Galaxies and Extragalactic Astronomy

Active Galactic Nuclei

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Question

What are AGN?

Introduction

- Active Galactic Nuclei (AGN) are powerful sources of radiation residing at the centre of 1-10% of all galaxies
- Galaxies hosting an AGN are known as active galaxies

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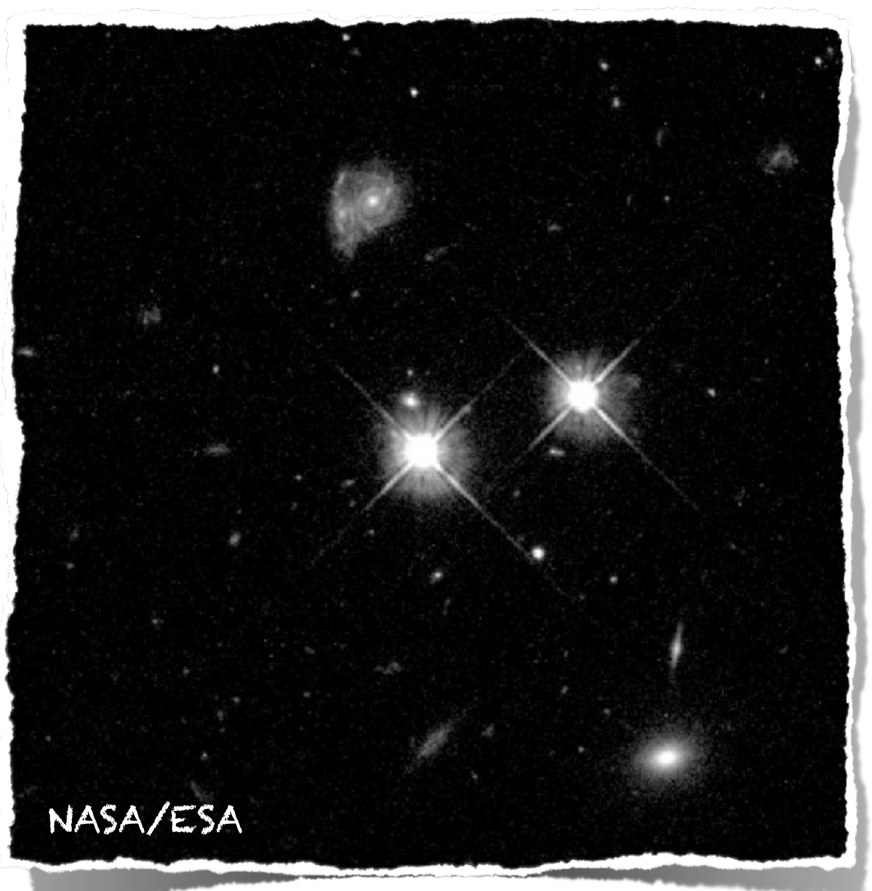

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A) Star within the Milky Way

B) Quasar:
9 billion light-years away

C) Elliptical galaxy:
7 billion light-years away

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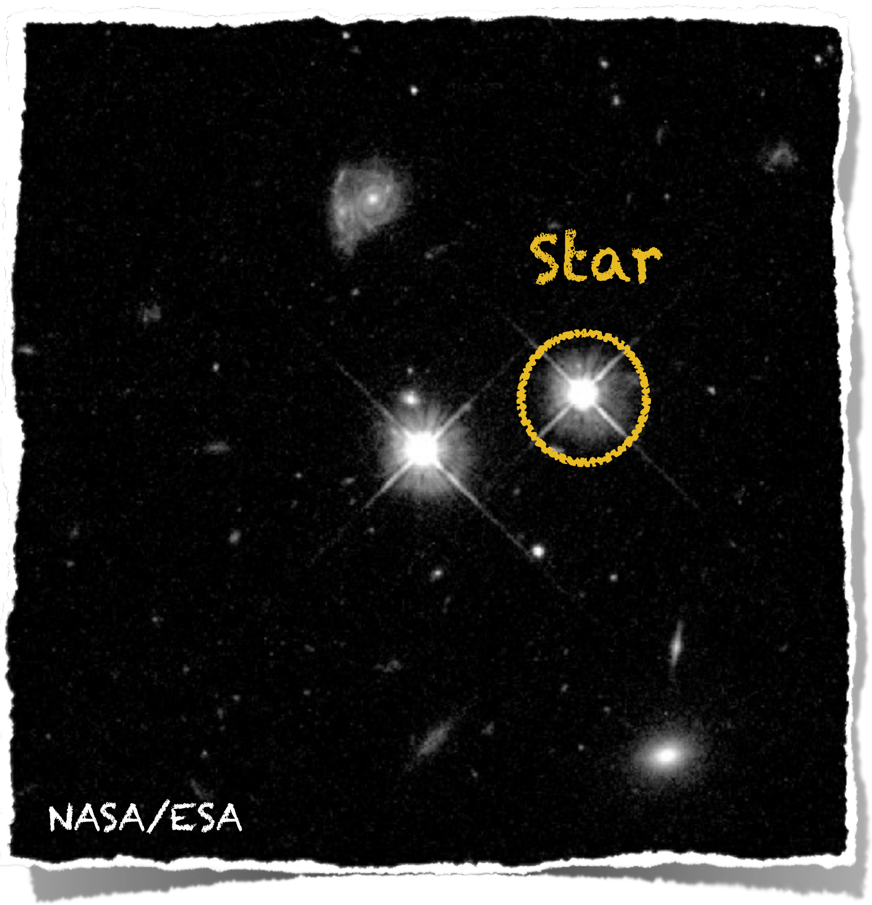

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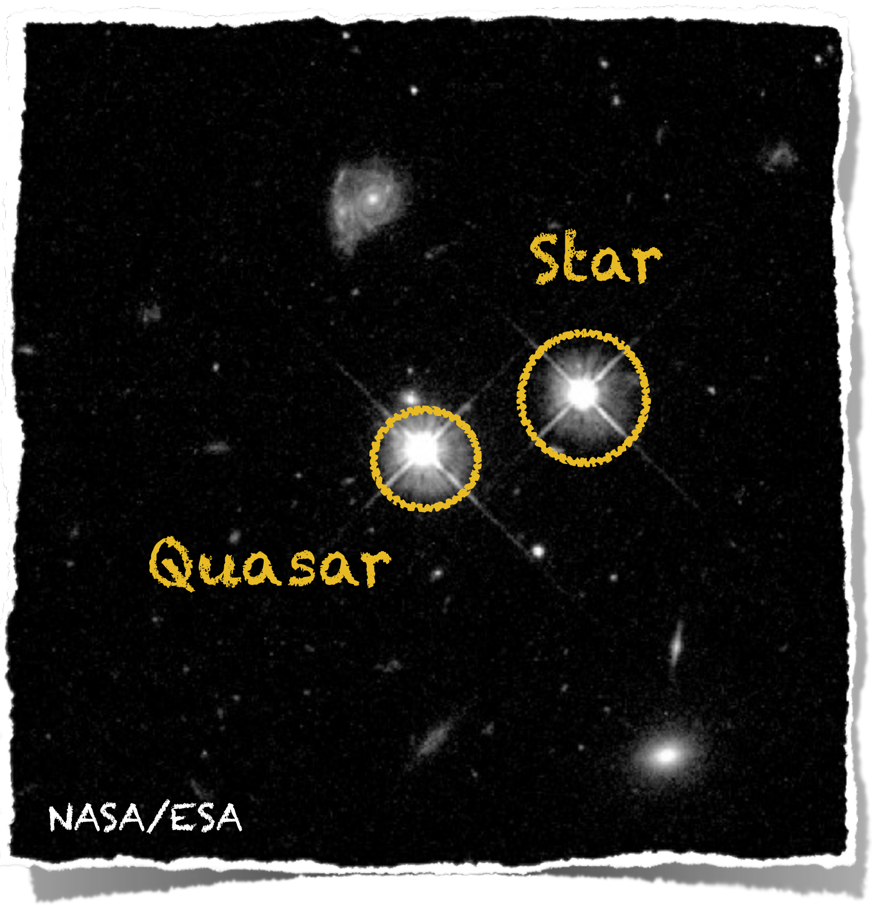

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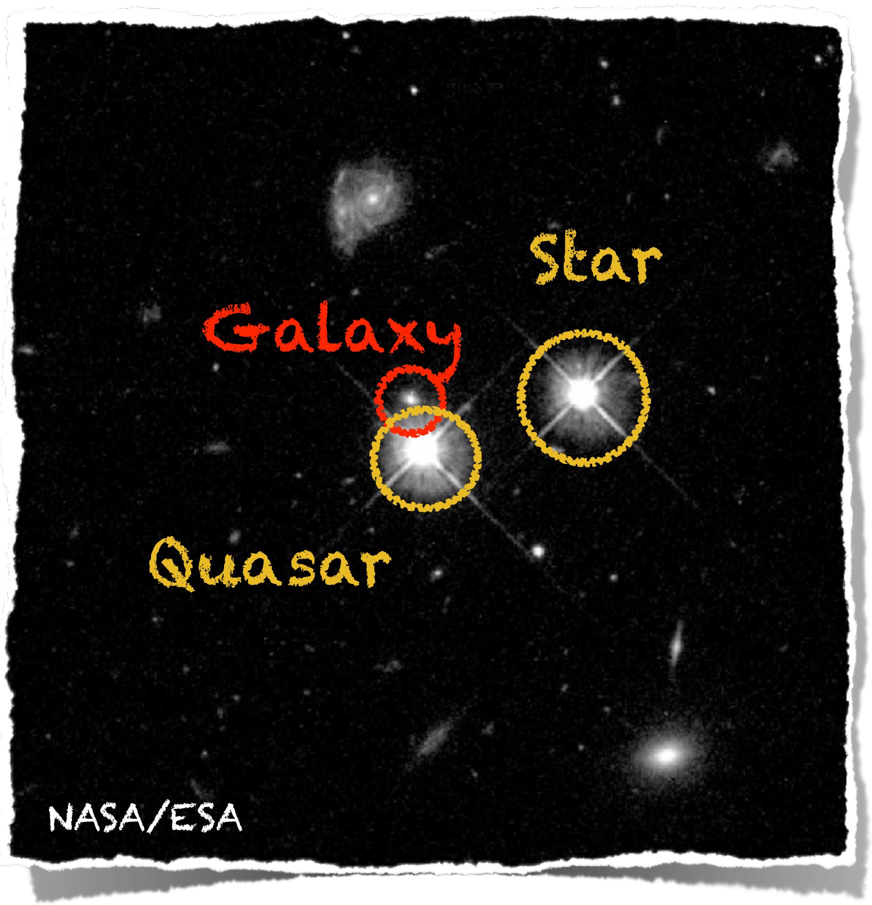

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- Huge span of observed AGN luminosities: $L \sim 10^{40}$-10^{47} erg/s
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Quasar 3C273:
Magnitude = 12.8
Virgo constellation
Distance: ~2.5 billion light years

Historial discovery

INITIAL AIM: clarify the nature of "spiral nebulae"

- Fath (1908), Lick Observatory:

  spectrum of NGC1068 ➜ emission lines as in planetary nebulae

- Confirmed by Slipher (1917) at Lowell

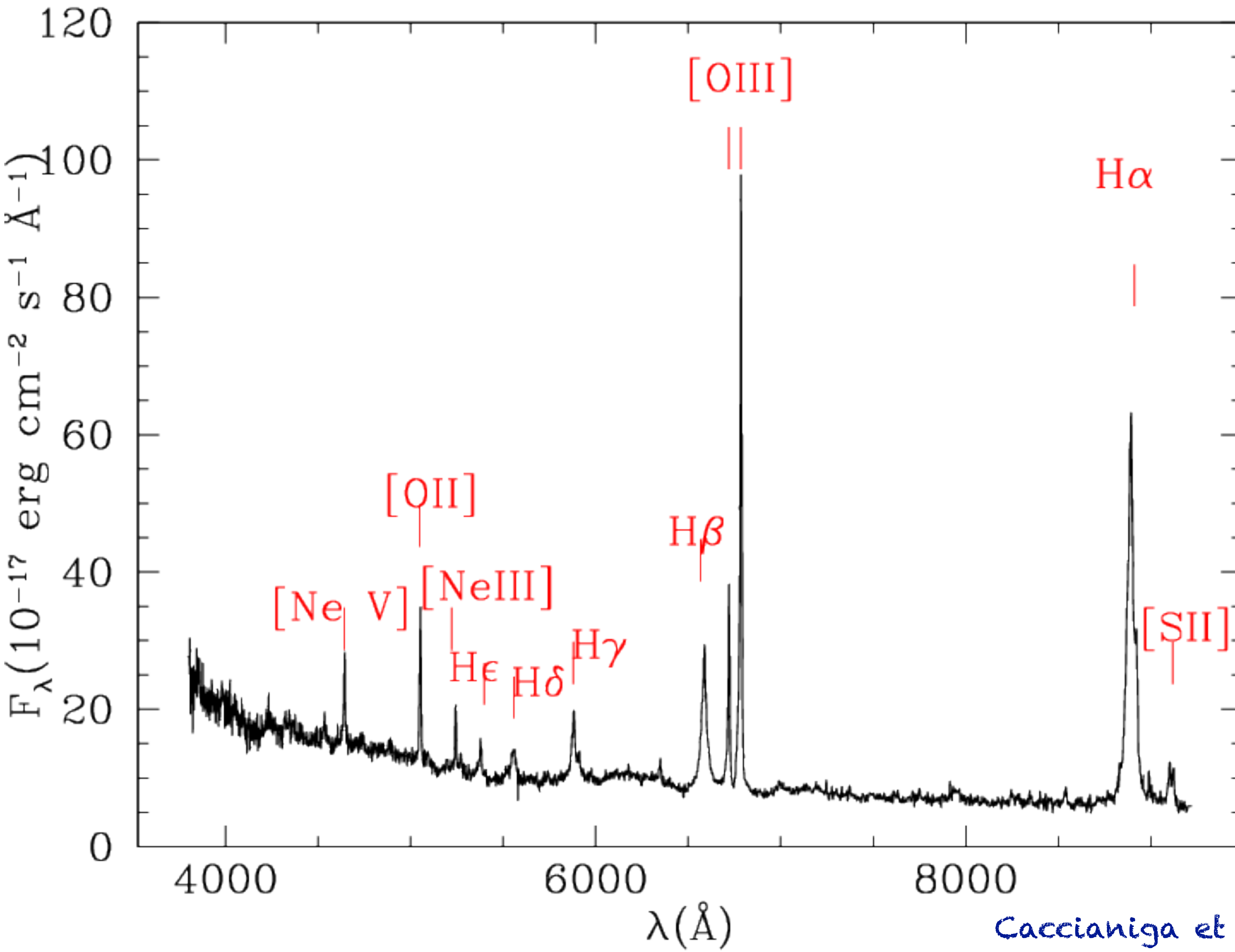
- Hubble (1926) studied more systems

- Seyfert (1941,1943): galaxies whose spectra show high-ionization emission lines, forbidden emission lines, broad emission lines from small, bright nucleus

➜ **Seyfert galaxies**

M51 spiral nebula
Ritchey (1910)

Seyfert spectrum: high-ionization, forbidden, and broad emission lines



Caccianiga et al. (2014)

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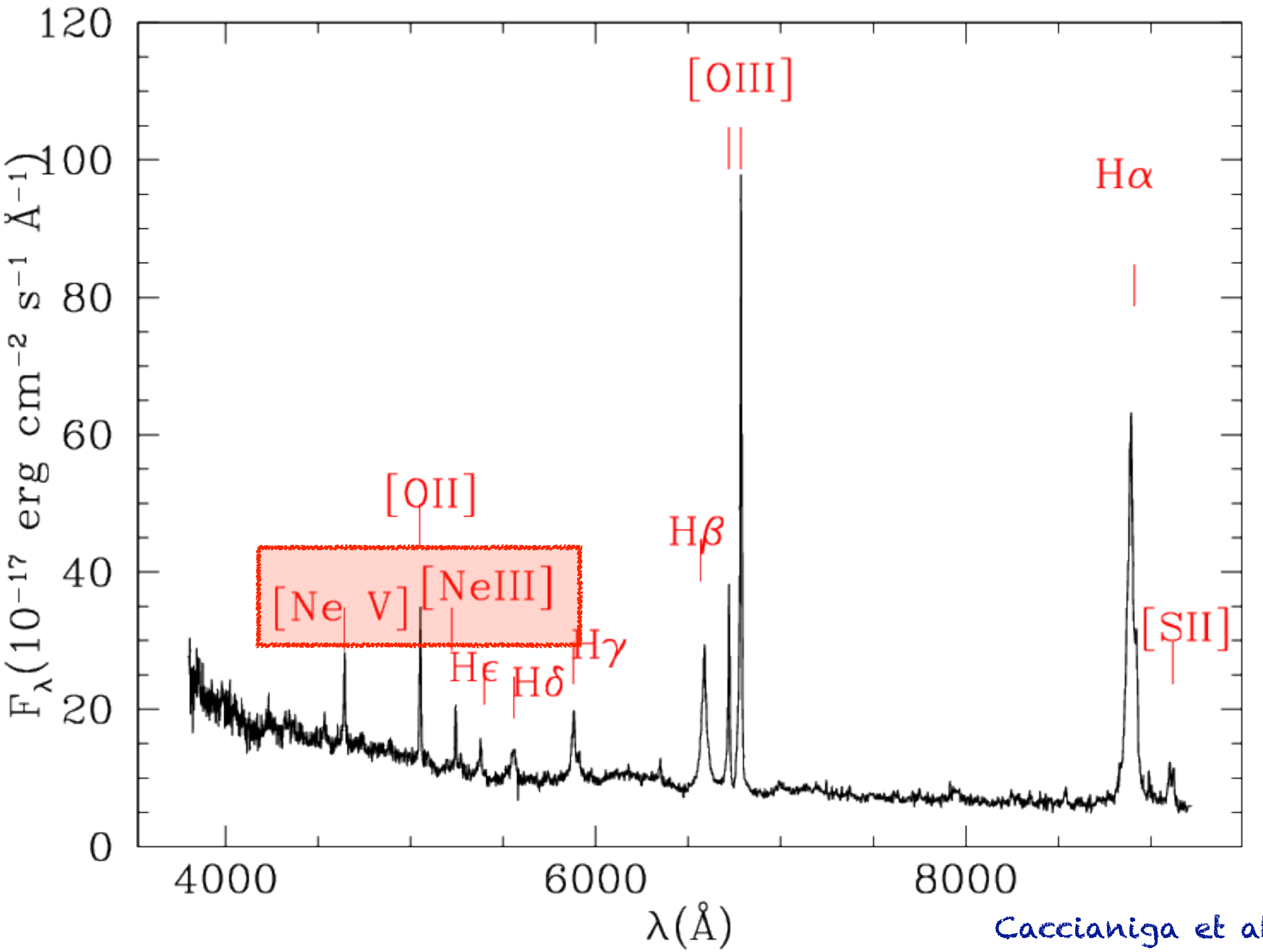

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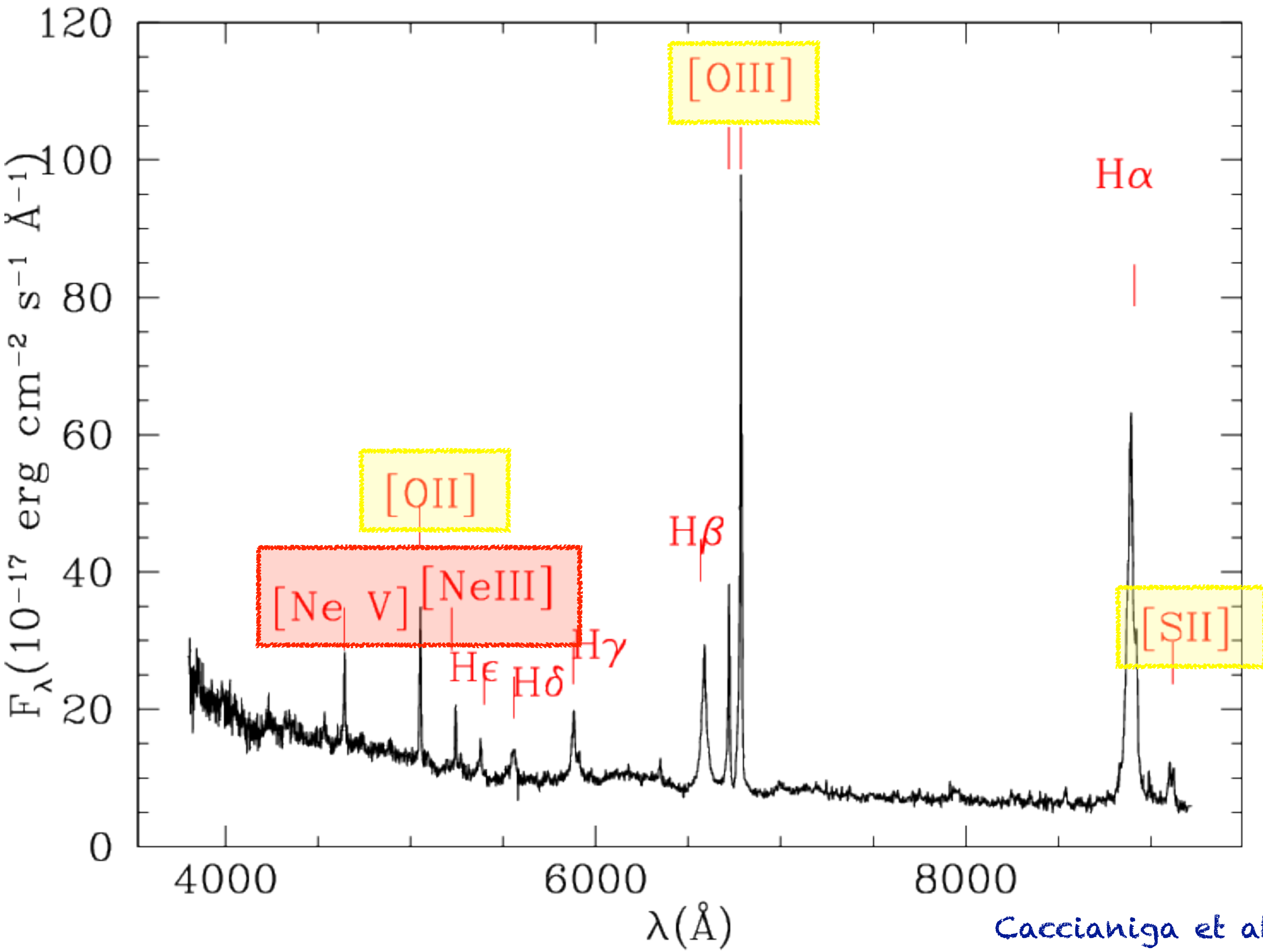

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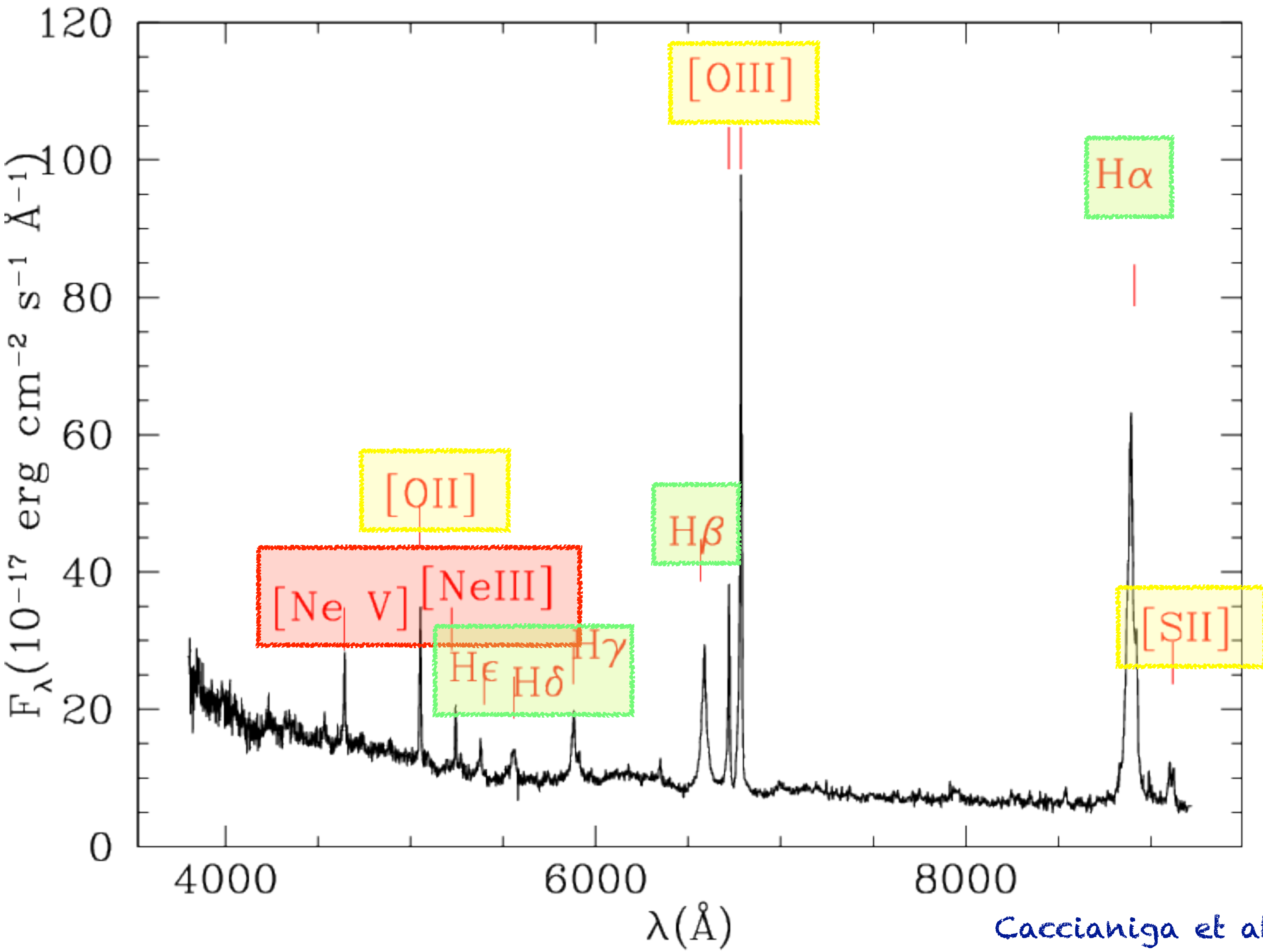

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Questions

Why are forbidden lines called forbidden?

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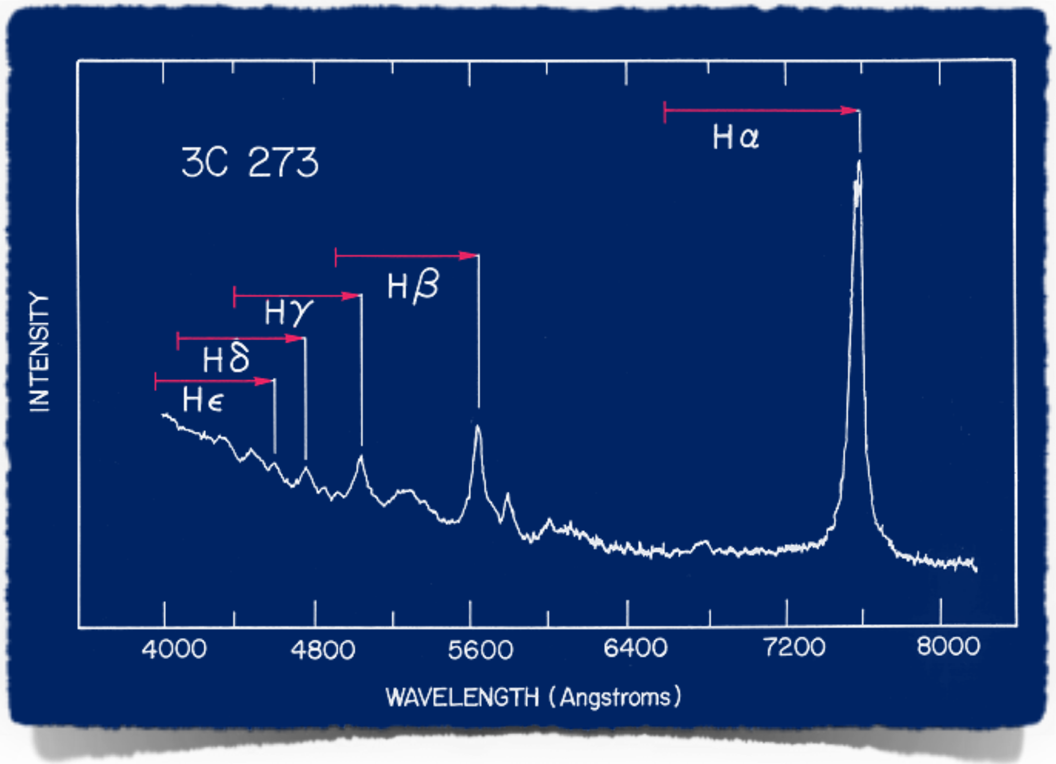
Why are forbidden lines called forbidden?

Why are broad lines broad?

Historial discovery

- After II World War with the development of radioastronomy, radiogalaxies were discovered

- Quasars were discovered in 1963 when Maarten Schmidt interpreted the optical emission lines of the known radio source 2C273 as redshifted hydrogen Balmer lines.



Bill Keel, UAlabama

Question

What powers AGN?

Supermassive black holes: the AGN central engine

- Current paradigm: the fundamental power source of all AGN is accretion onto a supermassive black hole
- Presence of a supermassive black hole at the center of most galaxies predicted by galaxy formation models…

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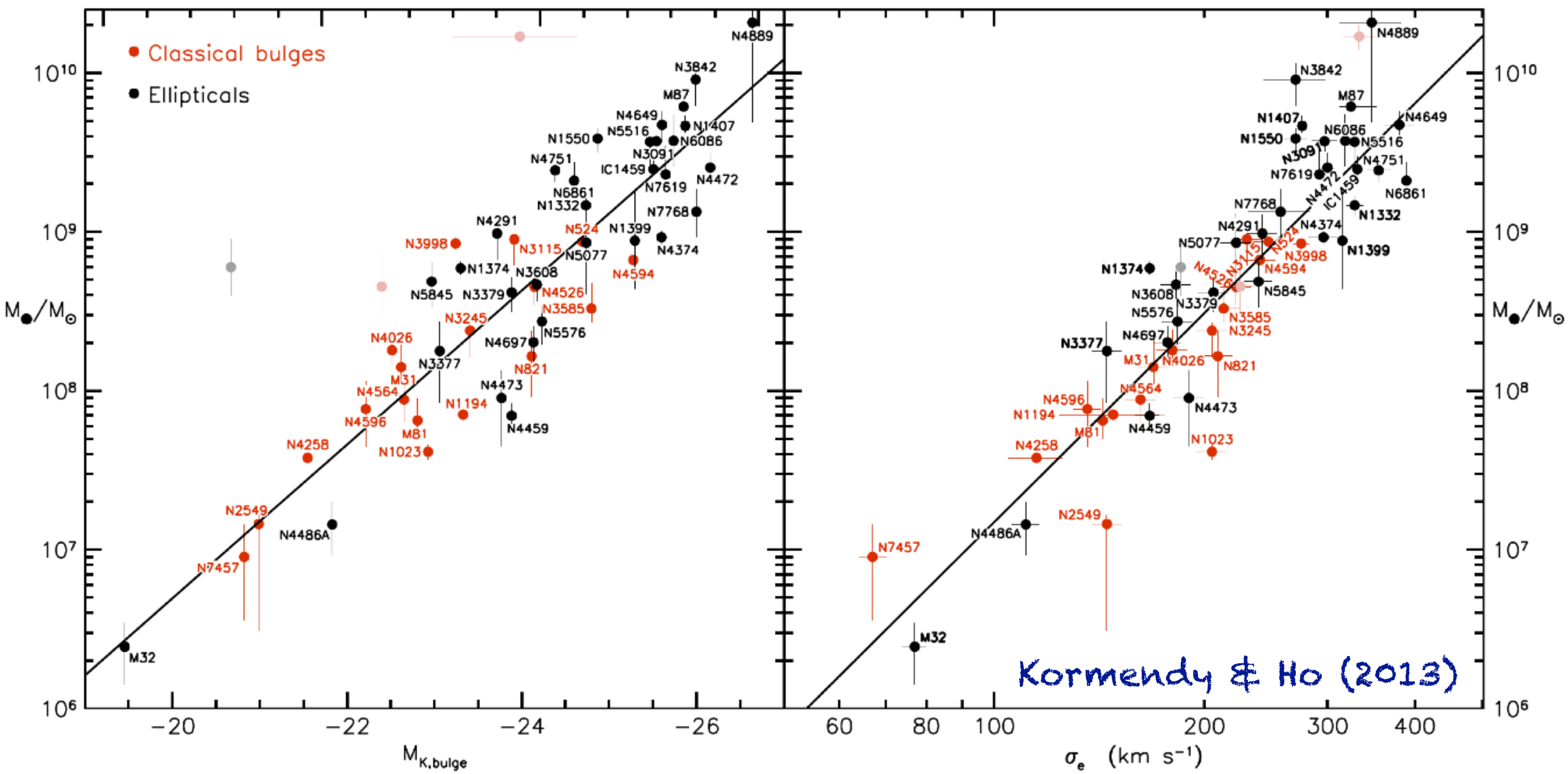

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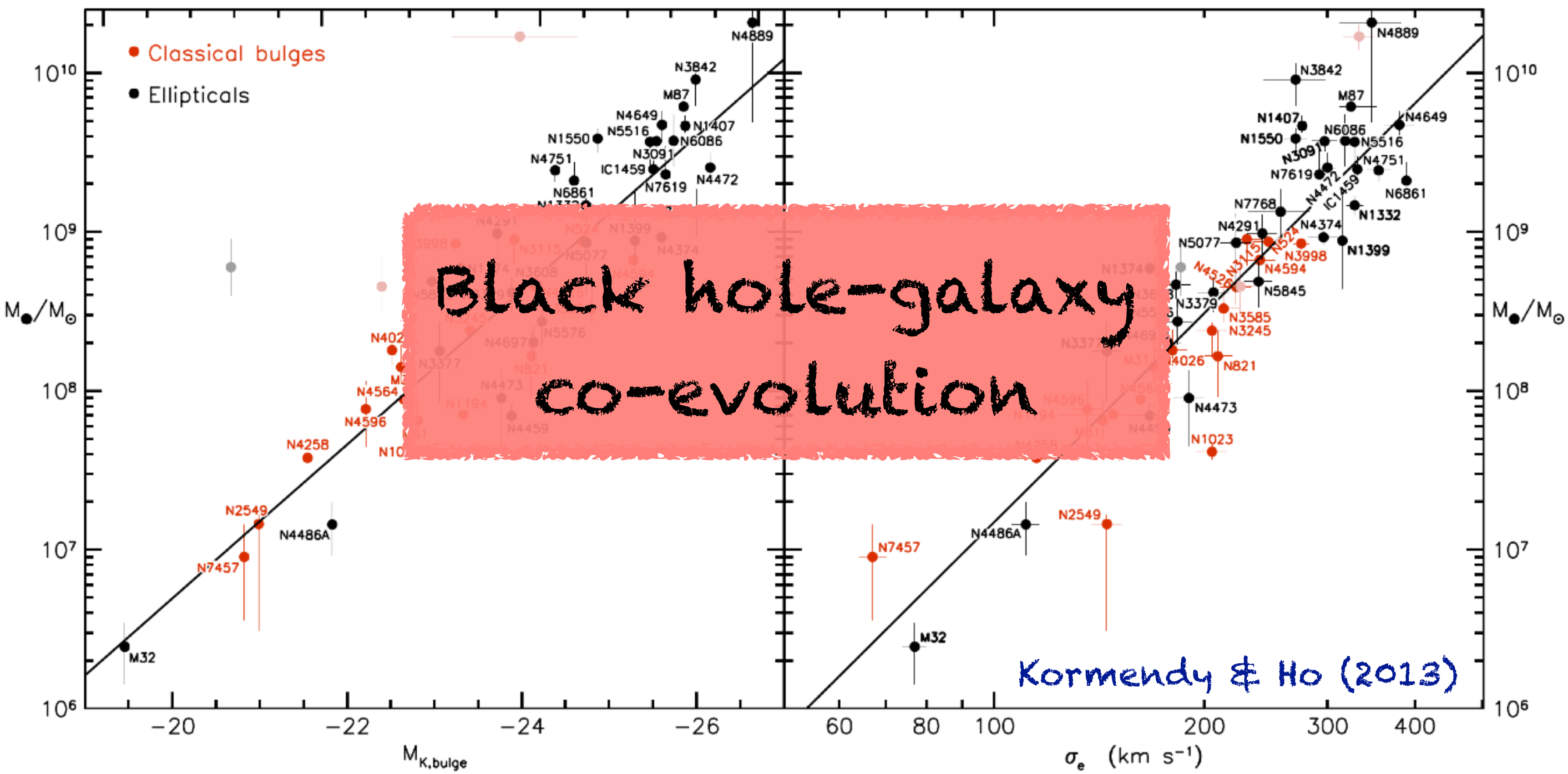

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Accretion onto the supermassive black hole

- significant quantities of gas are deposited onto the central parts of a galaxy and enter the region where the black hole mass dominates the gravitational potential

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- stellar mass loss associated with a nuclear star cluster
- non-axisymmmetric potentials resulting from galactic bar formation

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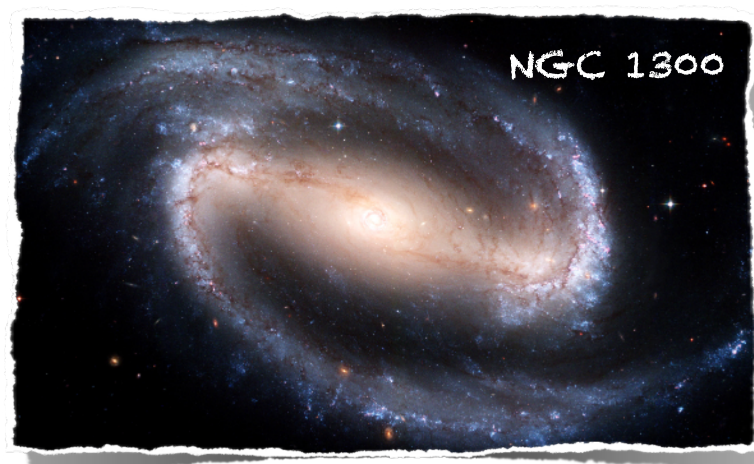
VLT/NASA



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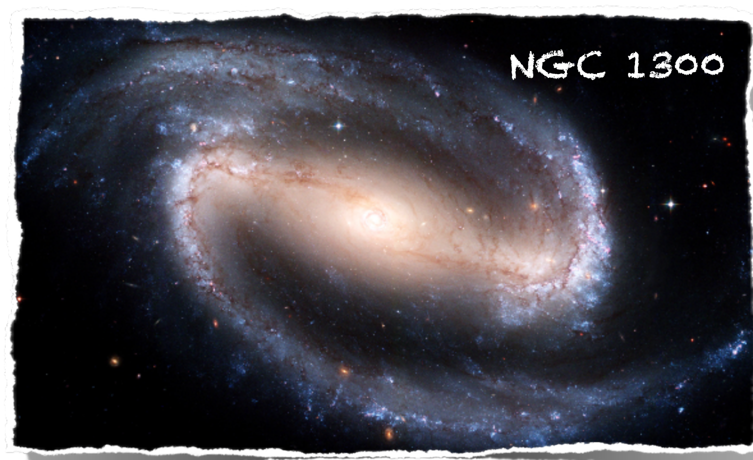

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Supermassive black holes: the AGN central engine

Merger-driven processes

- non-axisymmmetric potentials resulting from a nearby companion galaxy can further increase the mass flow rate onto the central regions

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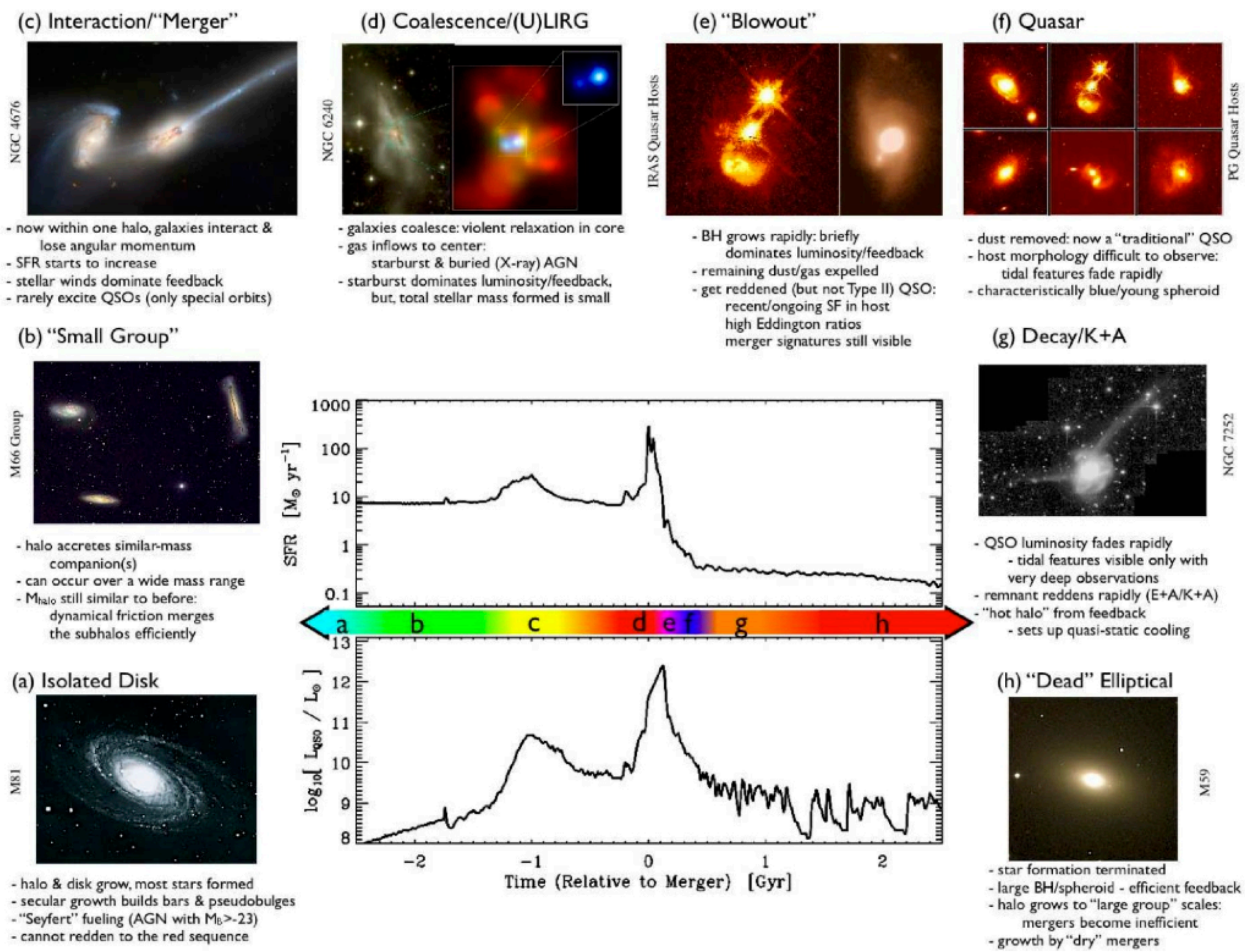

Hopkins et al. (2008)

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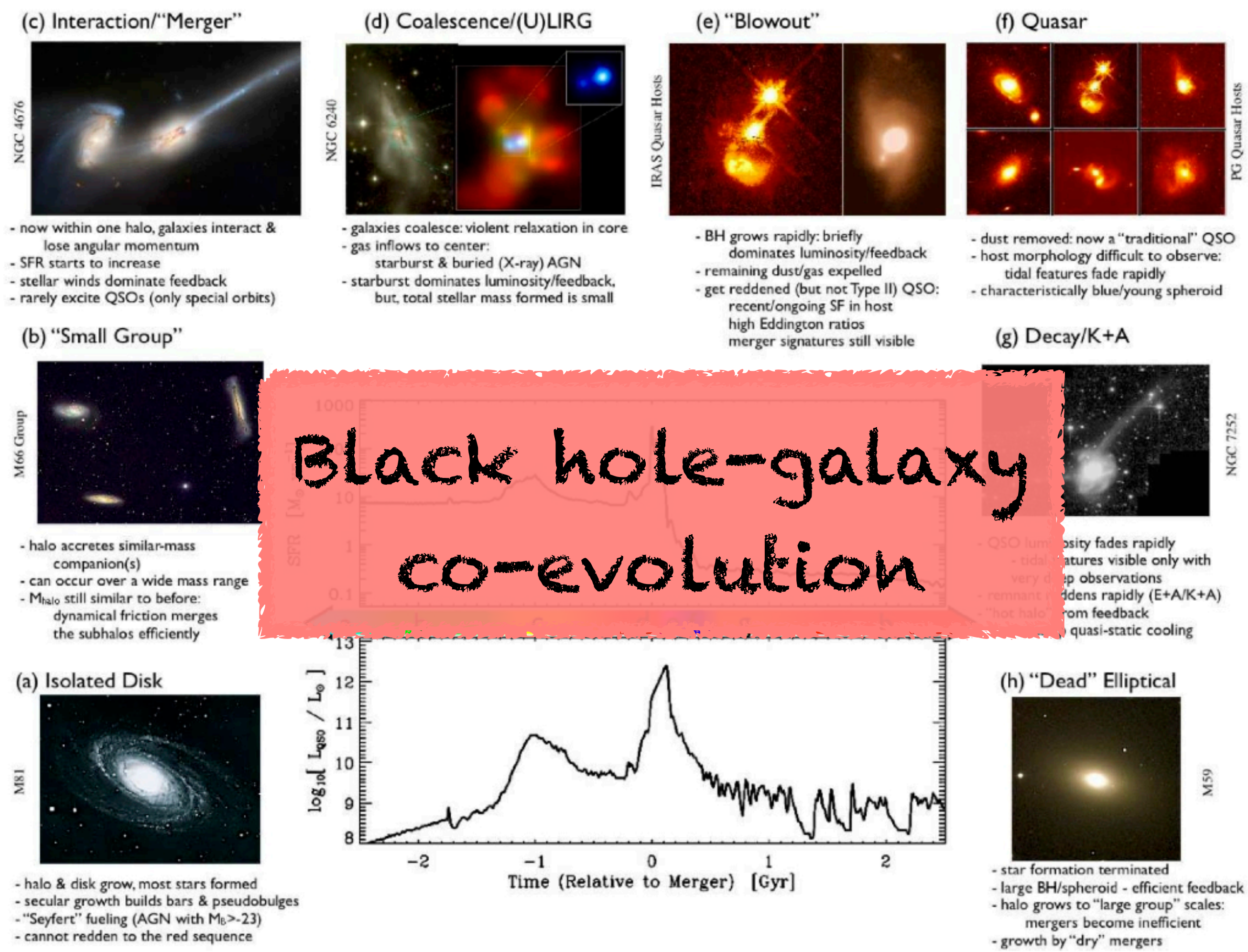

