# Black Holes and Active Galactic Nuclei

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May 7, 2015

# Observation



Optical: NASA: Hubble Telescope (1990-2014)

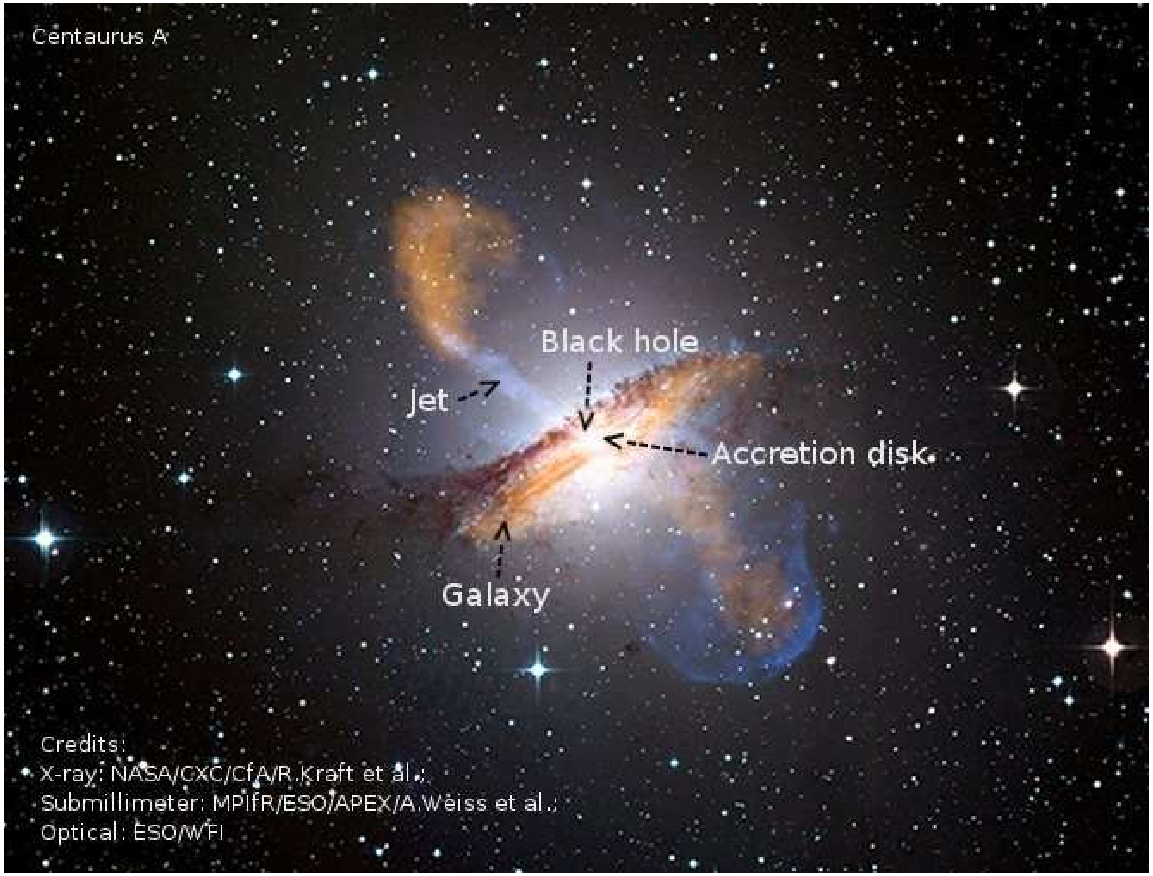
Infrared: ESA: Herschel Telescope (2009-2013)


Radio: NRAO: VLA (1980-)

X-ray: ESA: XMM-Newton (1999-2016)

# Centaurus A






- Centaurus A (Cen A) = the closest active galactic nucleus to us, $d \sim 3.5$ Mpc (1 pc $\sim 3 \times 10^{18}$ cm), $M_{\rm BH} \sim 5.5 \times 10^7\ M_\odot$
- composite image (X-ray, optical, and radio)

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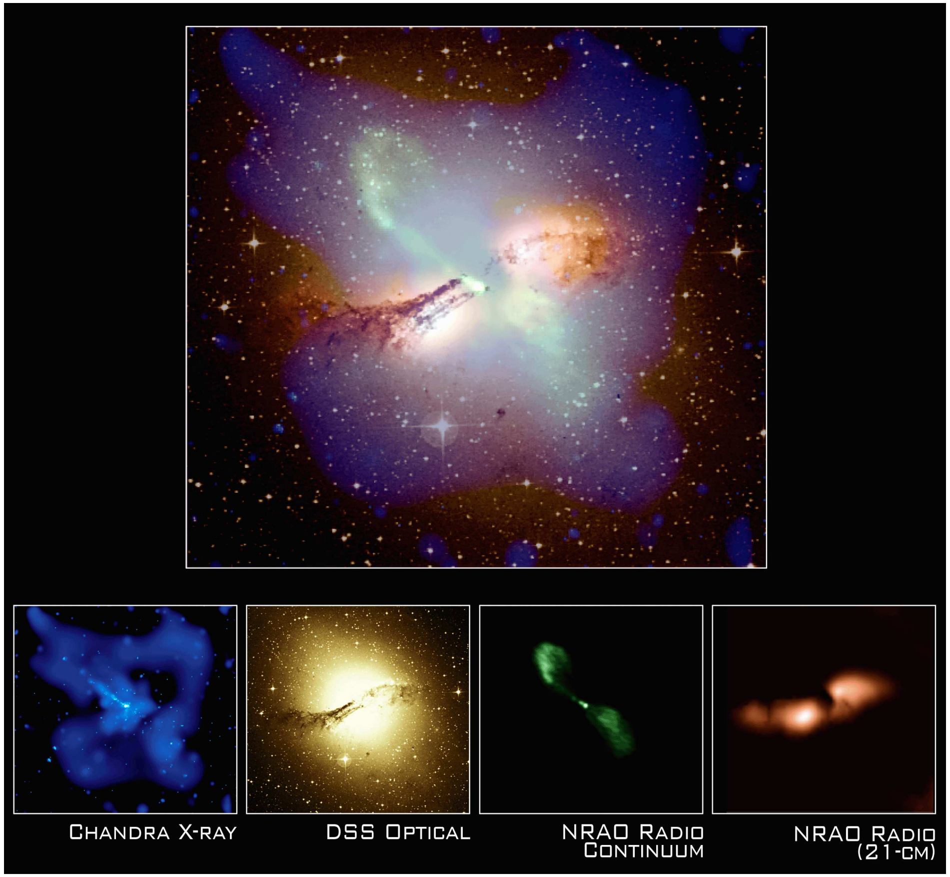


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# SUMARY



- Black hole formation
- Supermasive black holes and determination of black hole parameters (mass and spin)
- Clasification of active galactic nuclei (unification scheme)
- Active galactic nuclei feedback

