Brussels / Bonn?

The program for this meeting

	Thursday, June 24th, Room 0.02	
16:00-16:20	E. Ros	*Introduction of participants; goals and milestones of the WG*
16:20-16:40	R. Keppens & Z. Meliani	*RH and MHD models for AGN jet propagation and deceleration*
16:40-16:55	A. Niedzwiecki	*X/γ-ray studies of the central engine*
16:55-17:10	M. Kadler	*Observing BH at high frequencies*
17:10-17:25	L. Popovic	*AGN Spectral Lines and SMBH*
17:25-17:35	S. Antón	*GAIA and QSOs*
17:35-18:00	A. Lobanov	*Probing the vicinity of SMBH with radio interferometry*
	Friday, June 25th, Room 0.02	
09:00-09:15	L. Caramete	*BH candidates in the nearby universe*
09:15-09:30	L. Gergely	*SMBH binaries*
09:30-09:45	J. Roland	*Determination of the characteristics of BBH using VLBI observations*
09:45-10:15	E. Ros & all	*Discussion: Brainstorming, connection with the other WGs, potential for Synergies*

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Welcome to the WG#4, let's start to work