Black hole-galaxy co-evolution

Hopkins et al. (2008)

Supermassive black holes: accretion disk

- Gas inevitably posses a non-zero angular momentum when it enters the region dominated by the potential of the black hole

→ the inflowing gas will form a flattened, rotationally-supported structure:

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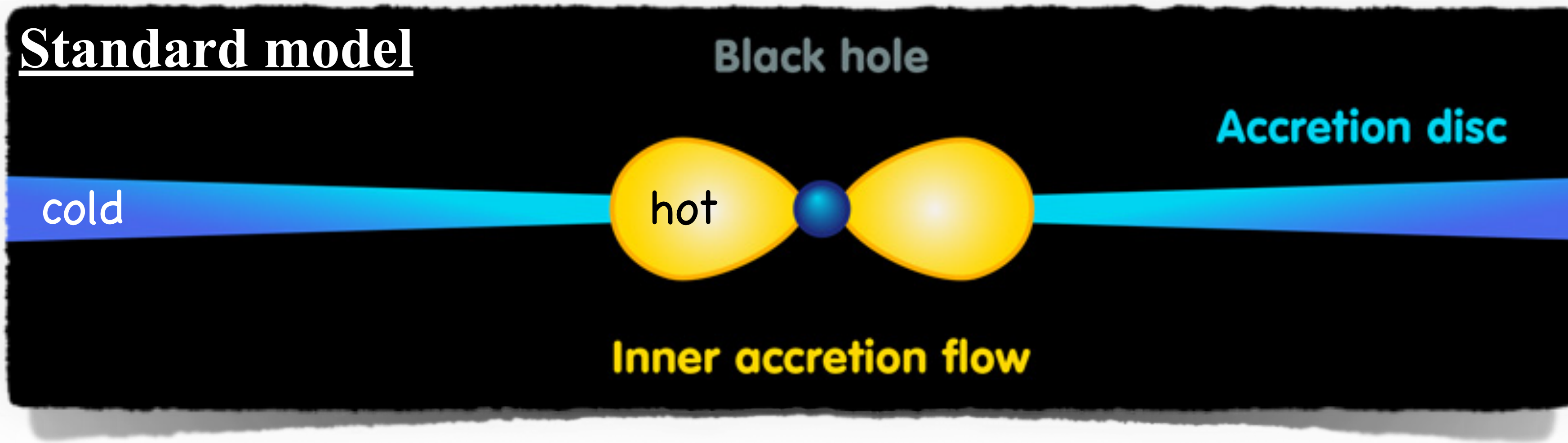


advection-dominated cooling, radiatively inefficient

high radiative cooling efficiency

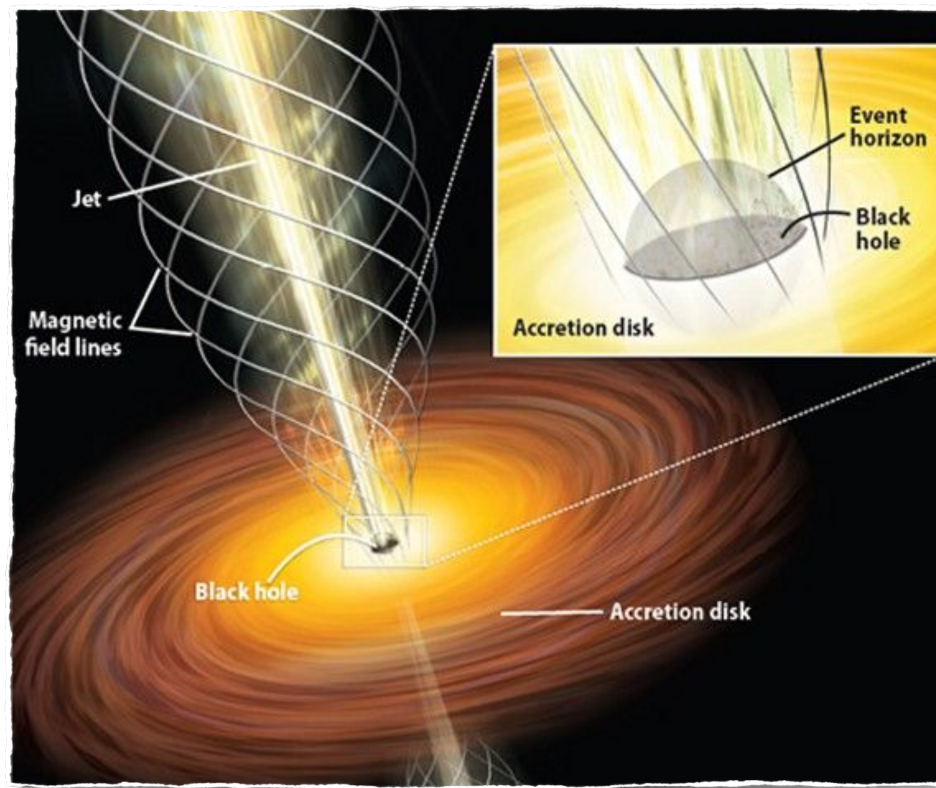
Sketch adapted from A. Müller, MPE

Supermassive black holes: accretion disk

- Accretion disks "viscosity" transports angular momentum outwards and allows matter to flow inwards

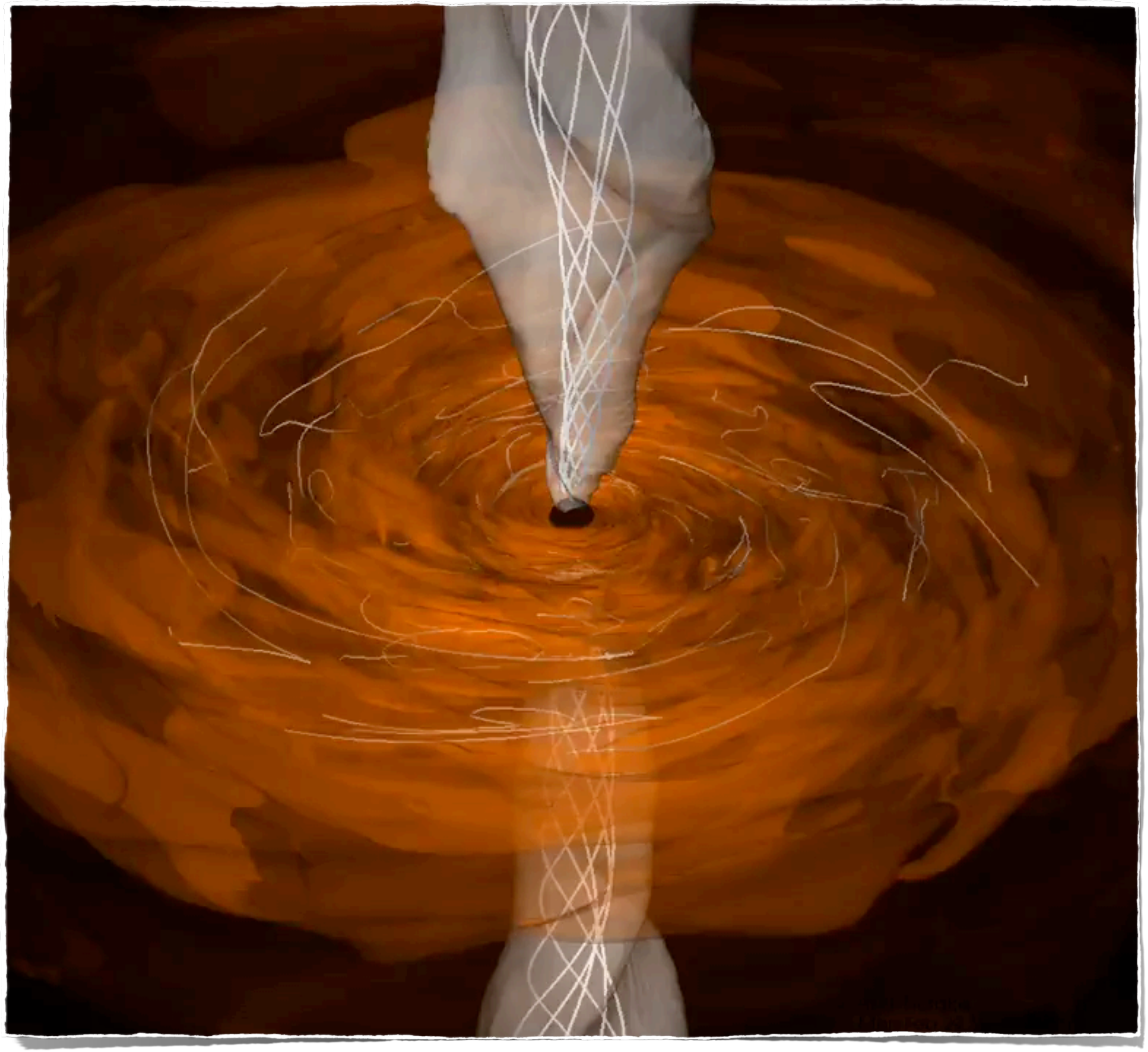
- The gravitational potential energy of the infalling material is transformed into observable radiation and kinetic energy of jets/outflows

- A self-sustaining magnetic dynamo probably provides the required angular momentum transport



Roen Kelly

Supermassive black holes: jet-accretion disk



Hotaka Shiokawa

Supermassive black holes: jet-accretion disk

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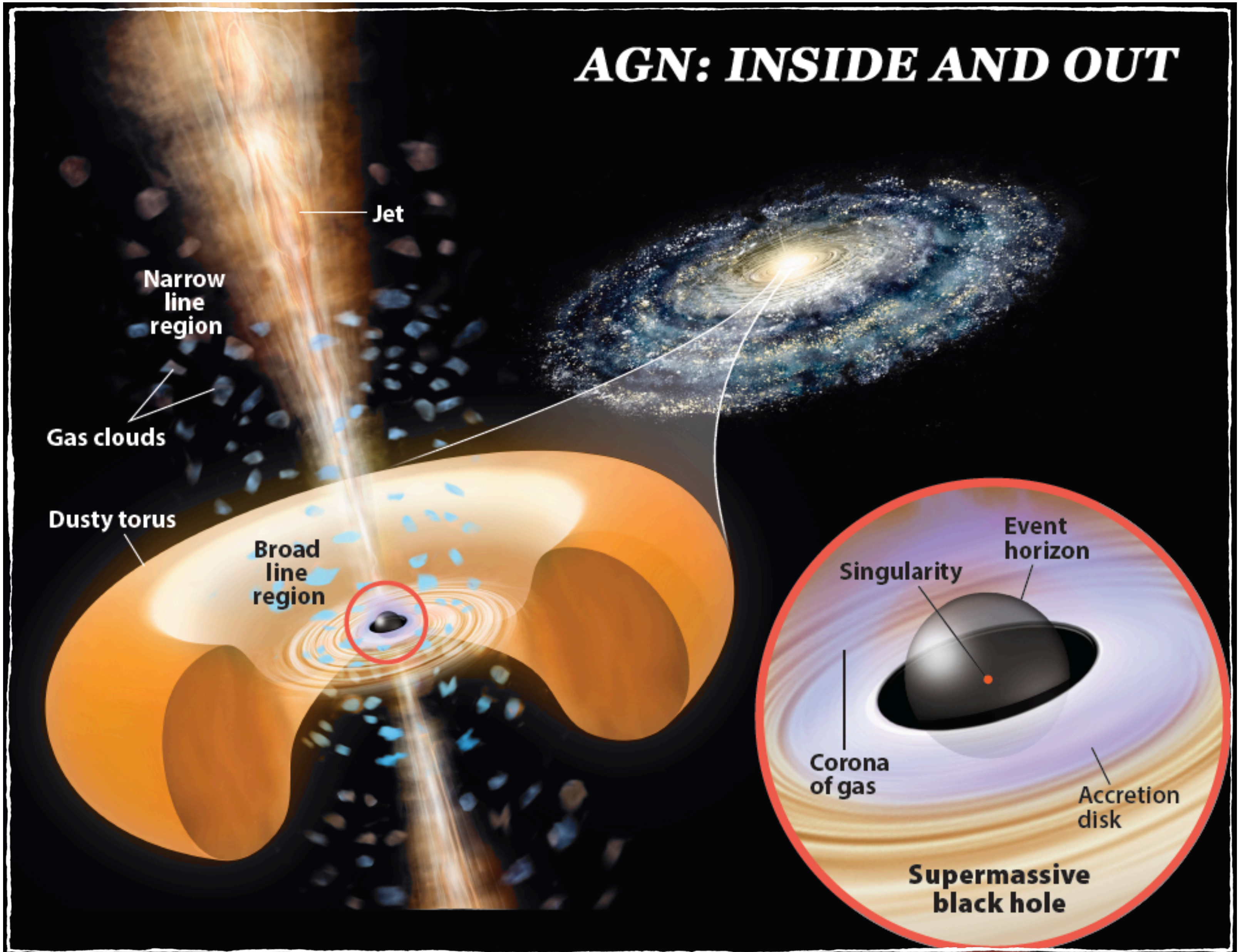
AGN components according to Unified Model



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- Black hole anatomy

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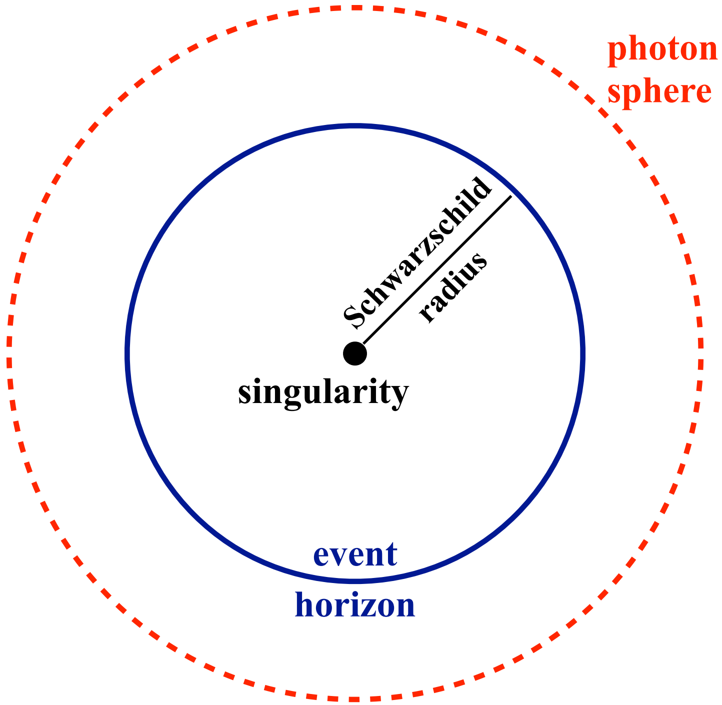

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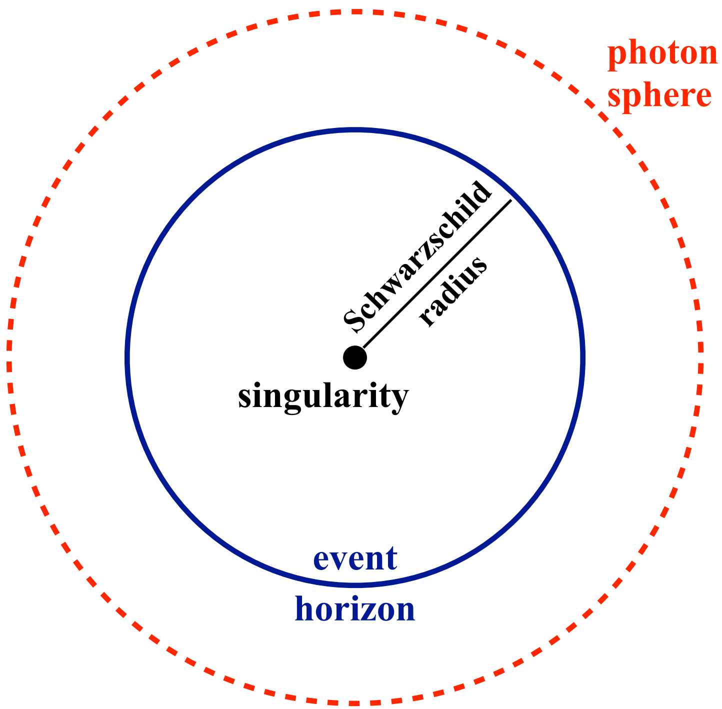

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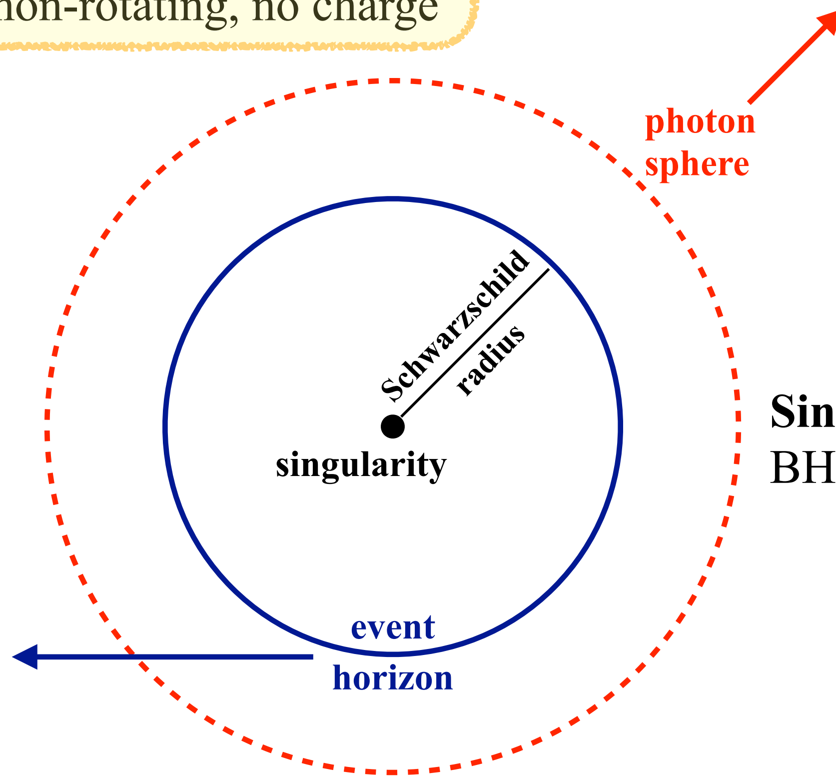
Photon sphere
Photons moving on tangential trajectories are trapped in circular orbits around the BH
Radius = $1.5 \times R_{Sch}$



Singularity
BH density & gravity = ∞

Event horizon
Boundary region within nothing can escape

Schwarzschild radius
Radius of event horizon
$R_{Sch} = 2GM/c^2$

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Unified model of AGN:

All AGN contain the same components, simply viewed at different angles

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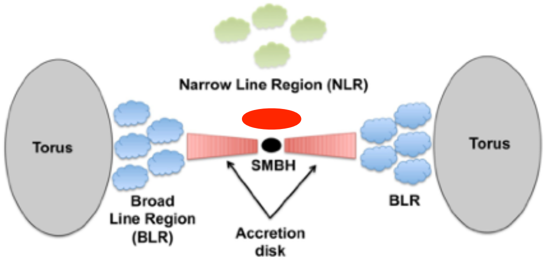

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- Accretion disk and corona:

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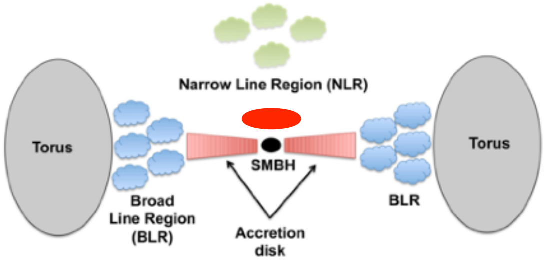

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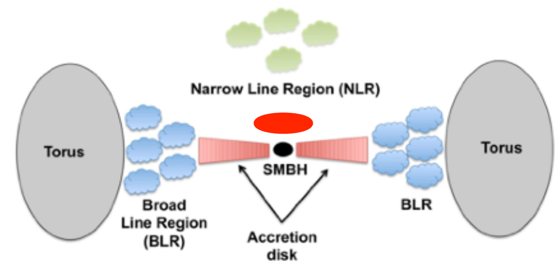

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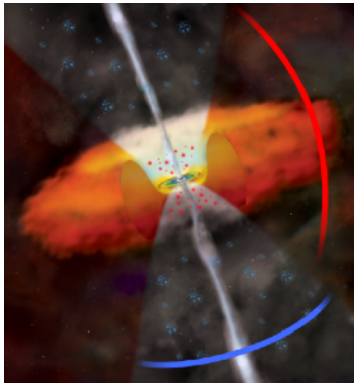
- Broad line region:

  - Dense gas clouds orbiting central engine at distances 0.1-1 pc
  - High velocity (~2000 km/s)
  - Ionized by continuum emission coming from accretion disk: produces broad emission lines

AGN components according to Unified Model

- Narrow line region:

- Low-density gas clouds at distances 100pc - 4kpc from central engine
- Lower velocity (~500 km/s)
- Ionized by accretion disk and massive stars, produces intense narrow forbidden emission lines



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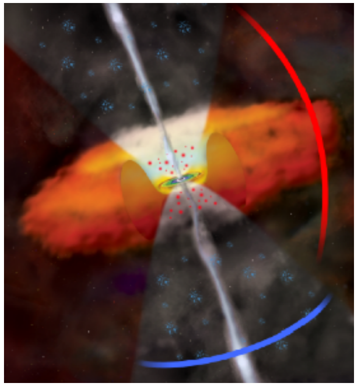

- Cold gas and dust that surrounds the central engine at a distance of up to 10 pc
- Constitutes the source of material used by the accretion disk to feed the SMBH
- Its dust grains absorb the optical radiation coming from the nucleus and re-radiate it at infrared (IR) wavelengths
- Has a non-uniform clumpy structure

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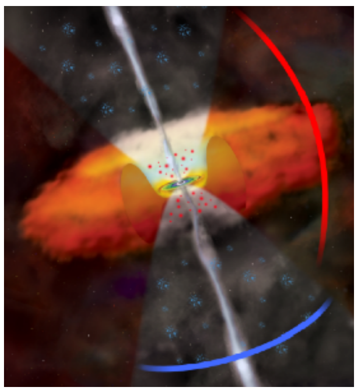

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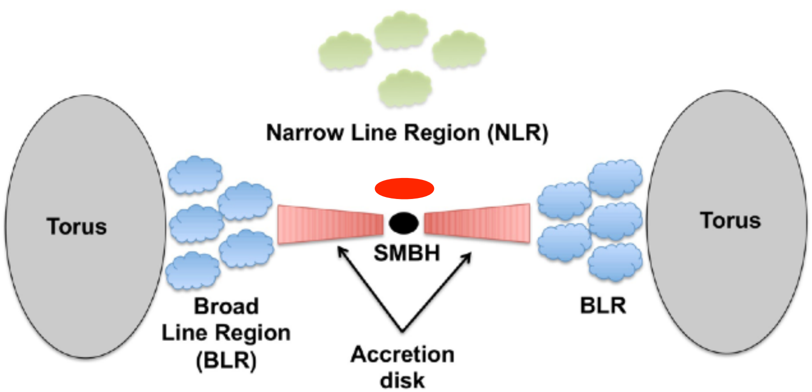
- Jets:

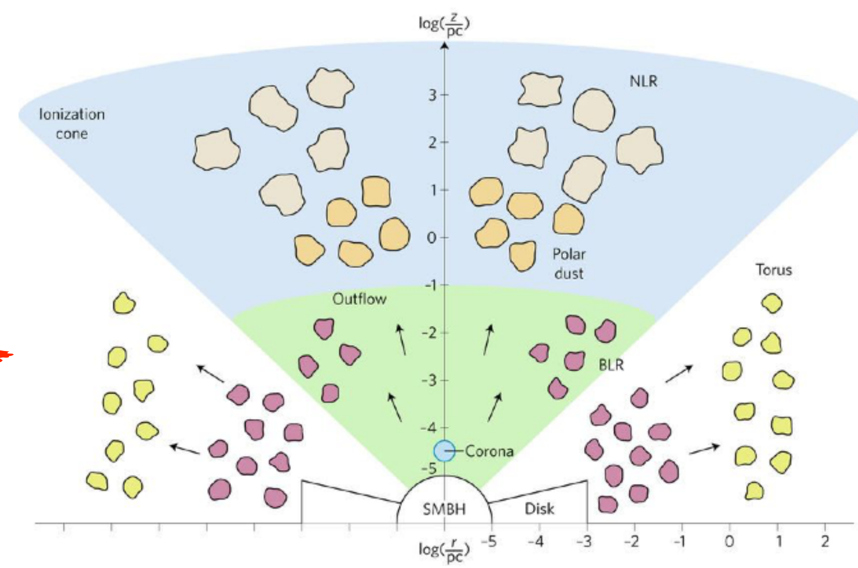
- Pair of highly collimated relativistic plasma outflows emerging in opposite directions from within 10-100R_{Sch} from the black hole
- Can extend beyond the host galaxy, several kpc or Mpc
- Radiate in all wavebands from radio to gamma-rays via synchrotron and inverse-Compton emission processes

AGN components according to Unified Model

A new view of AGN heated dust:

- Thanks to mid-infrared interferometry & imaging
- Polar dust component in addition to torus





Ramos Almeida & Ricci (2017)

Question

How do we know there is a SMBH?

Data supporting the presence of a SMBH

How do we know there is a supermassive black hole?

$\boxed{\textbf{Virial theorem: } M \sim v^2 R/G}$

R: distance of clouds/star to black hole
v: velocity of gas/stars

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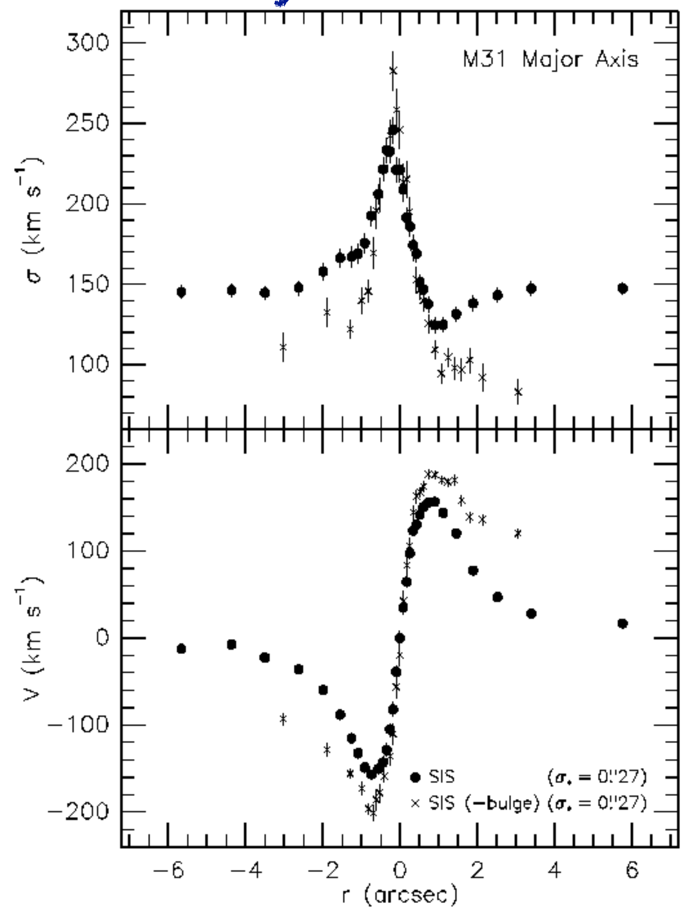
  Velocity dispersion of stars in many galaxies increases at the center (e.g. within 1 arcsec)

  mass concentration at the galactic nucleus: M_{BH}

Kormendy & Richstone (1995)



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- High-resolution imaging/spectroscopy reveal rotating disks in small radii

  ➜ indicates large masses: SMBH

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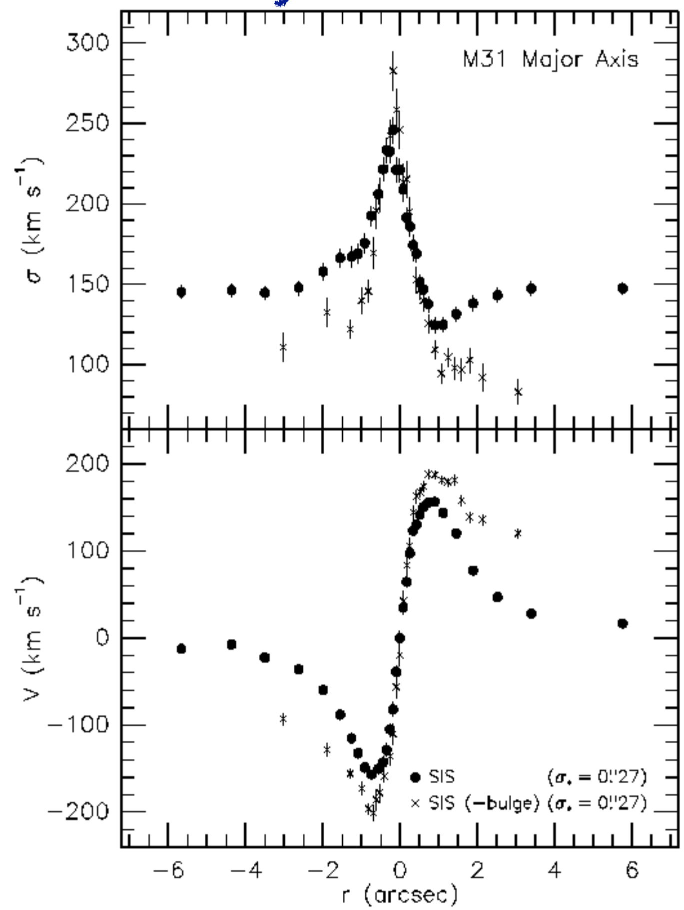

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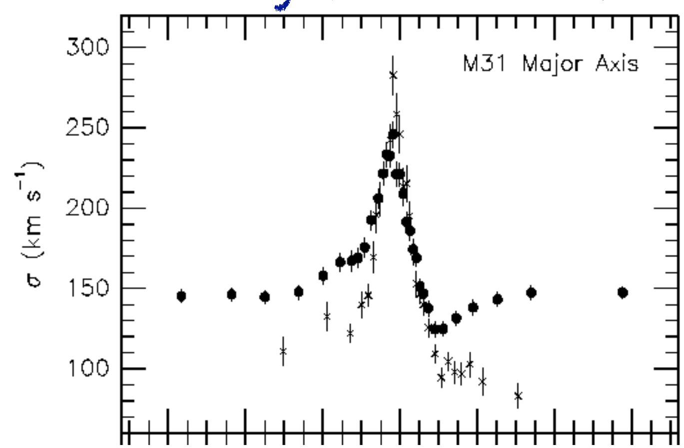

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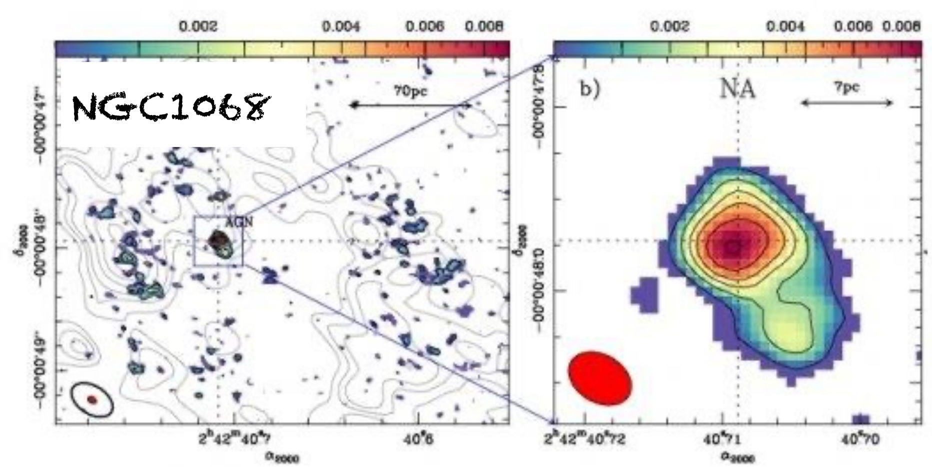
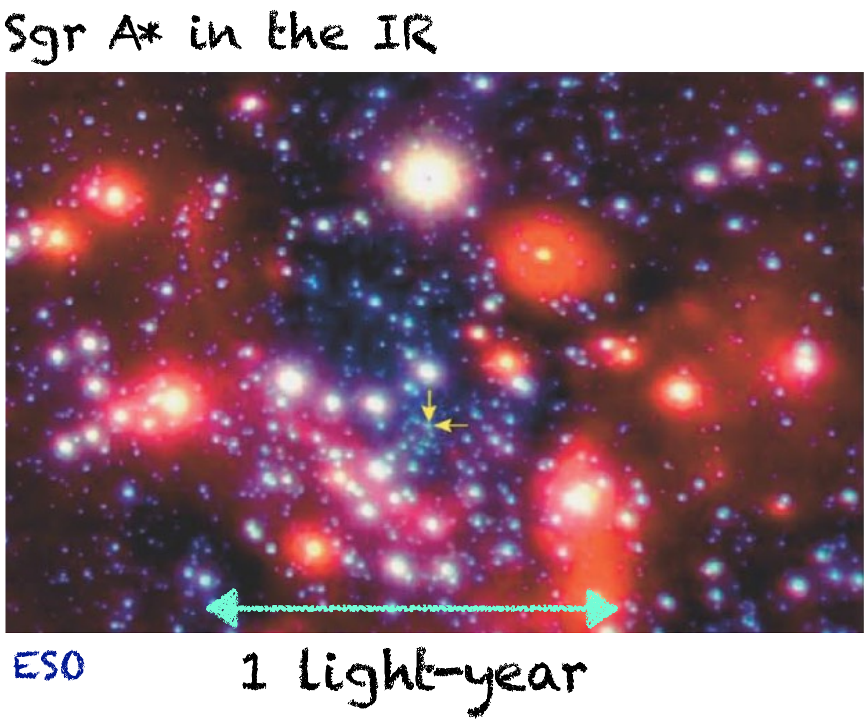
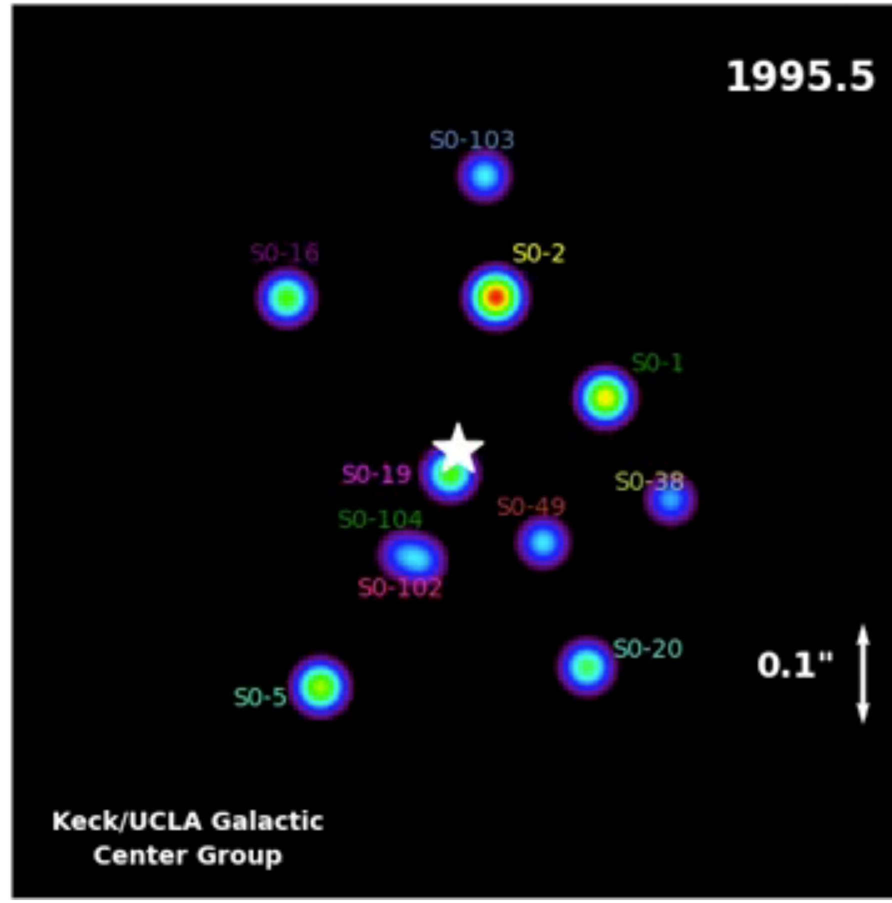


ALMA dust continuum, 694 GHz
García-Burillo et al. (2016)

Data supporting the presence of a SMBH

- Dynamics of stars around black hole





$$M_{BH} = 3x10^6\ M_\odot$$

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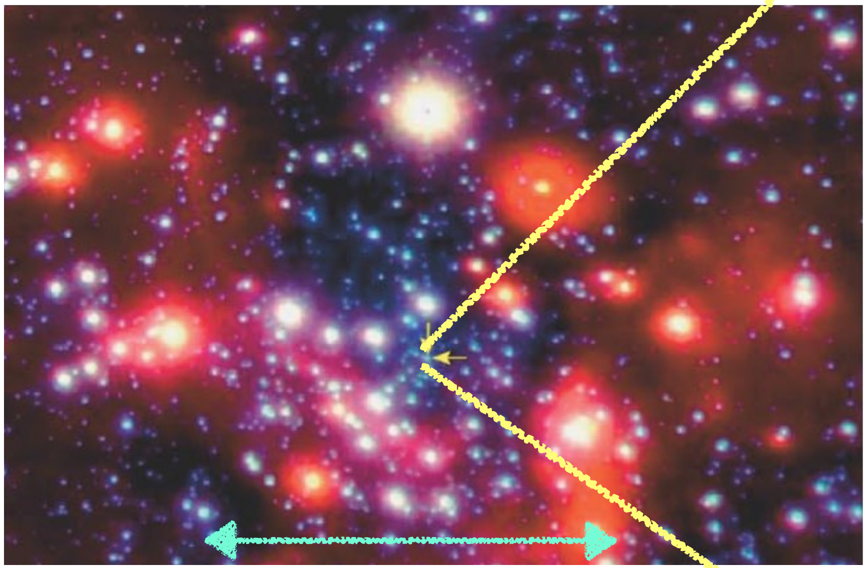
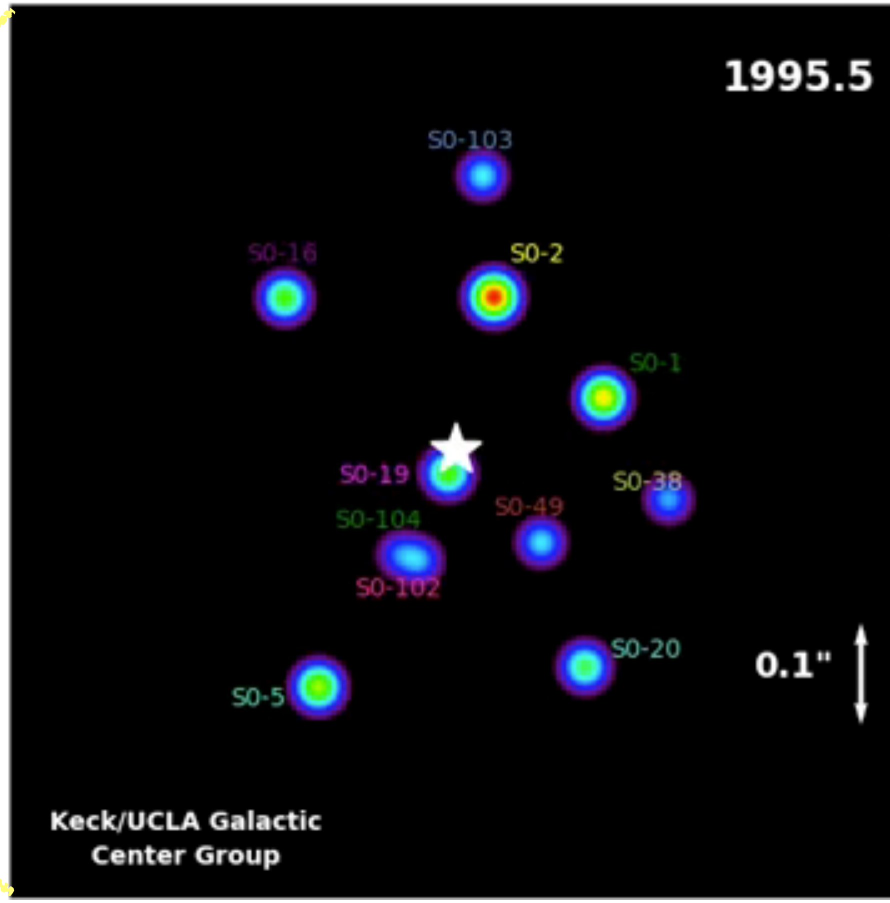
Sgr A* in the IR



ESO

1 light-year



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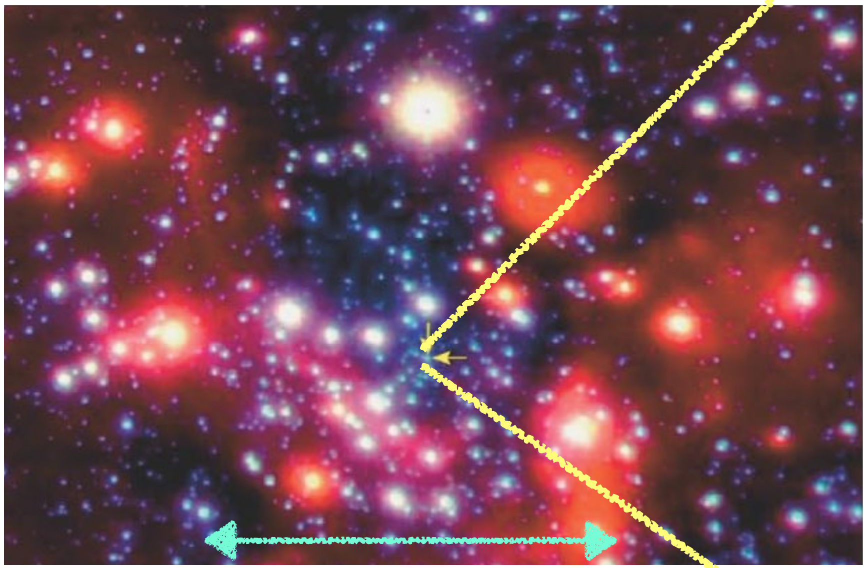
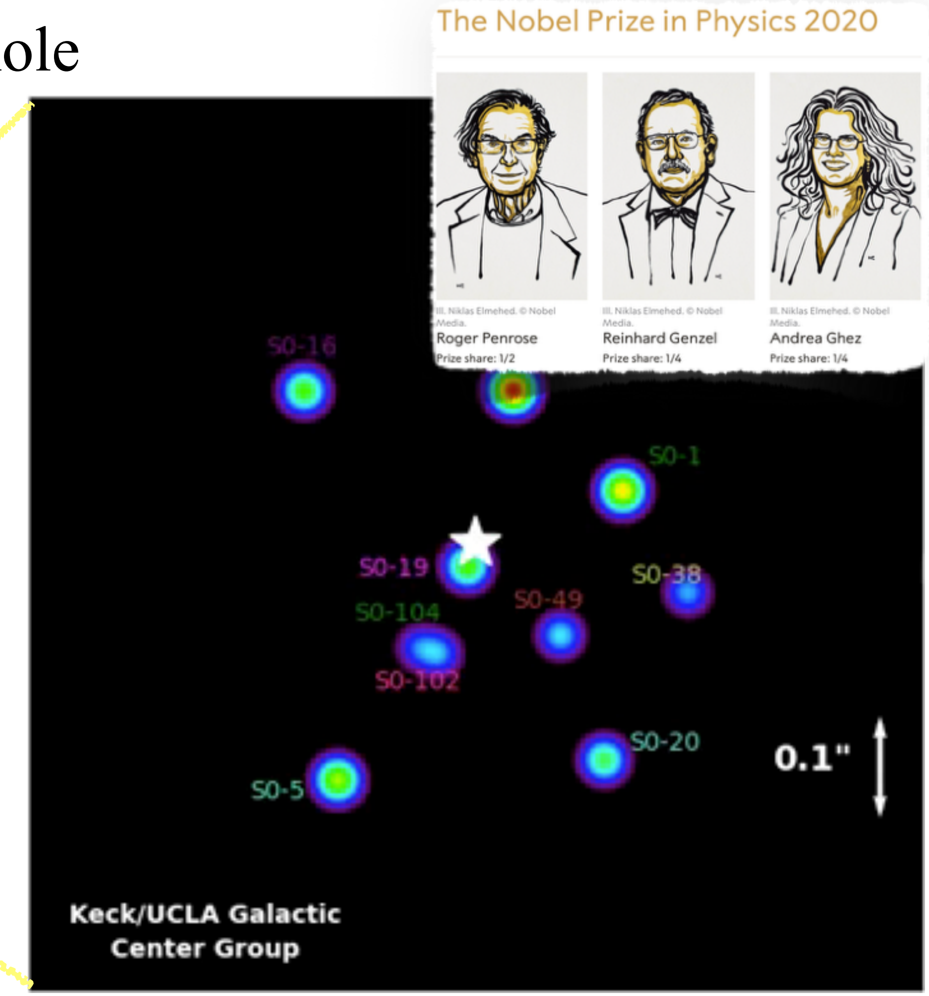
- Dynamics of stars around black hole