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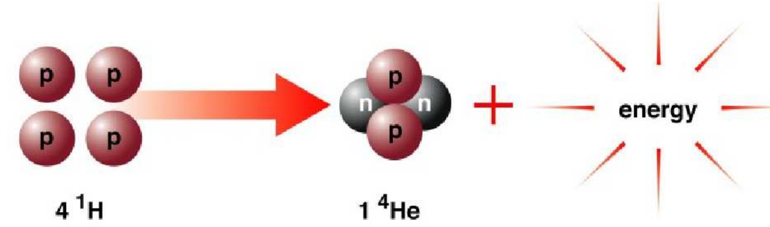
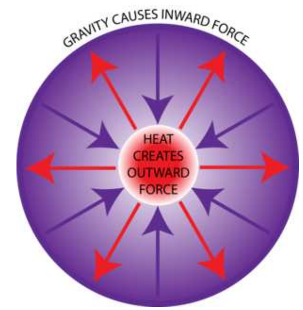
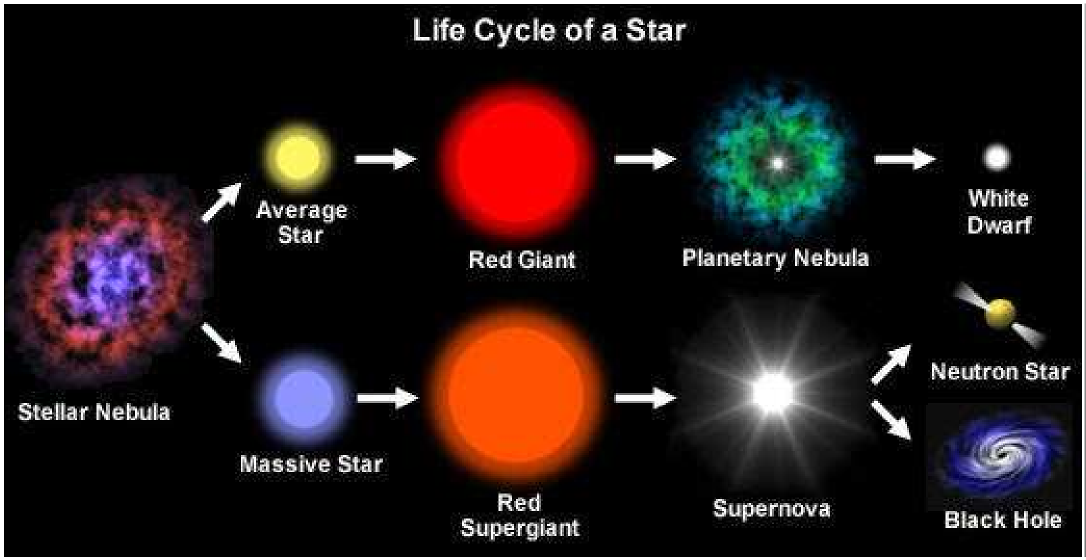
# Black hole formation

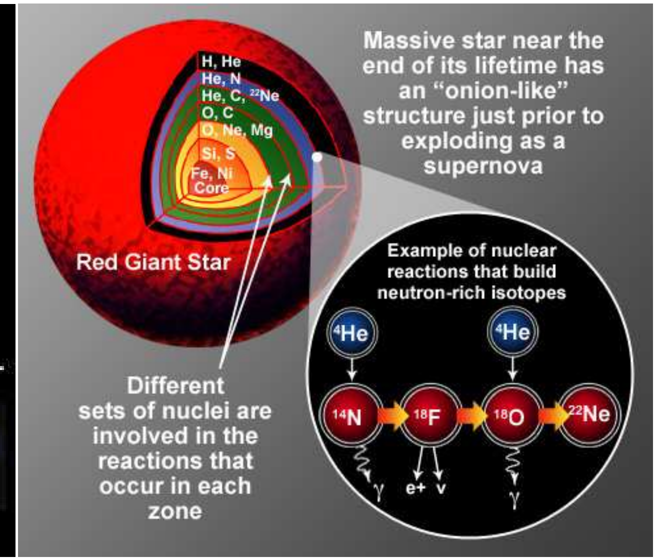


- gravitational colaps: gravitational force > pressure force
- mass after collapse for white dwarfs: $M < 1.4\,M_\odot$
- gravitational radius: $r = \frac{GM}{c^2} \sim 1$ for $M_{\rm BH} \sim 10^9\ M_\odot$



# Black hole formation

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BH formation
Supermassive BH
Hubble scheme
Kerr BHs
Accretion disks
BH jets
AGN unification
Radio dichotomy
BH mass
Iron line
Galaxy formation
AGN feedback

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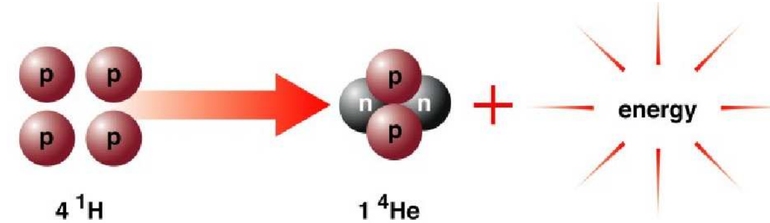
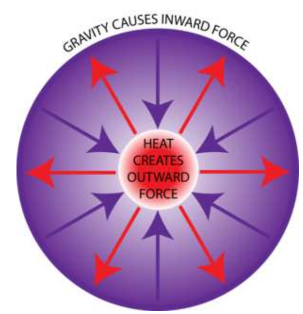
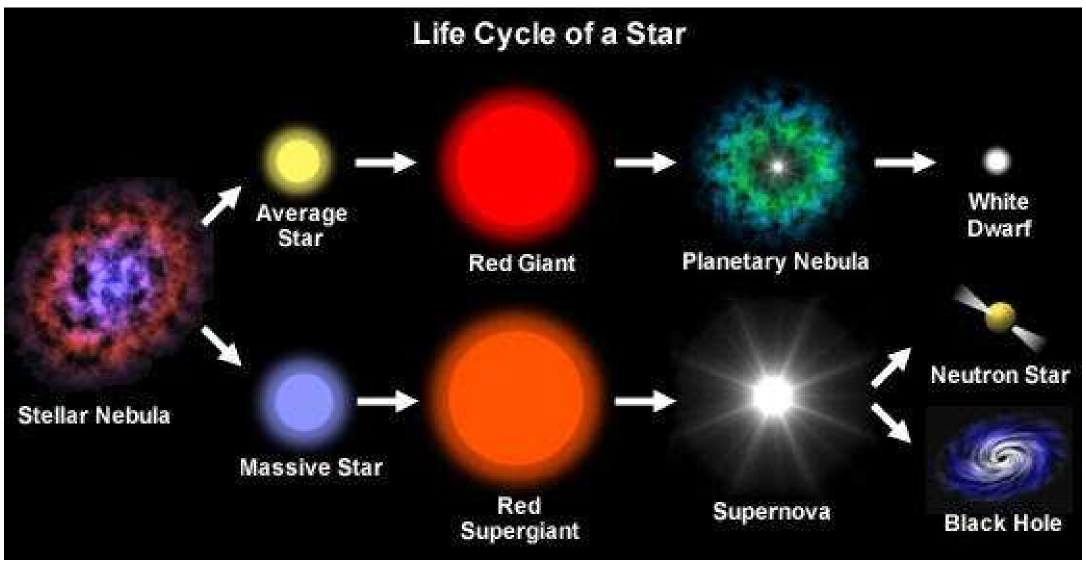
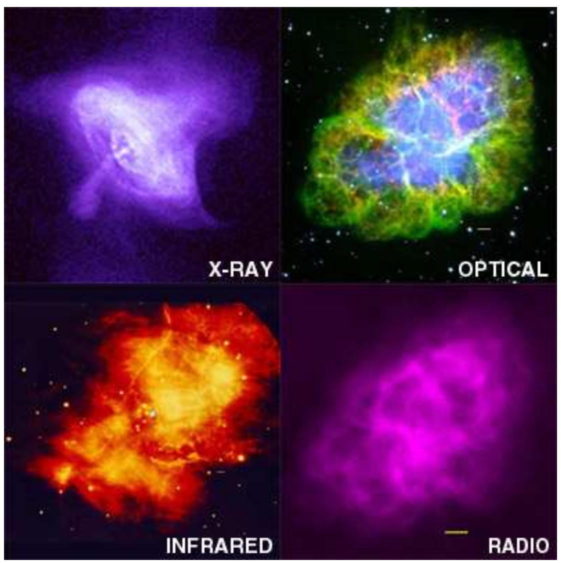