Sgr A* in the IR



ESO

1 light-year



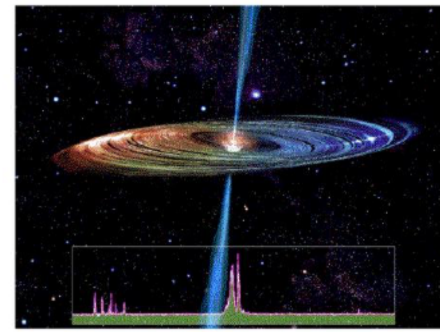
$M_{BH} = 3\text{x}10^6\ M_\odot$

Data supporting the presence of a SMBH

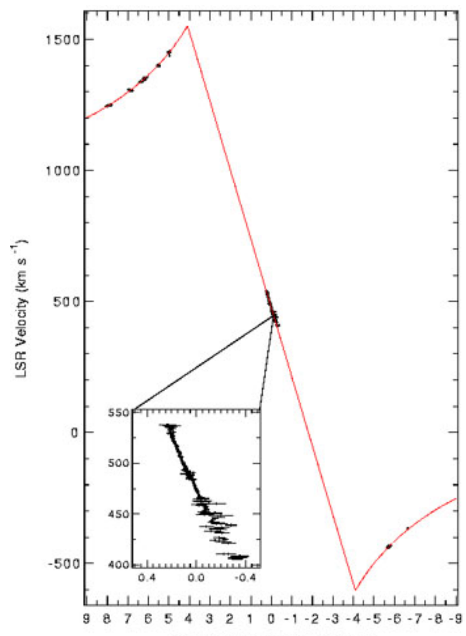
- Many AGN produce H_2O and OH masers

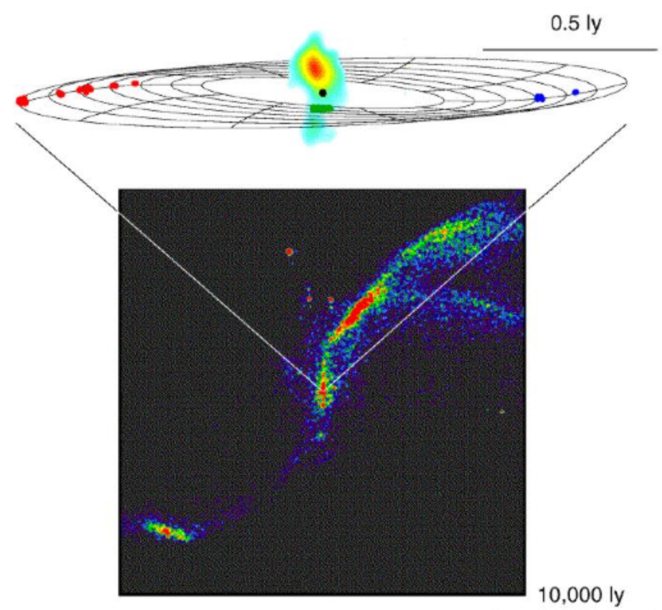
thanks to intrinsic narrow width of maser emission lines, velocity maps can be derived in very small radius via line frequency measurement with VLBI

Keplerian motion at ~0.5pc from the source
Potential dominated by point-like mass of ~$10^7\,M_\odot$



NGC 4258



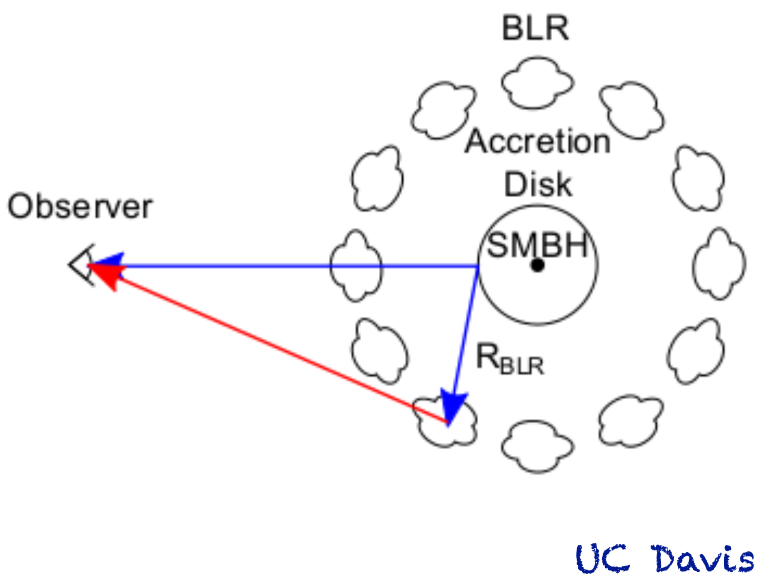


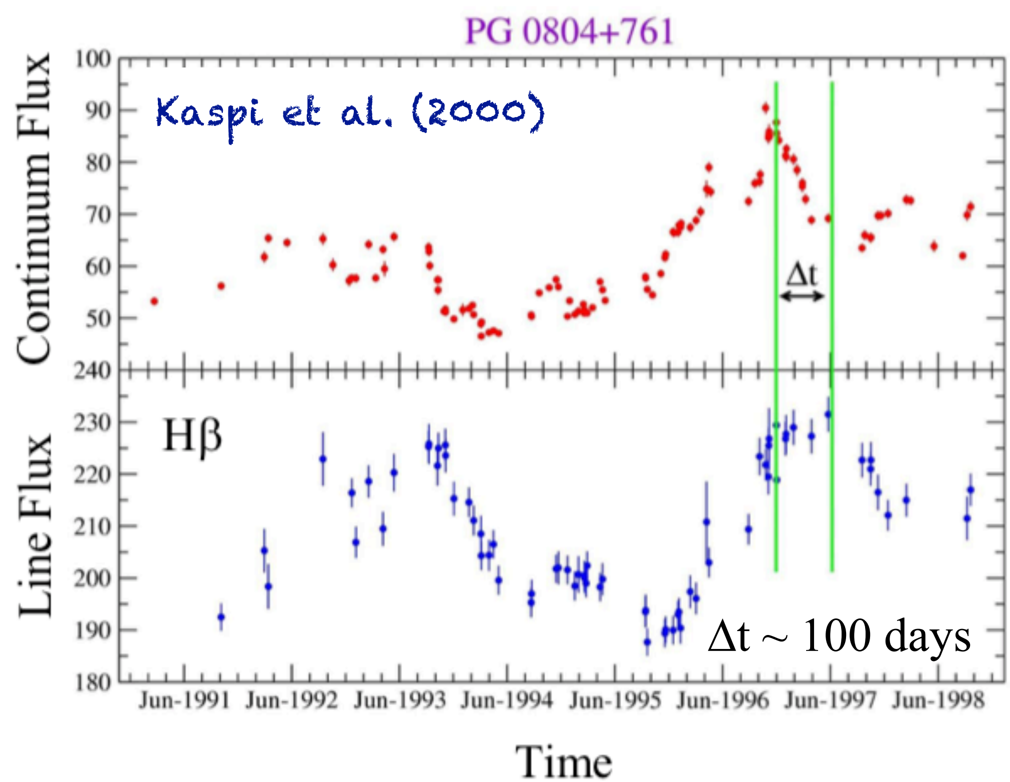
VLBI, 22 GHz
Miyoshi et al. (1995)

Data supporting the presence of a SMBH

- Reverberation mapping

  - measure time difference between variations in continuum emission & in broad line emission: ➜ distance between BLR and black hole





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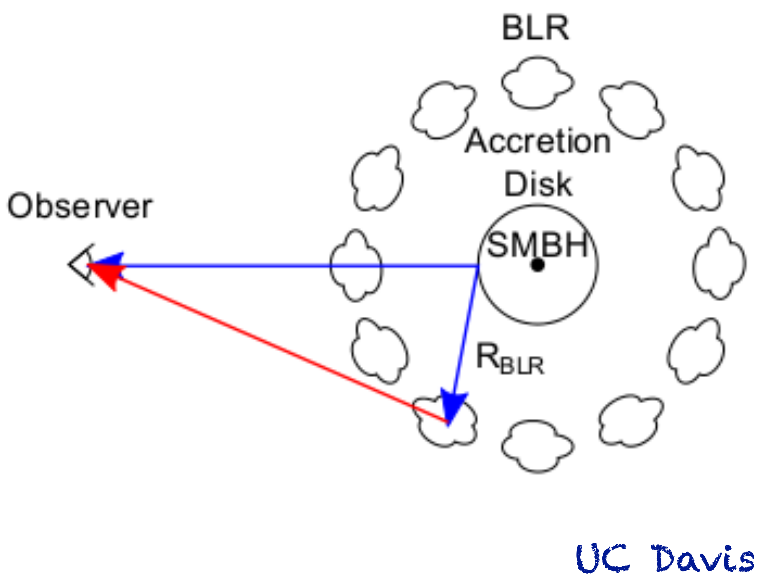

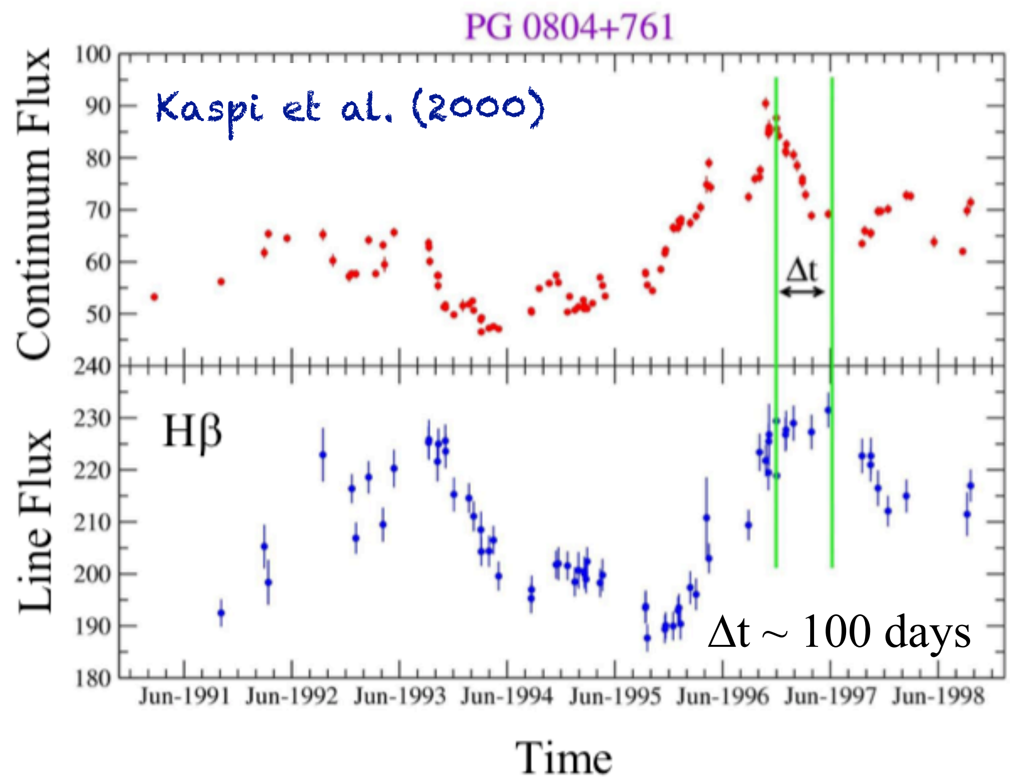

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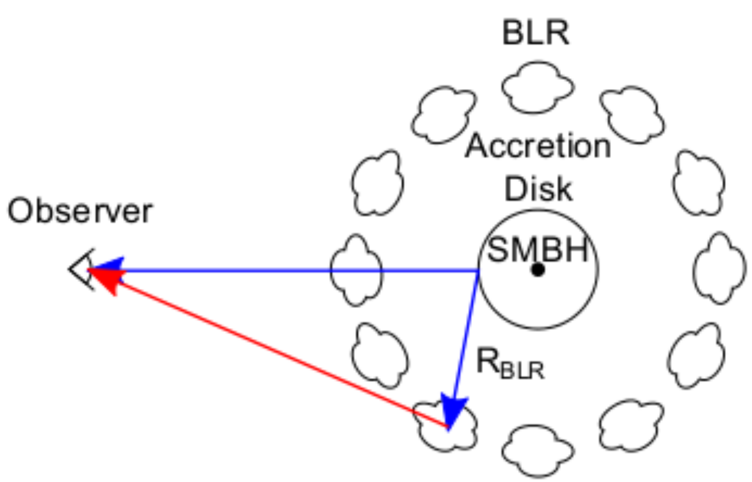
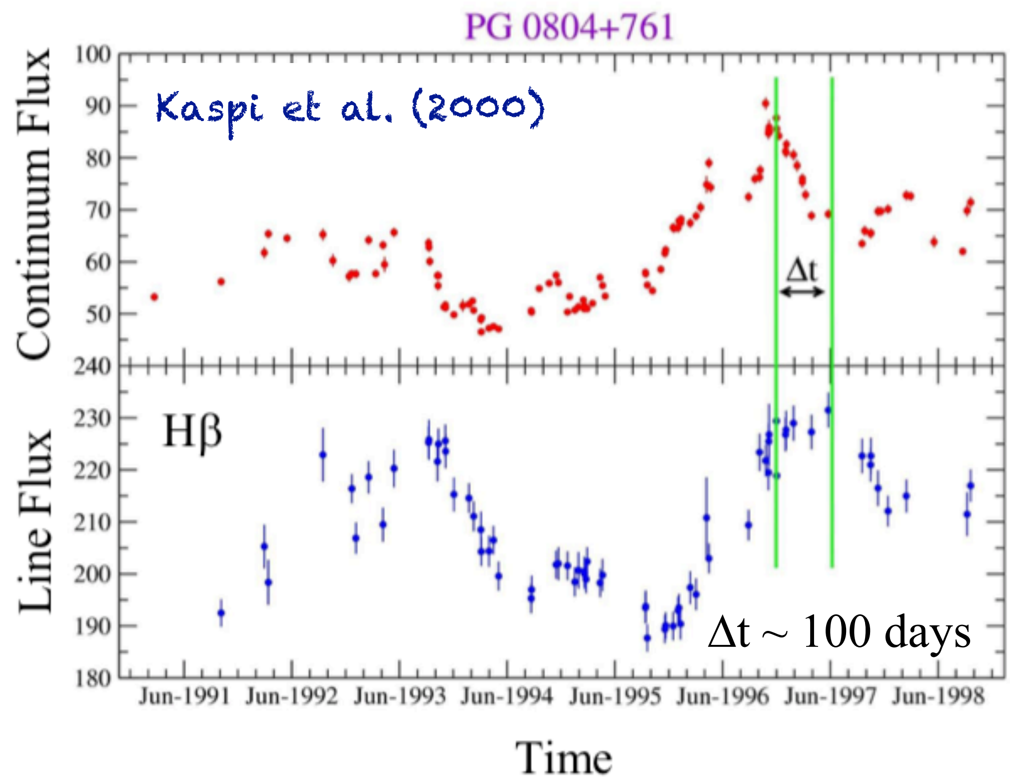
  - $M \sim v^2 R/G$ → black hole mass



UC Davis



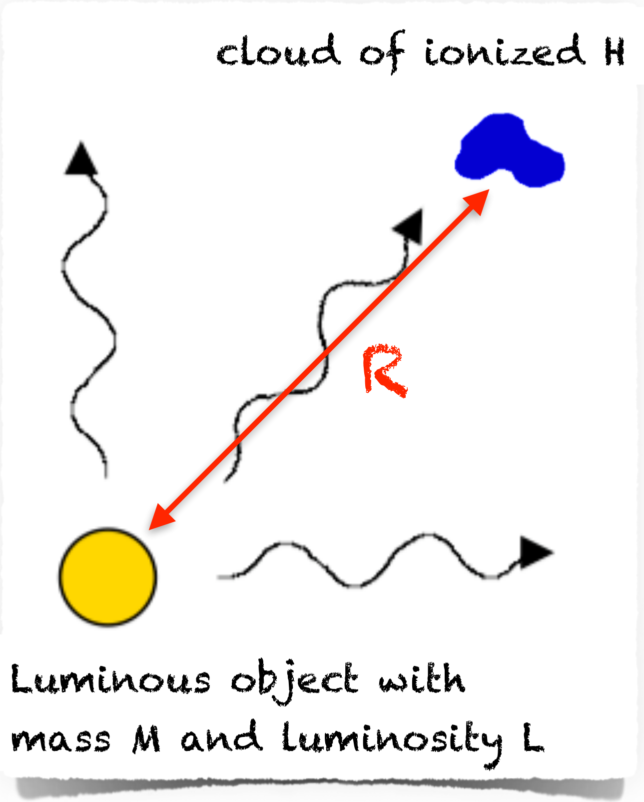
Data supporting the presence of a SMBH

- Accretion produces radiation pressure

  Flux: $F = L/4\pi R^2$

  Radiation pressure: $P_{rad} = F/c = L/4\pi R^2 c$

  Radiation force: $F_{rad} = P_{rad}\, \kappa(m_p+m_e)$



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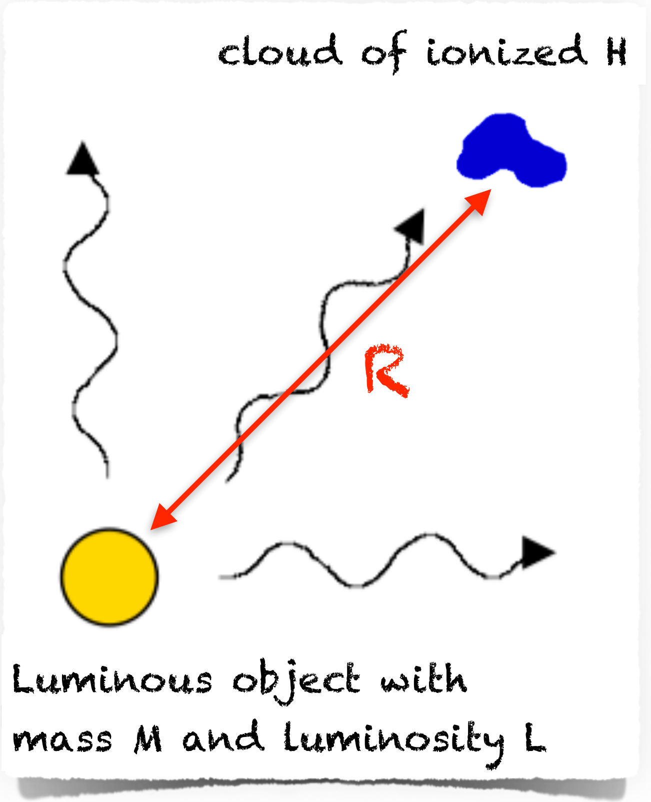
if accreting material is mostly ionized hydrogen and opacity is provided by Thomson scattering: cross-section from radiation pressure on electrons, but mass dominated by protons

$$\kappa = \sigma_T/m_p$$



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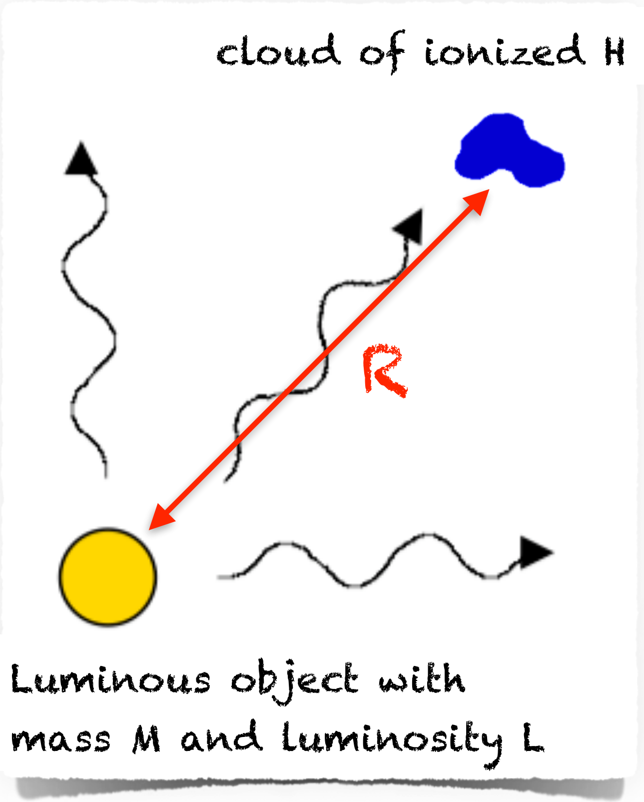

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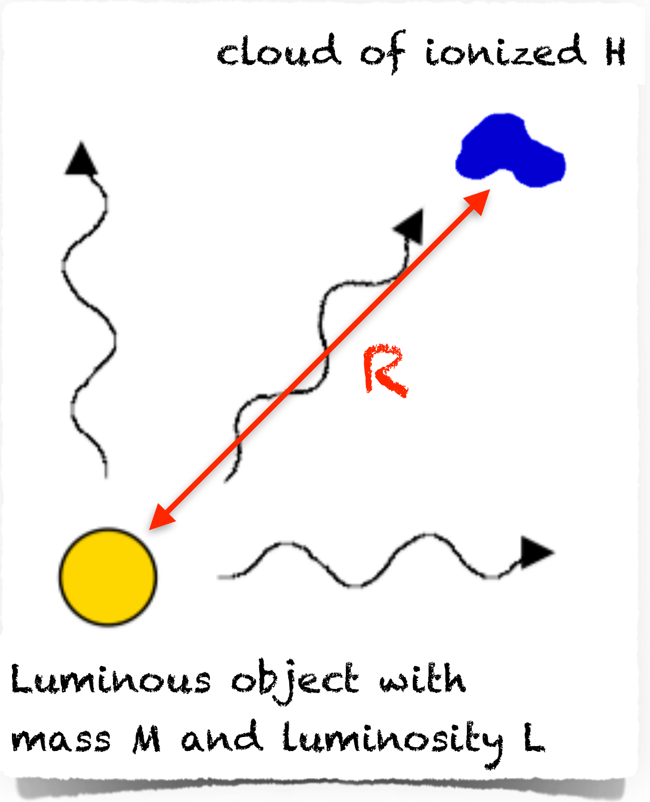

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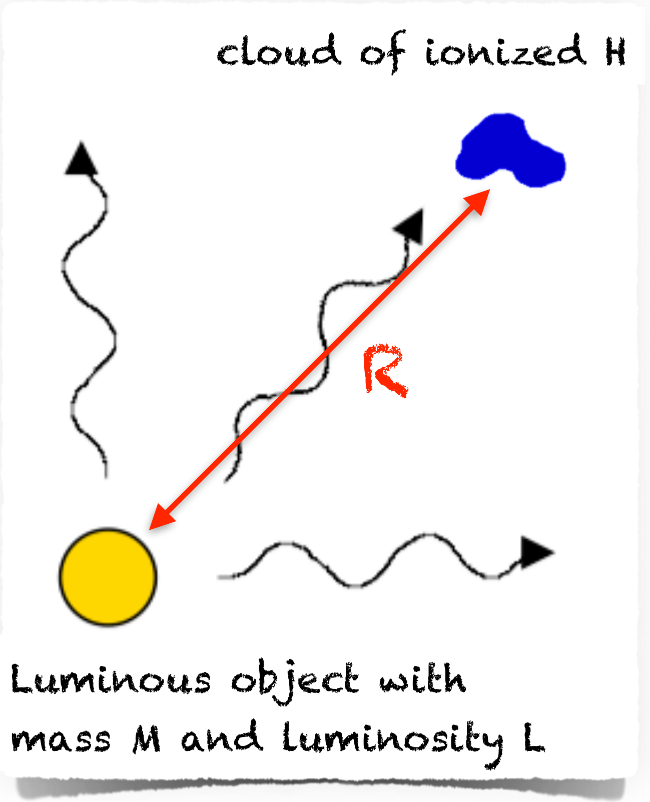

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Gravitational force: $F_{grav} = GM(m_p+m_e)/R^2 \sim GMm_p/R^2$

Data supporting the presence of a SMBH

Eddington limit or luminosity:
maximum luminosity at which
$F_{grav} = F_{rad}$

$$GMm_p/R^2 = L_{Edd}\,\sigma_T/4\pi R^2 c$$

$$L_{Edd} = 4\pi c G M m_p/\sigma_T$$

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$\boxed{\dot{M}_{Edd}\,(M_\odot/\mathrm{yr}) = 2.2 \times M_{BH}\,(M_\odot)/10^8}$

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Data supporting the presence of a SMBH

- Efficiency of matter conversion into energy, ε

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  Schwarzchild radius: $R_{Sch} = 2GMc^2$

  Most of optical/UV emission from $5R_{Sch}$

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(H burning into He has **ε** = 0.007)

The only process so efficient (apart from particle anihiliation) is accretion of matter onto massive compact object

Data supporting the presence of a SMBH

- Variability
  - Interval of variations $\Delta t \geq R/c$ (light crossing time) ➔ upper bound on R

    e.g.: $\Delta t \sim 10^5$ s => $R < 10^{-3}$ pc

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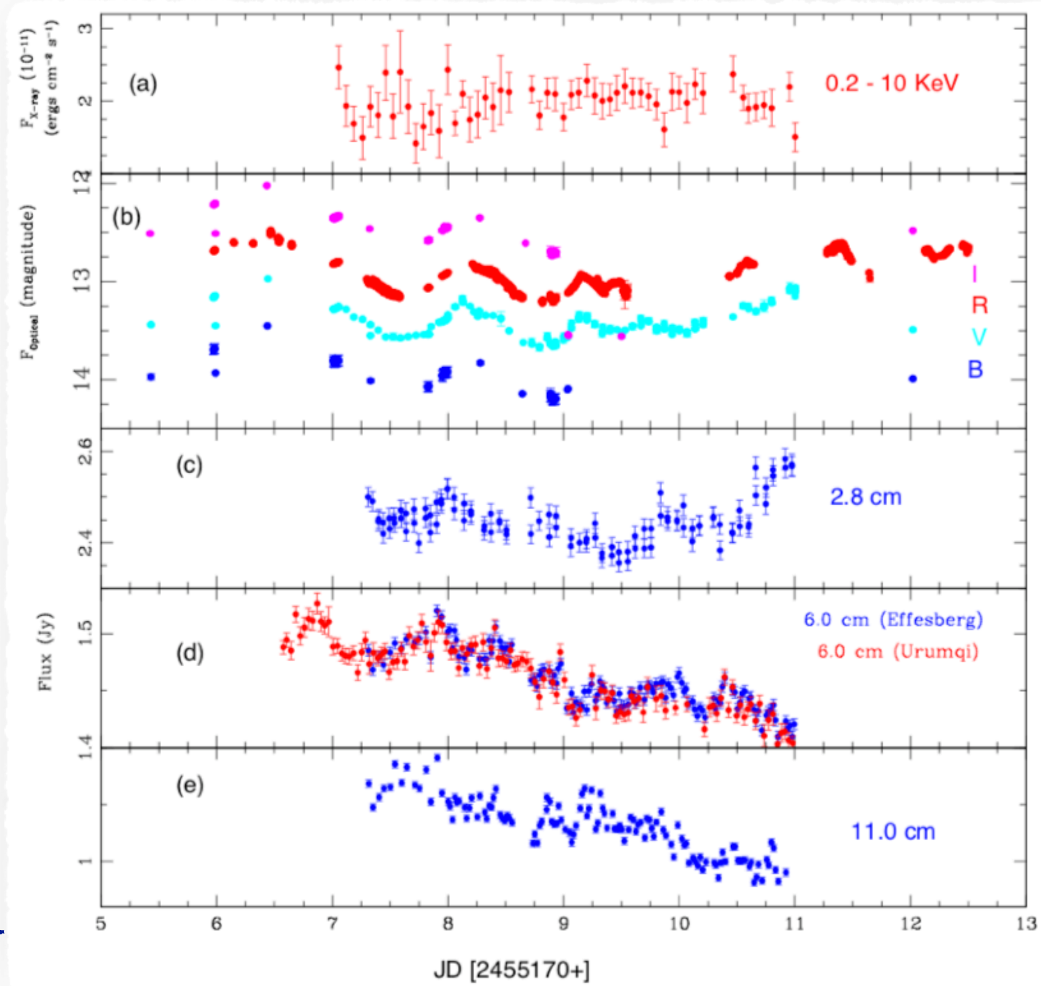

BL Lac S5 0716+714
Gupta et al. (2012)

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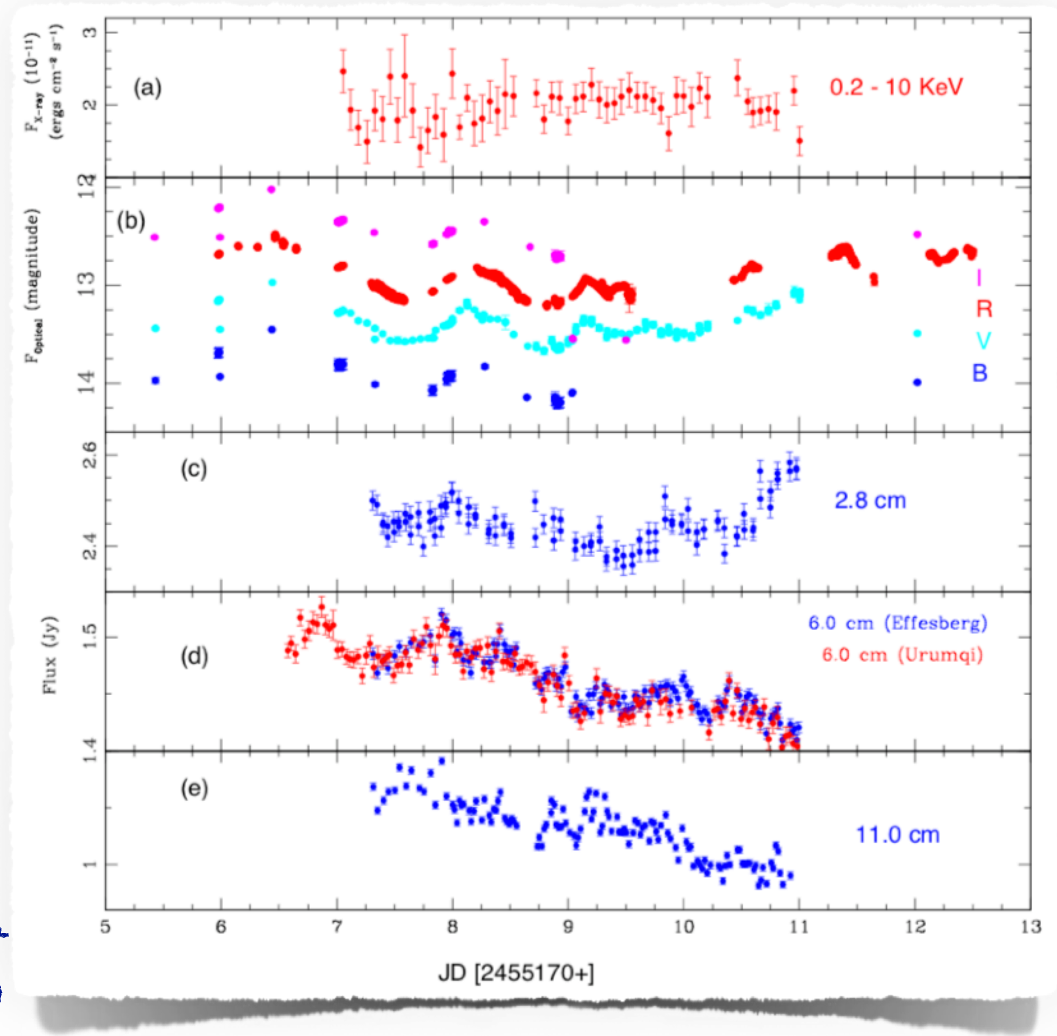
  - Mass from $M = L\Delta t/\varepsilon$

    $\varepsilon = 10\%$

    ⇒ $M \sim 10^{8\text{-}10}\, M_\odot$



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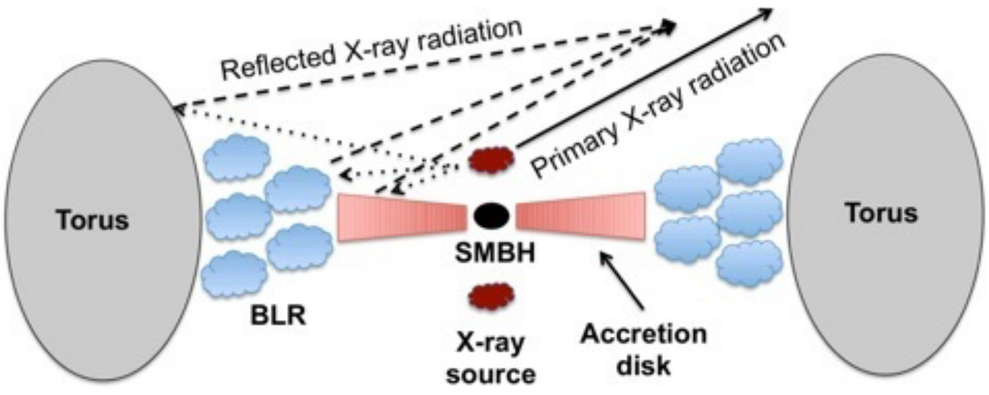
Data supporting the presence of a SMBH

- Broadened X-ray fluorescent Fe Kα emission lines



Claudio Ricci

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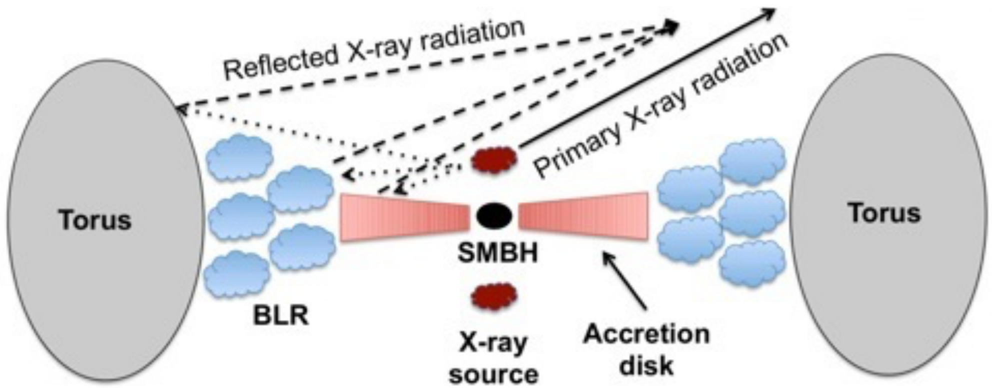

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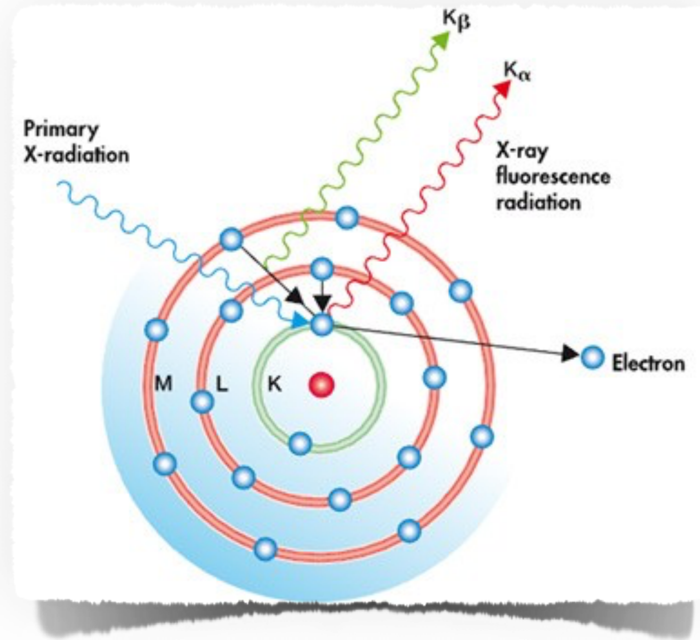

F. J. Aparicio Rebollo

Binding energy of the most internal electrons of the Fe atom = 7.1 keV. X-ray photons with energies higher than this threshold can be absorbed and produce photoelectric effect.

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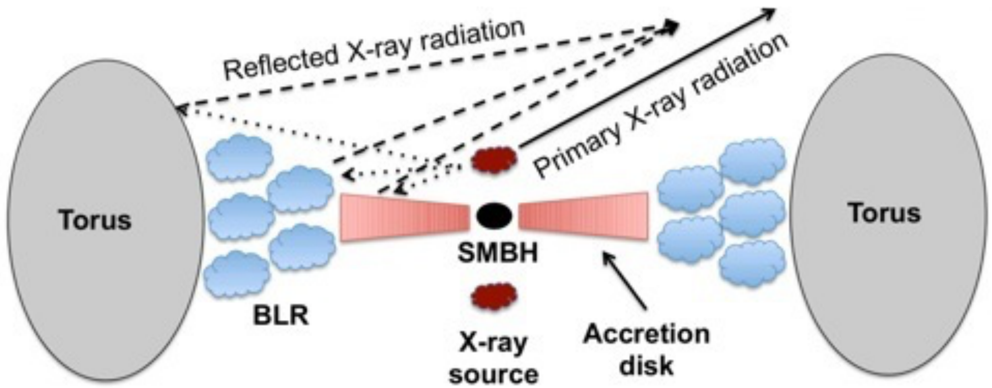

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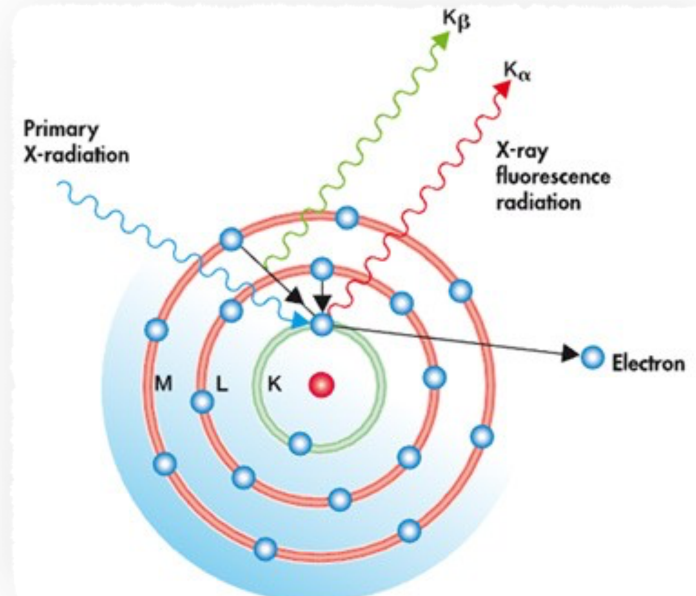

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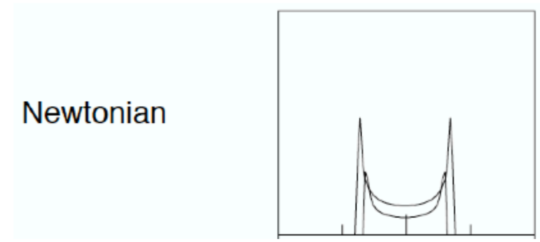
Emission line Fe Kα at 6.4 keV: produced by an X-ray photon (e.g. of 50 keV) that removes one electron from the K shell of Fe. Subsequent recombination of electrons in the higher levels => cascade of photons => fluorescence emission

Data supporting the presence of a SMBH

Emission line Fe Kα at 6.4 keV: thought to originate from the innermost regions of the accretion disk



Data supporting the presence of a SMBH

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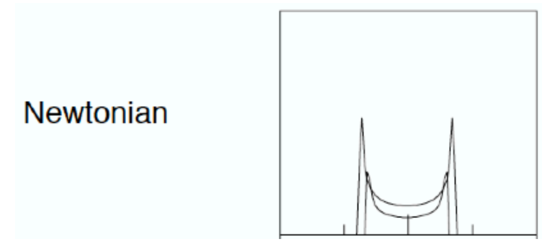
=> mildly-relativistic orbital velocities

=> strong gravitational field: gravitational redshift



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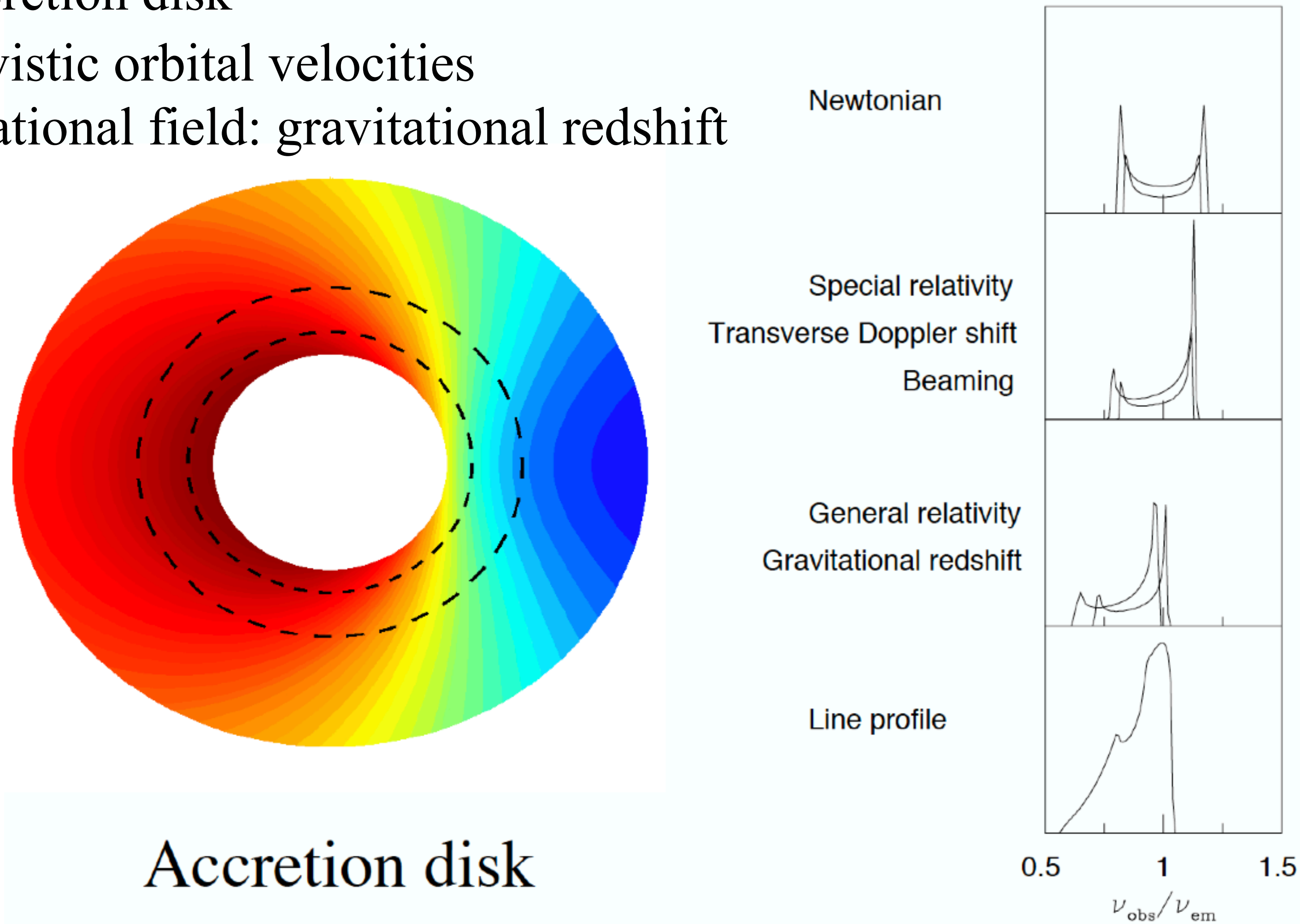

Fabian et al. (2000)

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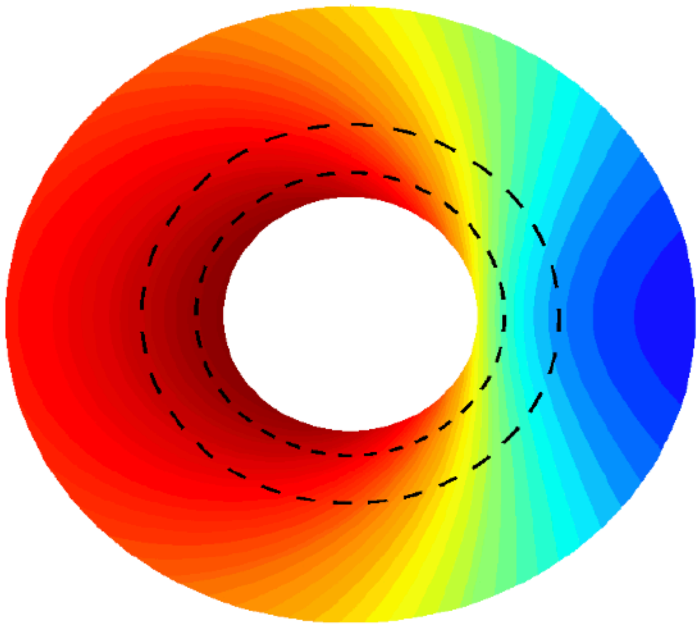
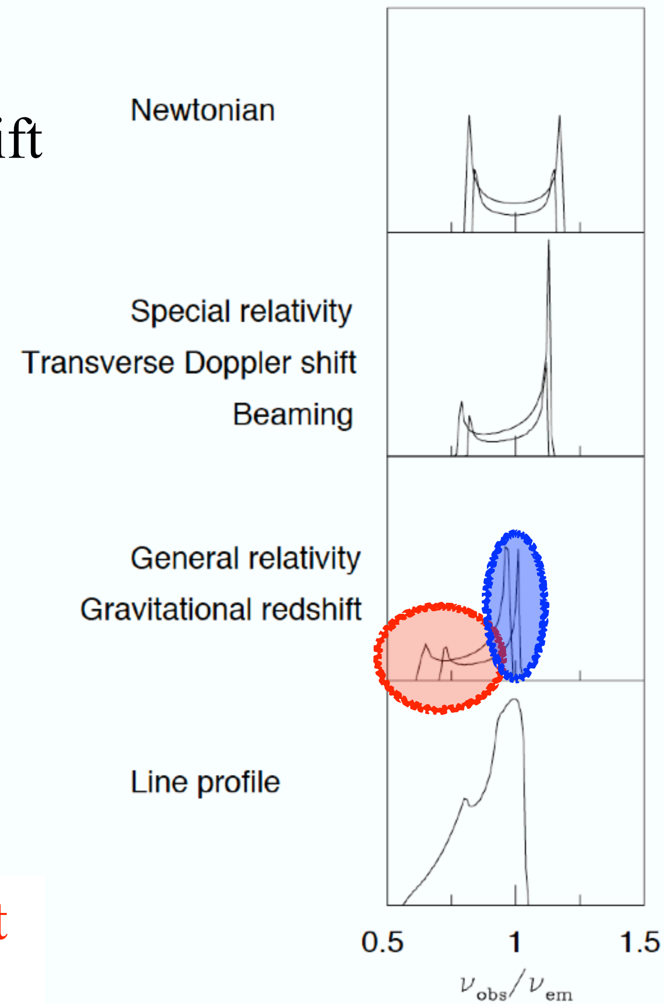




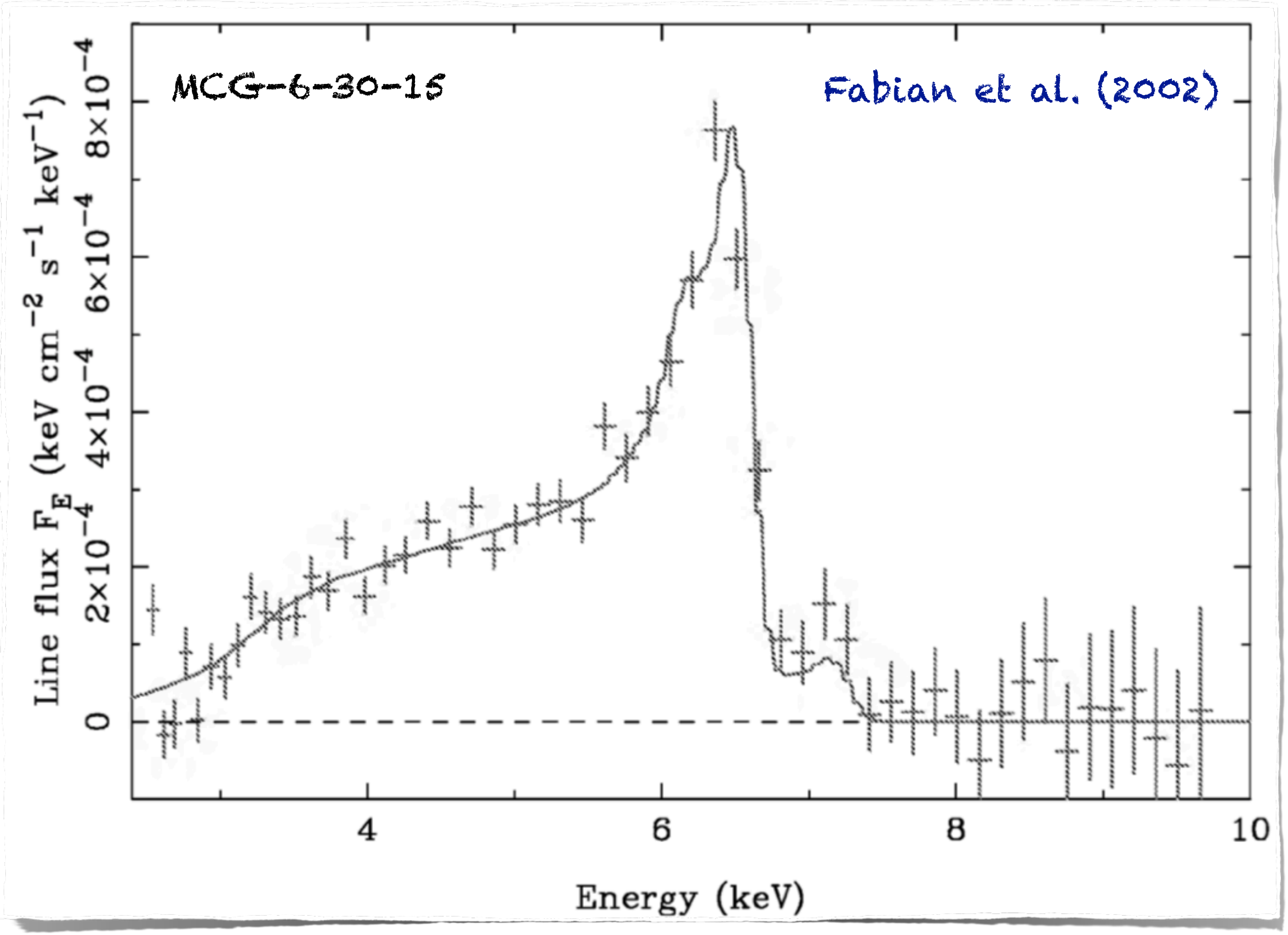
Skewed profile:

- extended red wing due to gravitational redshift

- prominent blue wing relativistically boosted due to high orbital velocities of the disk

Fabian et al. (2000)

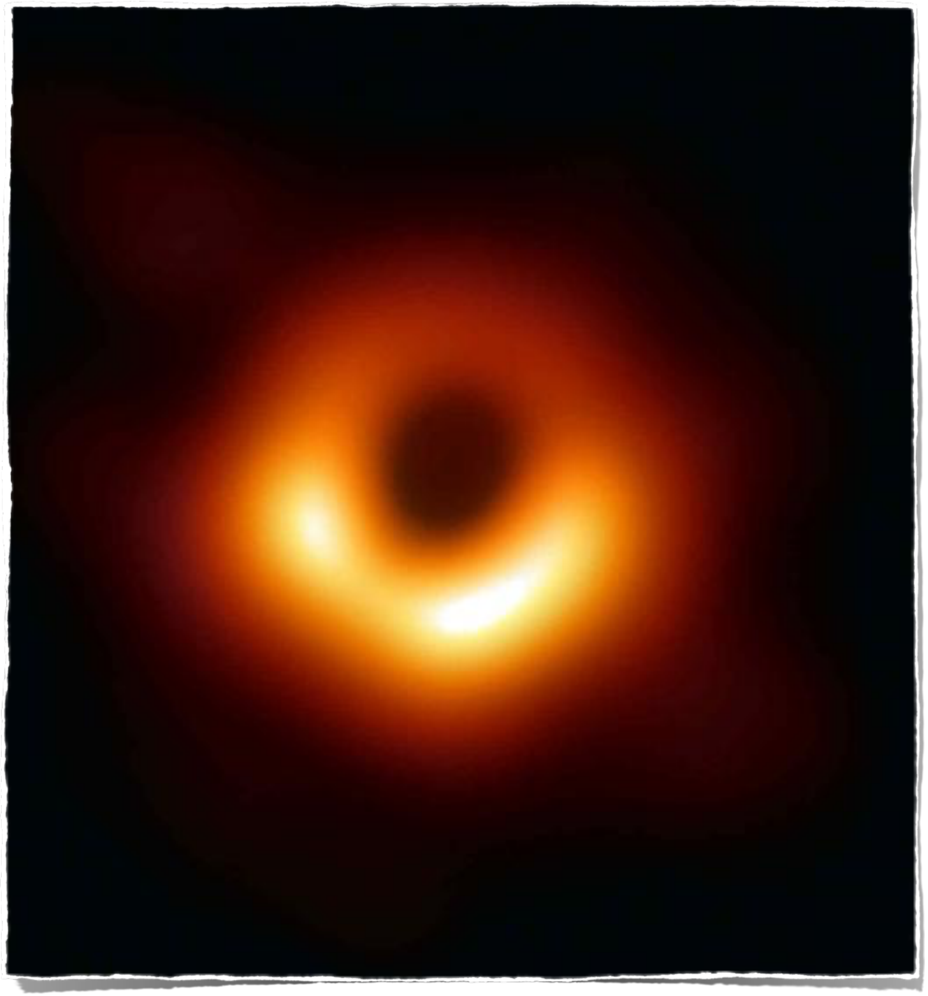
Data supporting the presence of a SMBH



Fe line profile in agreement with that expected from material in a thin accretion disk near a black hole

Data supporting the presence of a SMBH

- The first image of a black hole



ESO

Data supporting the presence of a SMBH

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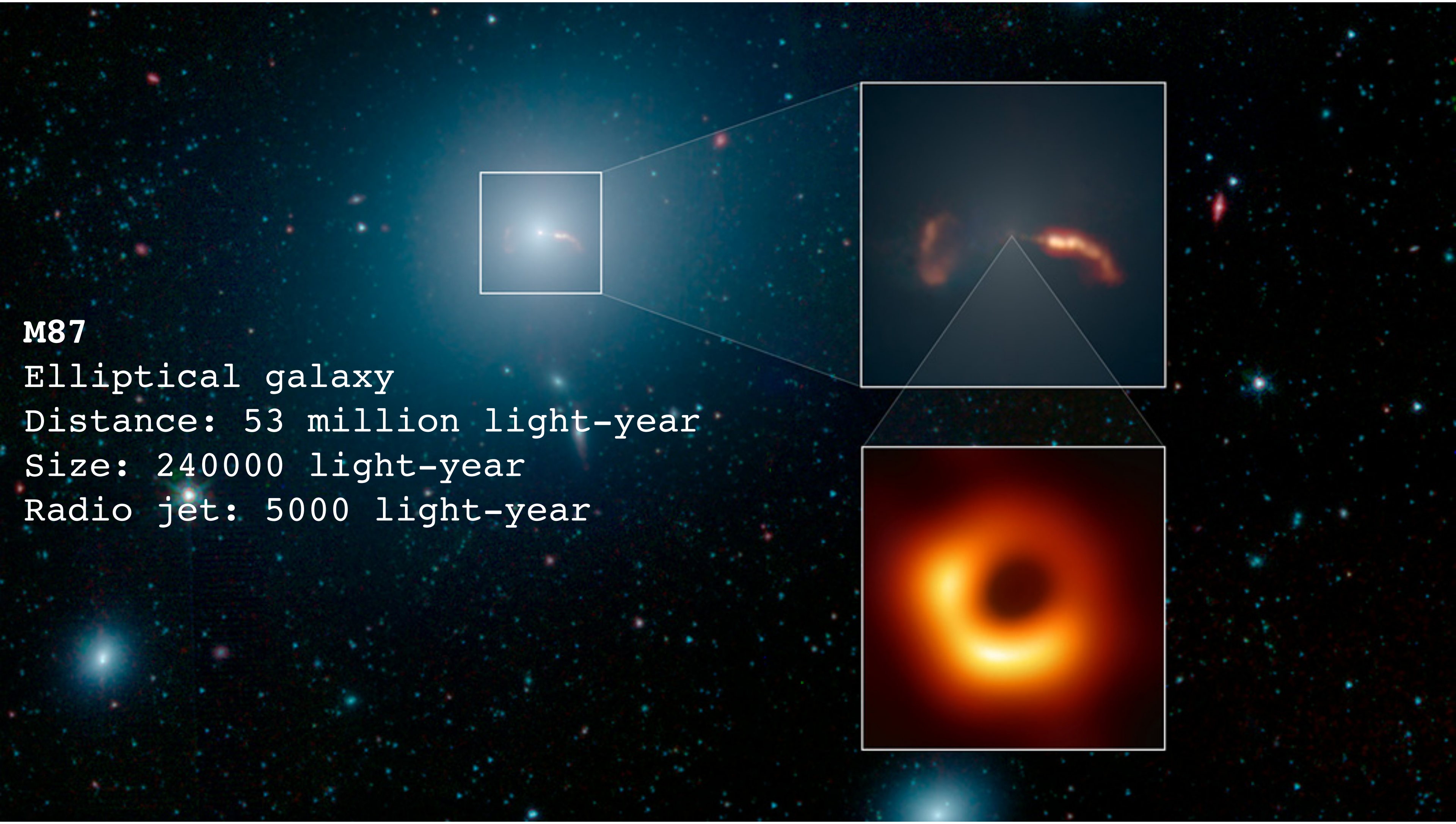


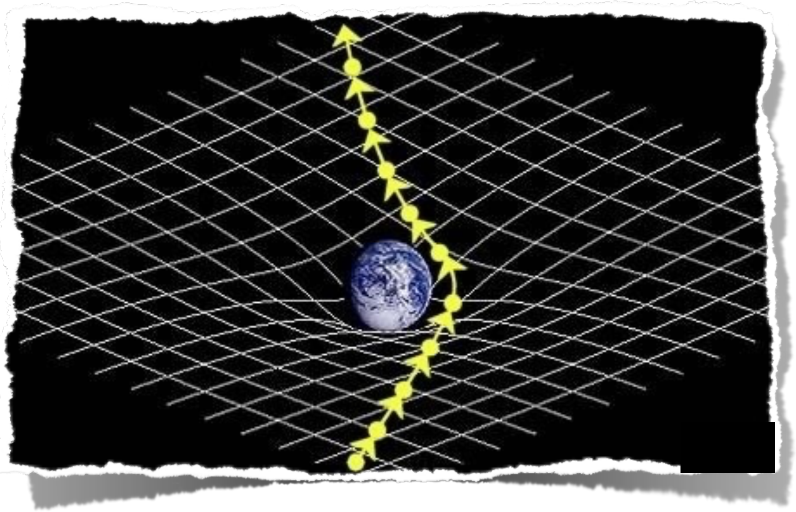
NASA/EHT collaboration

Question

What are we exactly seeing?

Data supporting the presence of a SMBH

Space-time curvature



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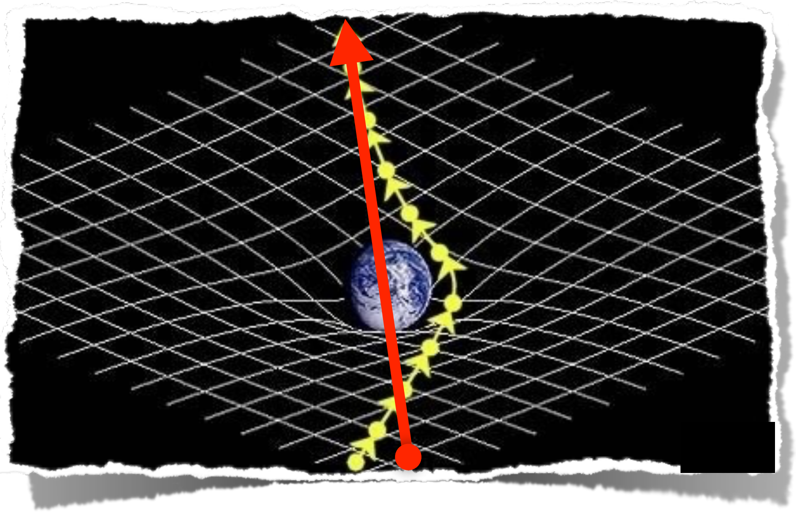

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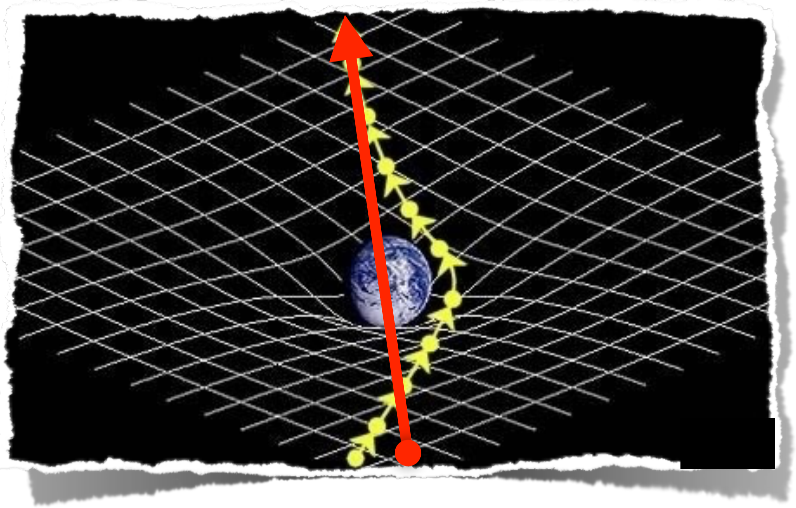
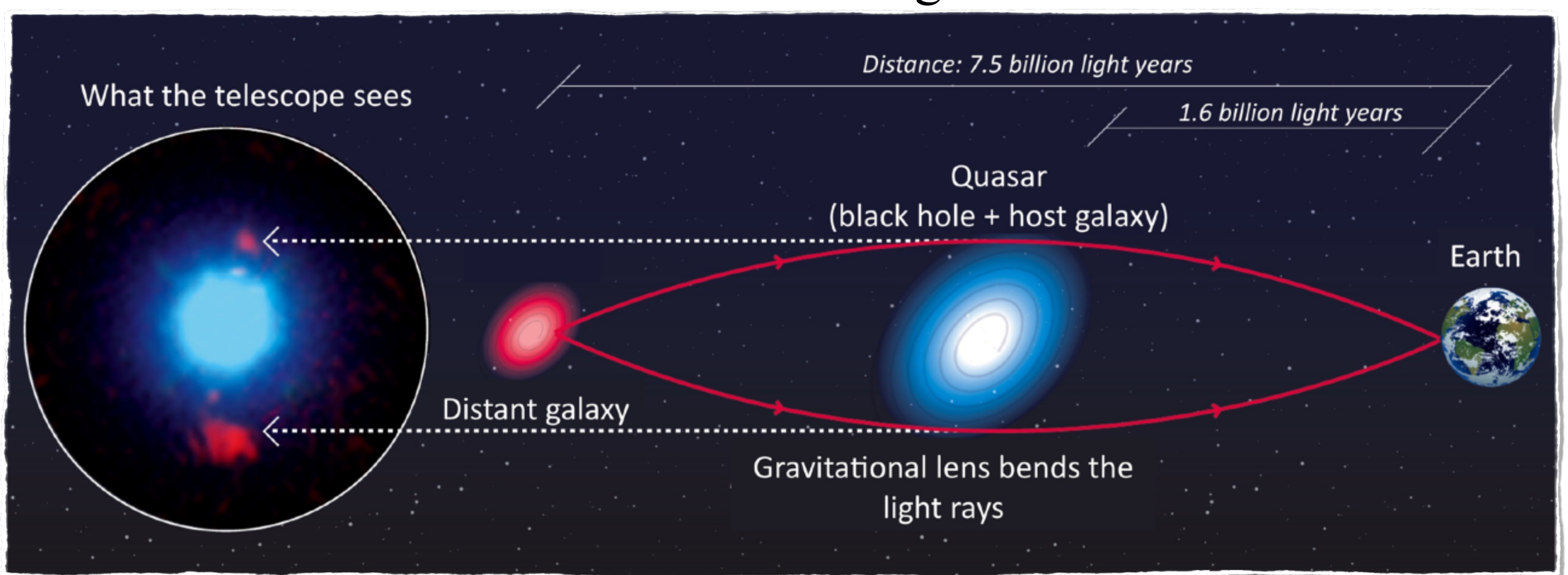


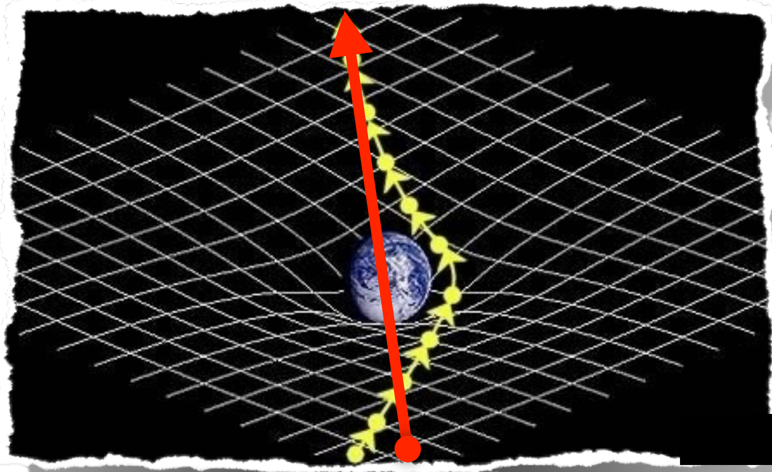
On galactic scales



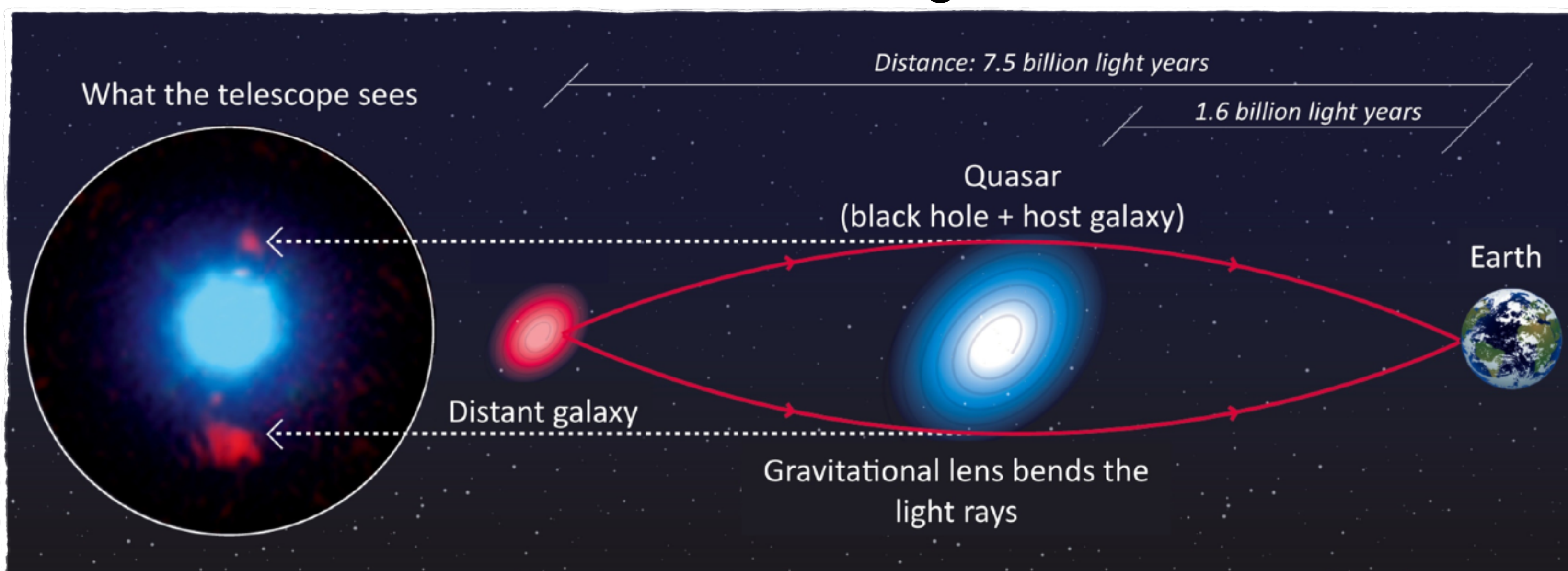
Astronomy Stack Exhange

Data supporting the presence of a SMBH

Space-time curvature



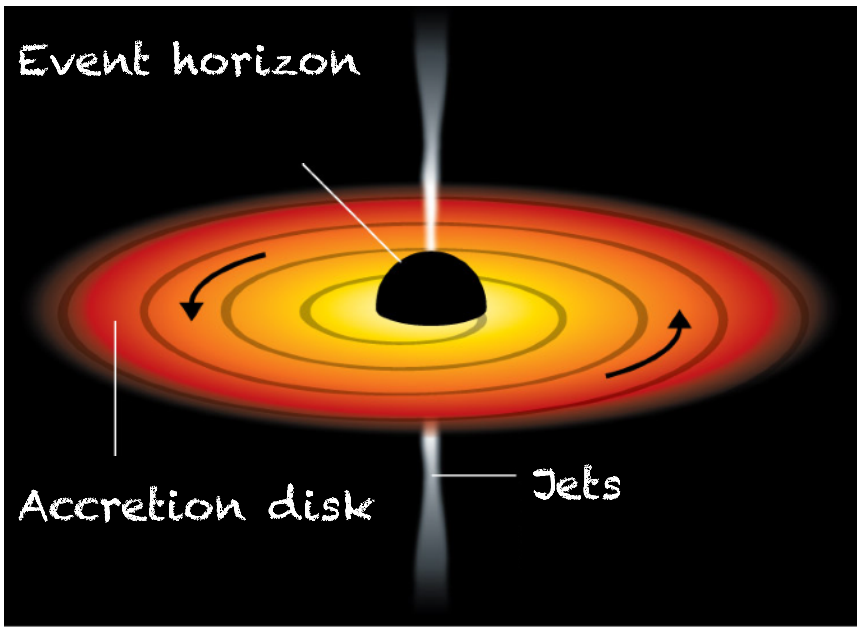
On galactic scales



Astronomy Stack Exhange

Data supporting the presence of a SMBH

The sketch...



Data supporting the presence of a SMBH

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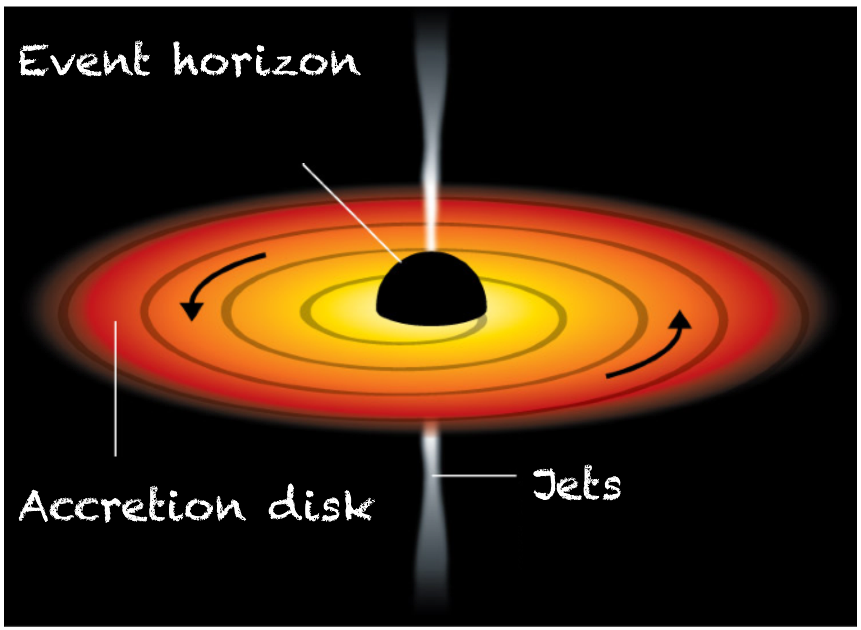
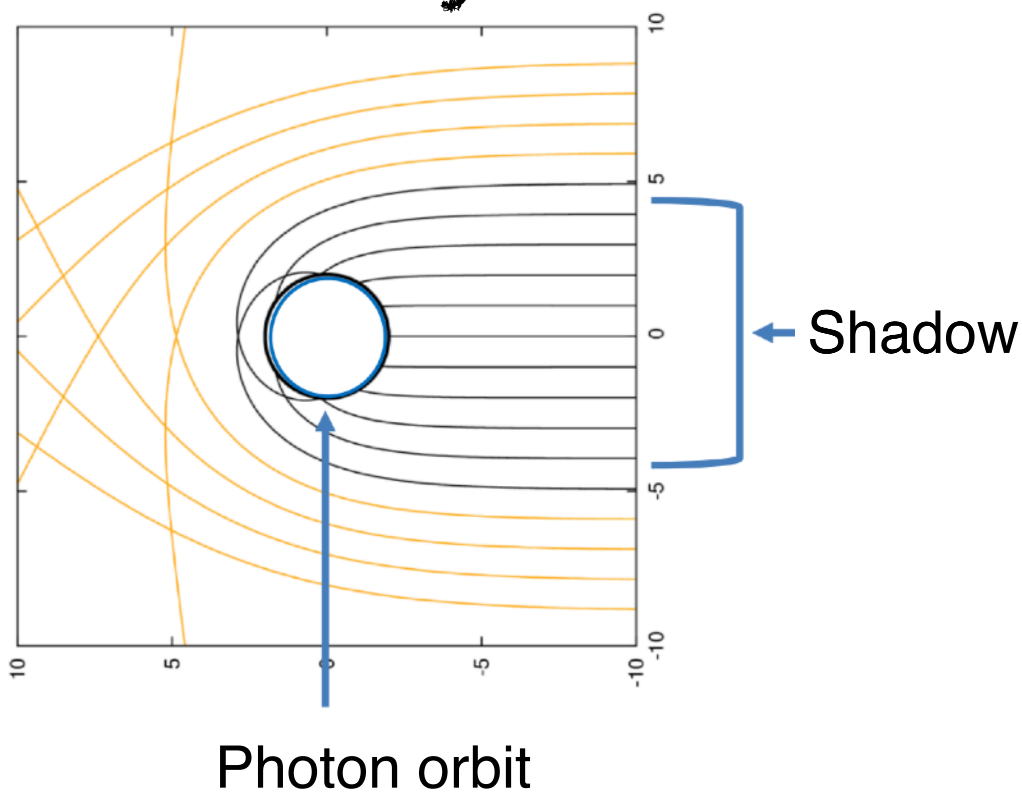
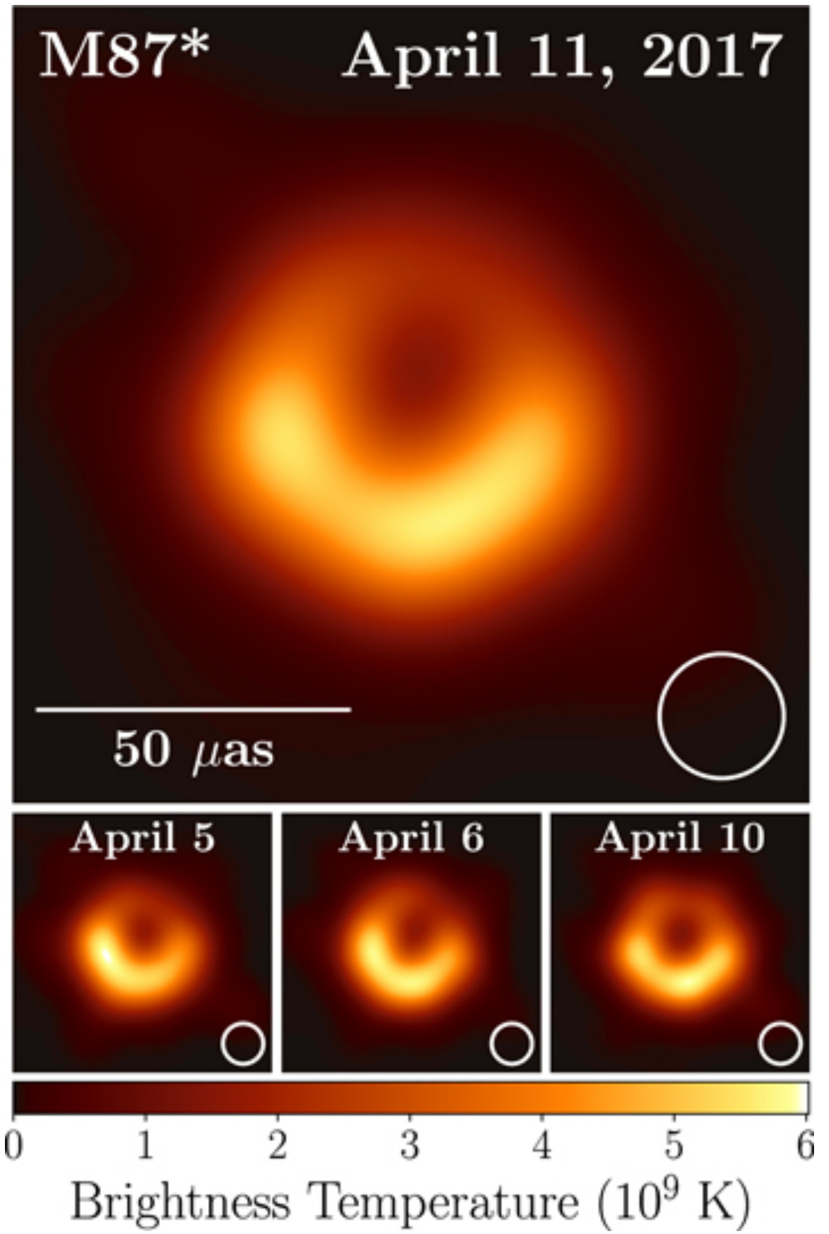


...the reality!



Data supporting the presence of a SMBH



Event horizon:
40.000 million km

EHT collaboration

Data supporting the presence of a SMBH

EHT collaboration

Data supporting the presence of a SMBH

SIMULATIONS

420 combinations of rotation and fluid composition

EHT collaboration

Data supporting the presence of a SMBH

SIMULATIONS

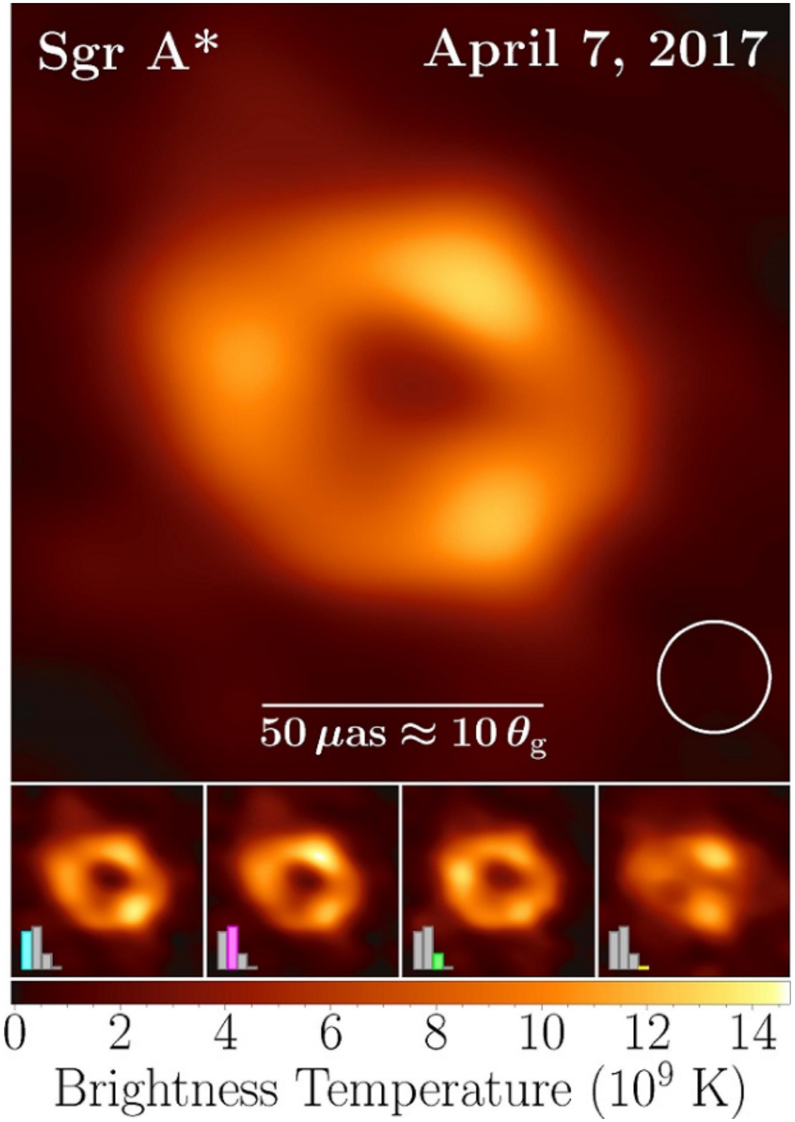
420 combinations of rotation and fluid composition

Plasma in clockwise rotation around the black hole

$M_{BH} = 6.5 \times 10^9 M_\odot$

EHT collaboration

Data supporting the presence of a SMBH



EHT collaboration

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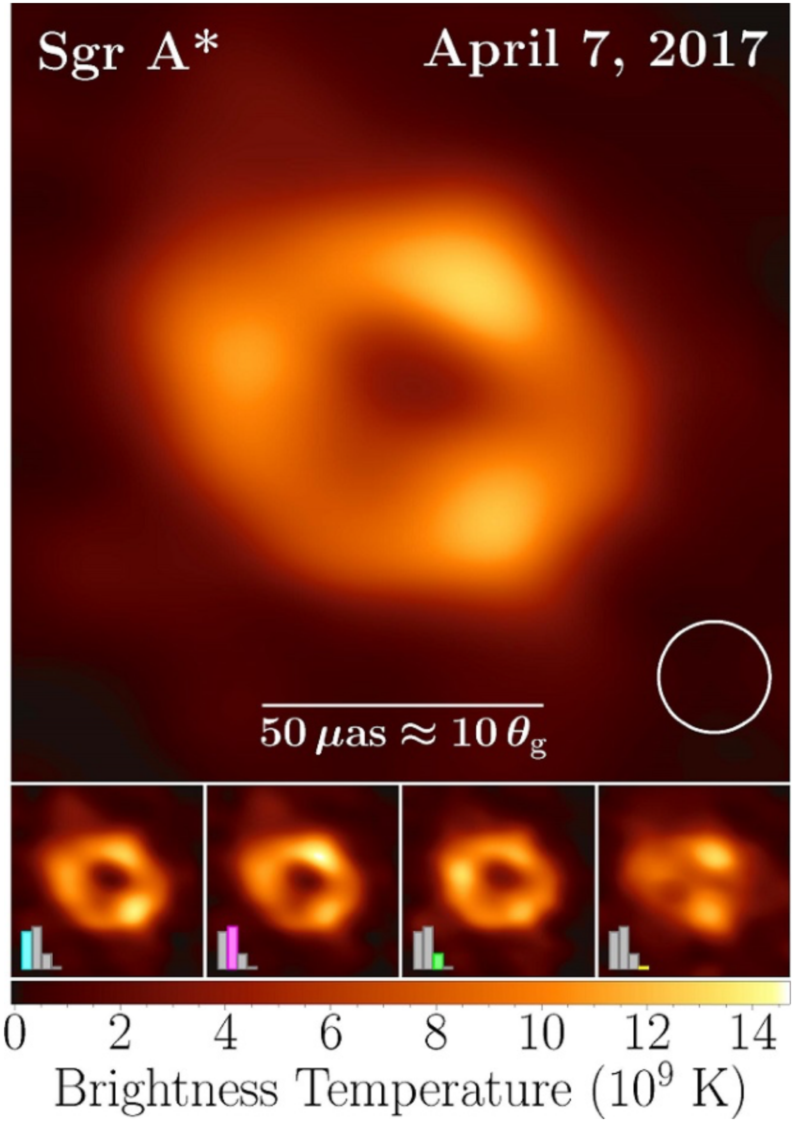
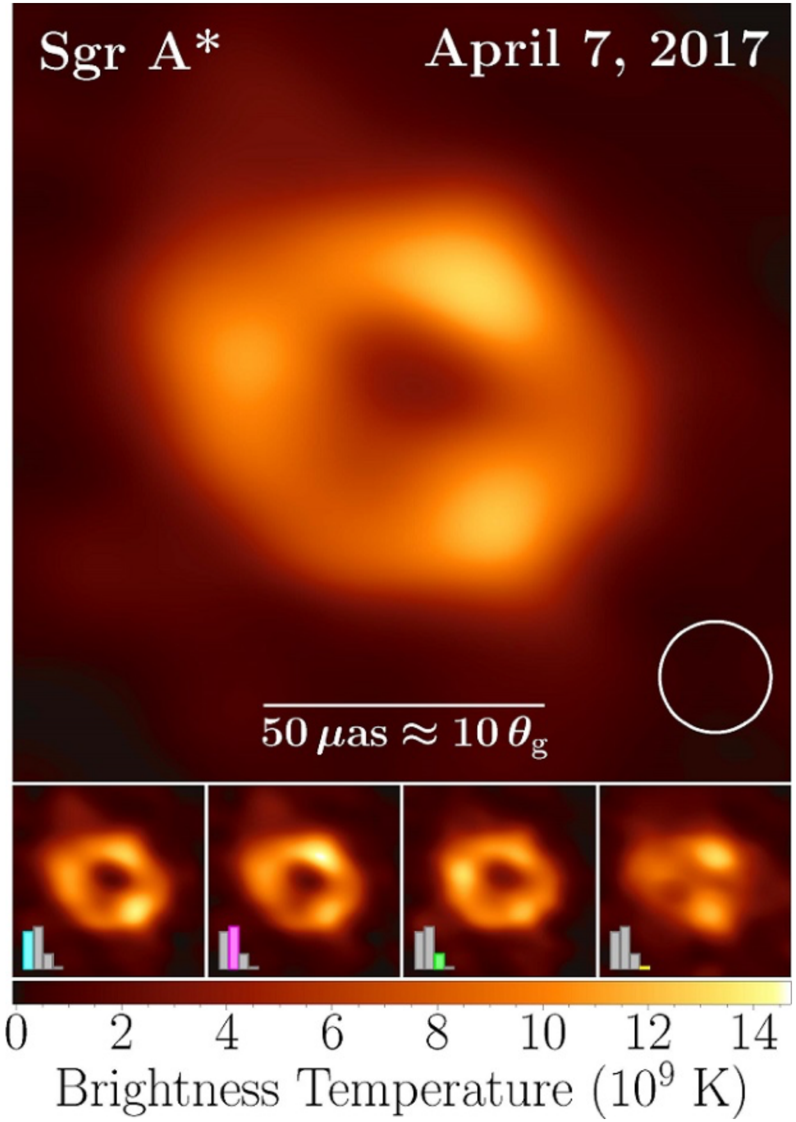


$M_{BH} = 4 \times 10^6 M_\odot$

Rotation period = 30 min

EHT collaboration

Data supporting the presence of a SMBH



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Frequency of the different images

EHT collaboration

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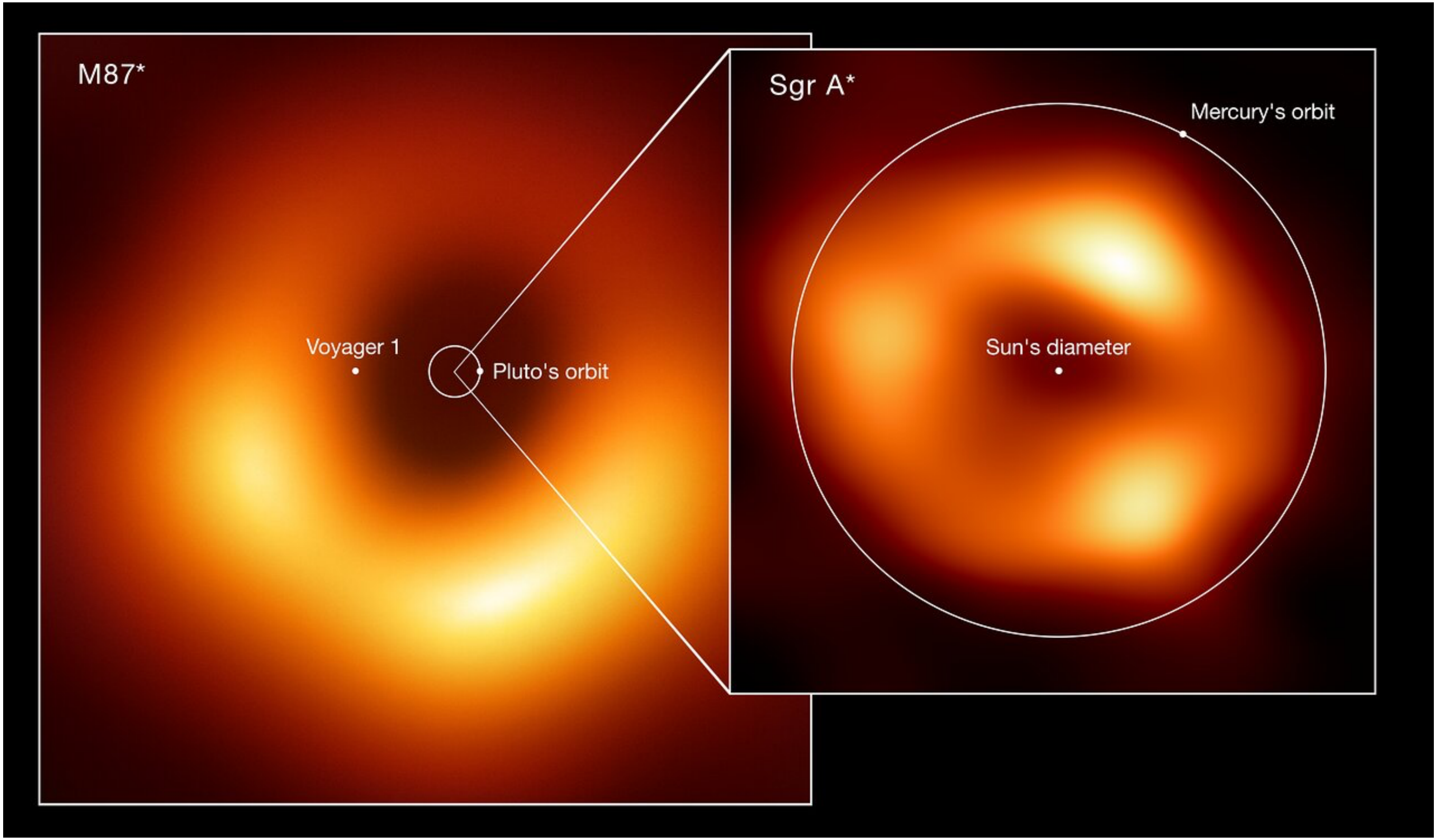


M87
Distance: 53 million light-year

Sgr A*
Distance: 27000 light-year

EHT collaboration

Question

How many AGN types do you know?