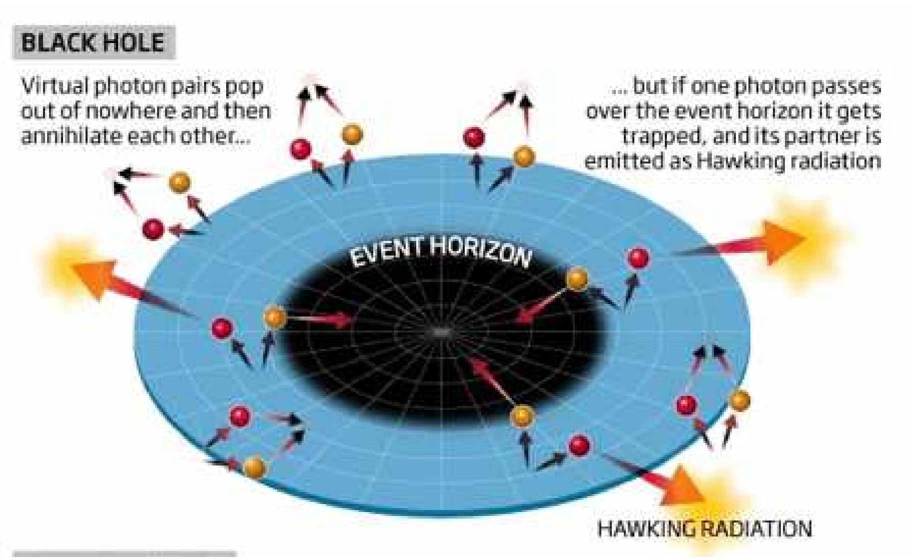



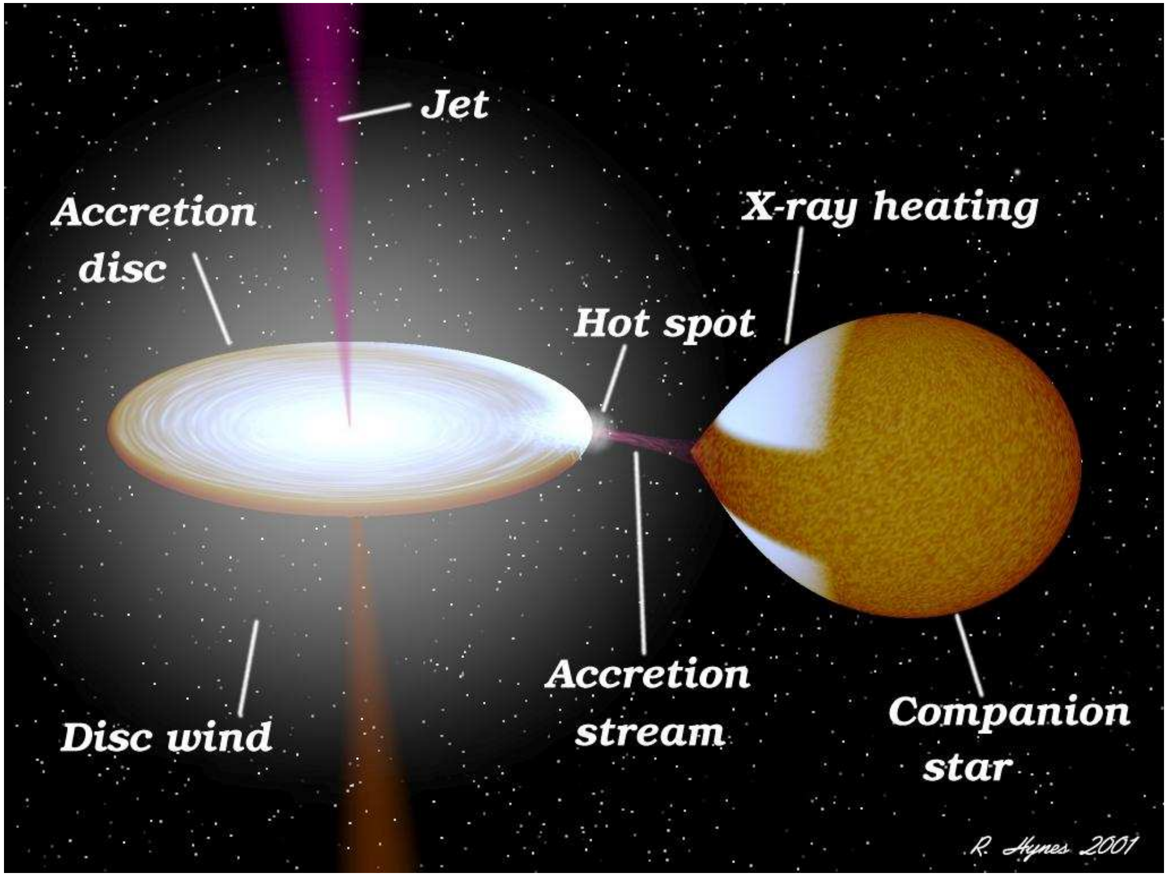
# Black hole formation



- supermassive black holes at the center of galaxies
  $M \sim 10^7 - 10^9 M_\odot$
- binary systems = stellar black holes
  $M \sim$ few/tens $M_\odot$
- primordial black holes
  at the atomic scale, Hawking radiation: black hole "evaporation"



# Black hole formation

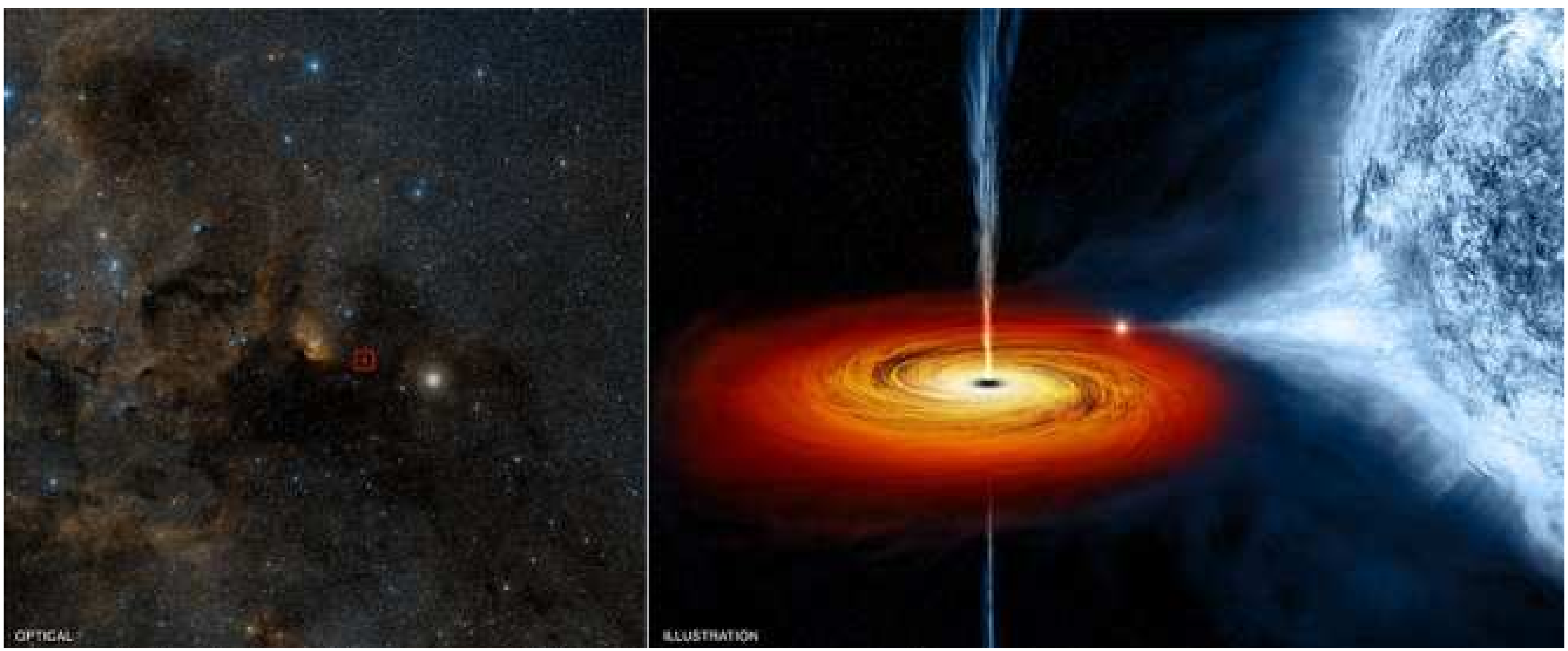



- X-ray emission due to hot gas in the accretion disk

# Black hole formation

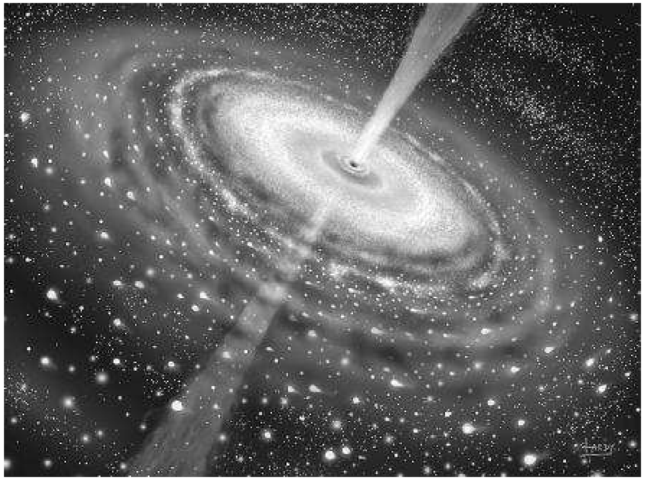


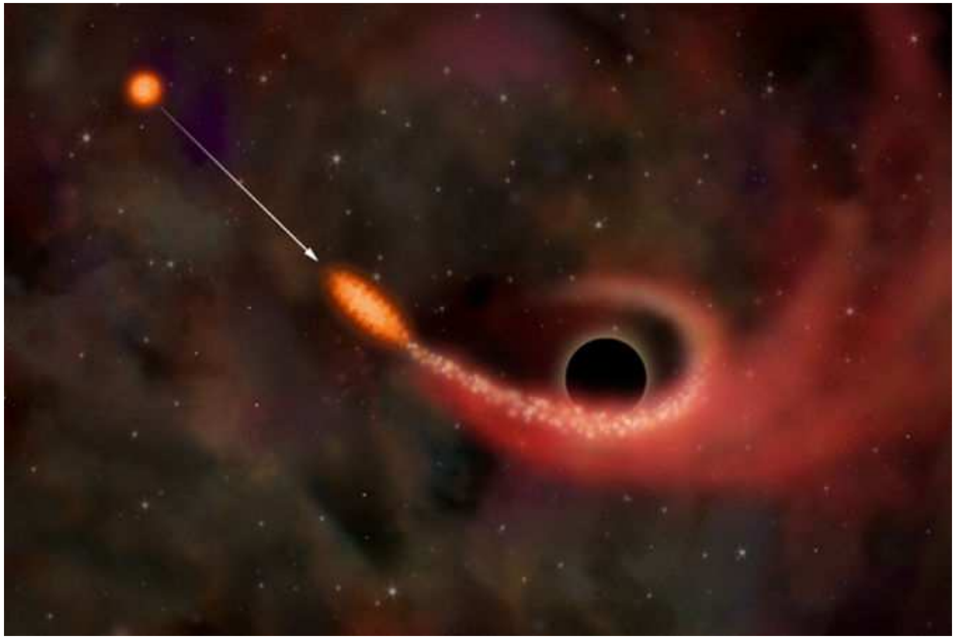
- Cygnus $X$-1: closest black hole to us, $5 \times 10^{16}$ km
- stellar black hole, $M \sim 14.8 \times M_{\odot}$
- horizon executes 800 rotations per seconds
- blue star, $M \sim 8 - 10 \times M_{\odot}$