AGN Zoology

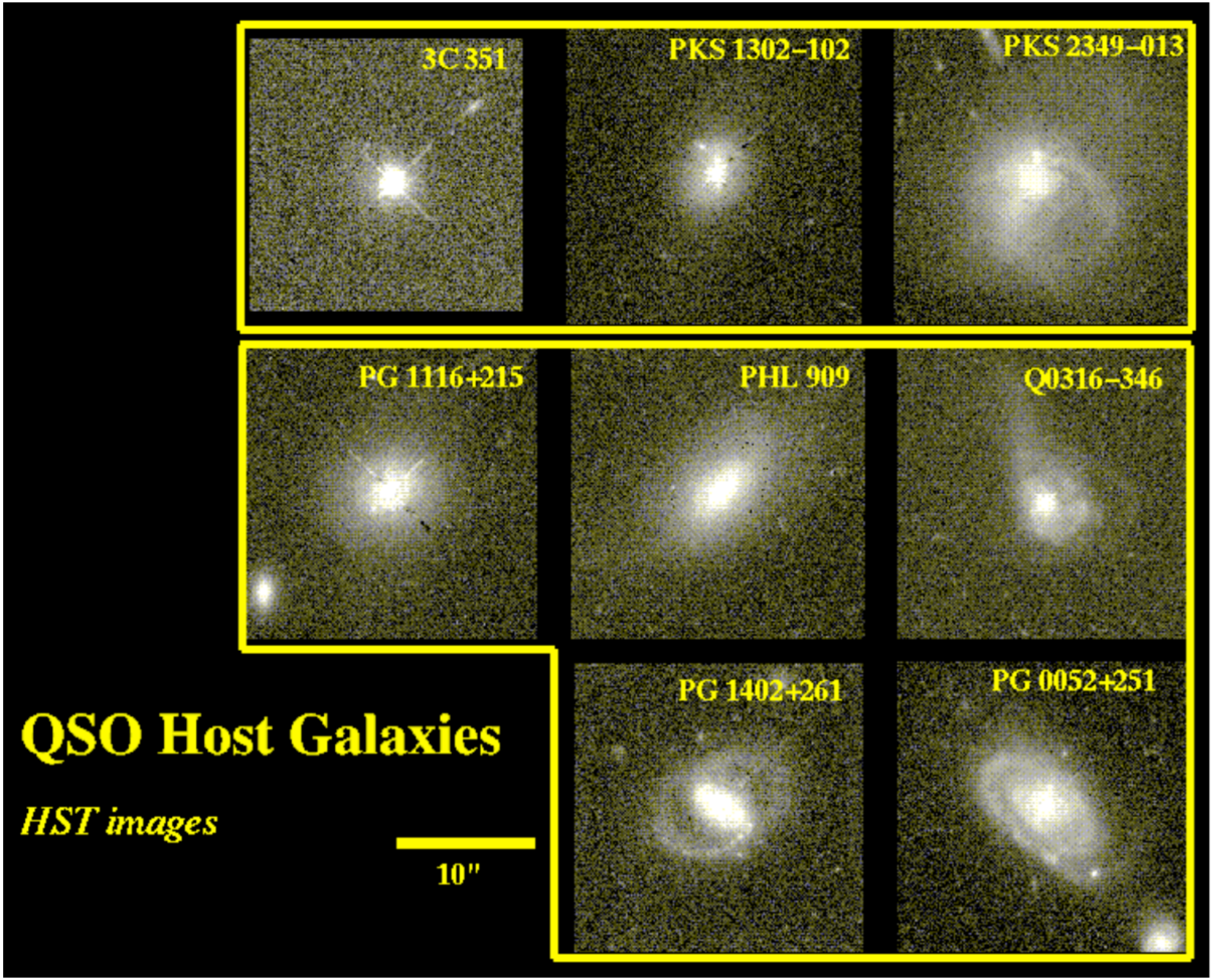
- Radio galaxies
- Radio Quasars
- BL Lac Objects
- Optically Violent Variables (OVV's)
- Radio Quiet Quasars (QSOs)
- Seyfert I galaxies (SyI)
- Seyfert II galaxies (SyII)
- Low Ionization Nuclear Emission-Line Regions (LINERs)

AGN Classification

- There is a large diversity in the nature of the observed radiation from different AGN
- The classification scheme has varied with time
- A fundamental division in the classification scheme is based on the radio properties of AGN:

radio-loud or radio-quiet

AGN Classification



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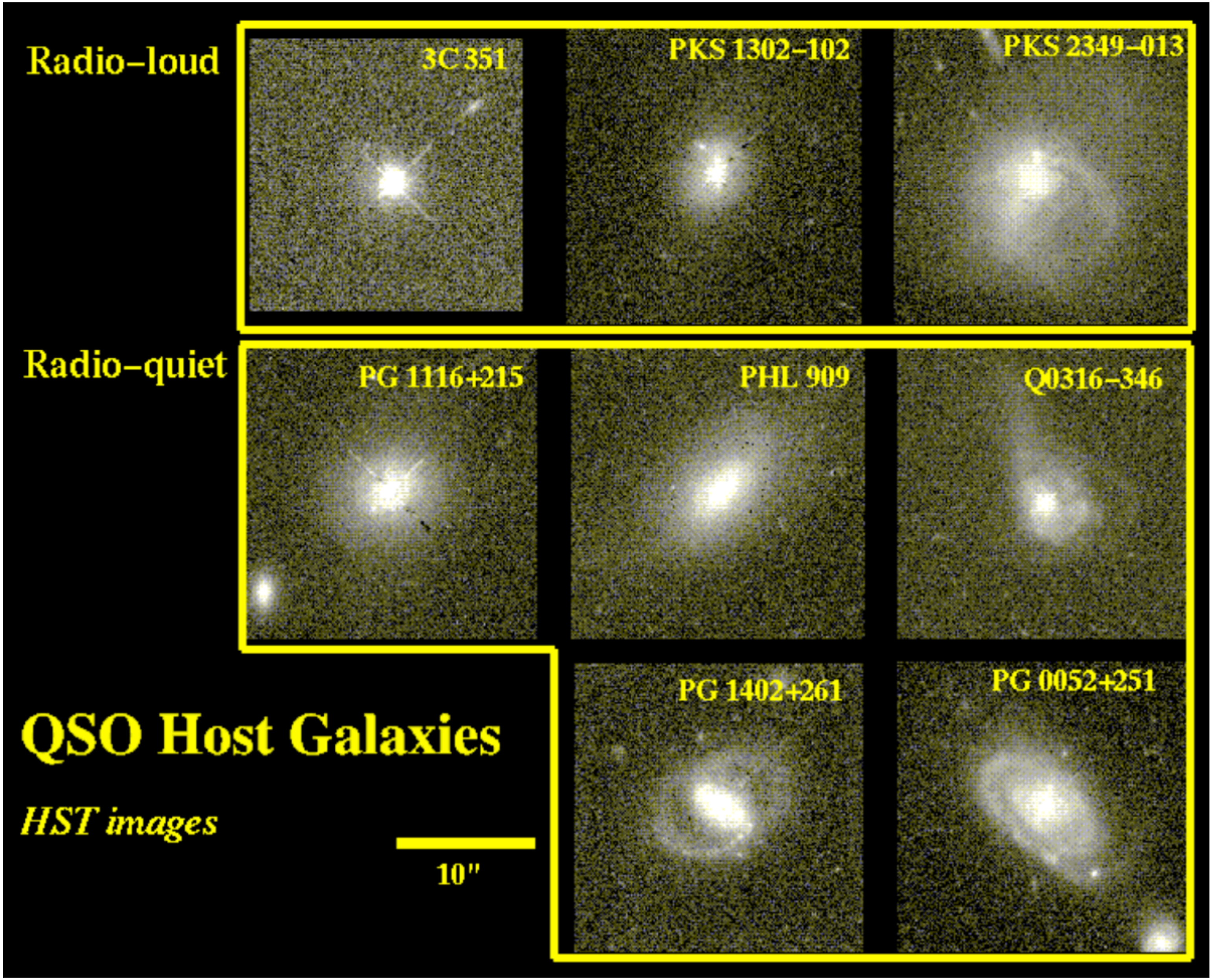

AGN Classification

Radio-quiet AGN

- Do not show large scale collimated jets (extent <0.5 kpc)
- Within radio-quiet AGN: classification on the basis of optical/UV spectral properties

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Seyfert I galaxies/radio-quiet quasars

- Spectrum is complex and multicomponent
- Presence of broad (FWHM~2000-20000 km/s) permitted optical/UV emission lines
- Possible presence of low-ionization broad lines (MgIIλ2798 and hydrogen lines) and high-ionization broad lines (CIVλ1549, OVIλ1035 and NeVIIIλ774)

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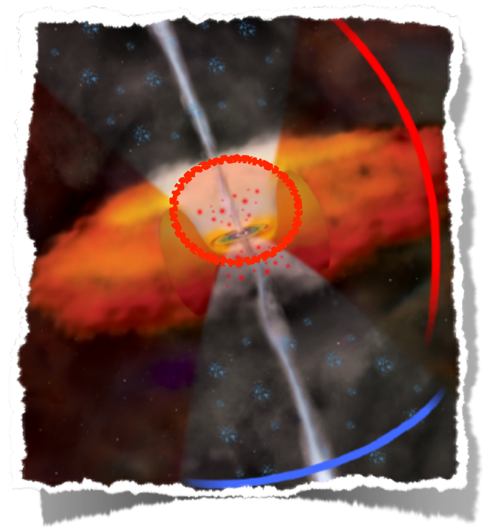

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Broad line region: dense ($n_e \sim 10^9$ cm^{-3}) photoionized clouds with small volume filling factor

AGN Classification

Seyfert I galaxies/radio-quiet quasars

- Line widths due to cloud motions
- Collisional de-excitation dominates over forbidden line emission due to high density
- Optical/UV narrow (~500 km/s) permitted and forbidden emission lines also present in spectra
- e.g.: hydrogen lines, [OII]λ3727, [OIII]λ5007, [NII]λ6583, [SII]λ6716/6731
- The NLR can be spatially resolved in nearby AGN and is found to have typical sizes of 0.1 kpc

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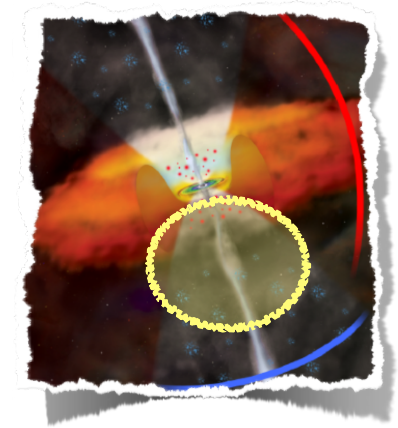


Narrow line region: material more teneous than BLR, at larger distances from black hole

AGN Classification

Seyfert I galaxies vs radio-quiet quasars

- Distinction between Seyfert I and radio-quiet quasar (RQQ or quasi-stellar object QSO) based on whether the galaxy or AGN is discovered first

- SyI are generally lower-luminosity than RQQ:
  Dividing luminosity $L_{bol} \sim 10^{45}$ erg/s, $L_X \sim 10^{42}$ erg/s

- In practice, SyI and RQQs form a continous sequence in luminosity

- Both display strong continuum radiation from IR through gamma-ray wavelengths

- The higher-energy emission is often observed to vary rapidly

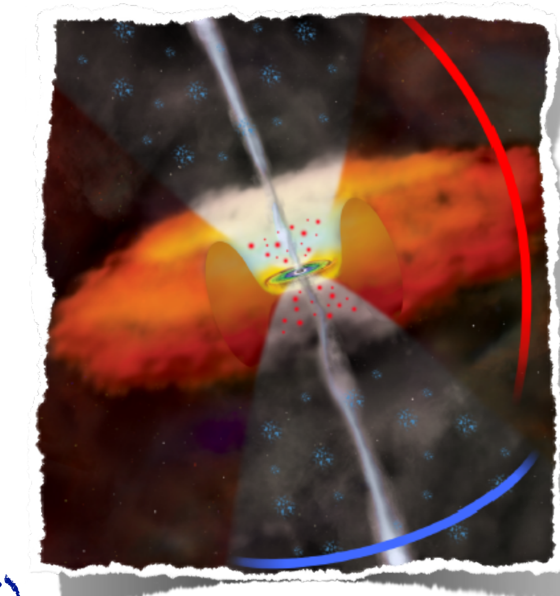
AGN Classification

Seyfert II galaxies

- Their spectra display narrow permitted and forbidden emission lines

- Unlike SyI galaxies, no broad lines are observable and the optical/UV radiation is much weaker

- Some display broad optical/UV lines in polarimetry or NIR observations



Antonucci (1993), Urry & Padovani (1995)

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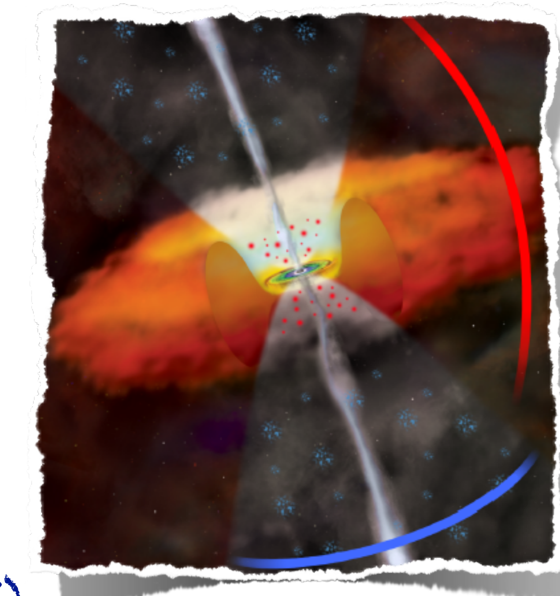

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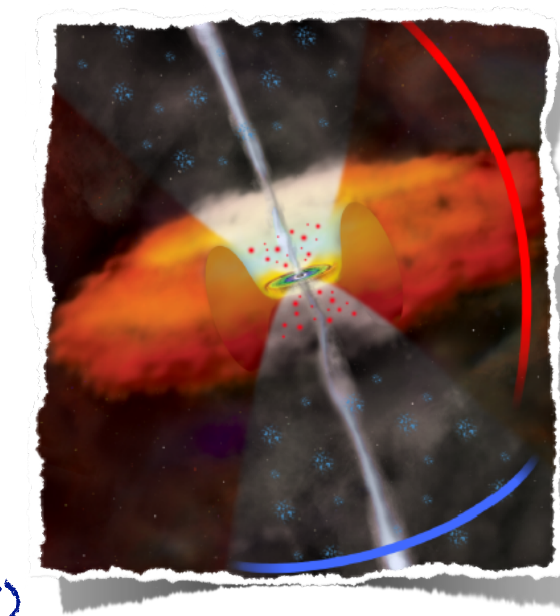
- X-ray observations reveal photoelectric absorption from cold gas presumably associated with the dust



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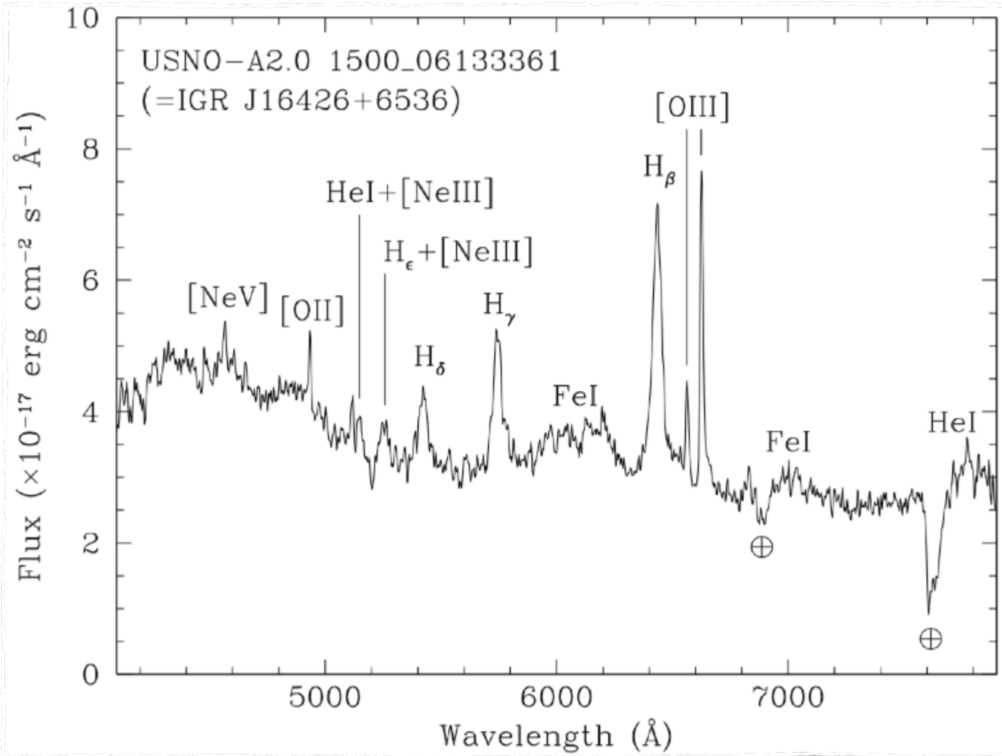
AGN Classification

Narrow line Seyfert I galaxies (NLS1)

Masetti et al. (2009)



AGN Classification

Narrow line Seyfert I galaxies (NLS1)

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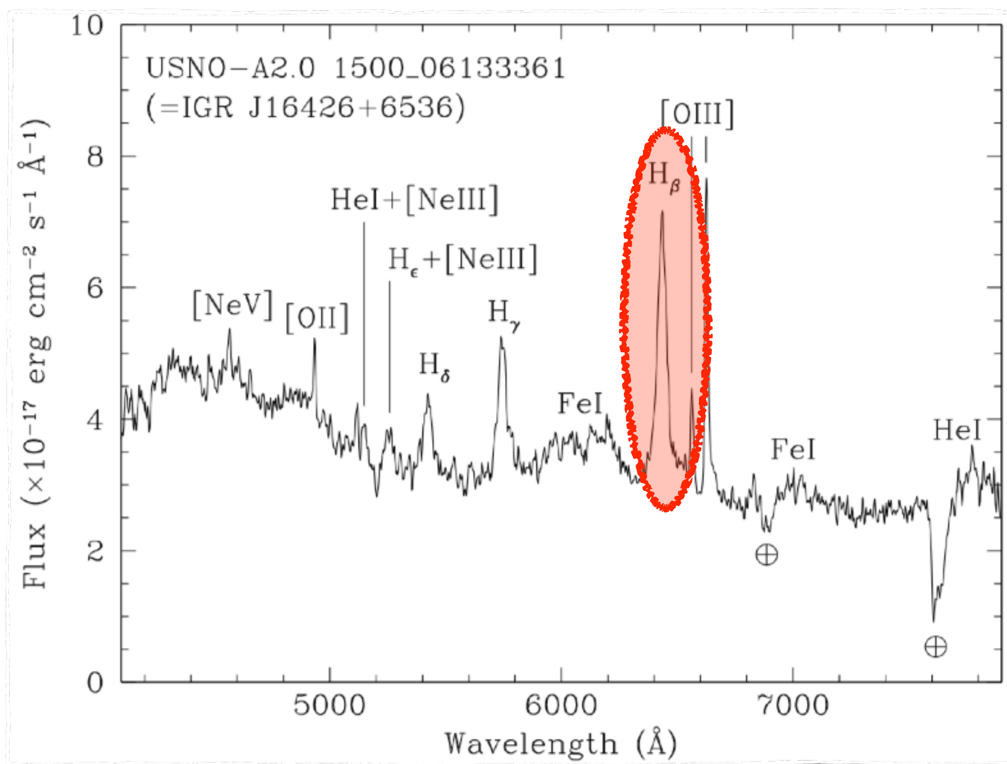
- Ratio [OIII]λ5007/Hβ < 3, a criterion used to differentiate SyI from SyII



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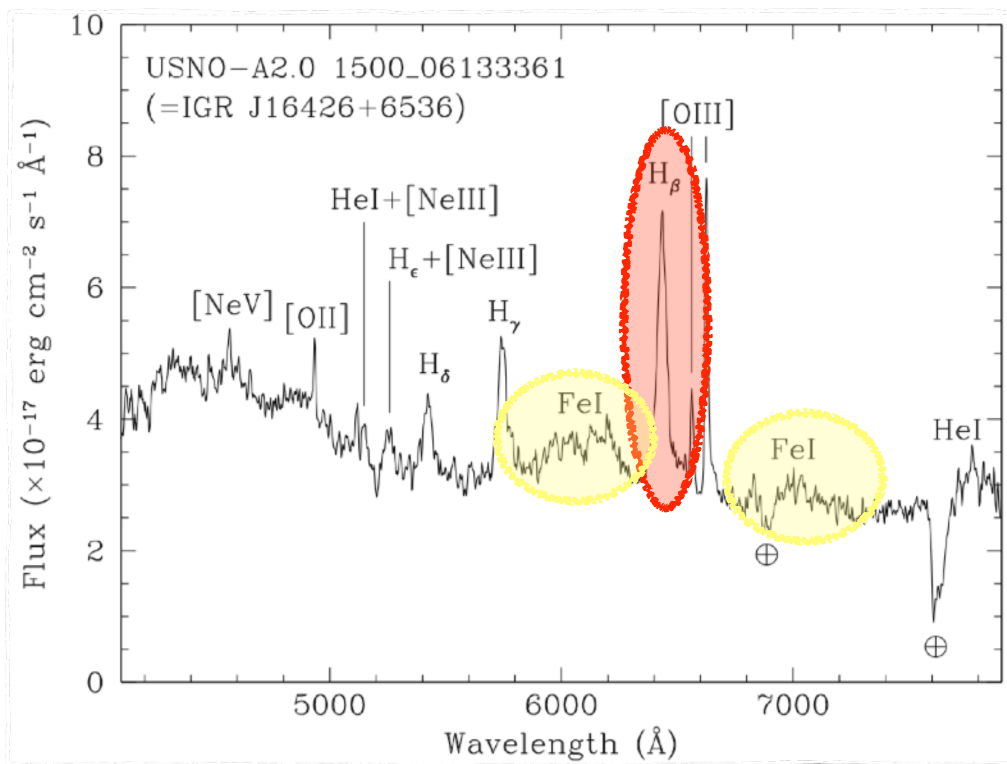
- Display strong optical line complexes due to FeII emission: FeII/Hβ > 0.5

- X-ray continuum softer and more variable than normal SyI



Masetti et al. (2009)

AGN Classification

Narrow Emission Line galaxies (NELGs)

- Show narrow (FWHM<1000 km/s) emission lines, typically of Hα, Hβ, [OIII]λ5007
- X-ray luminosities $L_x \sim 10^{42}$ erg/s (two orders of magnitude brighter than normal galaxies)
- Often classified as AGN but part of the emission may be due to star formation
- Good candidates for producing the X-ray background due to number of sources and hard spectra

AGN Classification

Radio-loud AGN

- Emit collimated jets of plasma that feed energy and high-energy particles into extended halo or lobe. Large-scale jet (extent > 0.5 kpc). The halo can be > 1Mpc
- Jets and radio halo: sources of continuum radio emission (synchrotron emission from relativistic electrons in jet/halo plasma

Perseus cluster
Minihalo

Radio, optical
Gendron-Marsolais et al. (2017)
NRAO, NASA, SDSS

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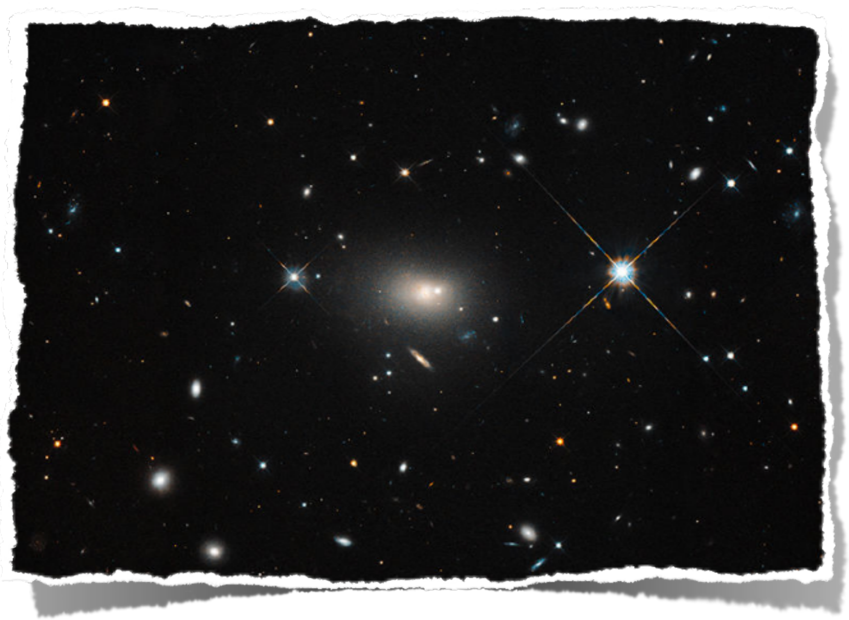
Hercules A



X-ray, radio, optical
NASA, NRAO

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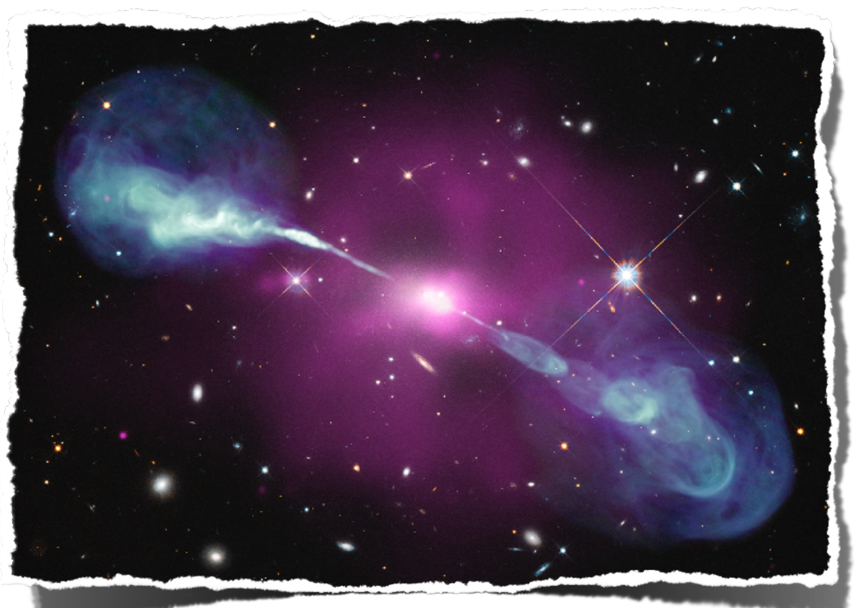

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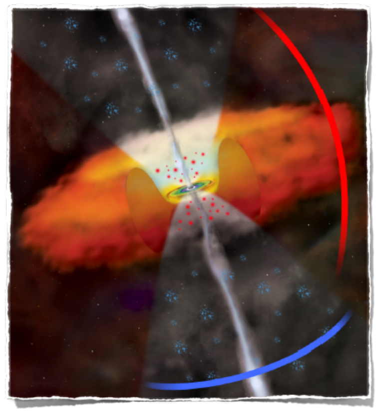
AGN Classification

Radio-loud AGN

- Some present only one observable jet



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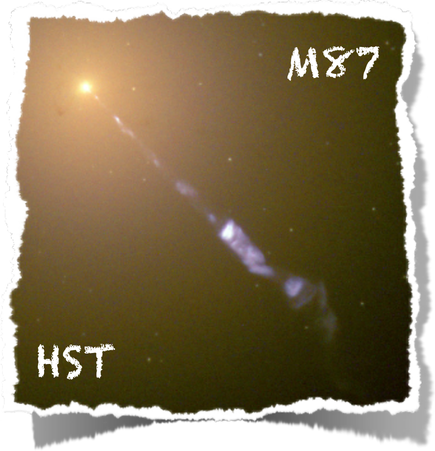

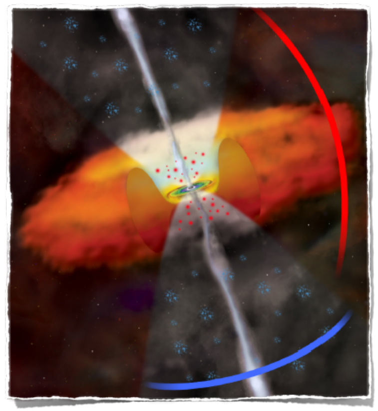

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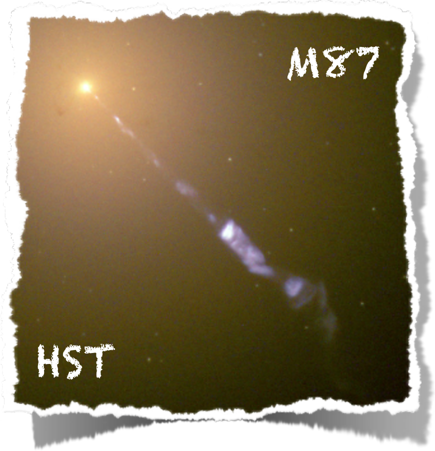

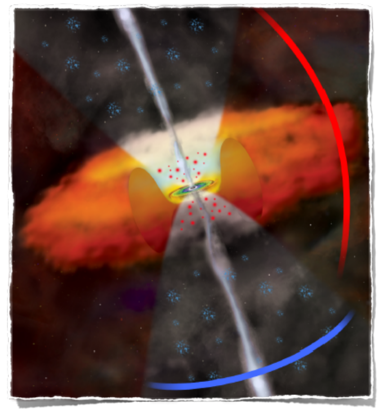

Antonucci (1993), Urry & Padovani (1995)

- Outflowing blobs within the jets

AGN Classification

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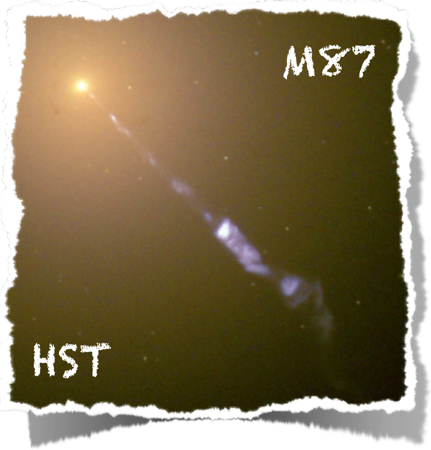

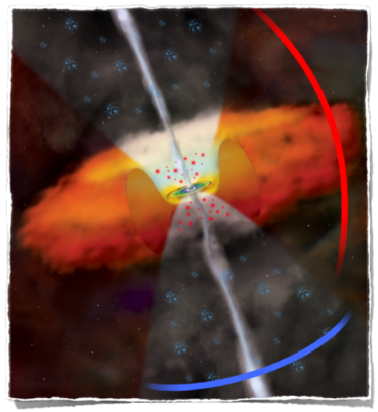

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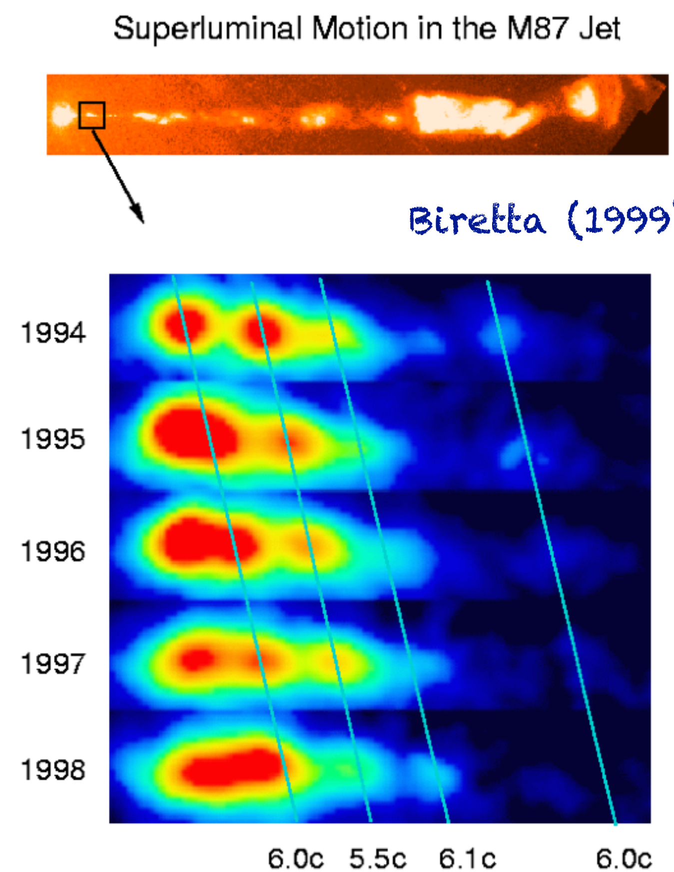

Biretta (1999)

- Outflowing blobs within the jets

  Blobs superluminal motion:
  apparent proper motion can exceed *c*.
  This results from relativistic motion in a direction ~towards the observer

AGN Classification

Radio-loud AGN

- Within radio-loud AGN: classification on the basis of both radio morphology and optical/UV spectral properties

AGN Classification

Radio-loud AGN

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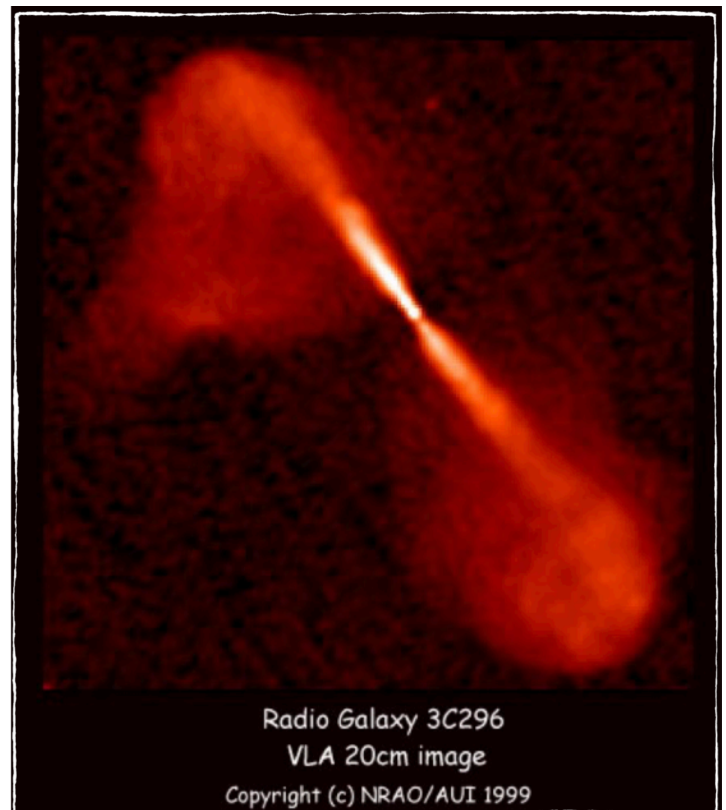
FR-I (Fanaroff-Riley-I) radio galaxies

- Edge-darkened morphology: radio surface brightness profile falls continuously from nucleus to the edge of radio lobes
- Low luminosity ($L_{radio} < 10^{42}$ erg/s)
- Display narrow emission lines from NLR, but no broad emission lines



AGN Classification

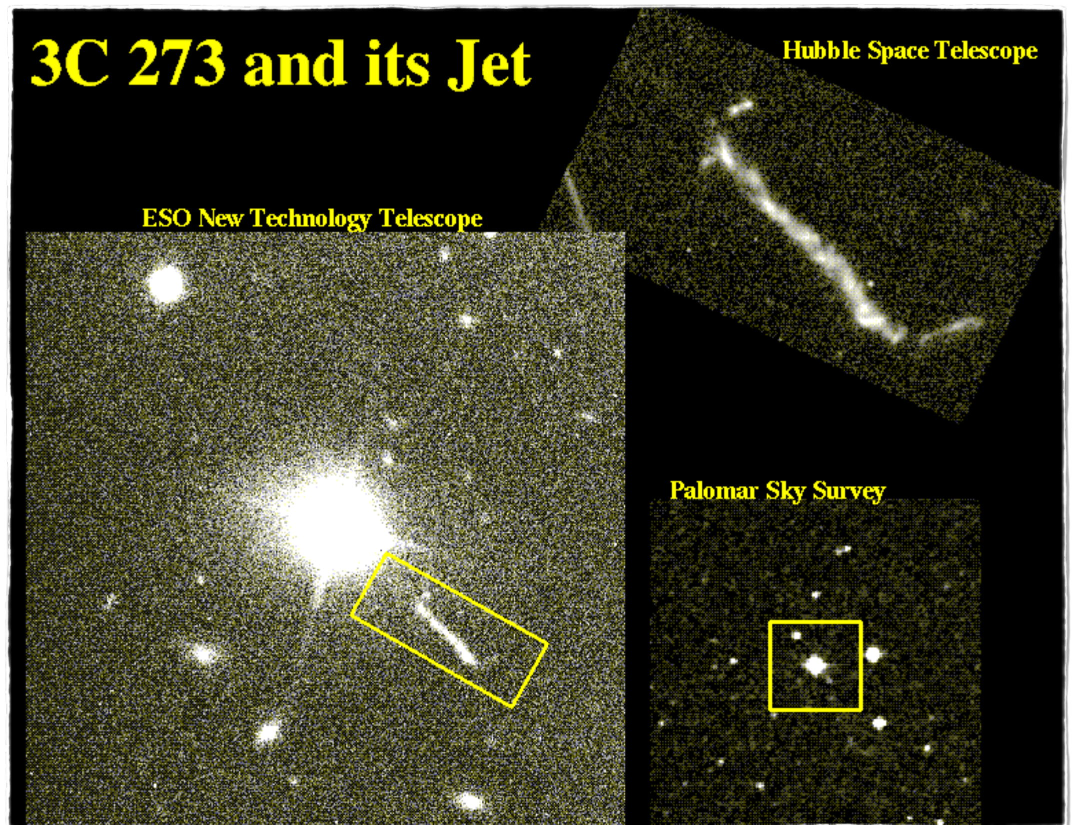
FR-II (Fanaroff-Riley-II) radio galaxies

- Edge-brightened morphology: nucleus apart, radio surface brightness low at the centre and dramatically brightens towards edge of halo due to jet(s) terminating at strong shocks
- High luminosity ($L_{radio} > 10^{42}$ erg/s)
- Optical properties either SyI-like or SyII-like: broad line radio galaxies (BLRG) and narrow line radio galaxies (NLRG), respectively

AGN Classification

Radio-loud quasars (RLQ)

- Blurred distinction between BLRG and RLQ (or simply quasar)
- RLQ = BLRG in which AGN continuum emission dominates over radio emission
- RLQ often posses one-sided jets with superluminal motion



AGN Classification

Blazars

- Radio-loud objects displaying very strong and variable continuum at all wavelengths
- High optical polarization ($\geq 3\%$)
- Optical/UV emission lines very weak or absent

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Sub-classification:

AGN Classification

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Sub-classification: optically-violent variable (OVV)

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- Flat radio spectrum: flat-spectrum radio quasars (FSRQ)

AGN Classification

AGN bestiary

Beast	Point like	Broad-band	Broad lines	Narrow lines	Radio	Variable	Polarized
Radio-loud quasars	YES	YES				SOME	SOME
Radio-quiet quasars	YES	YES				WEAK	WEAK
Broad line radio galaxies (**FR 2 only**)	YES	YES				WEAK	WEAK
Narrow line radio galaxies (FR1 and FR2)	NO	NO				NO	NO
OVV quasars	YES	YES				YES	YES
BL Lac objects	YES	YES				YES	YES
Seyferts type 1	YES	YES				SOME	WEAK
Seyferts type 2	NO	YES				NO	SOME
LINERs	NO	NO				NO	NO

Krolik

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Krolik

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OVV quasars	YES	YES				YES	YES
BL Lac objects	YES	YES				YES	YES
Seyferts type 1	YES	YES				SOME	WEAK
Seyferts type 2	NO	YES				NO	SOME
LINERs	NO	NO				NO	NO

Krolik

AGN Classification

AGN bestiary

Beast	Point like	Broad-band	Broad lines	Narrow lines	Radio	Variable	Polarized
Radio-loud quasars	YES	YES	YES	YES	YES	SOME	SOME
Radio-quiet quasars	YES	YES	YES	YES	WEAK	WEAK	WEAK
Broad line radio galaxies (**FR 2 only**)	YES	YES	YES	YES	YES	WEAK	WEAK
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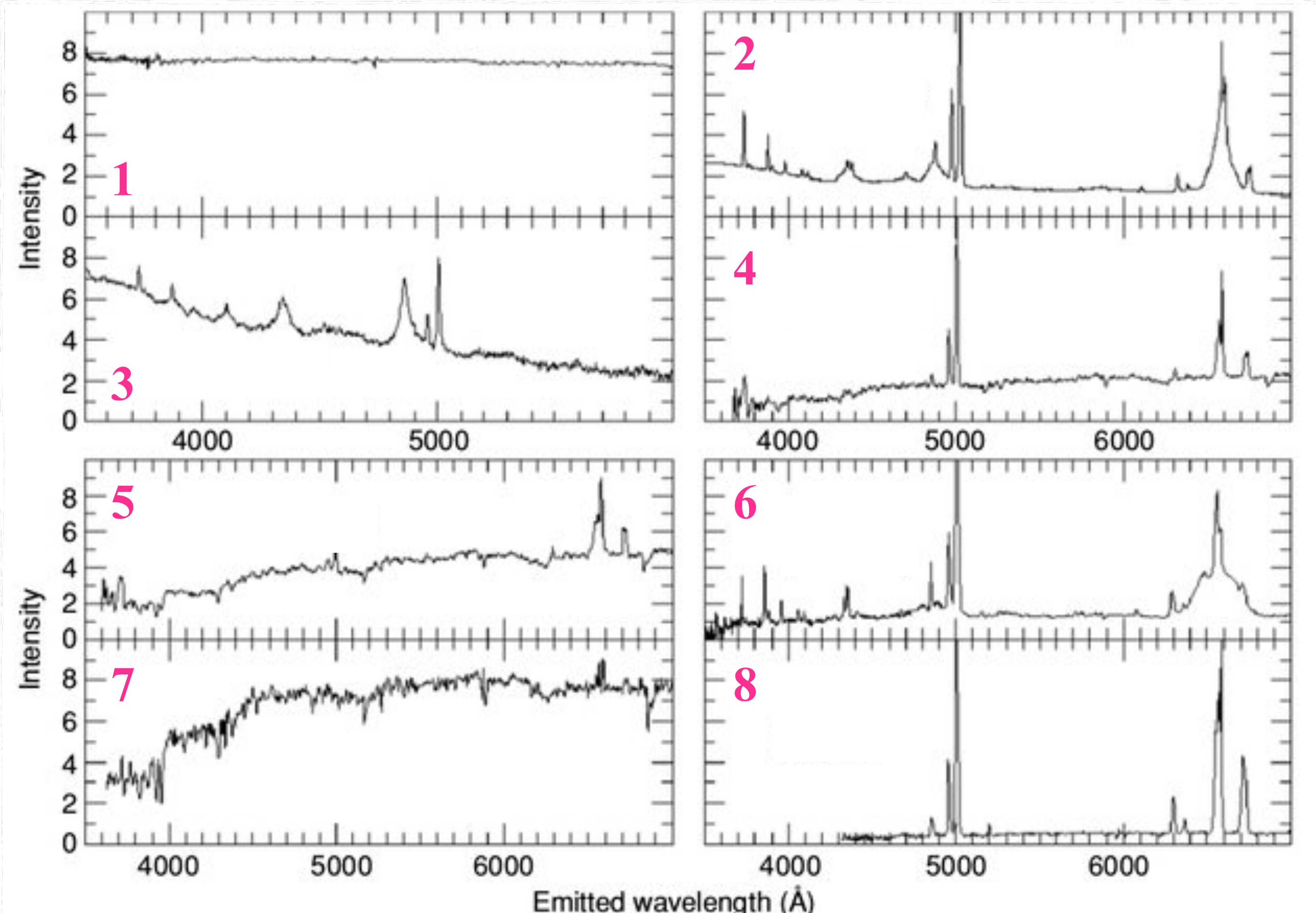
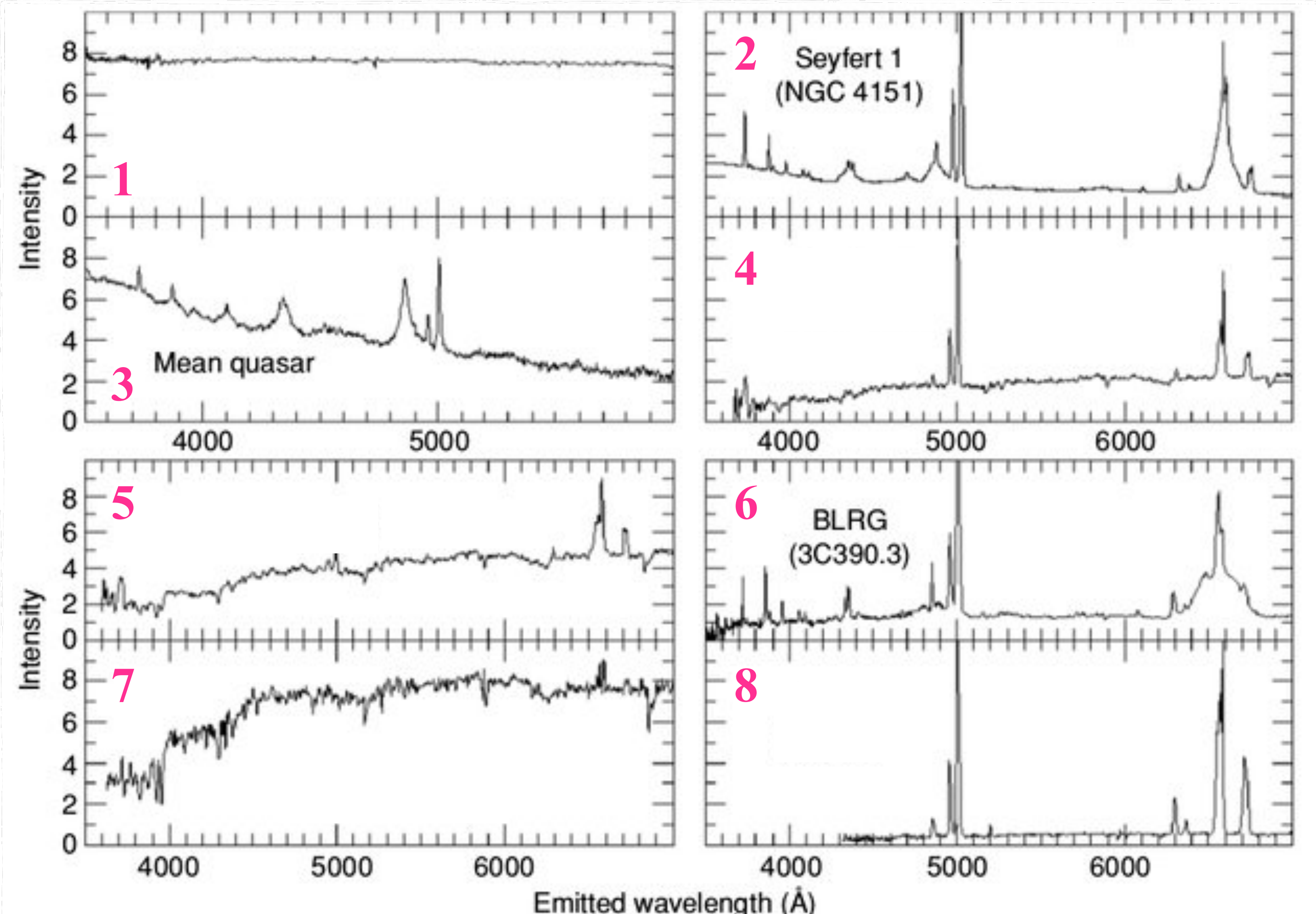
Krolik