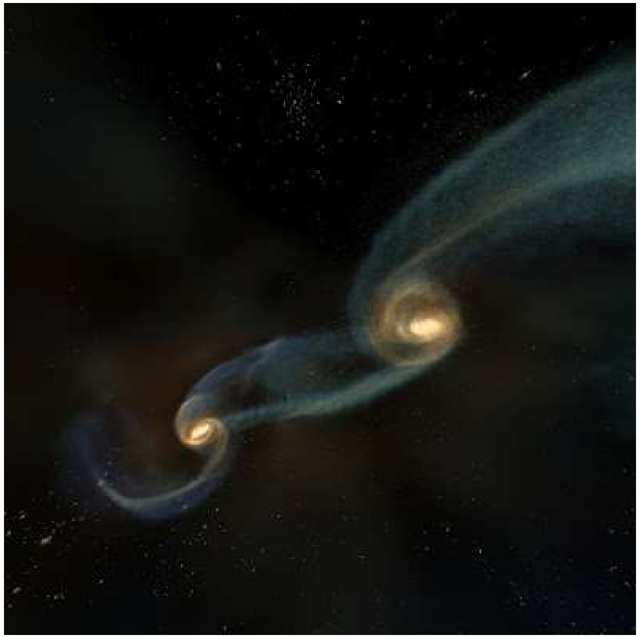


# Supermassive black hole growth

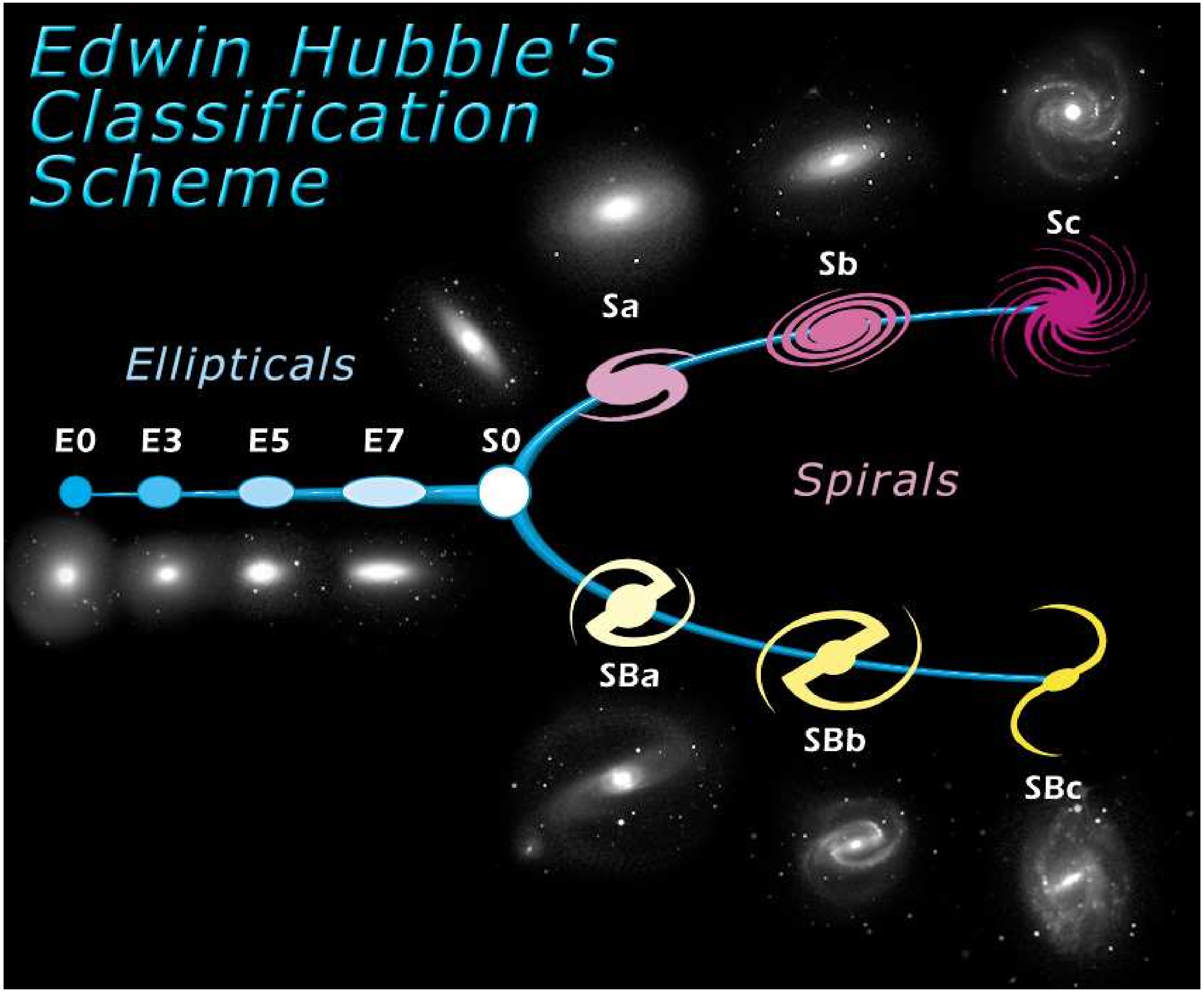
- by accretion of gas and dust from the interstellar medium of the galaxy
- through star disruption
- galaxy meargers







- 4 forms: elliptic, spiral, lenticular, and irregular



- Kerr space-time symmetries, Killing vectors: $\xi_t = (\partial_t)$, $\xi_\phi = (\partial_\phi)$
- Kerr (1963) metric in Boyer-Lindquist (1967) coordinates $(t, r, \theta, \phi)$:

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4Mar\sin^2\theta}{\Sigma} dt\, d\phi + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2Ma^2 r\sin^2\theta}{\Sigma}\right) \sin^2\theta\, d\phi^2$$

geometrical functions: $\Delta = r^2 - 2Mr + a^2$, $\Sigma = r^2 + a^2\cos^2$

$a = J/(Mc)$, BH spin

- energy-momentum tensor: $T_{\mu\nu}$
- conservation laws of energy, $\mathbf{E} \equiv \mathbf{T} \cdot \partial/\partial t$, and of angular momentum, $\mathbf{J} \equiv \mathbf{T} \cdot \partial/\partial\phi$

- event horizon = singularity of the BL coordinates, $\Delta = 0$:

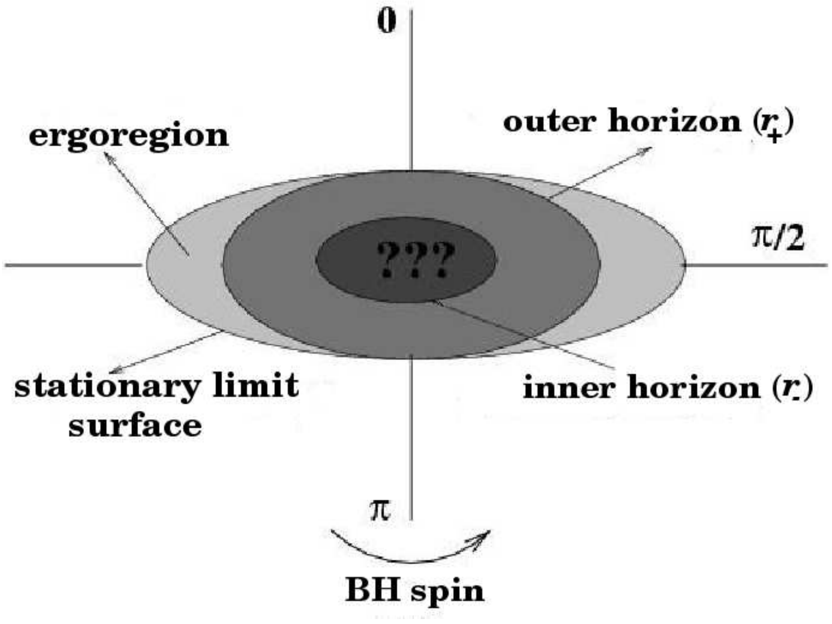
$$r_\pm = M \pm \sqrt{M^2 - a^2} = r_g(1 \pm \sqrt{1 - a_*}),\ r_g = GM/c^2 \text{ gravit. radius}$$

$$a_* = a/r_g,\ \boxed{-1 \leqslant a_* \leqslant 1},\ \text{BH spin parameter}$$

- ergosphere (stationary limit surface): time-like Killing vector becomes null

$$\xi_t \cdot \xi_t = g_{tt} = 0$$

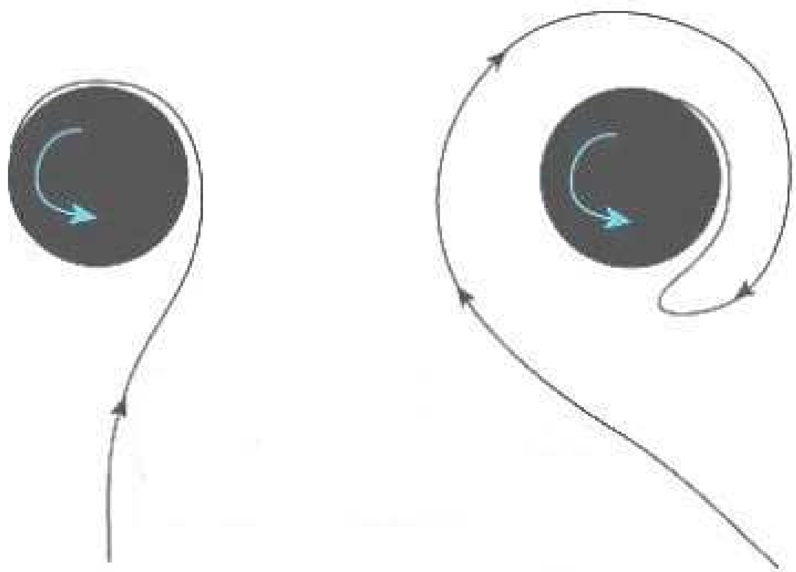
$$(r_{sl})_{\theta=\pi/2} = 2\,r_g$$

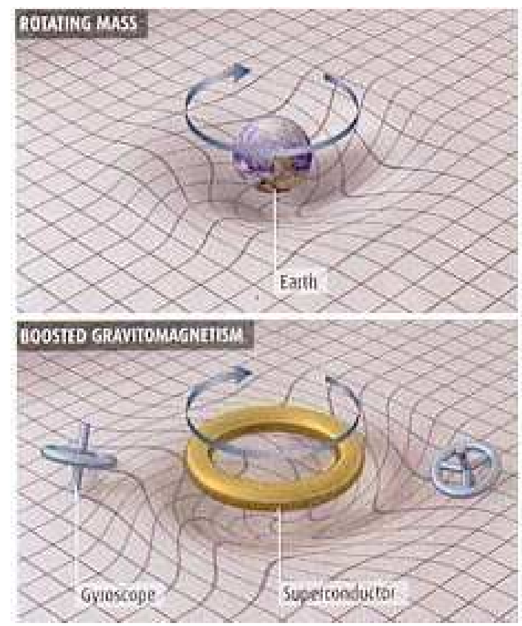


# Kerr Black Holes

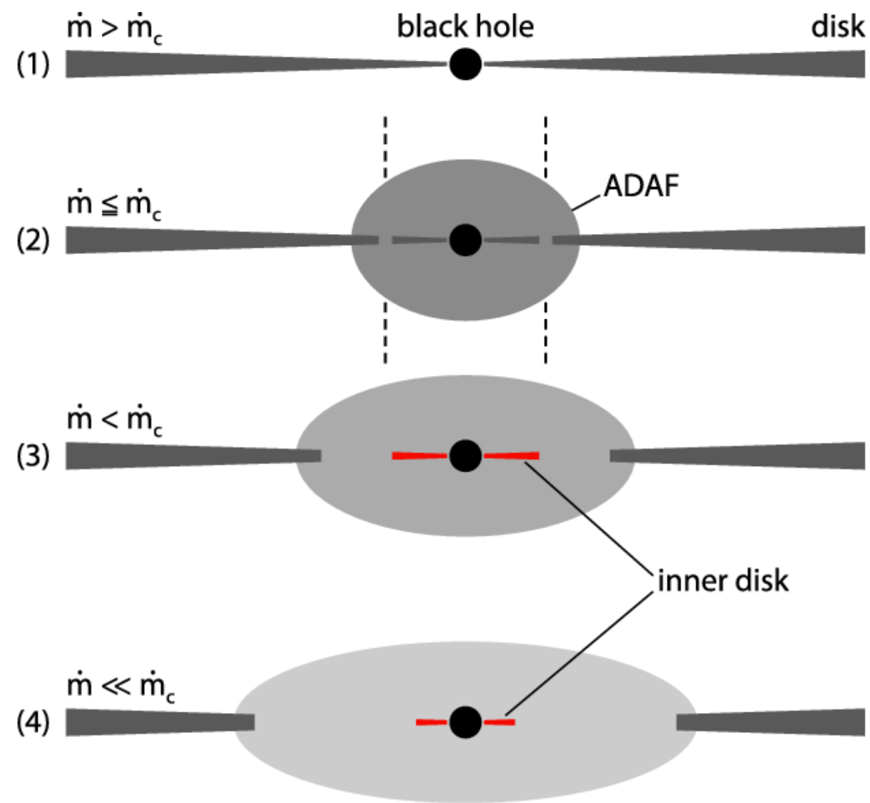


- frame-dragging effect: nothing inside the ergosphere can remain at rest with respect to distant observers, it must co-rotate with the BH rotation

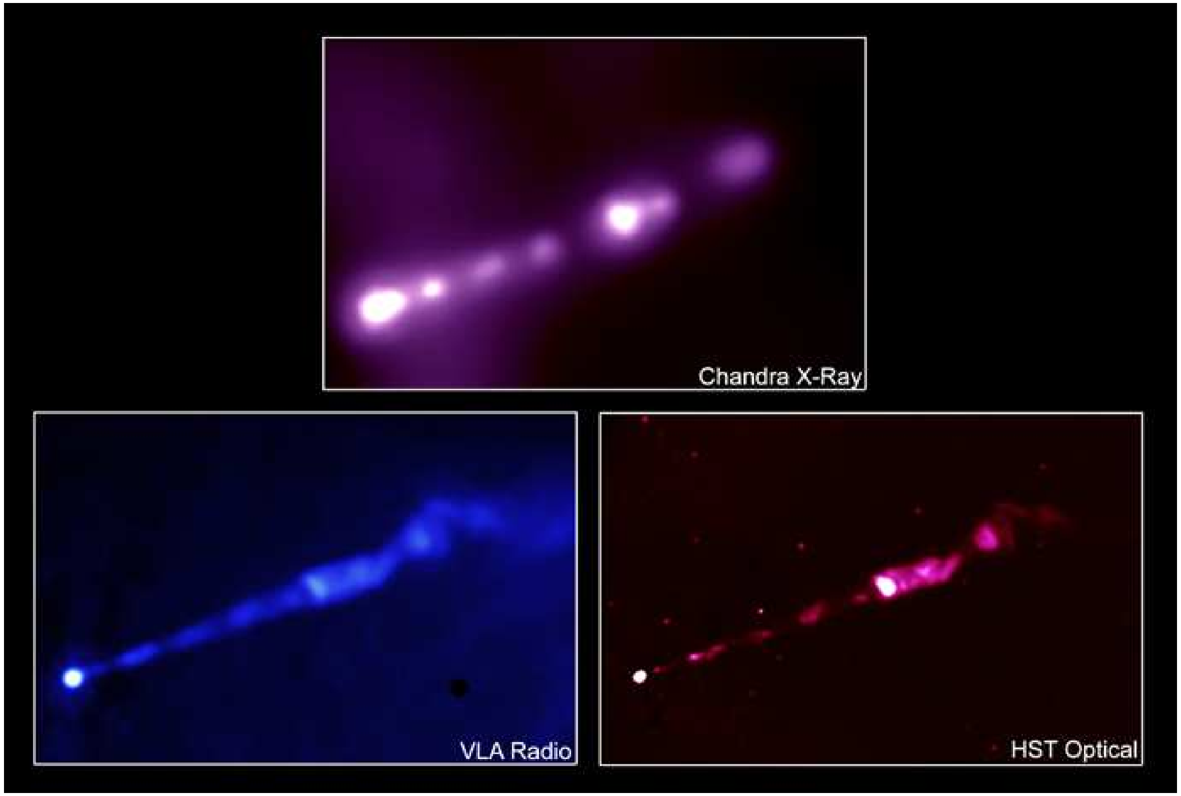




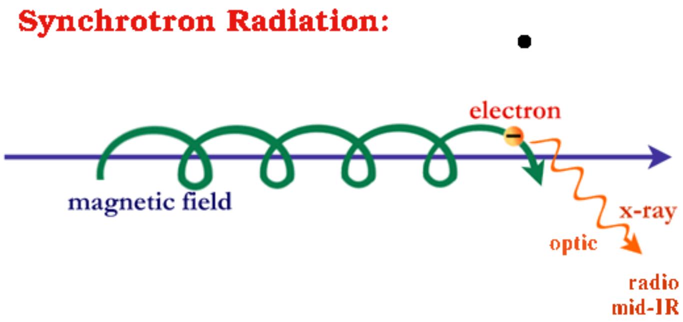
- geometrically thin, optically thick disk reaching inward to the last stable orbit (for accretion rates between a few percent up to almost the Eddington rate)
- hot optically thin, geometrically extended advection-dominated flow (ADAF)