AGN Classification: find the Seyfert 1 & BLRG



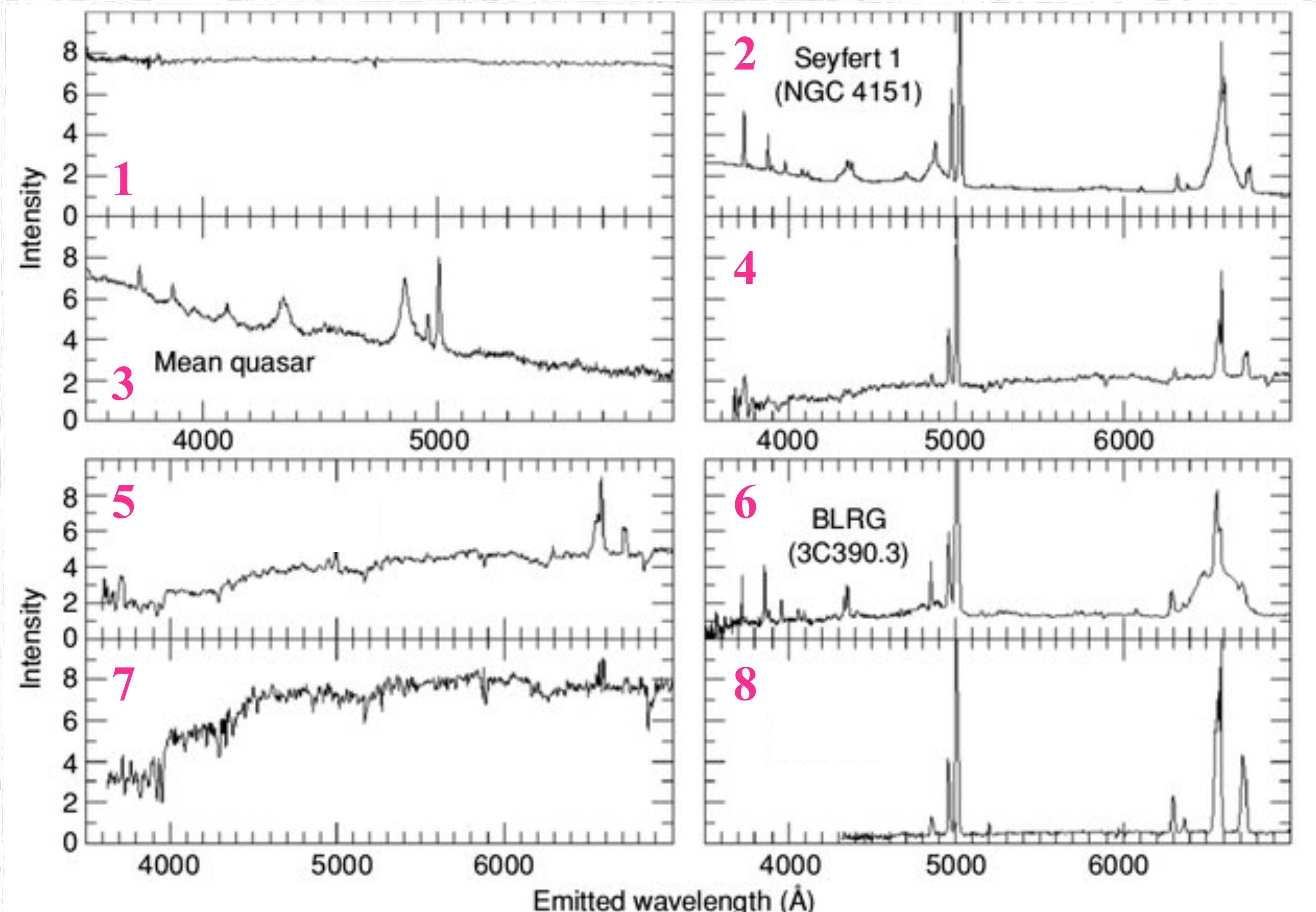
Irham Taufik Andika

AGN Classification: find the Seyfert 1 & BLRG



Irham Taufik Andika

AGN Classification: find the Seyfert 2 & NLRG



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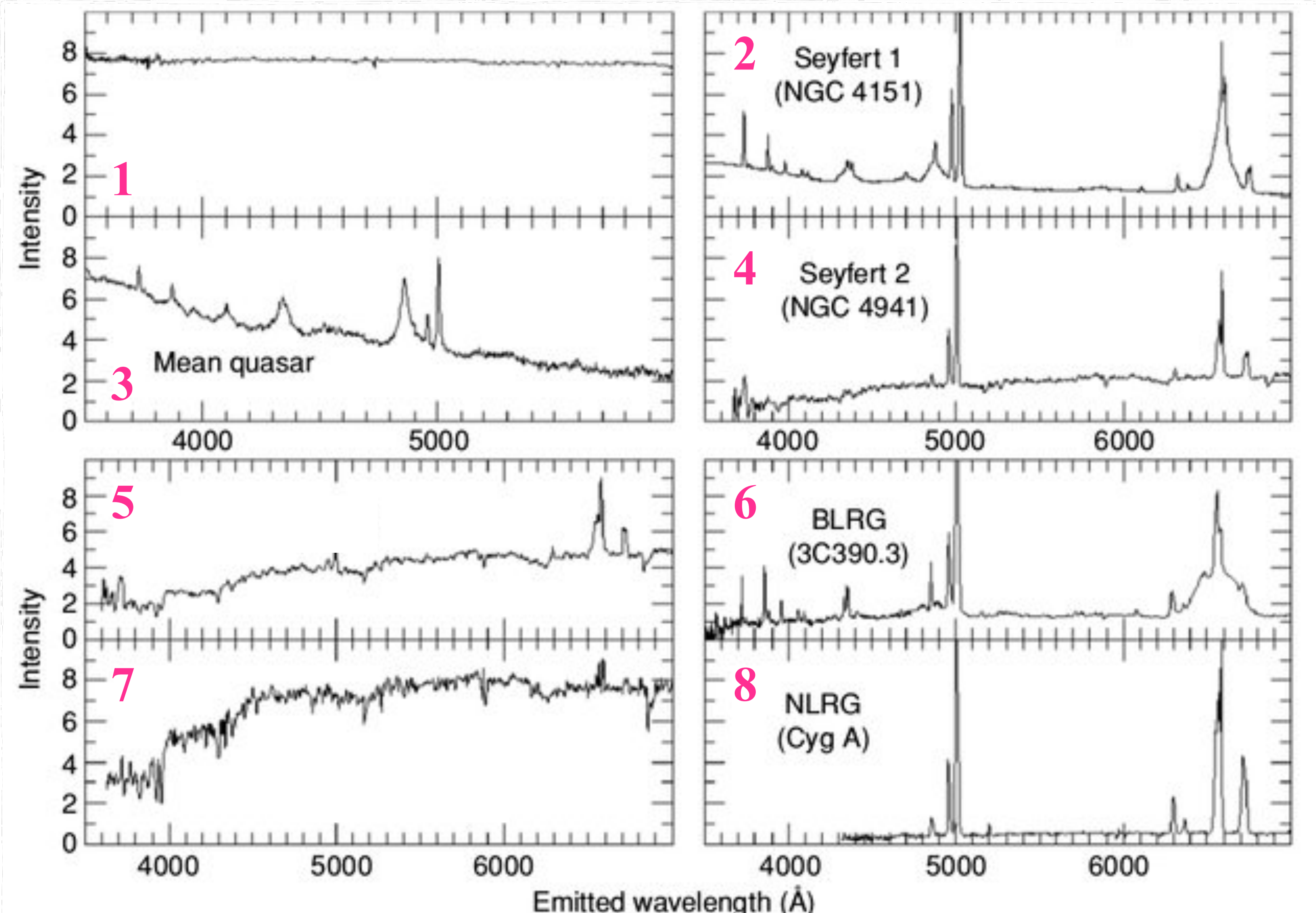
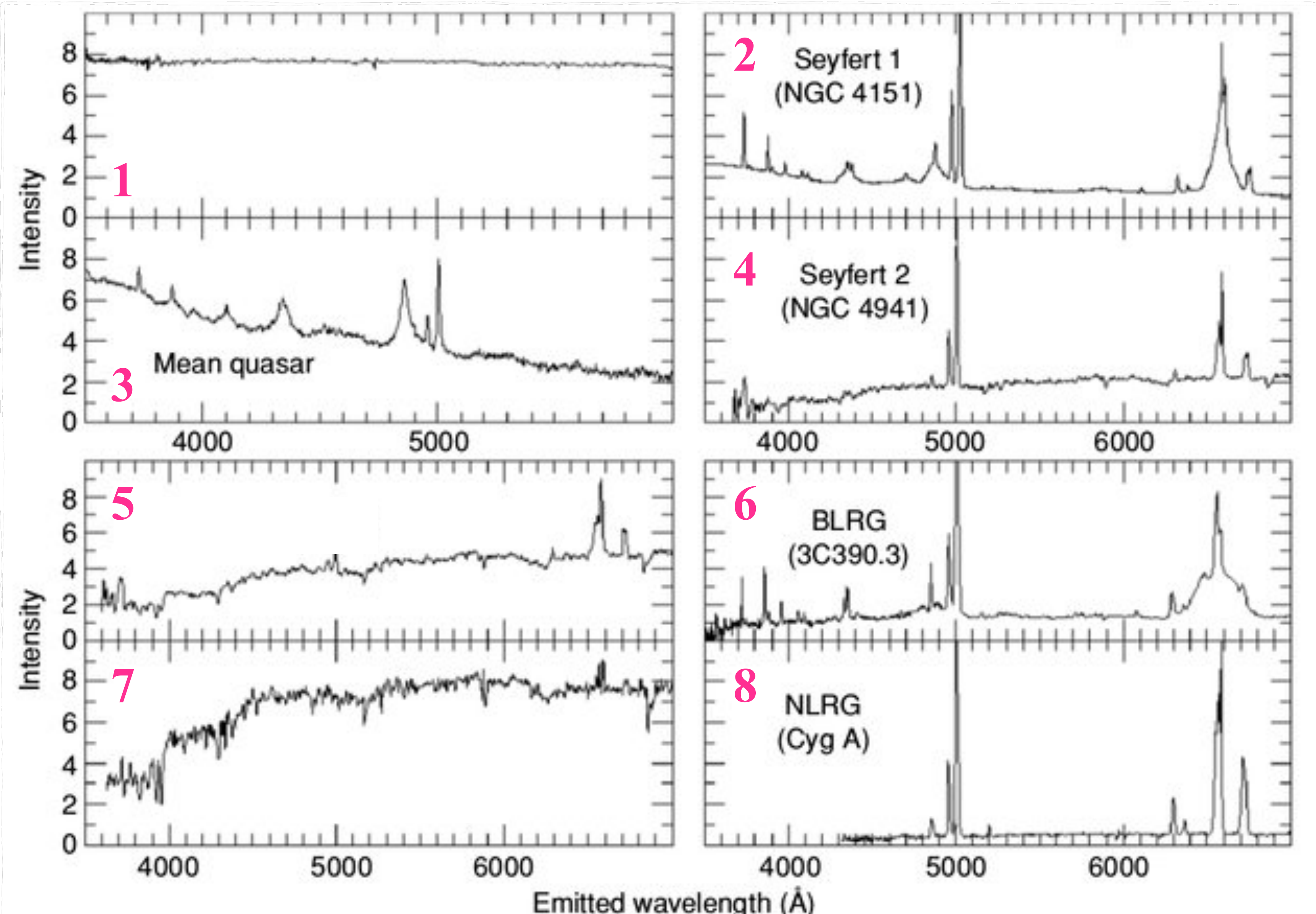


Irham Taufik Andika

AGN Classification: find the BL Lac



Irham Taufik Andika

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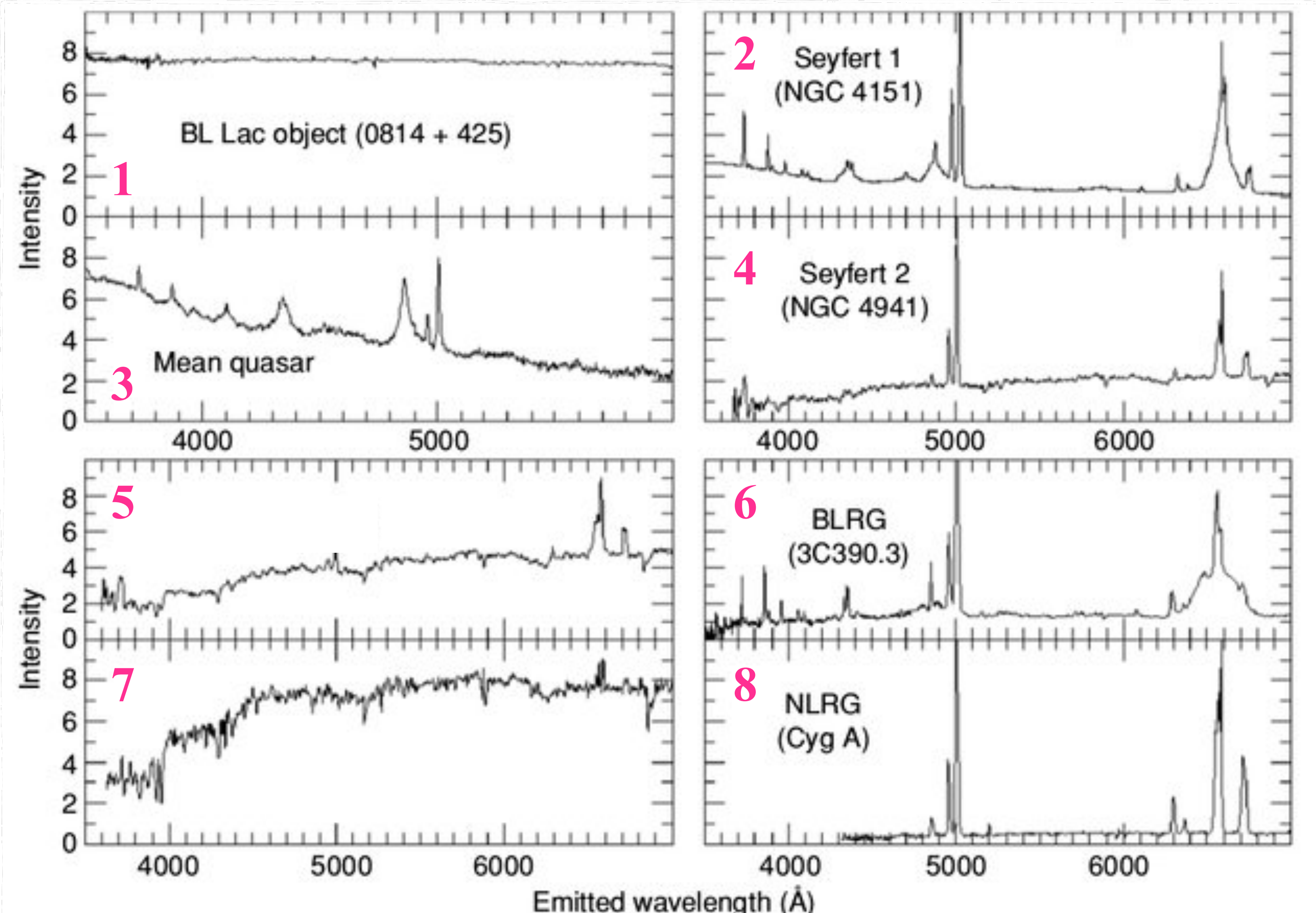
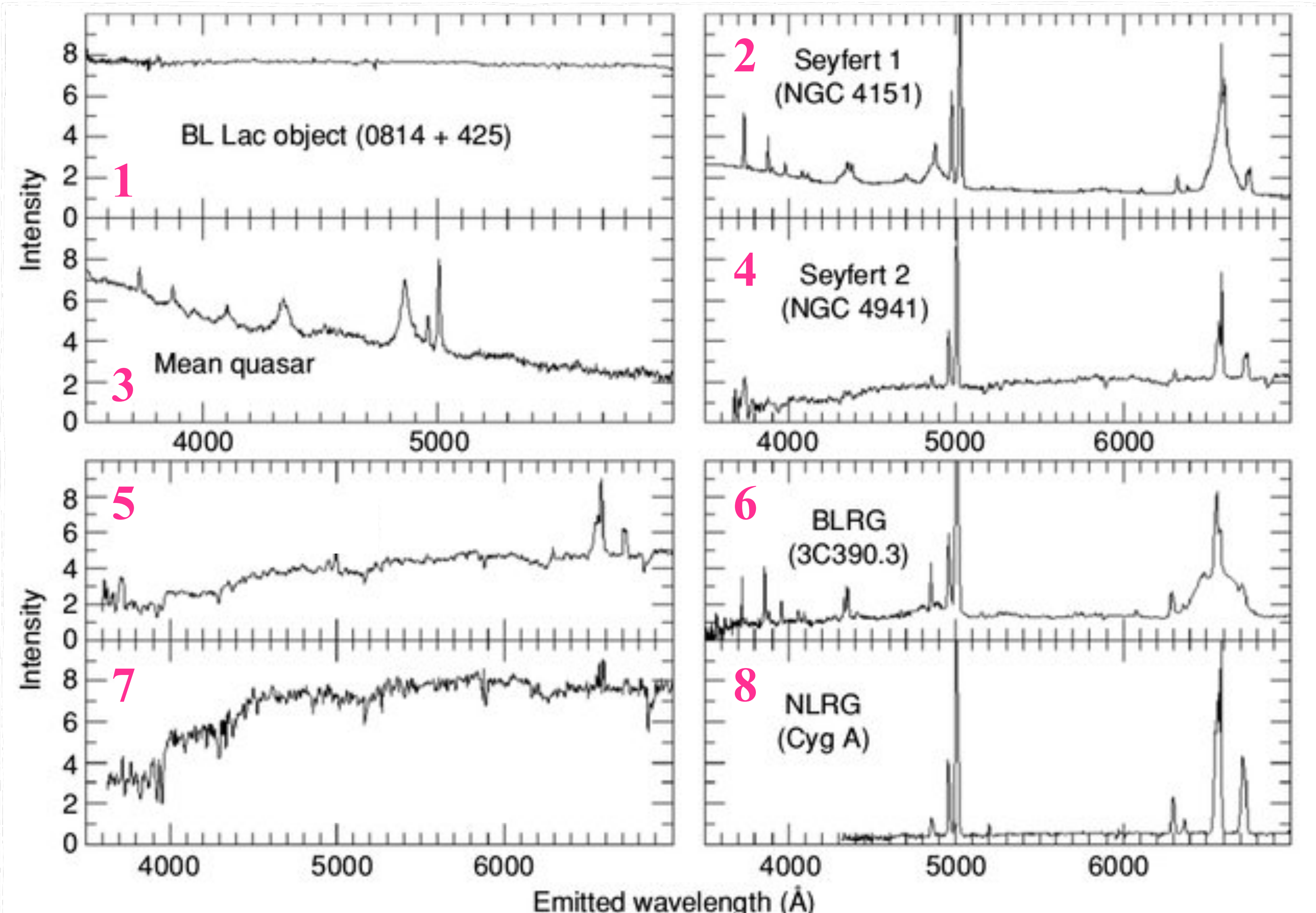


Irham Taufik Andika

AGN Classification: find the normal galaxy



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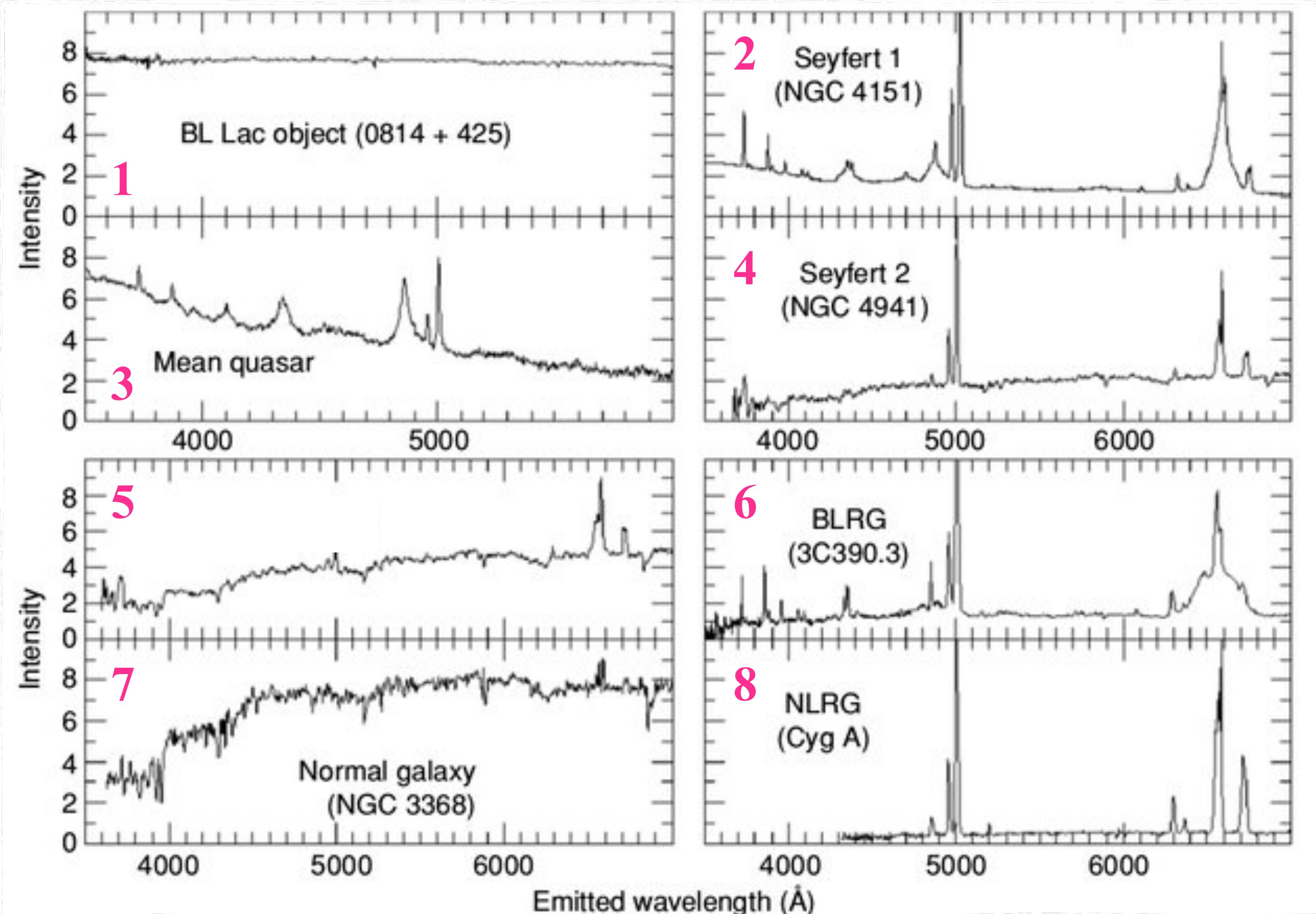

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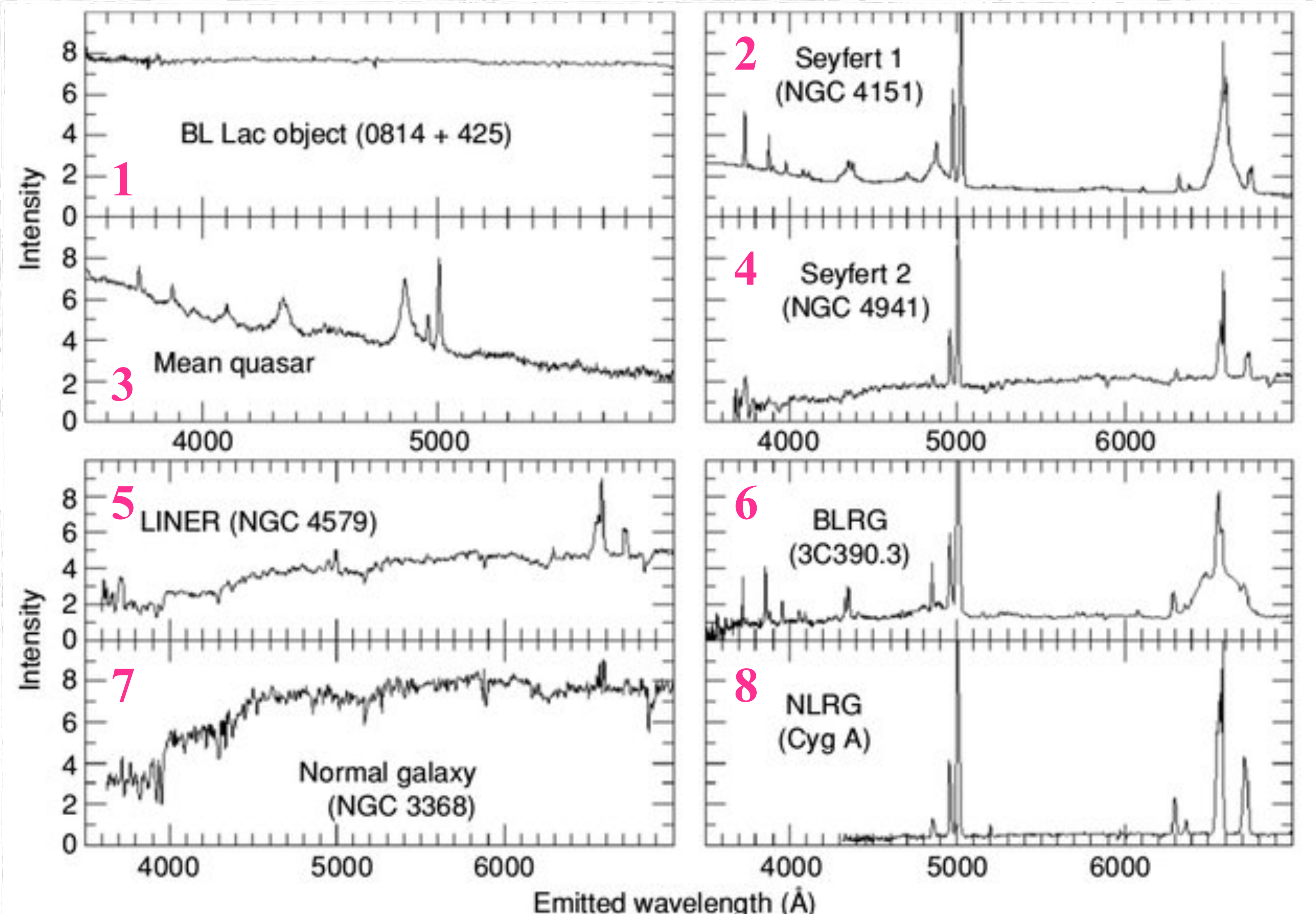
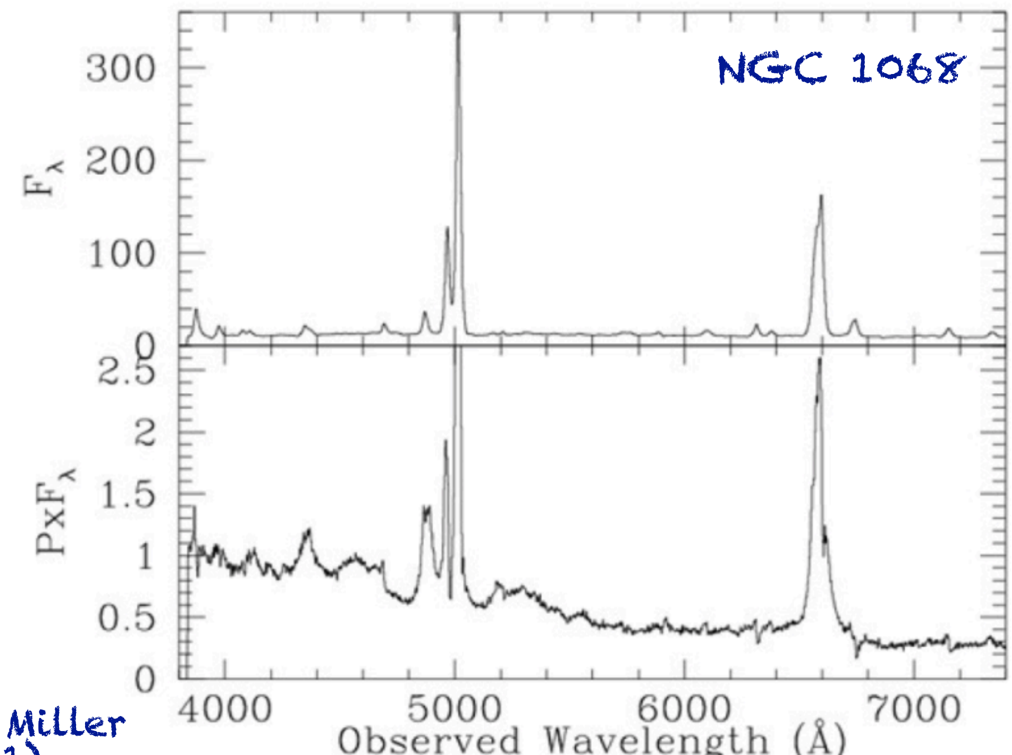


Irham Taufik Andika

Radio-Quiet AGN unification

- Strongest unification for SyI and SyII galaxies
- Prototypical SyII galaxy NGC1068: broad optical emission lines when observed in polarized light. If polarization due to scattering, there are directions from which NGC1068 displays a SyI spectrum



Miller & Antonucci (1983), Antonucci & Miller (1985), Miller, Goodrich & Mathews (1991)

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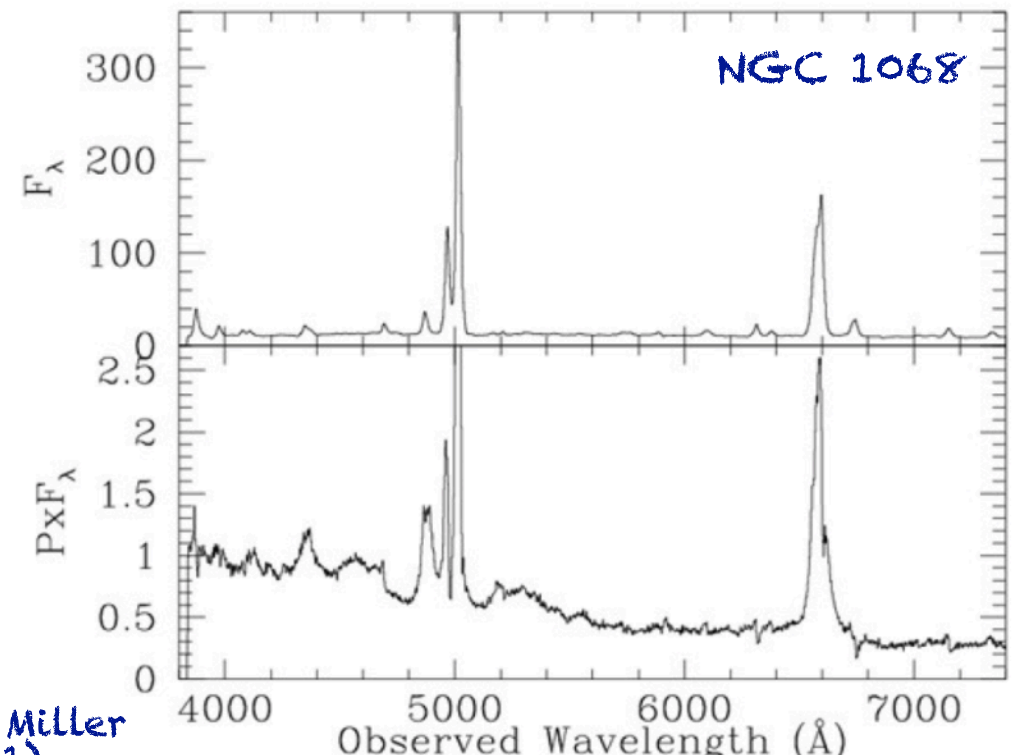
SyII appear to be SyI with BLR and continuum radiation heavily obscured



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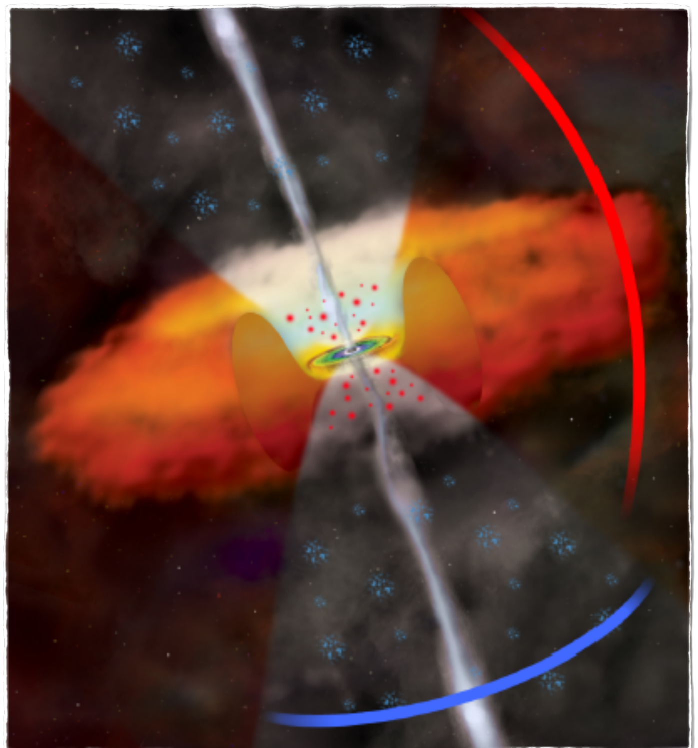
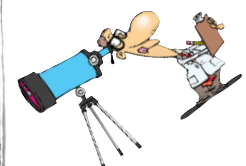
Radio-Quiet AGN unification model

Antonucci & Miller (1985): all Seyfert galaxies possess a dusty torus in between the BLR and NLR that intercepts the sight of the BLR



Type 2



Antonucci (1993), Urry & Padovani (1995)

AGN Unification

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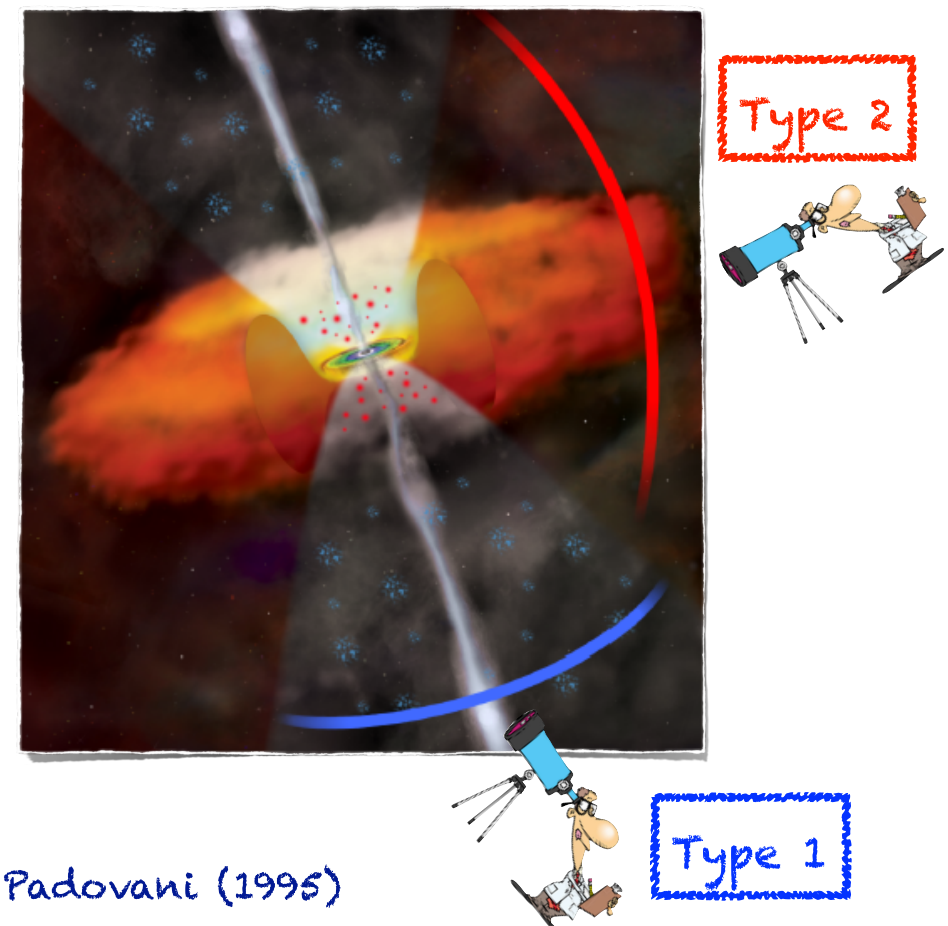

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Radio-Loud AGN unification

- Blazars, radio-loud quasars and FR-II galaxies unified under a similar scheme to the Seyfert one
- The only difference is the inclusion of relativistic jets of synchrotron emitting plasma

⇒ Relativistic beaming and Doppler shifts: source of anisotropy in addition to torus obscuration

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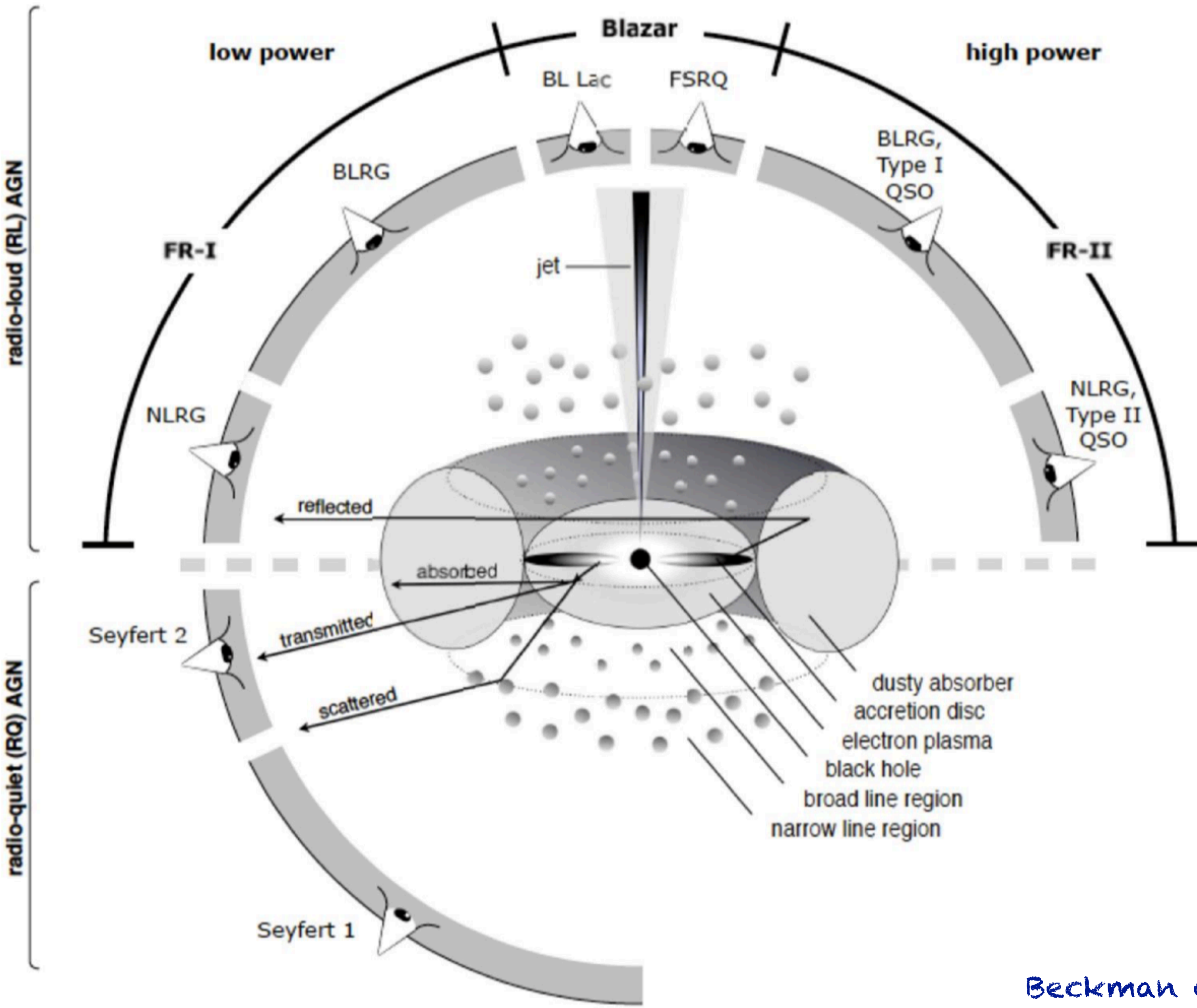
- RLQ: line-of-sight closet (but not within) jet cone. Continuum strongly beamed but does not swamp emission from BLR
- FR-II BLRG: larger orientation angle, central continuum flux falls
- FR-II NLRG: yet larger angle, torus obscures central continuum source and BLR

AGN Unification

The observed properties, and thus the classification, of a given AGN depend upon its **orientation**

AGN Unification



Beckman et al. (2012)

AGN Unification: caveats

Caveats

- Unclear how FR-I radio galaxies fit into the unification scheme
- Source power rather than orientation produces different radio morphologies for FR-I and FR-II
- E.g. blazars can be beamed FR-I, but there is a lack of BL FR-I

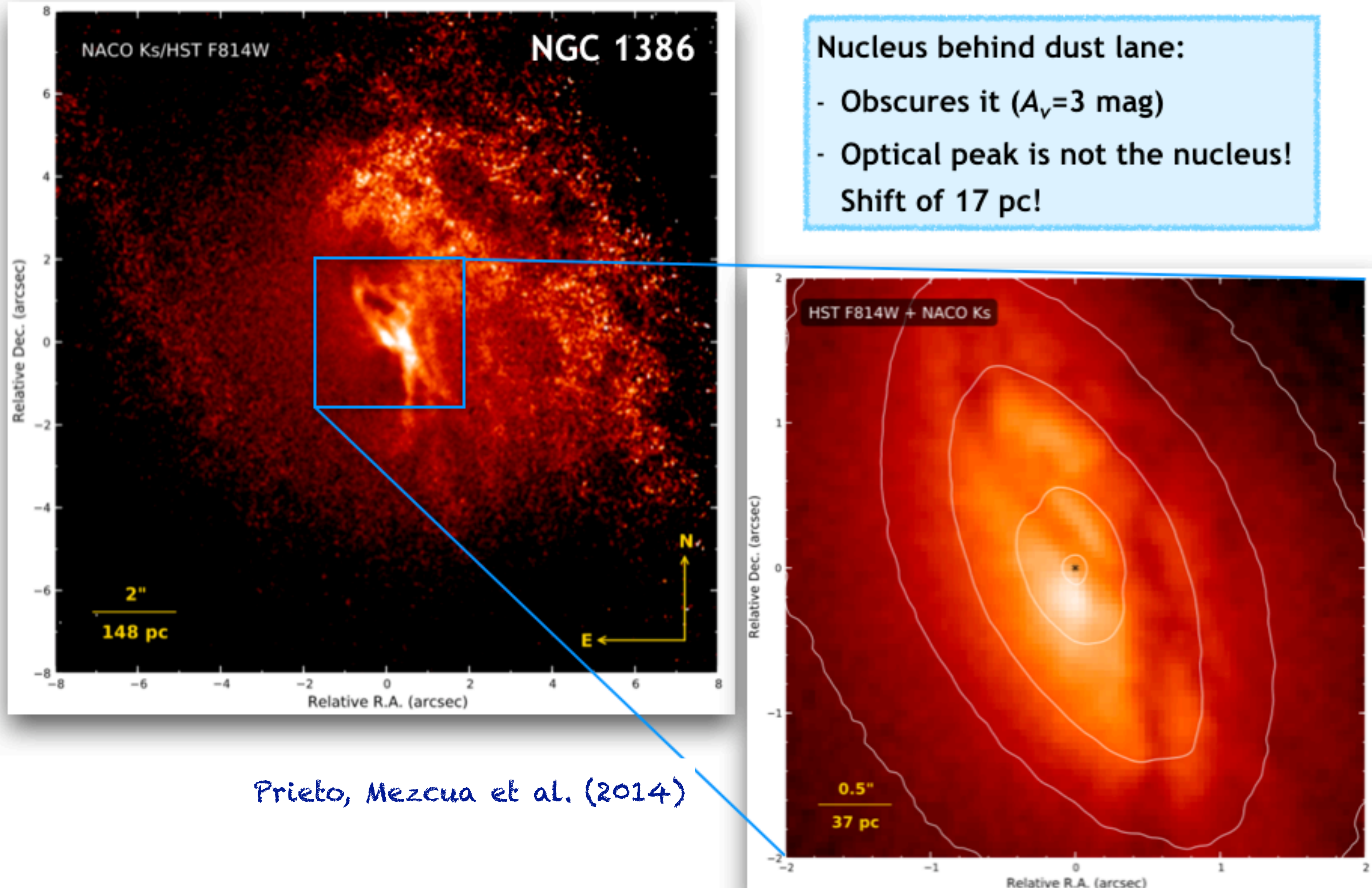
  ➡ torus has small opening angle? absence of BLR in FR-I sources?

- Dust lanes from galactic scales can explain nuclear obscuration in some low-luminosity type 2 AGN

AGN Unification: caveats

Nucleus behind dust lane:

- Obscures it (A_V=3 mag)
- Optical peak is not the nucleus! Shift of 17 pc!



Prieto, Mezcua et al. (2014)

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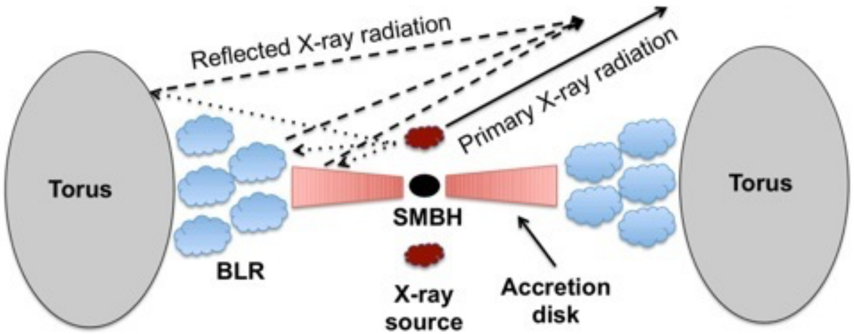
  - ⇨ torus has small opening angle? absence of BLR in FR-I sources?
- Dust lanes from galactic scales can explain nuclear obscuration in some low-luminosity type 2 AGN
  - ⇨ no torus needed to obscure BLR?