- accretion rate: $\dot{m} = \frac{dm}{dt}$; luminosity: $L = \dot{m}c^2$
- Eddington accretion rate: $\dot{M}_{\rm Edd} = L_{\rm Edd}/(\varepsilon c^2) = 4\pi GM/(\varepsilon \kappa_{\rm T} c)$, where $\varepsilon$ = efficiency of converting the accreting rest mass-energy into radiation energy, and $\kappa_{\rm T}$ = Thomson opacity

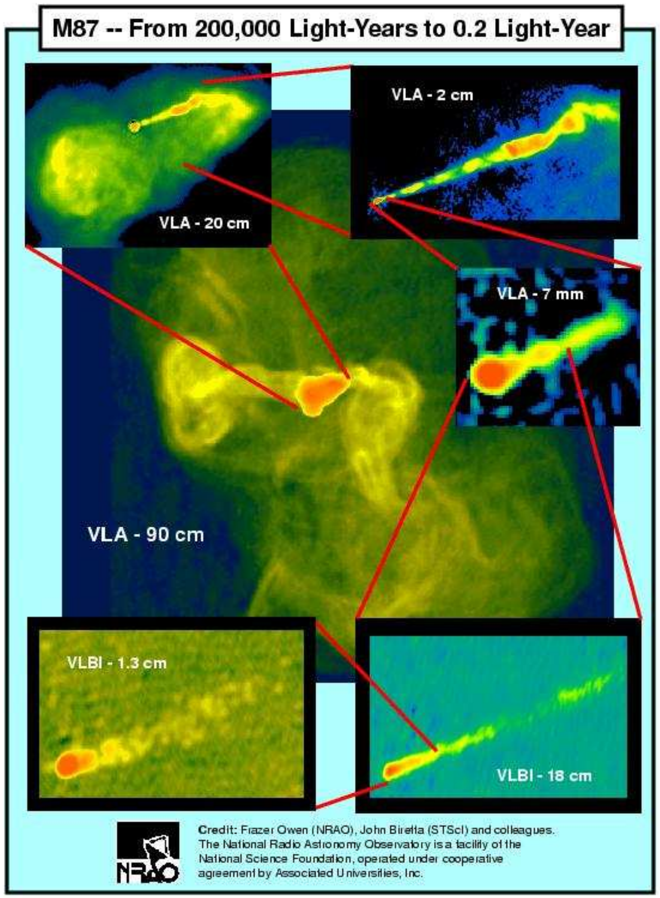



- synchrotron emission over the whole spectrum (from $X$-ray to radio)



# Black hole jets








- better resolution with VLBI (Very Long Base Interferometry); shorter long waves
- correlator: interference of coherent radio waves from VLBI stations

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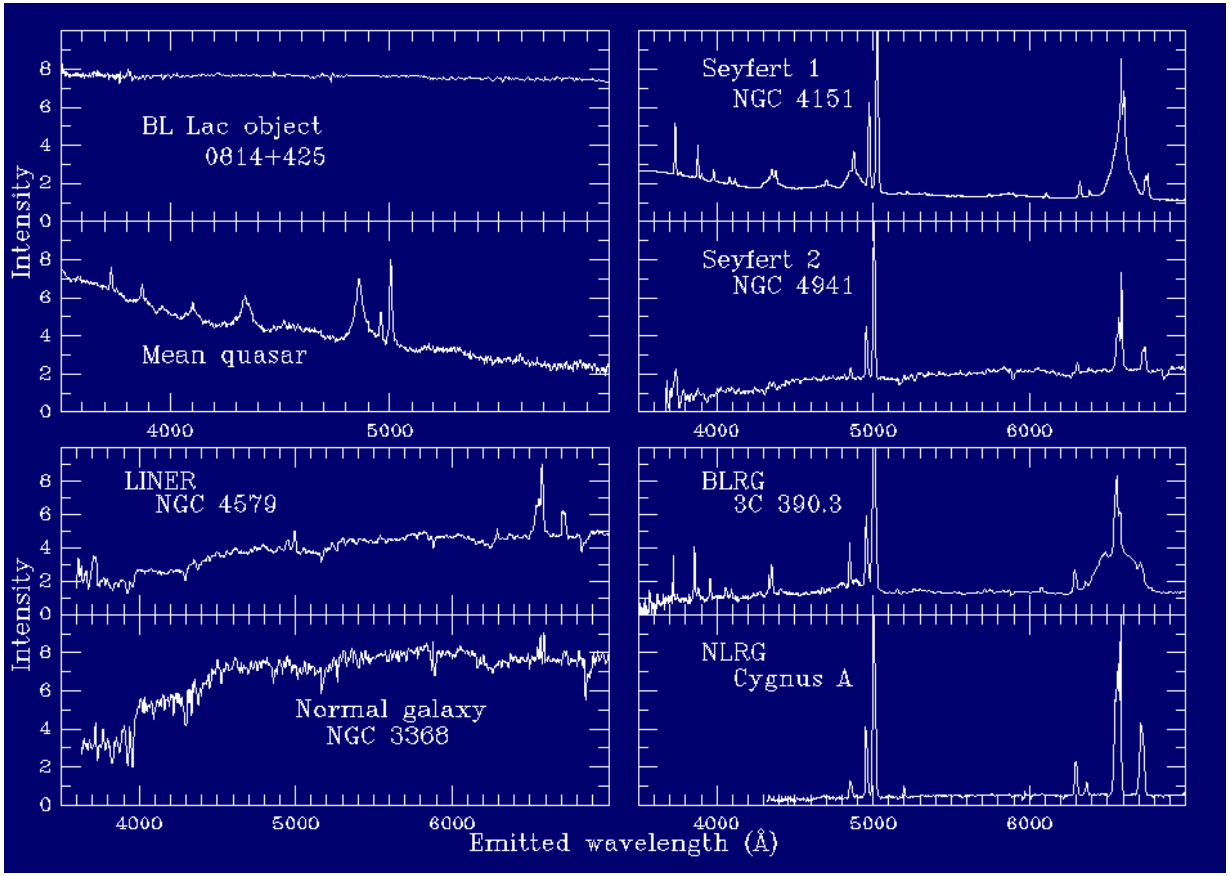
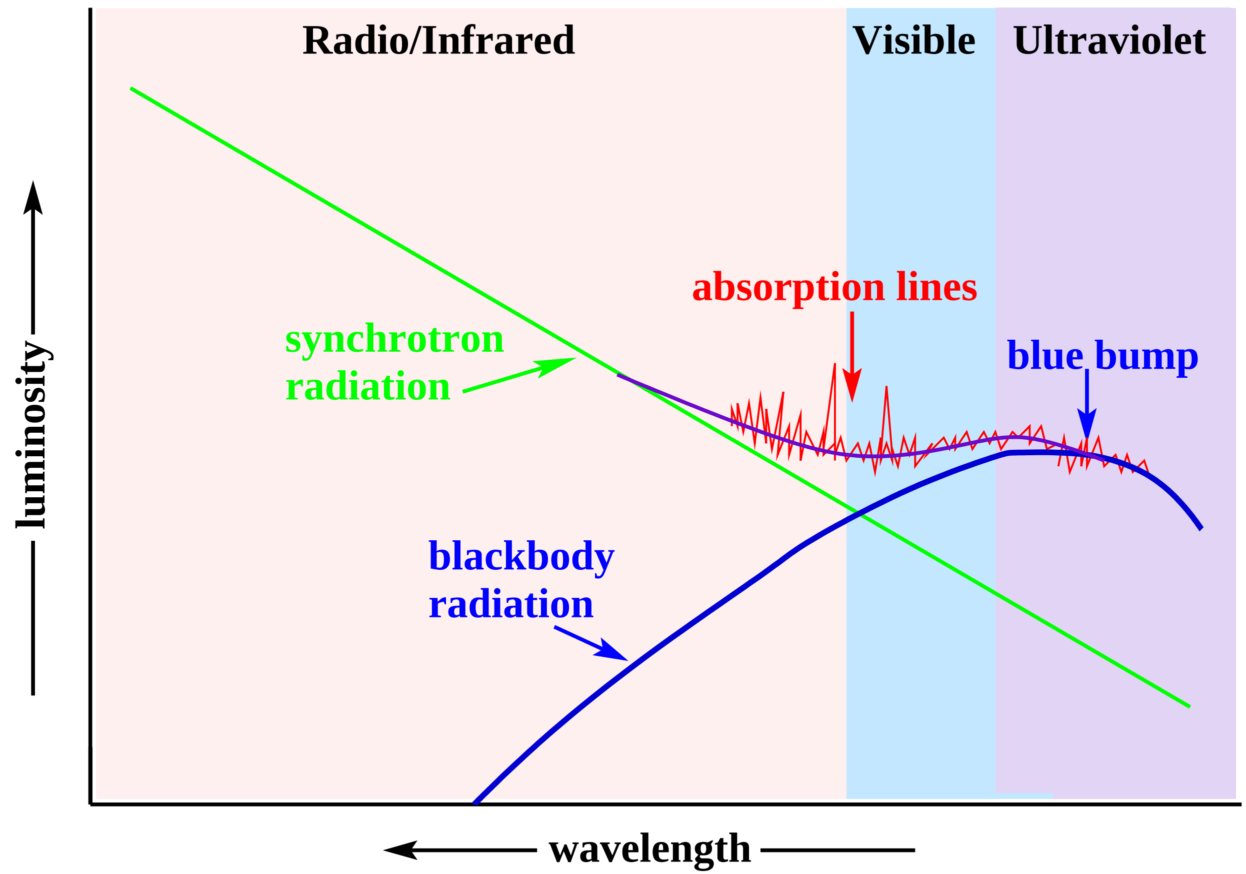