X-ray Spectral Energy Distribution (SED)



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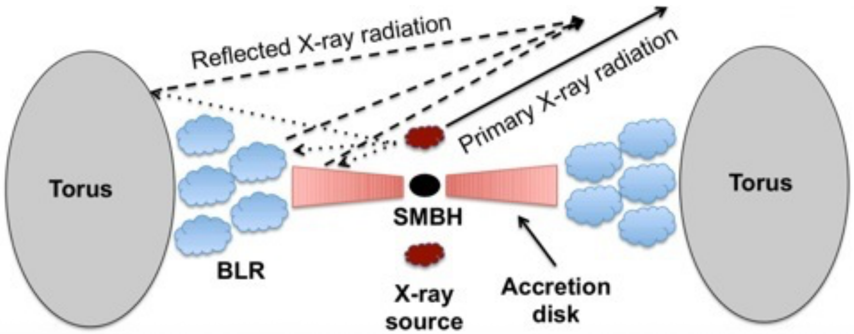
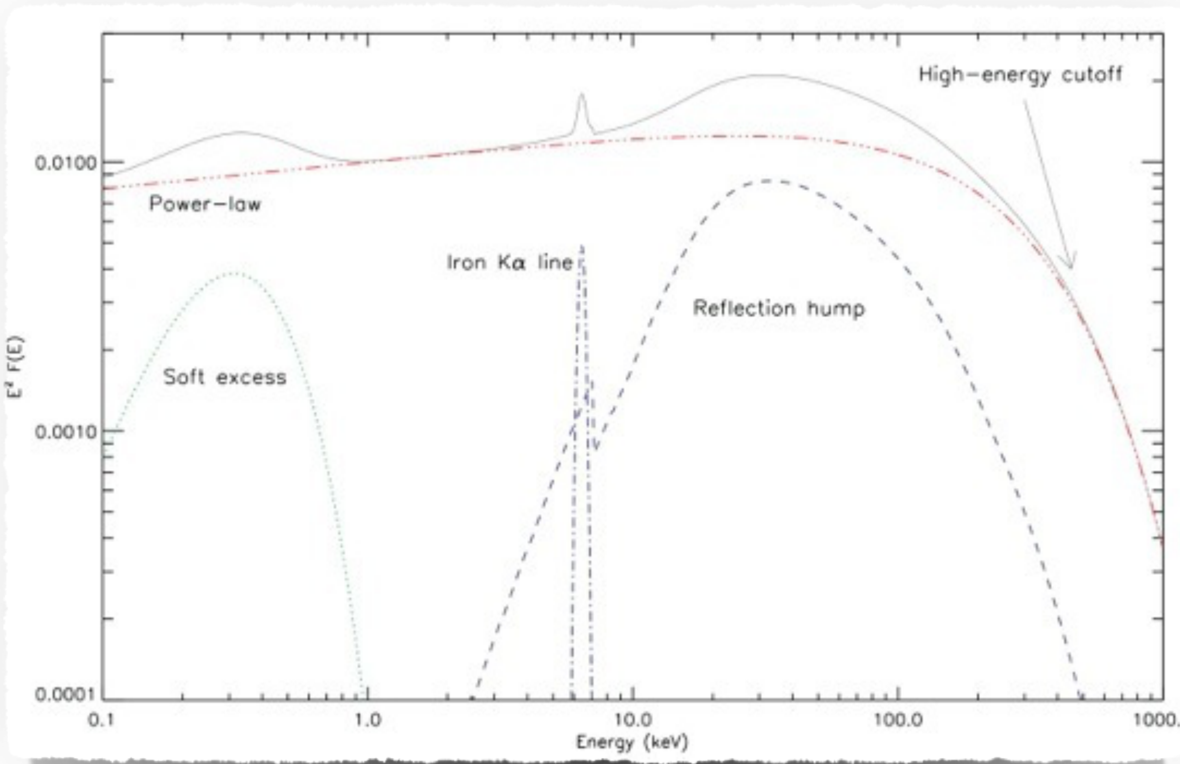


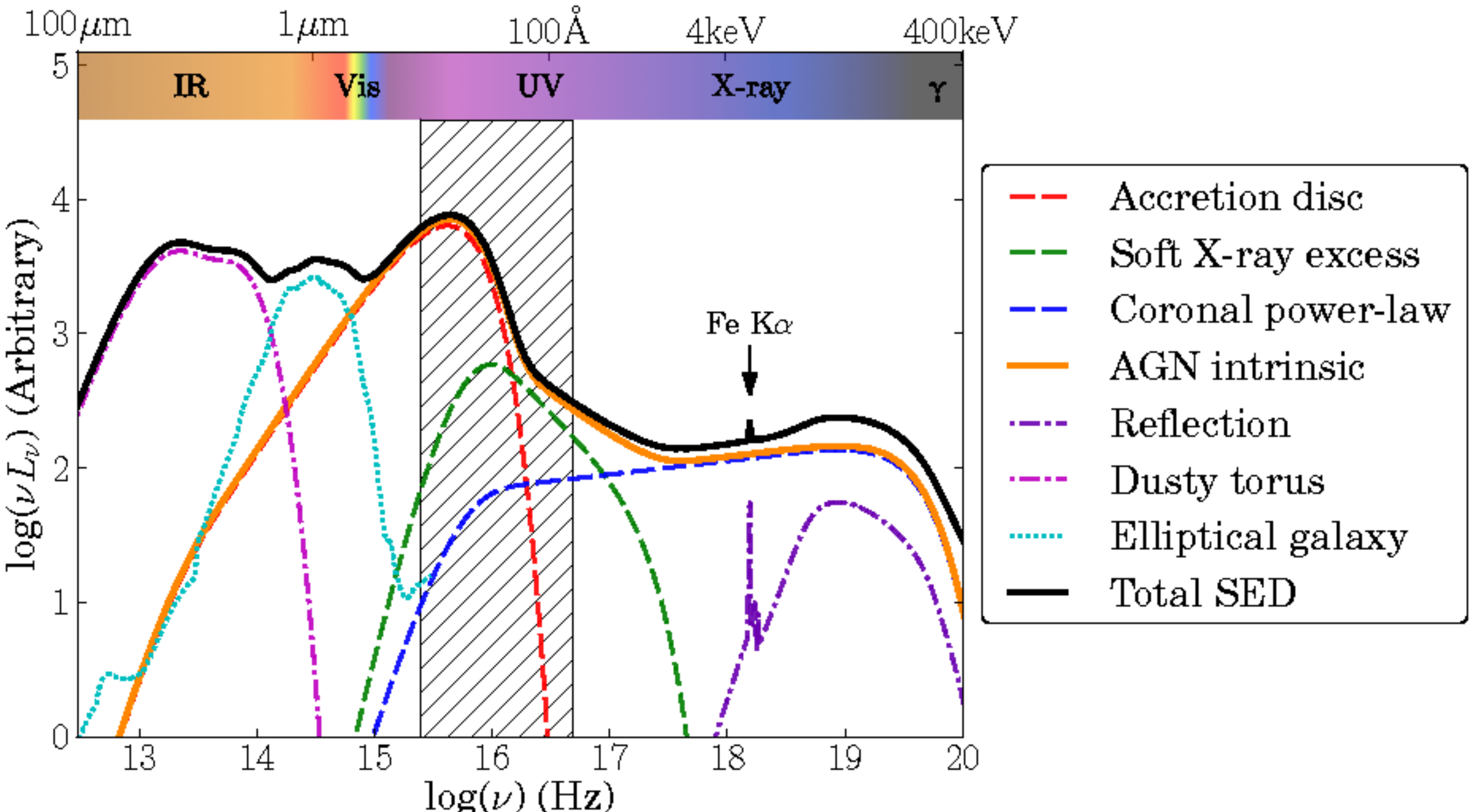


Primary X-ray radiation:
power-law, Γ=1.8-2 (Γ=1-α)

Reflected X-ray radiation:
- reflection continuum, peak at 30-40 keV
- Fe Kα line at 6.4 keV
- soft excess at ~2 keV

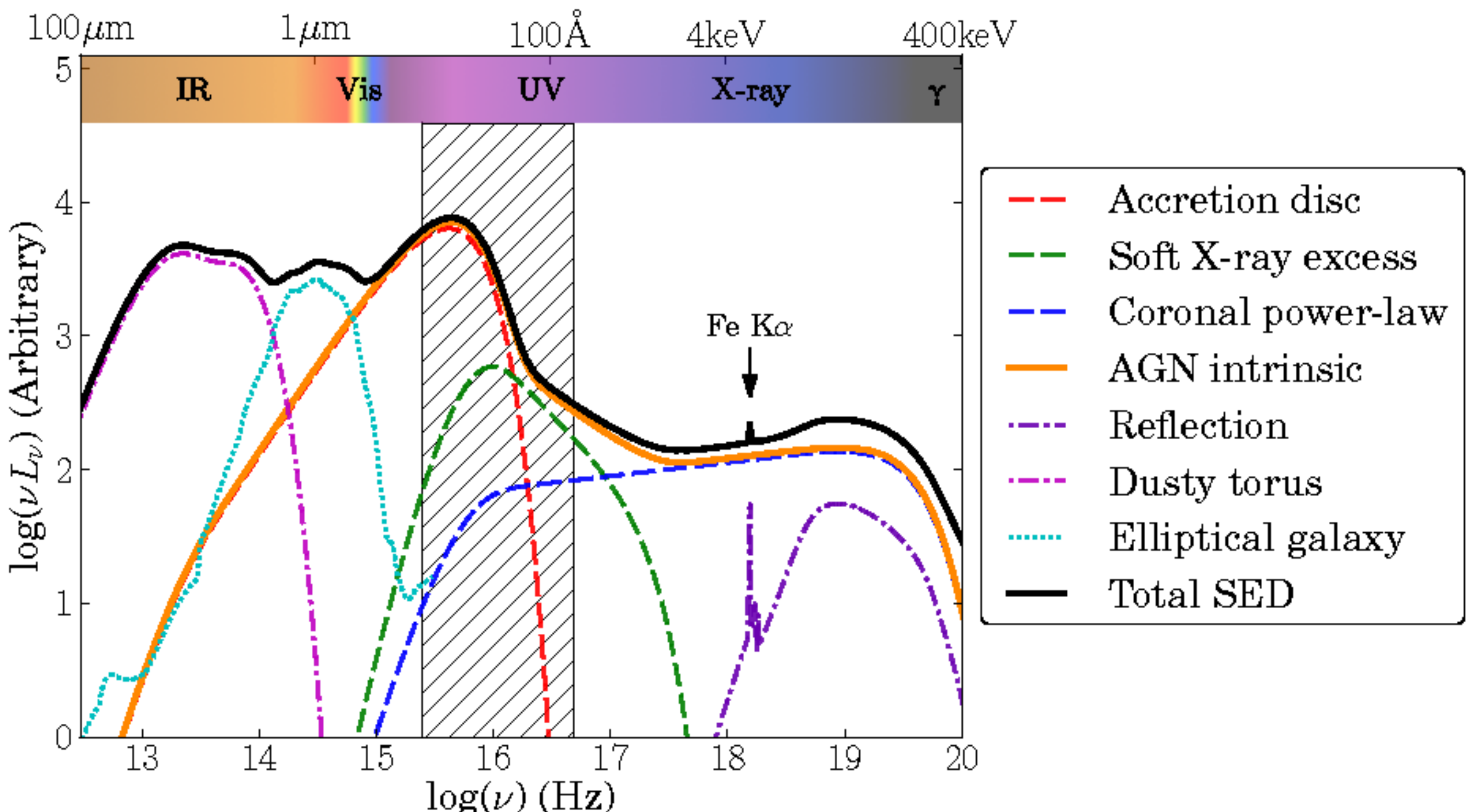
Claudio Ricci

AGN Spectral Energy Distribution



Collinson et al. (2017)

AGN Spectral Energy Distribution



Largely unobservable due to absorption in the IGM

Collinson et al. (2017)

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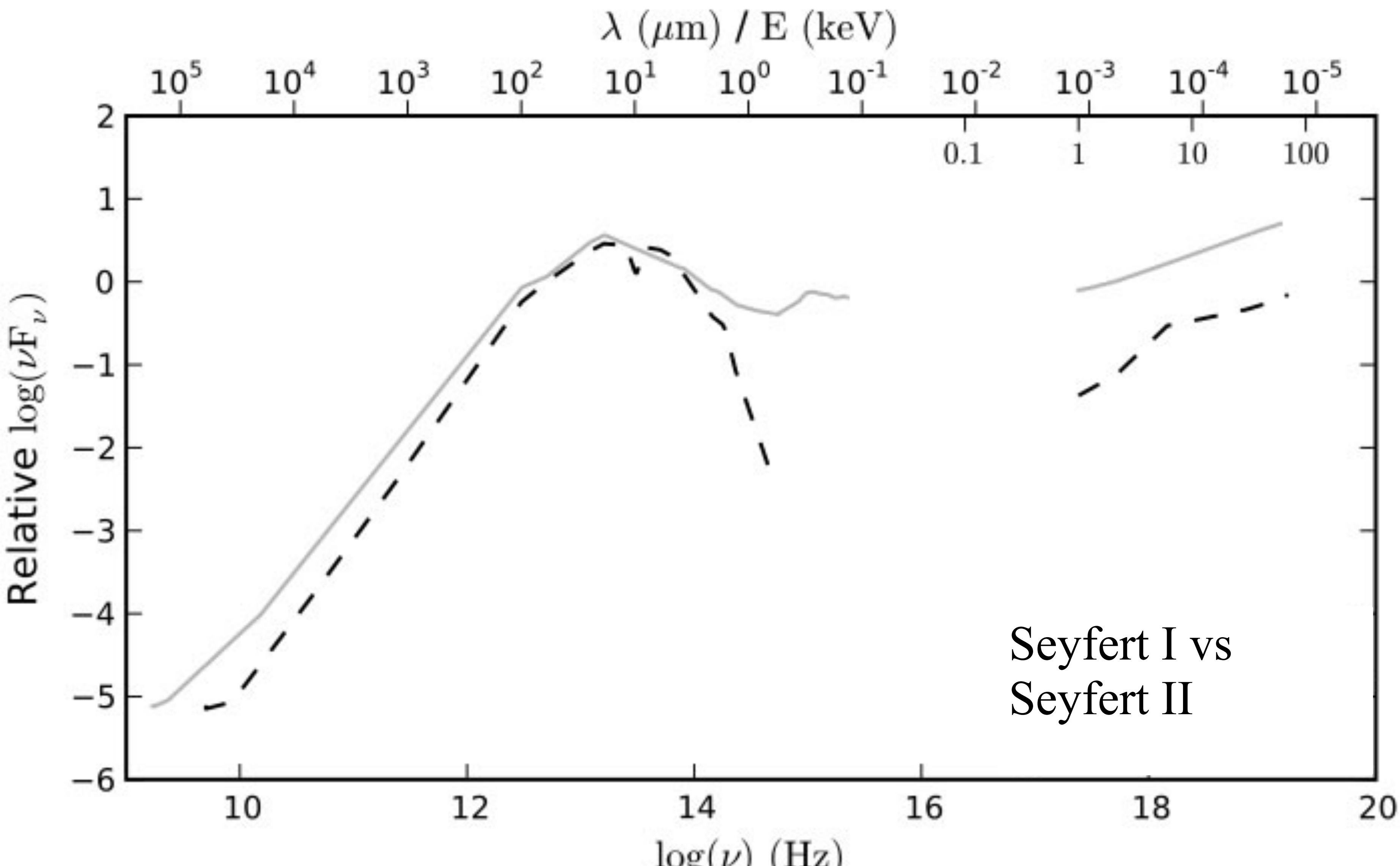

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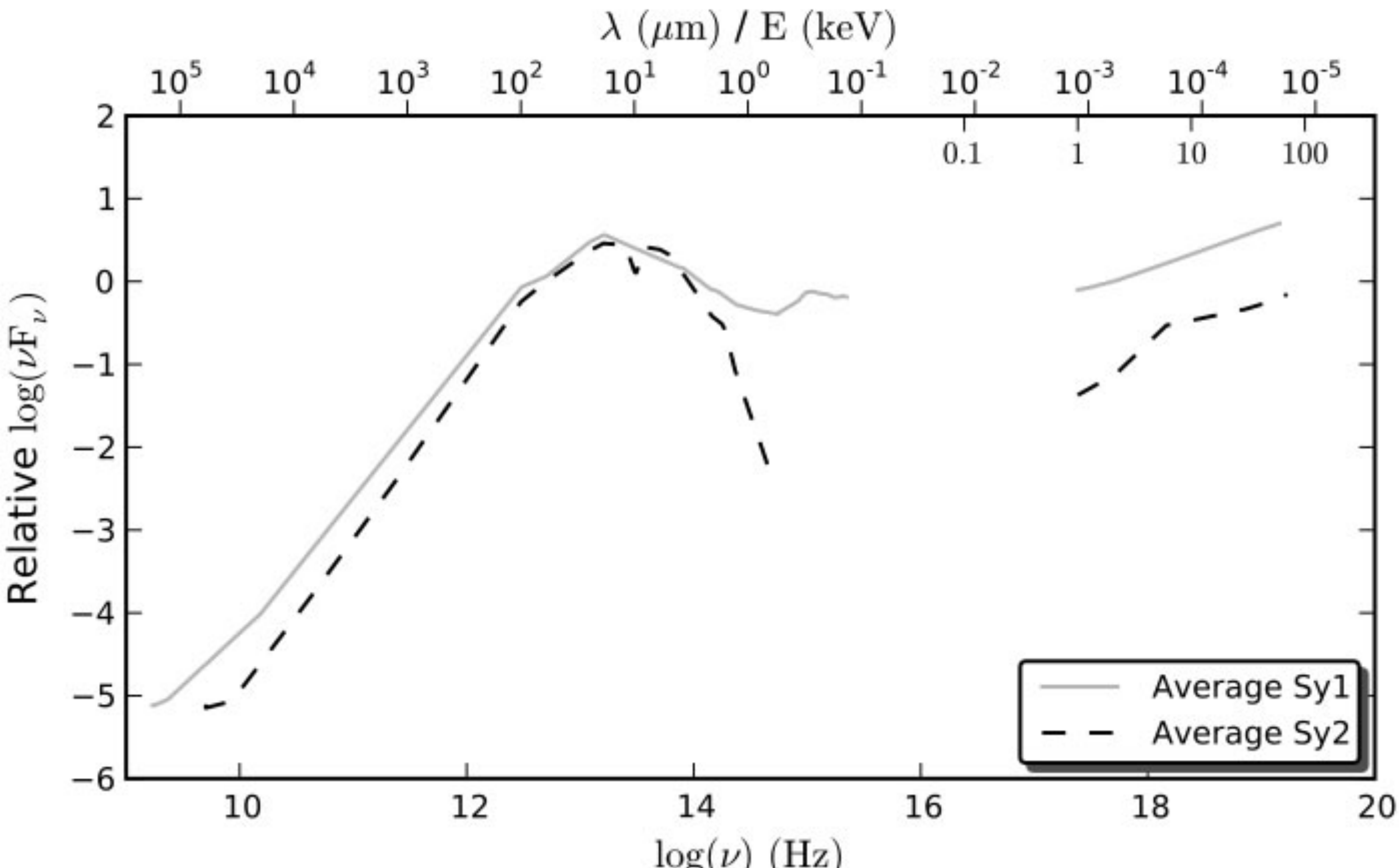


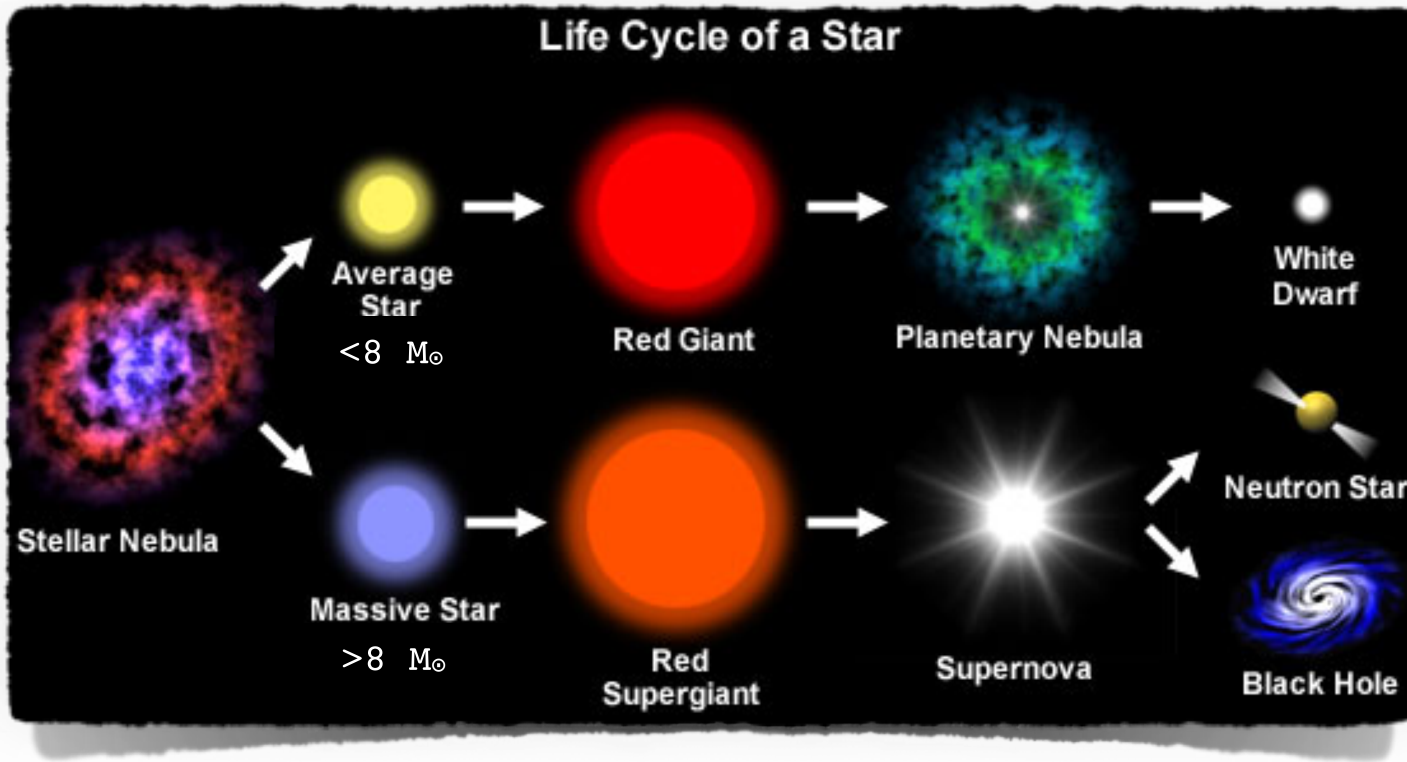
Prieto et al. (2010)

Question

How do SMBHs form?

How do stellar-mass black holes form?

Stellar-black hole formation



NASA

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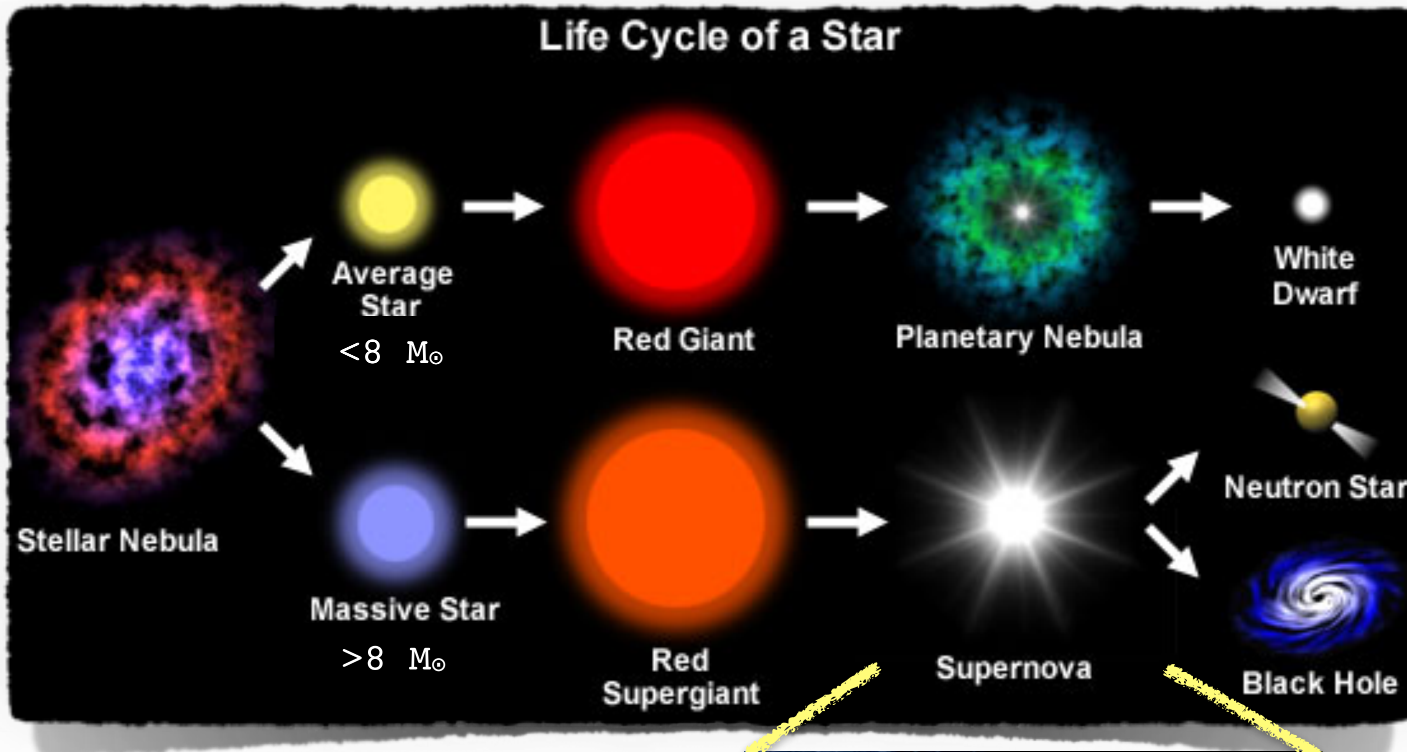
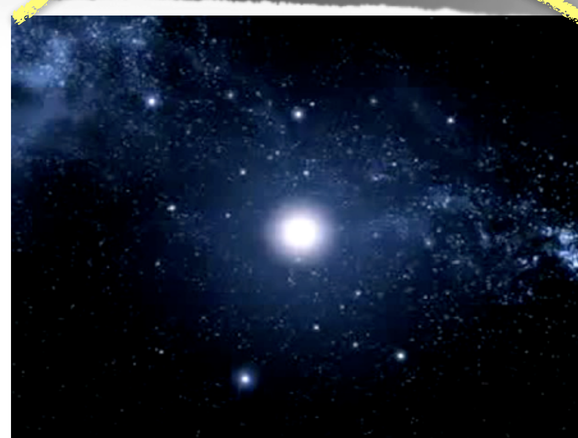


NASA

Crab nebula
(year 1054)



ESA/HST

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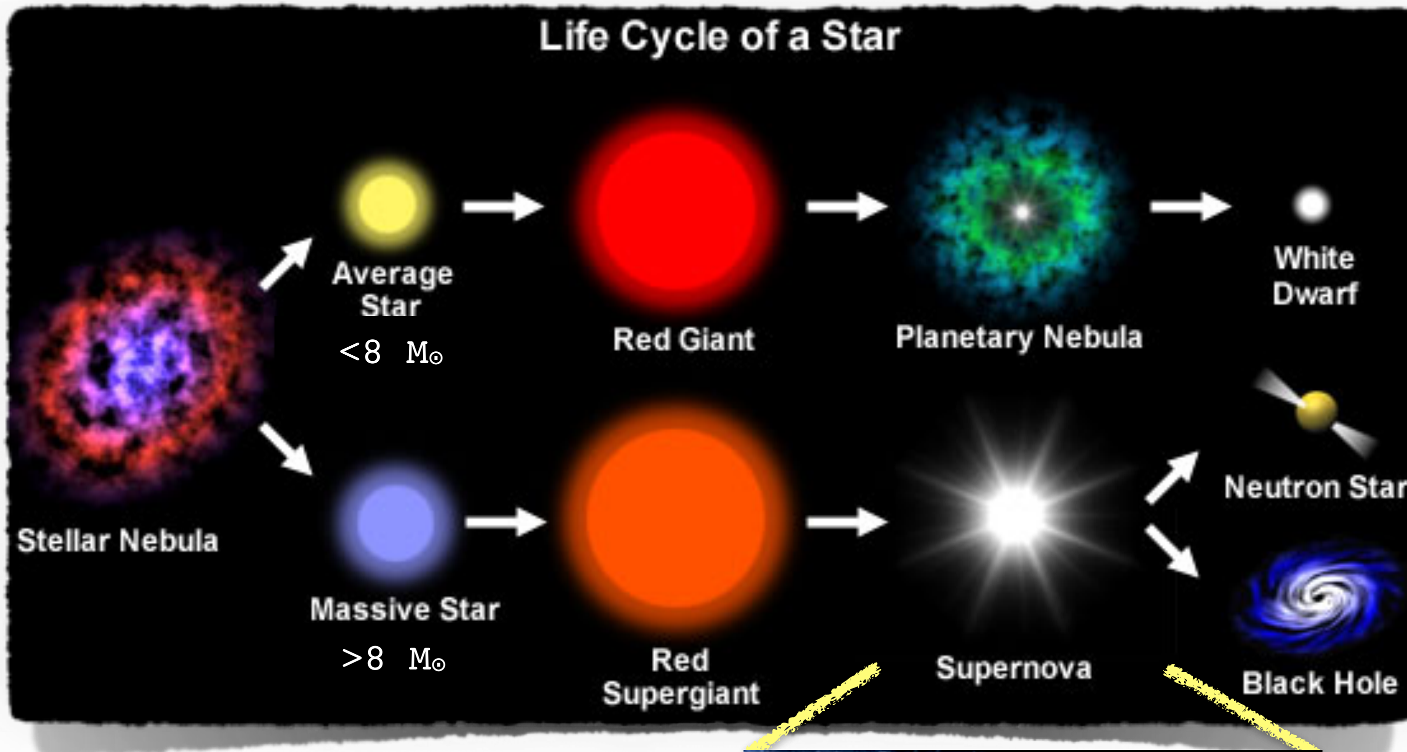

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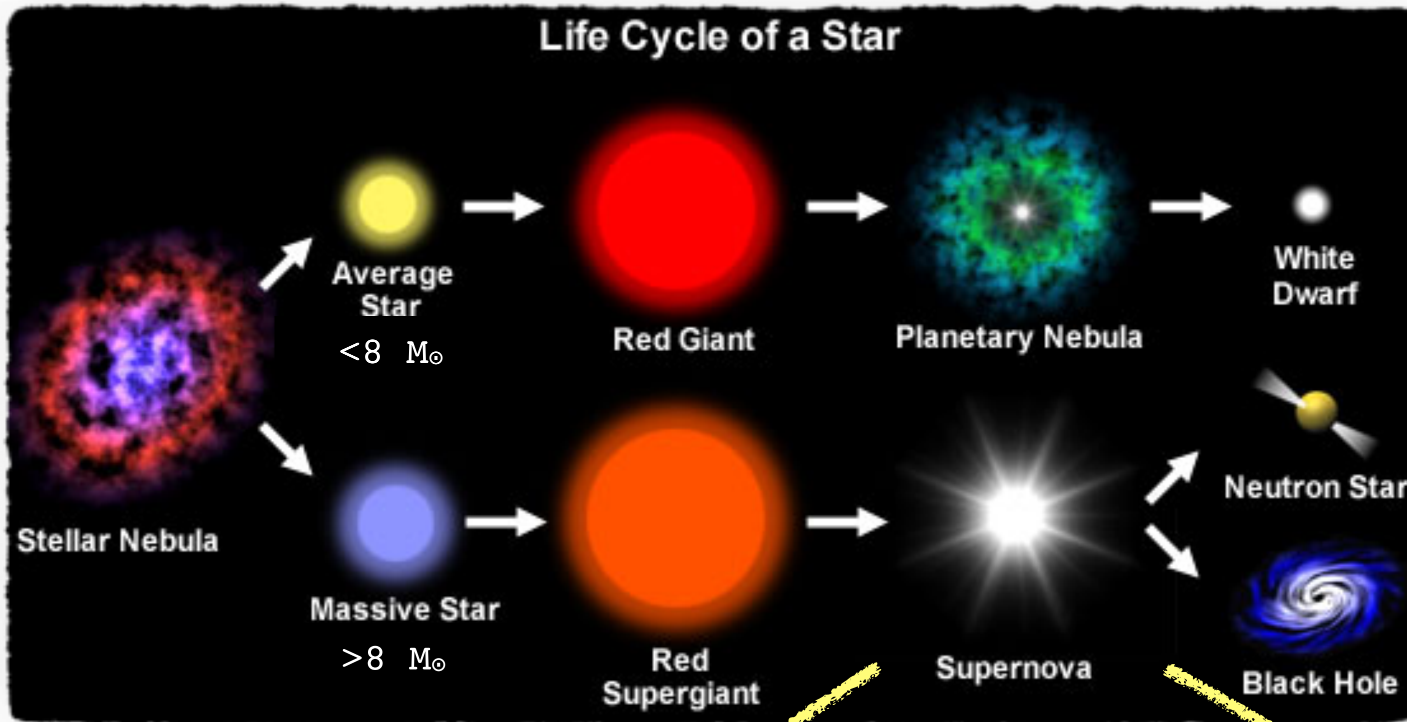


NASA

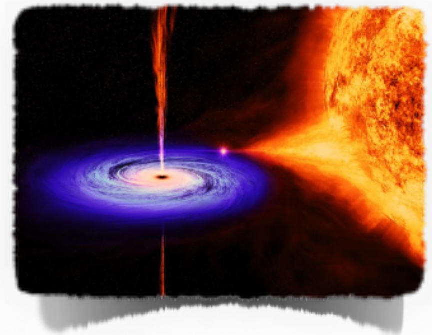
Crab nebula (year 1054)

ESA/HST

How do SMBHs form?

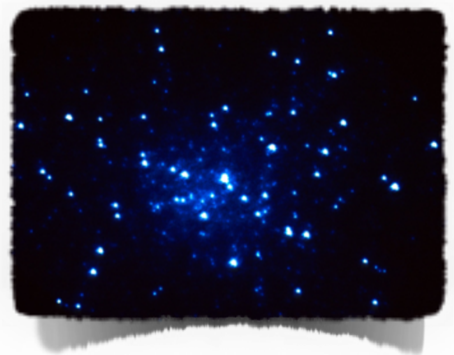
SMBH formation

- Slow accretion onto stellar-mass black hole



NASA

- Mergers of stellar-mass BHs in stellar cluster + slow accretion



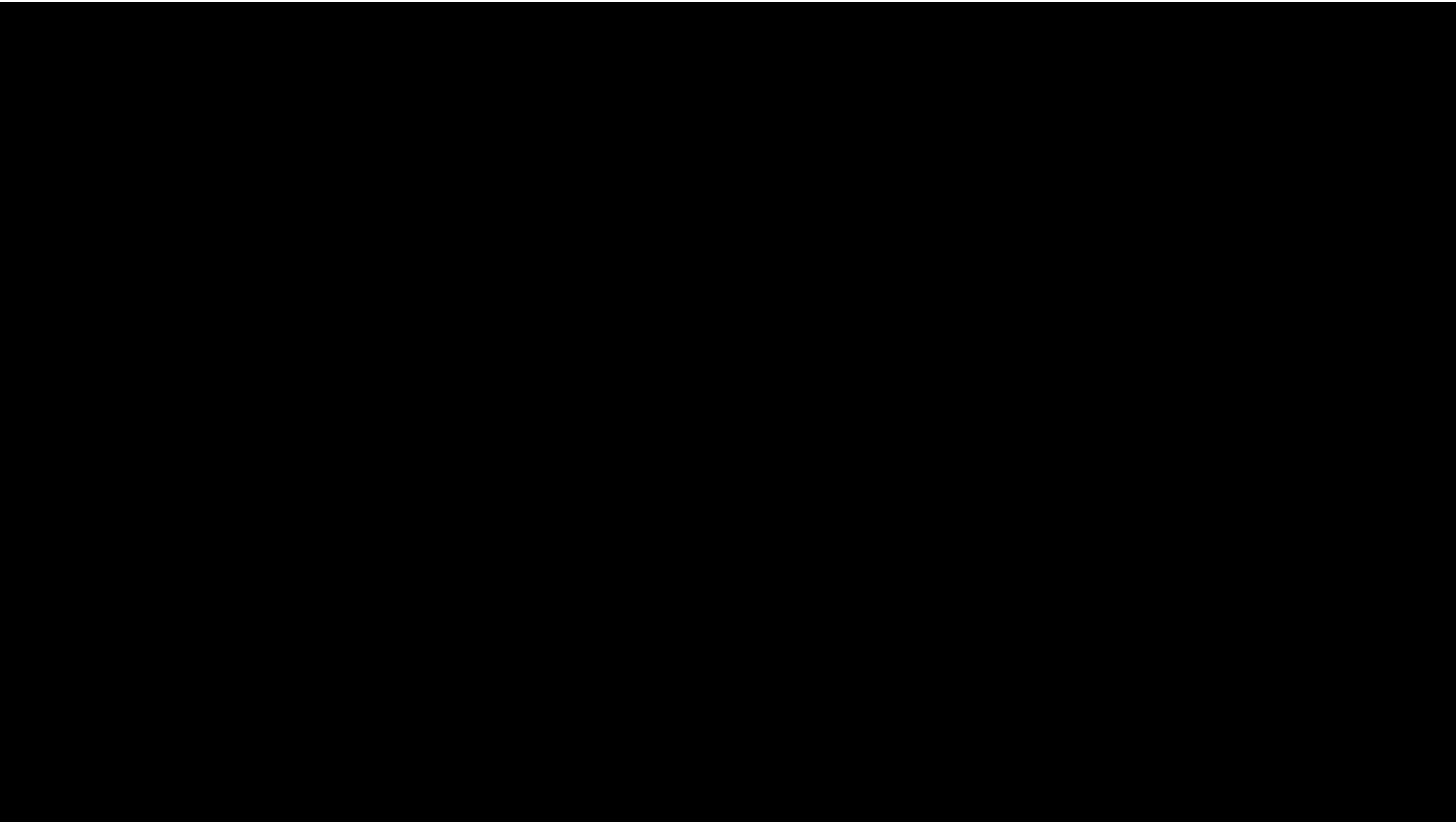
NASA

- SMBH merger in galaxy merger

HST

How do SMBHs form?

Galaxy merger: simulation vs observations



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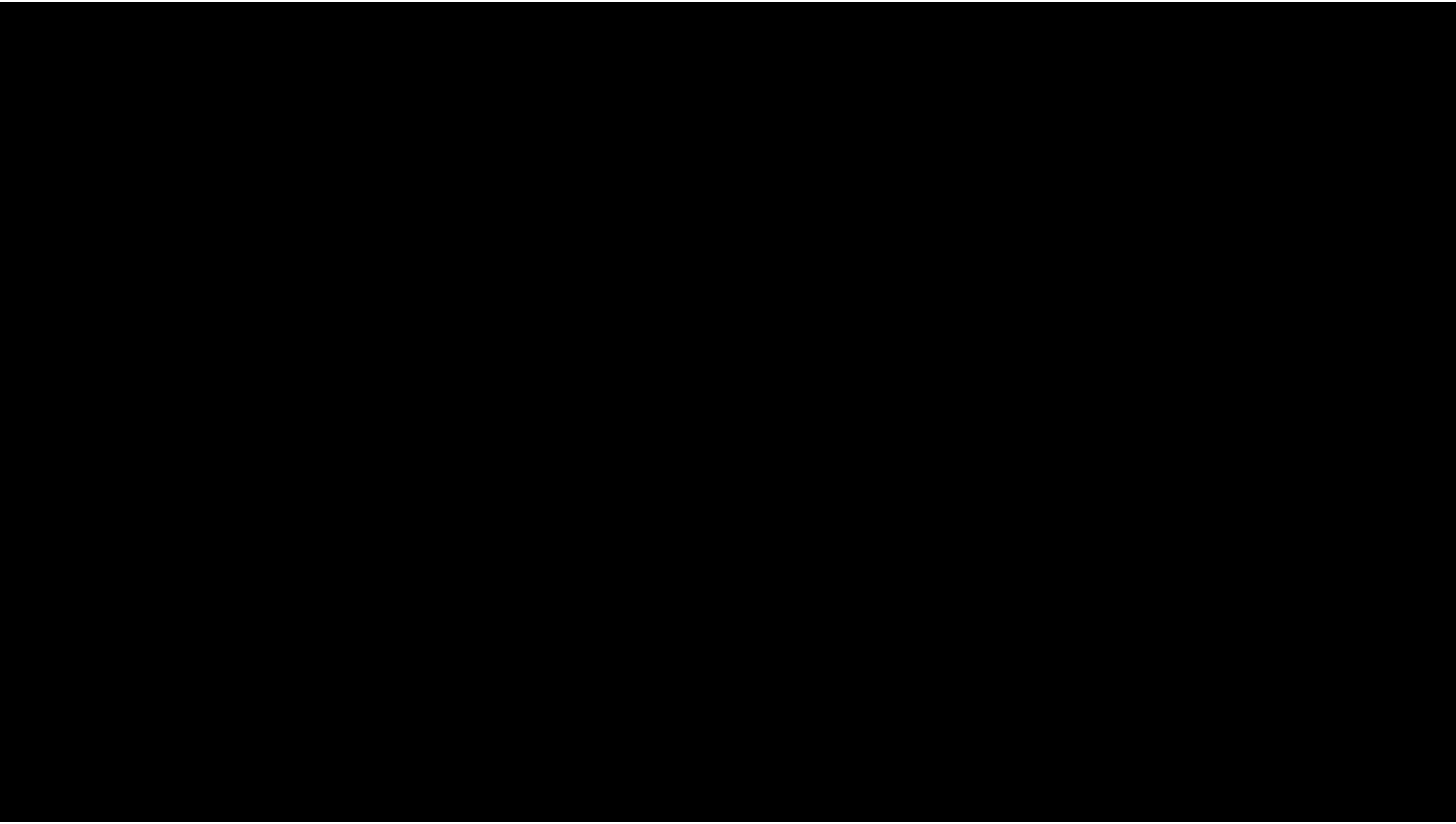
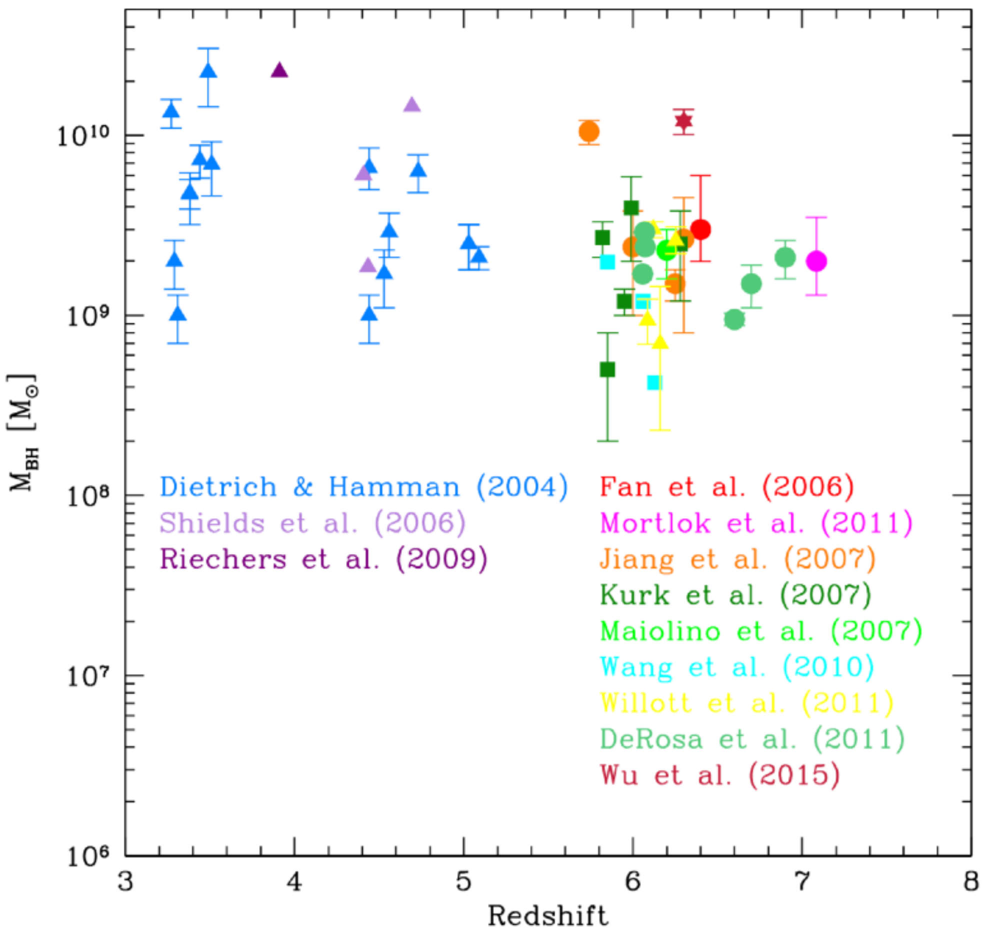


HST

How do SMBHs form?

The challenge of the first quasars

- Quasars of 10^{10} $M_{\odot}$ already existed when Universe was < 1 Gyr



Valiante et al. (2017)

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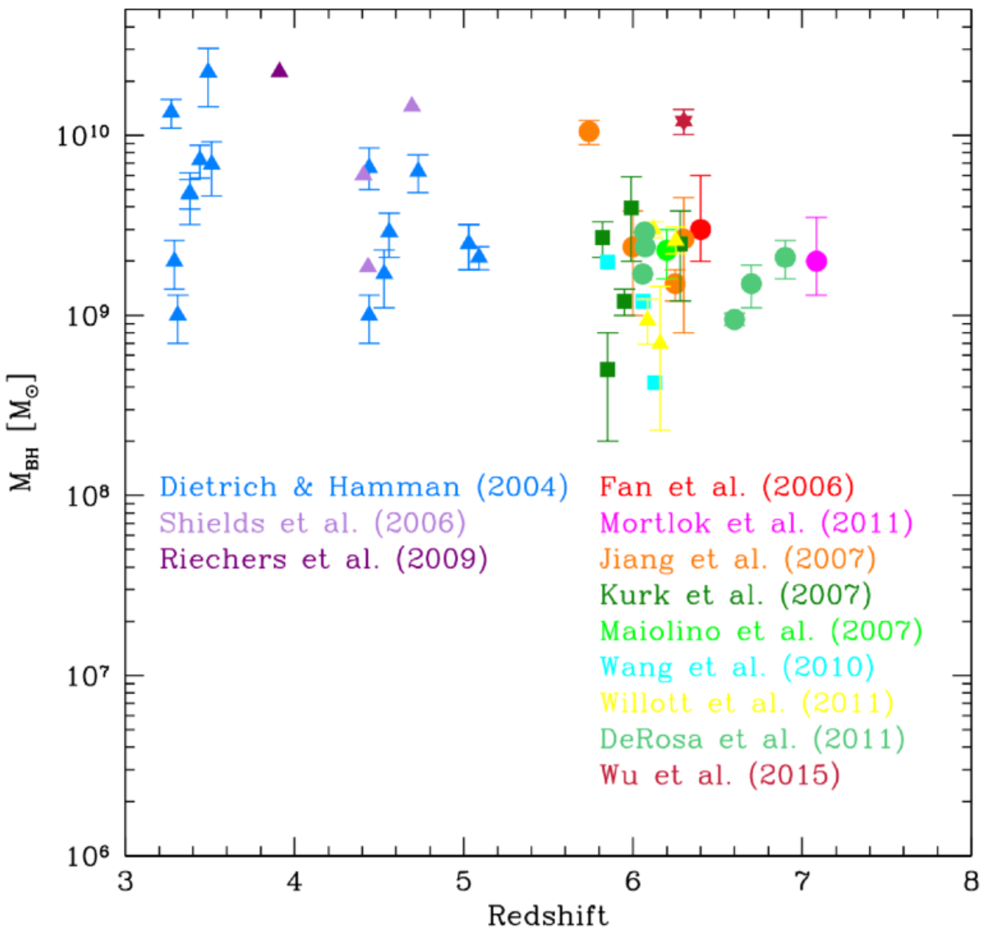


No time to grow from stellar-mass BHs!

Had to start as **seed BHs of 100 – 10^5 $M_\odot$**

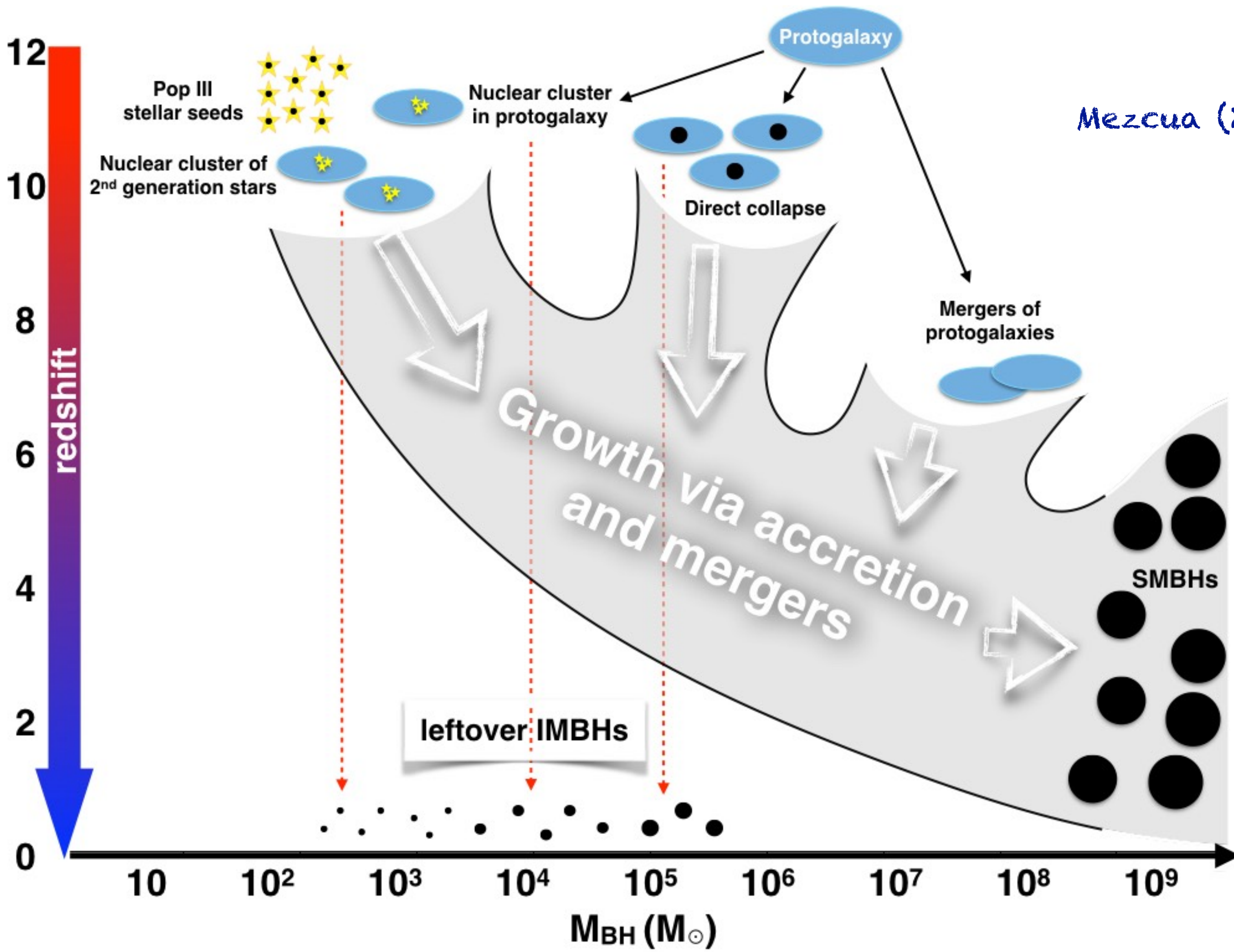
Grow fast via accretion and mergers

Valiante et al. (2017)

How do SMBHs form?

Seed black hole formation

Mezcua (2017)



How do SMBHs form?

Where can we find seed IMBHs?

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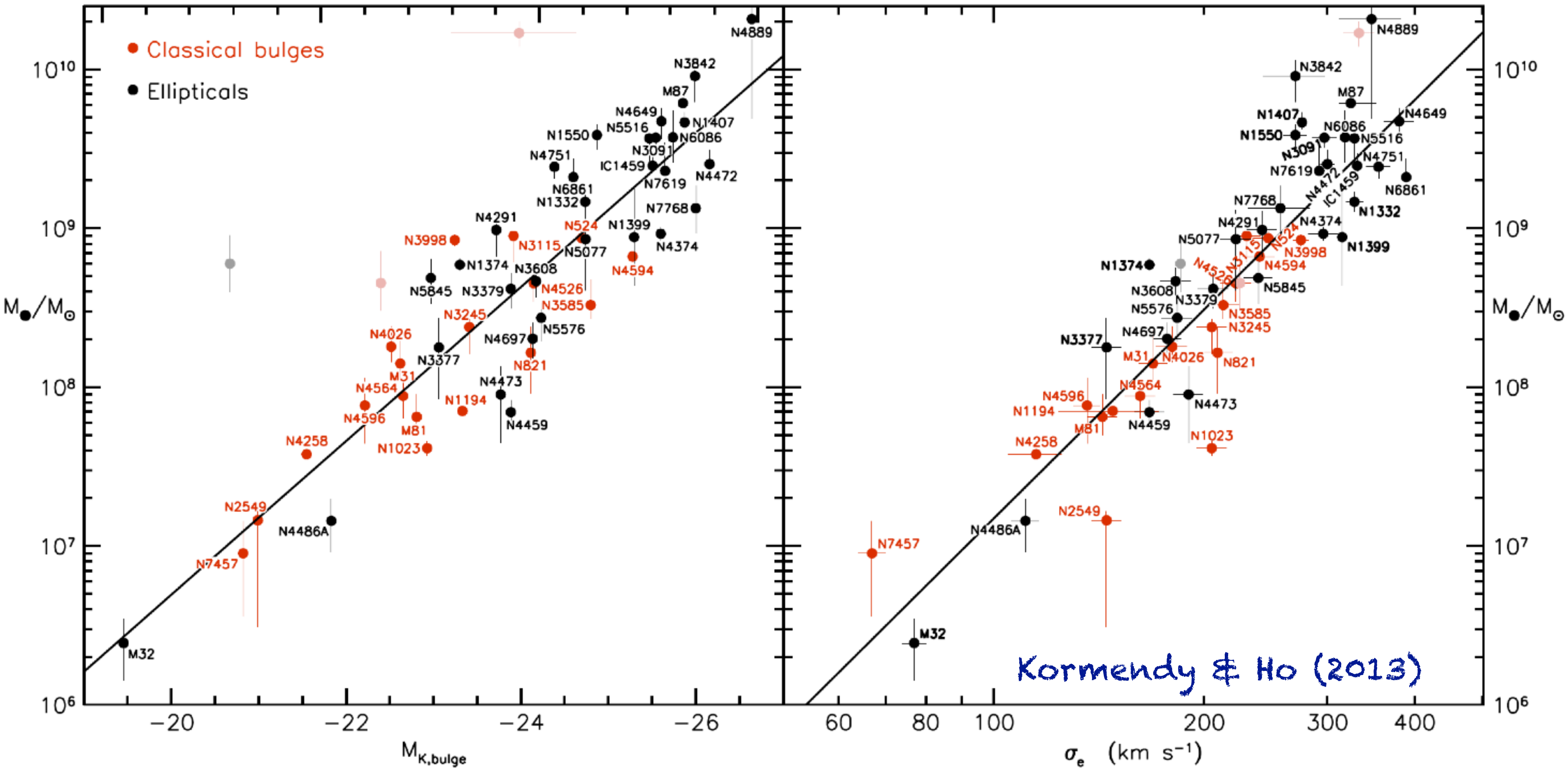

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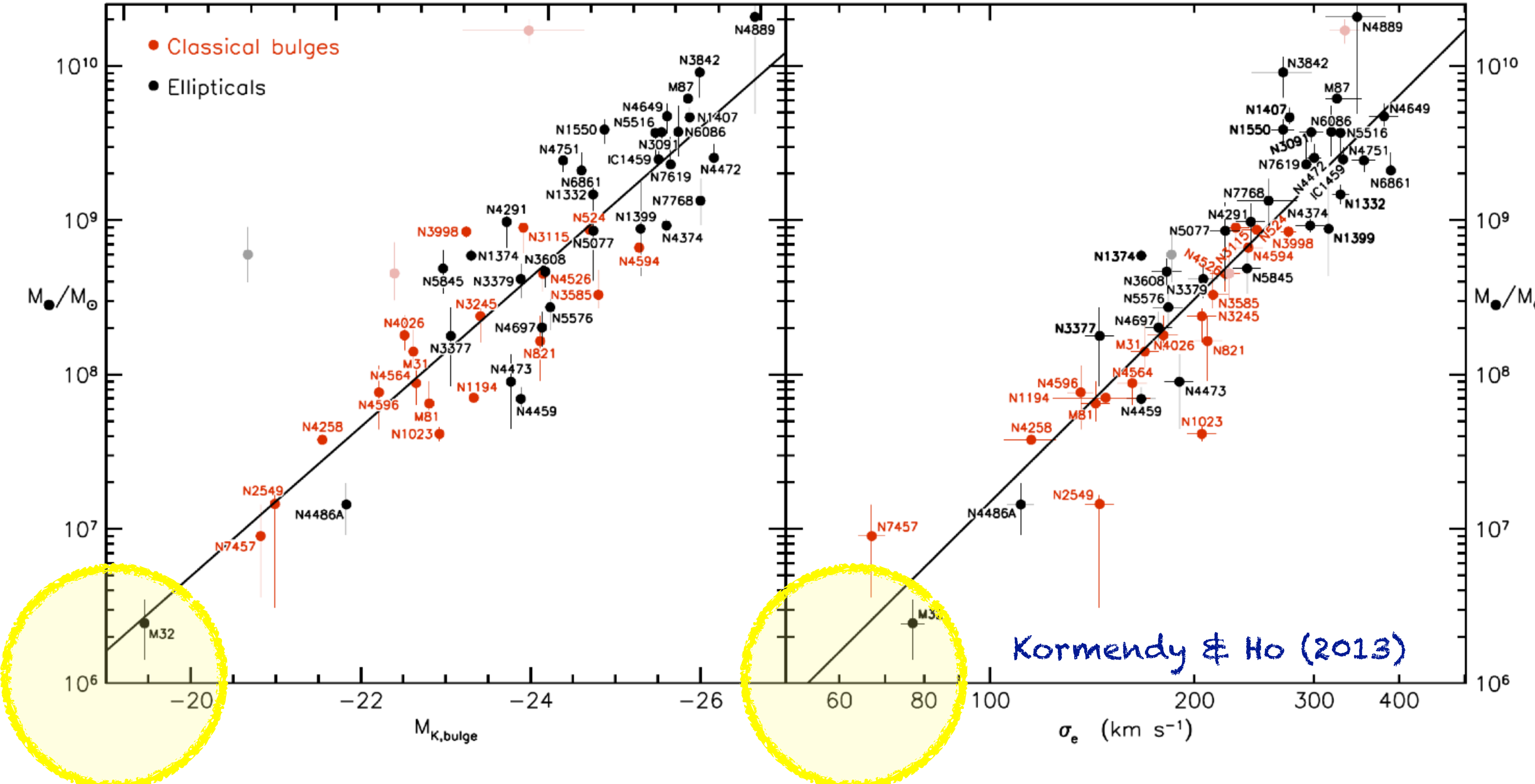

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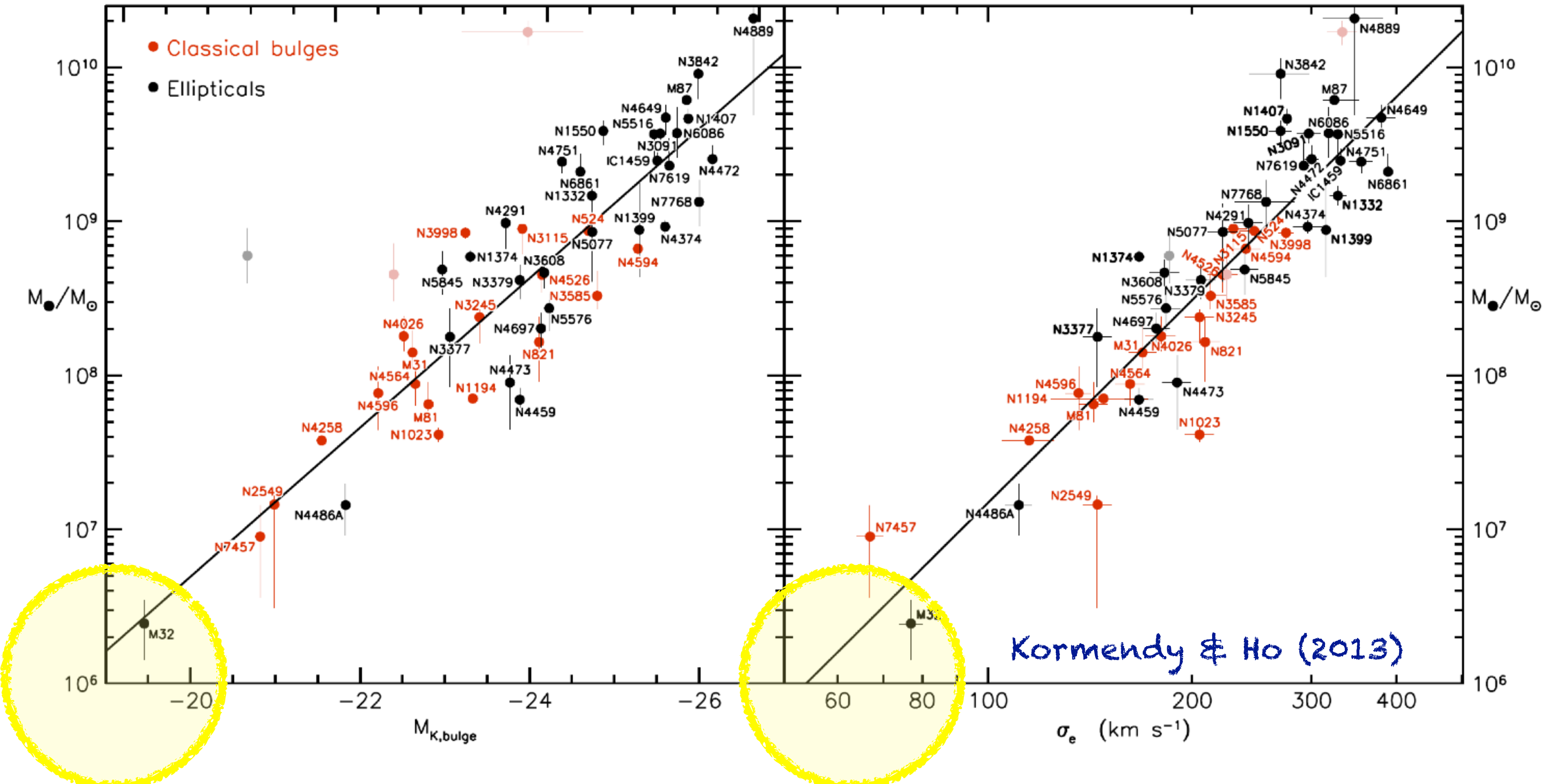
Where can we find seed IMBHs?

In dwarf galaxies!



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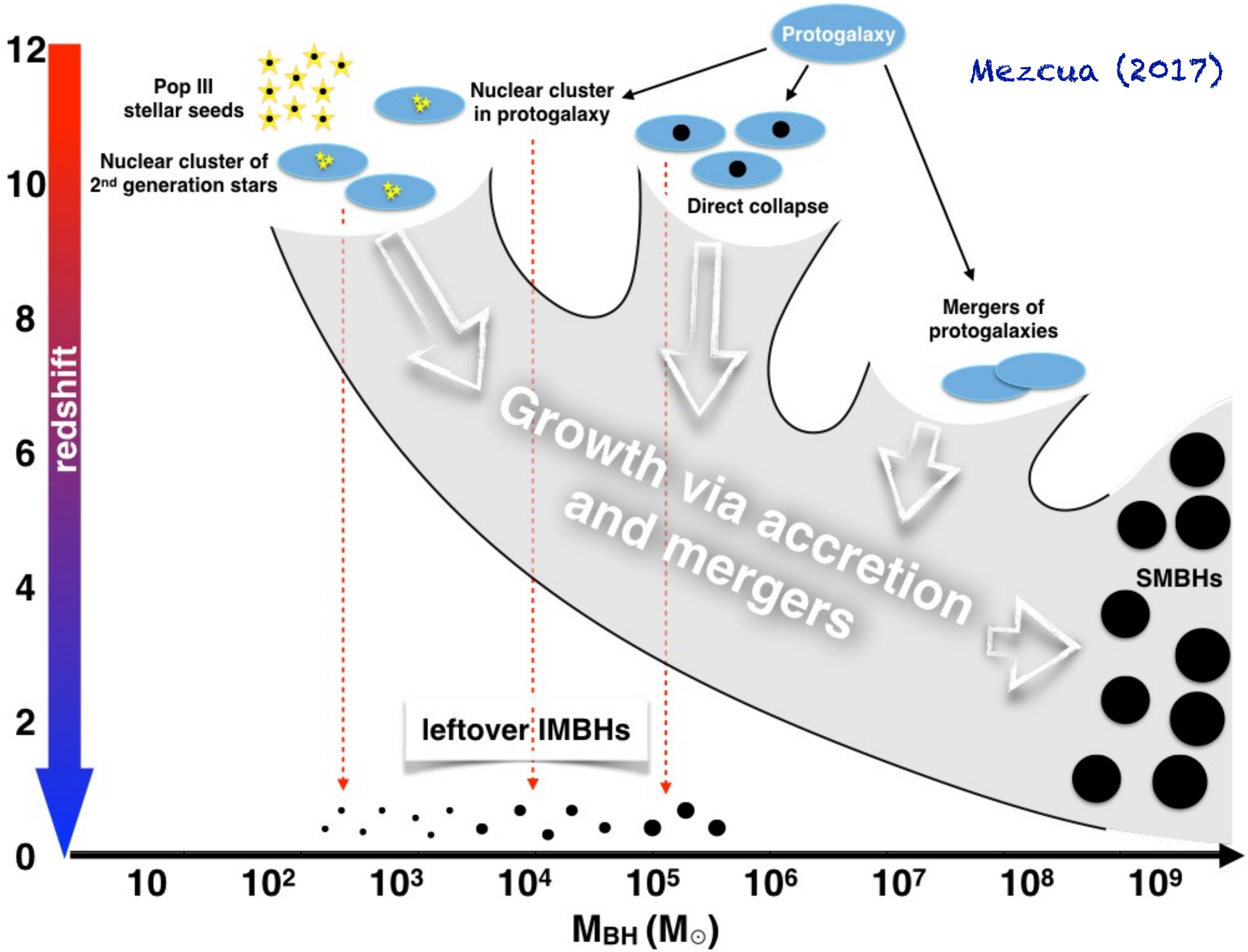

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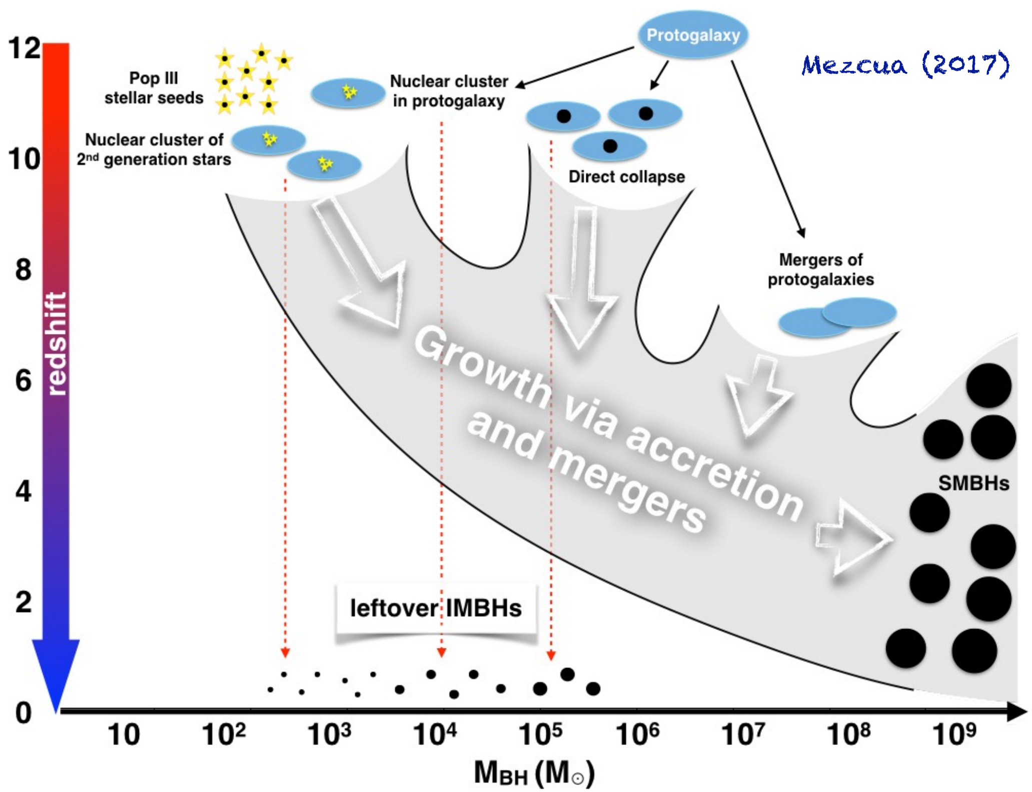

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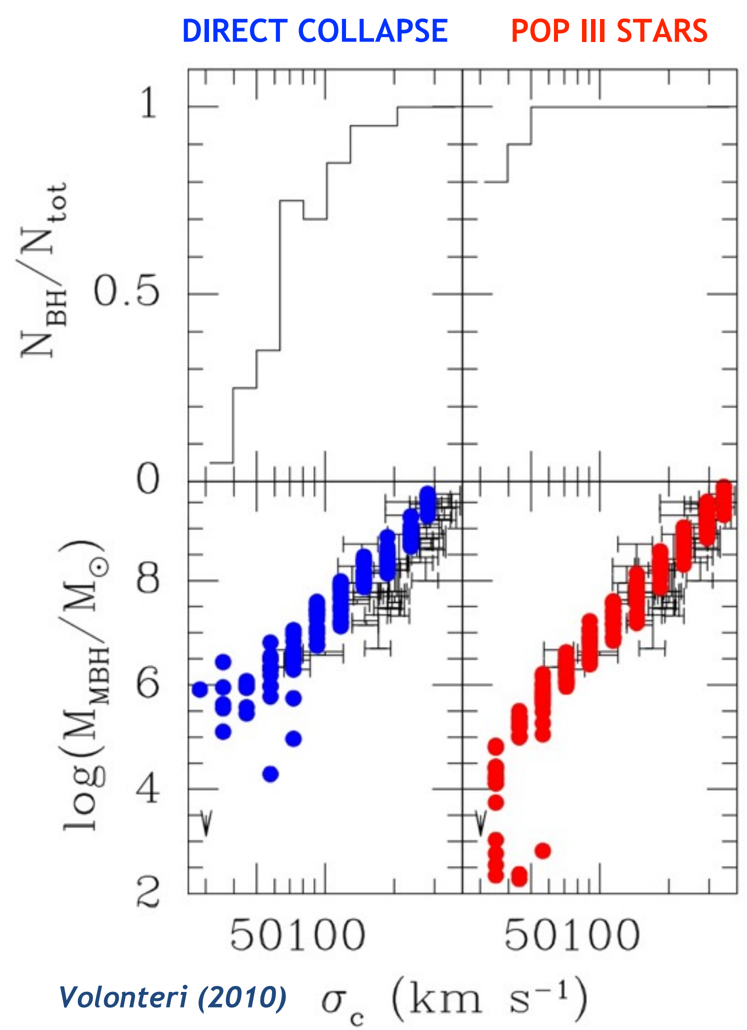

Volonteri (2010)

How do SMBHs form?

Dwarf galaxies

- Have low mass and low metallicity
- Do not (presumably) significantly grow through mergers and accretion
- Regulated by supernova feedback: stellar outflows - evacuate gas from nucleus
  - hamper BH growth

⇒ Resemble the first galaxies formed in the early Universe

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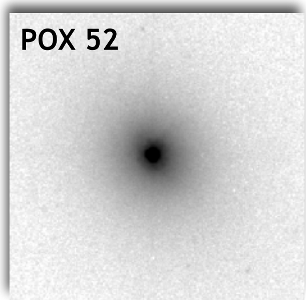
IMBHs as AGN in dwarf galaxies

- First two discoveries serendipitious:

  Broad emission lines ⇒ $M_{BH} \sim 3\times10^5\, M_\odot$

  X-ray emission ⇒ signature of accretion

Mt. Lemmon Sky Center



Thornton et al. (2008)

How do SMBHs form?

IMBHs as AGN in dwarf galaxies

- Searches using optical/IR emission lines:

  ~Hundreds of candidates, tens confirmed by X-ray emission

  Limited to z<1, M_{BH} ~10^4 -10^6 $M_\odot$ from broad lines

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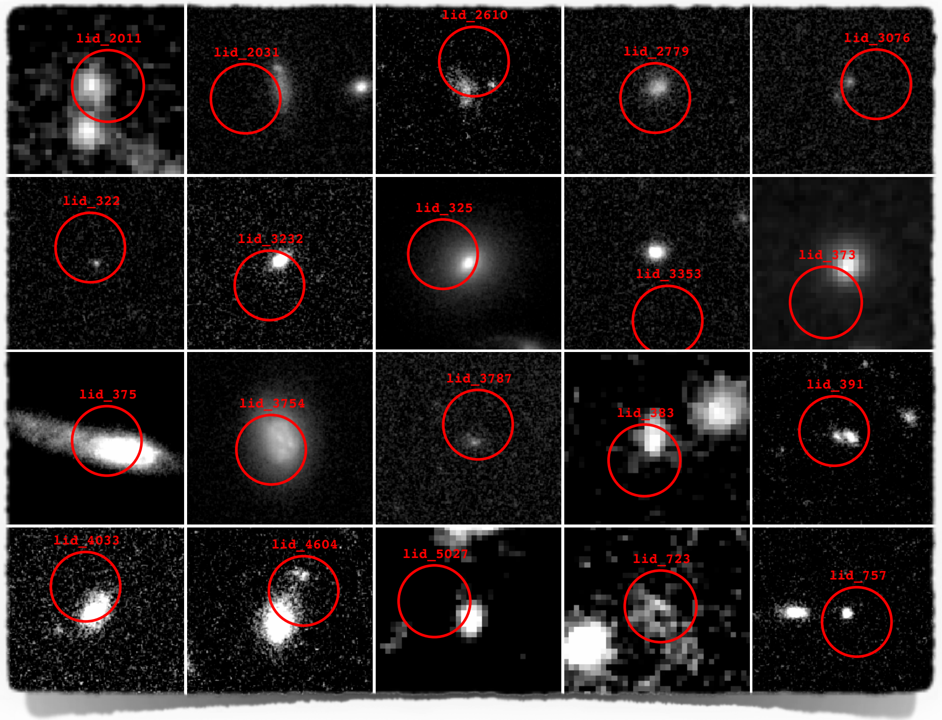

Mezcua et al. (2018)

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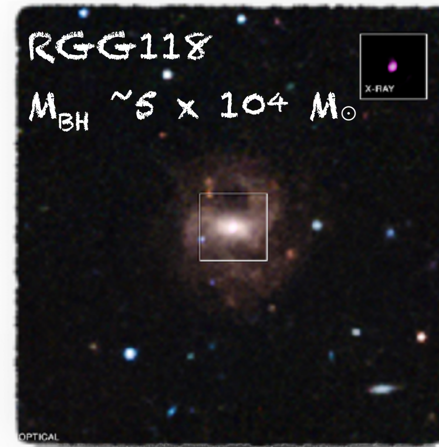

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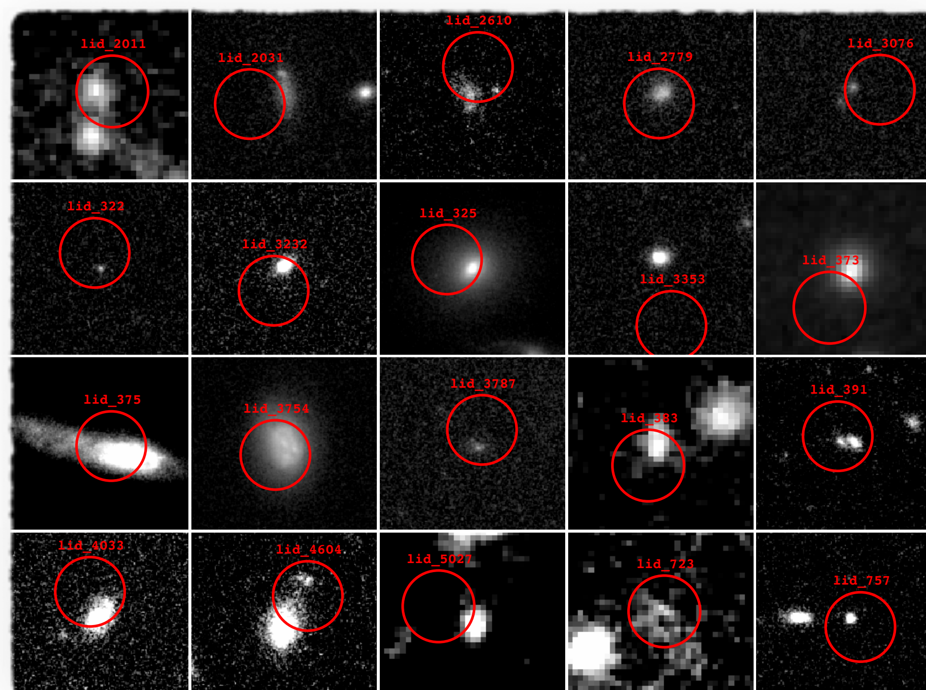
- At $z=10$?



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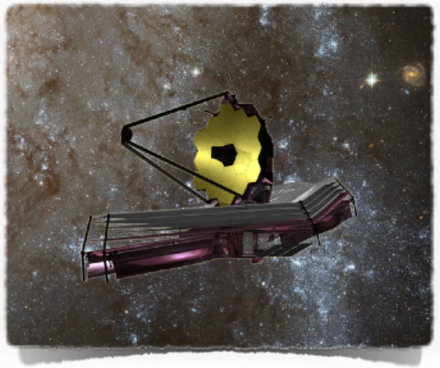
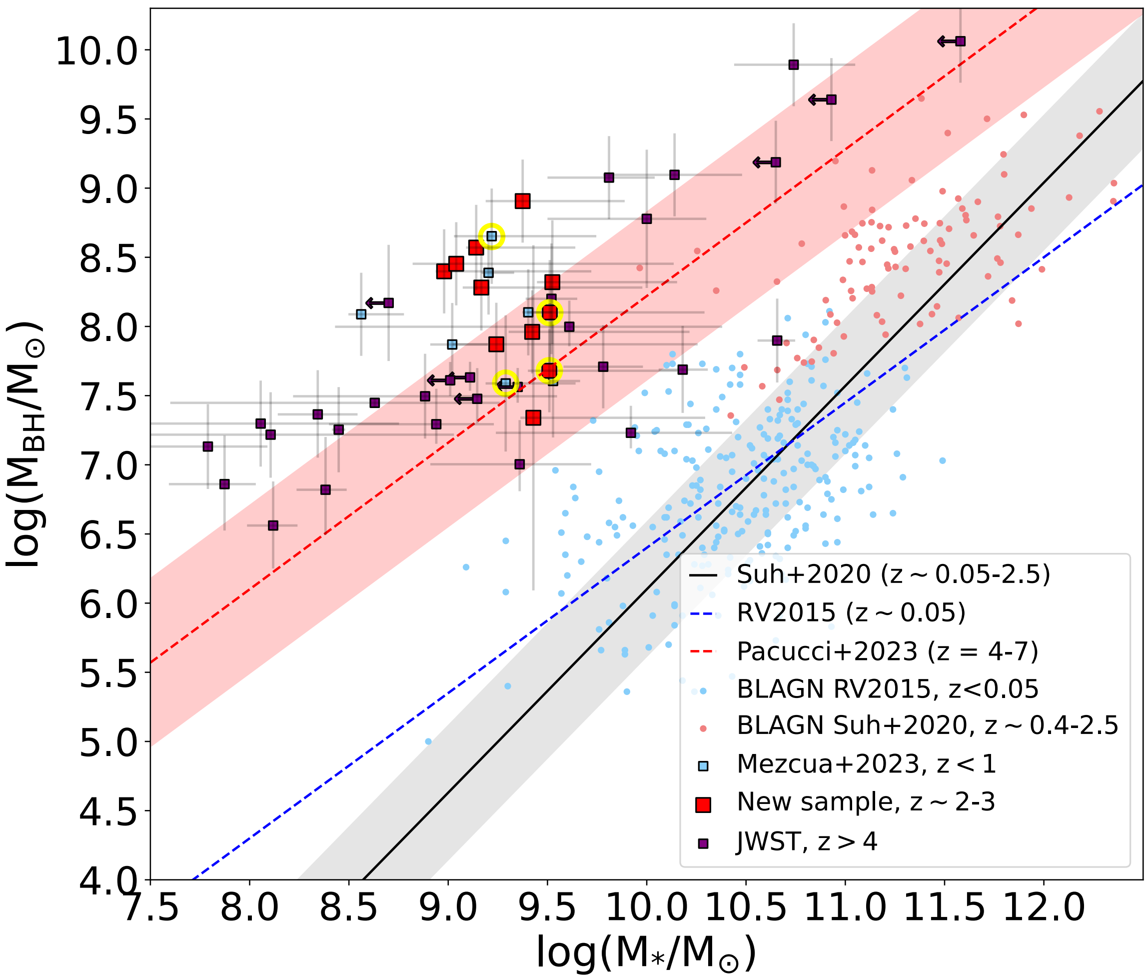
How do SMBHs form?

James Webb Space Telescope



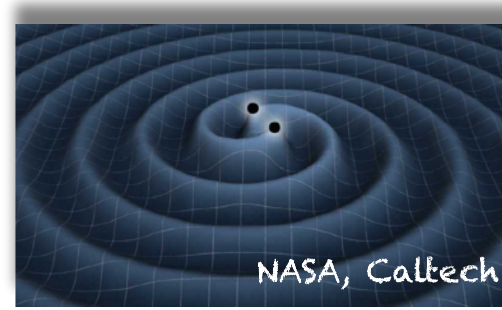
SMBHs in low-mass galaxies at z~4-10!!



How do SMBHs form?

Gravitational waves

- Waves in the space-time due to massive objects in motion (e.g. two BHs orbiting each other)
- Gravitational waves propagate at the speed of light
- They were predicted by Einstein's Theory of Relativity!!



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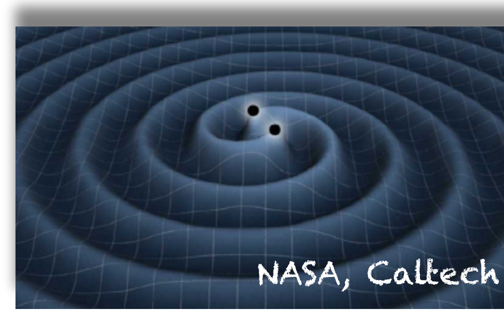
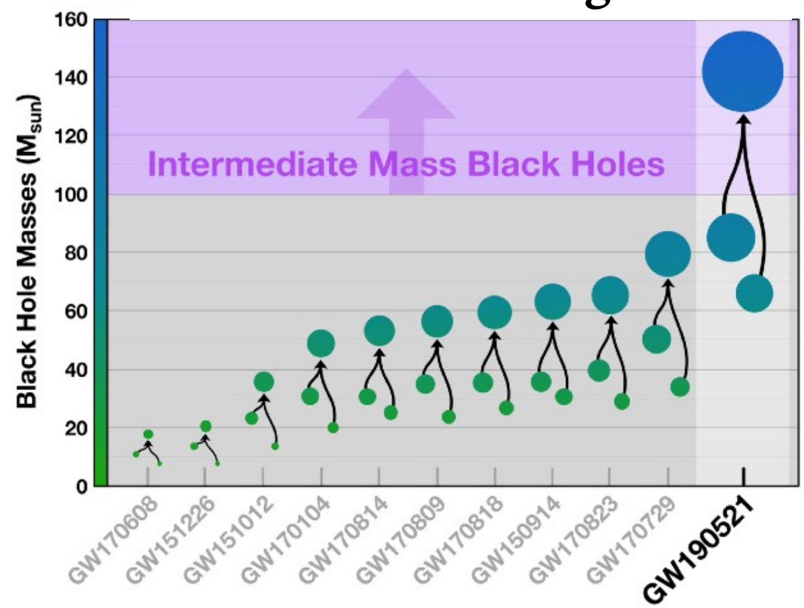


2020

Coalescence of two stellar-mass black holes yield an IMBH

Black hole mergers



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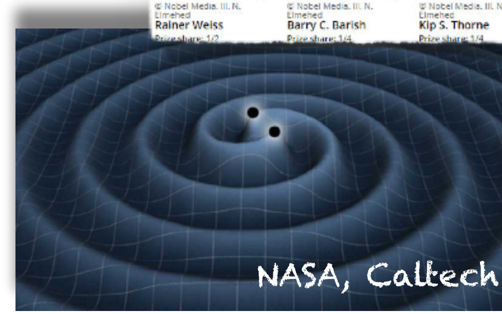

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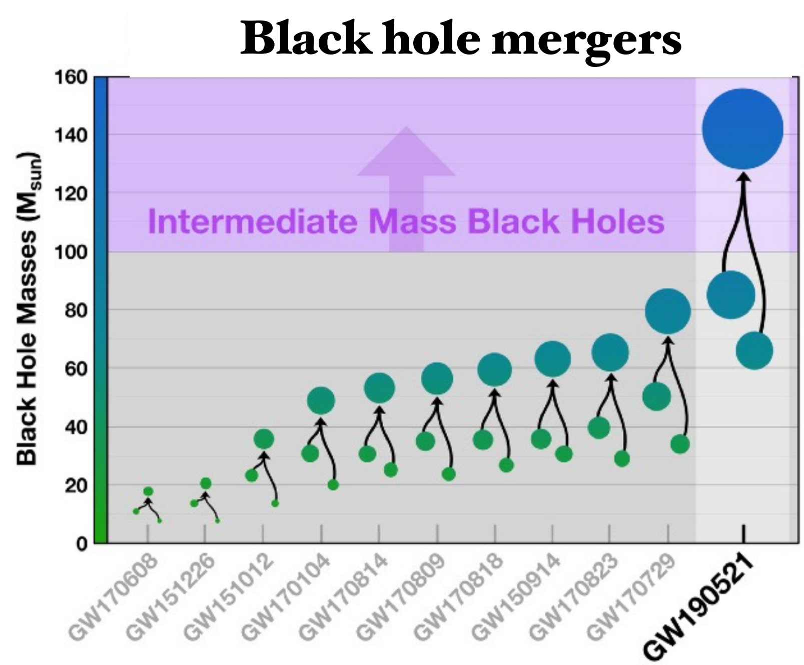
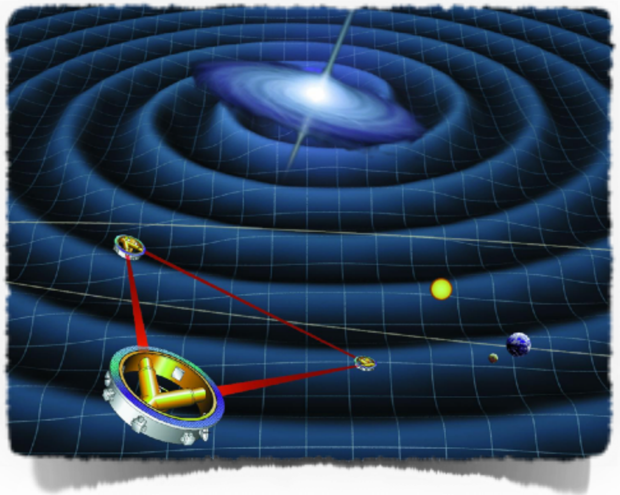


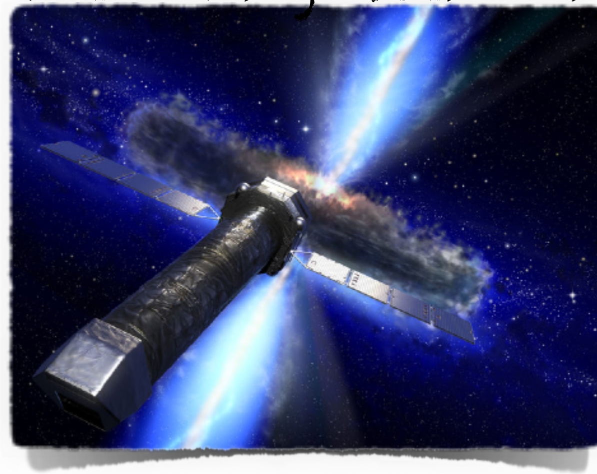
How do SMBHs form?

Wait for future observatories to detect seed BH at high-z

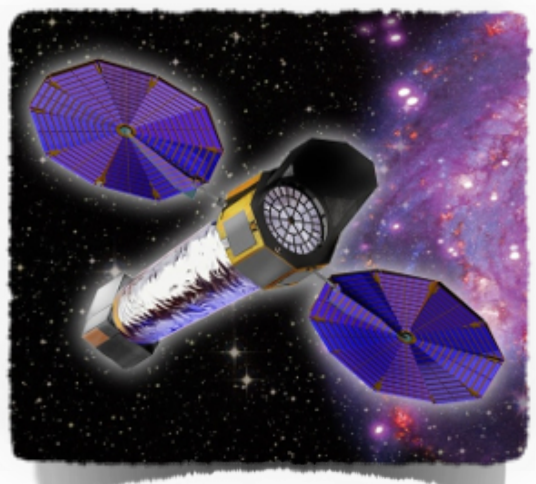
LISA (2034?)



Athena X-ray observatory (?)



Lynx X-ray observatory
(concept study)



Question

What have we learned?

AGN: summary

- AGN are powered by SMBHs (of $>10^6\ M_\odot$)
- Found in galaxies of all masses and types
- Observed AGN properties and classification depend on

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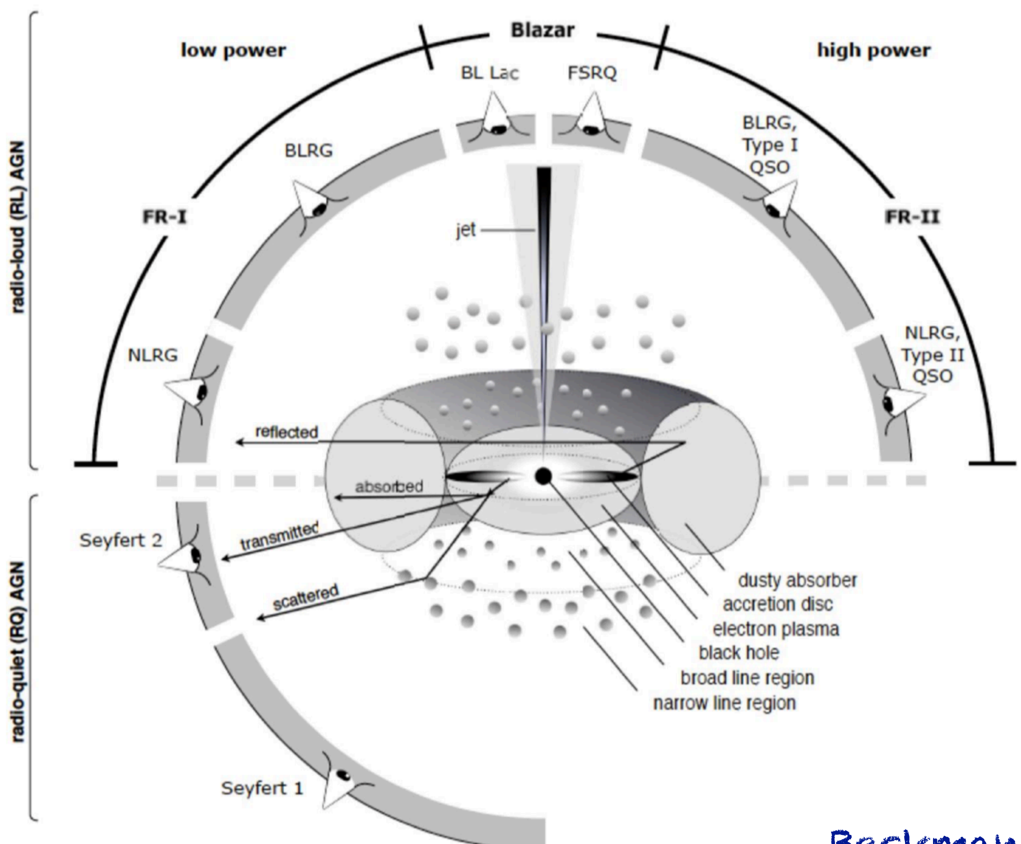

Beckman et al. (2012)

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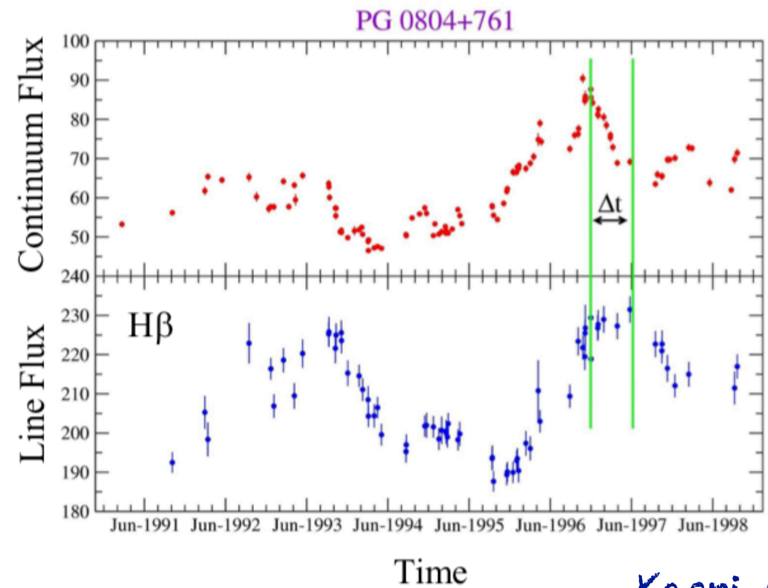

Kaspi et al. (2000)

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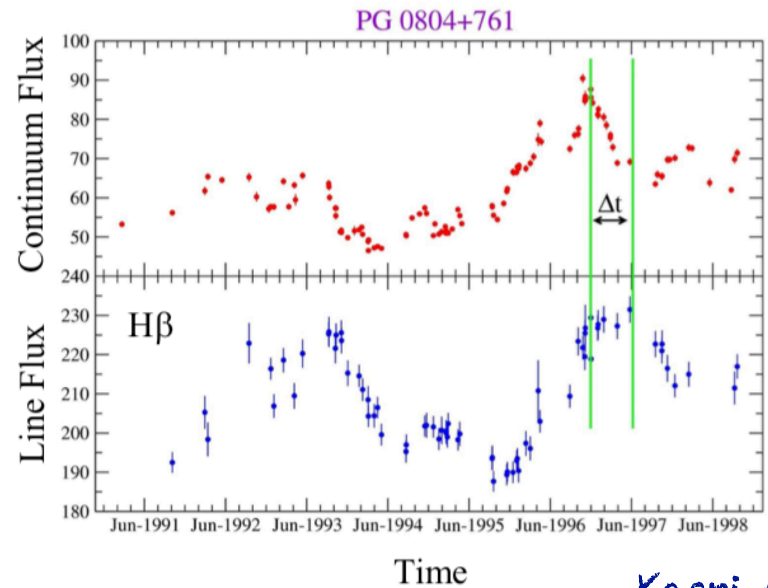

Kaspi et al. (2000)

- Quasars detect at z~7 (Universe ~0.8 Gyr old)

  SMBHs formed from seed IMBHs of 100 – 10^5 $M_\odot$

  Relics of seed IMBHs possibly found in local dwarf galaxies