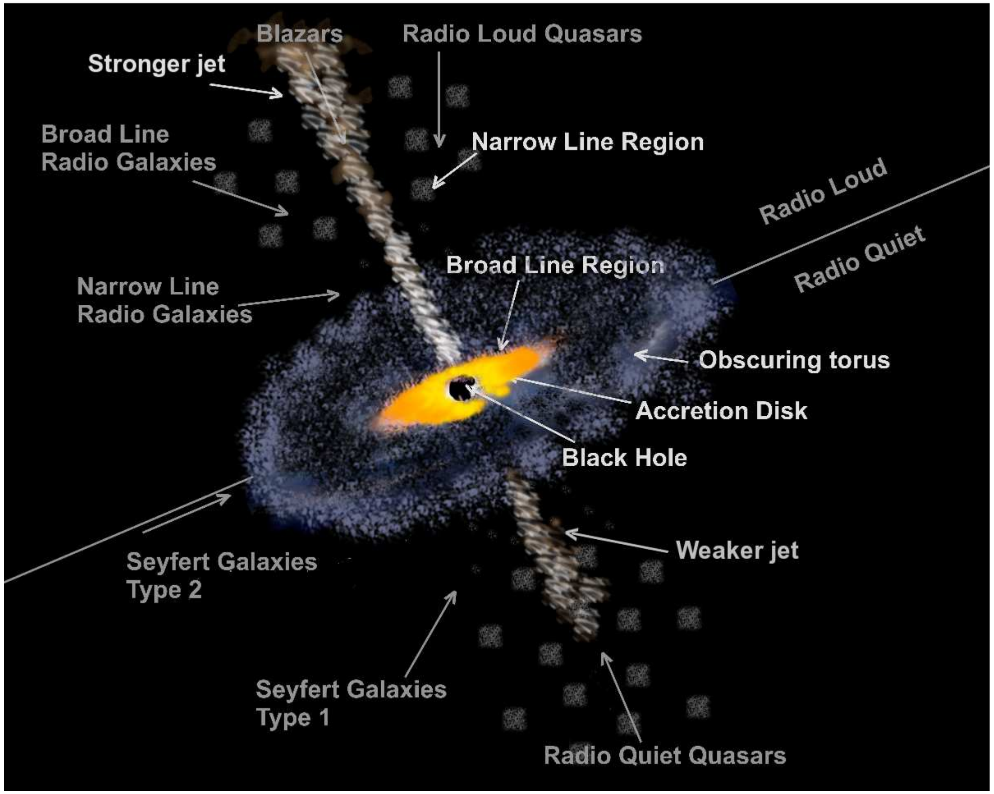

- Active galactic nuclei (AGN) = galaxies the center of which cannot be explained through standard stellar physics, a massive and dens stellar cluster or a stellar black hole

# Unification scheme of the AGN



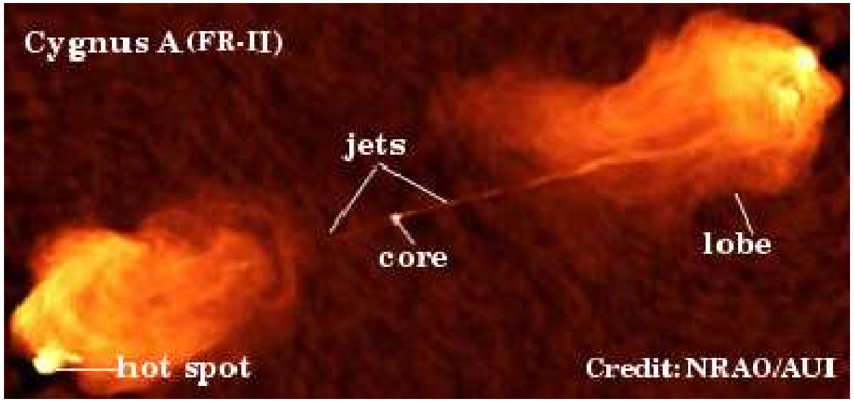



- power-law (non-thermal) radiation ($\nu^{-\alpha}$): jets
- blackbody (thermal) radiation: accretion disk



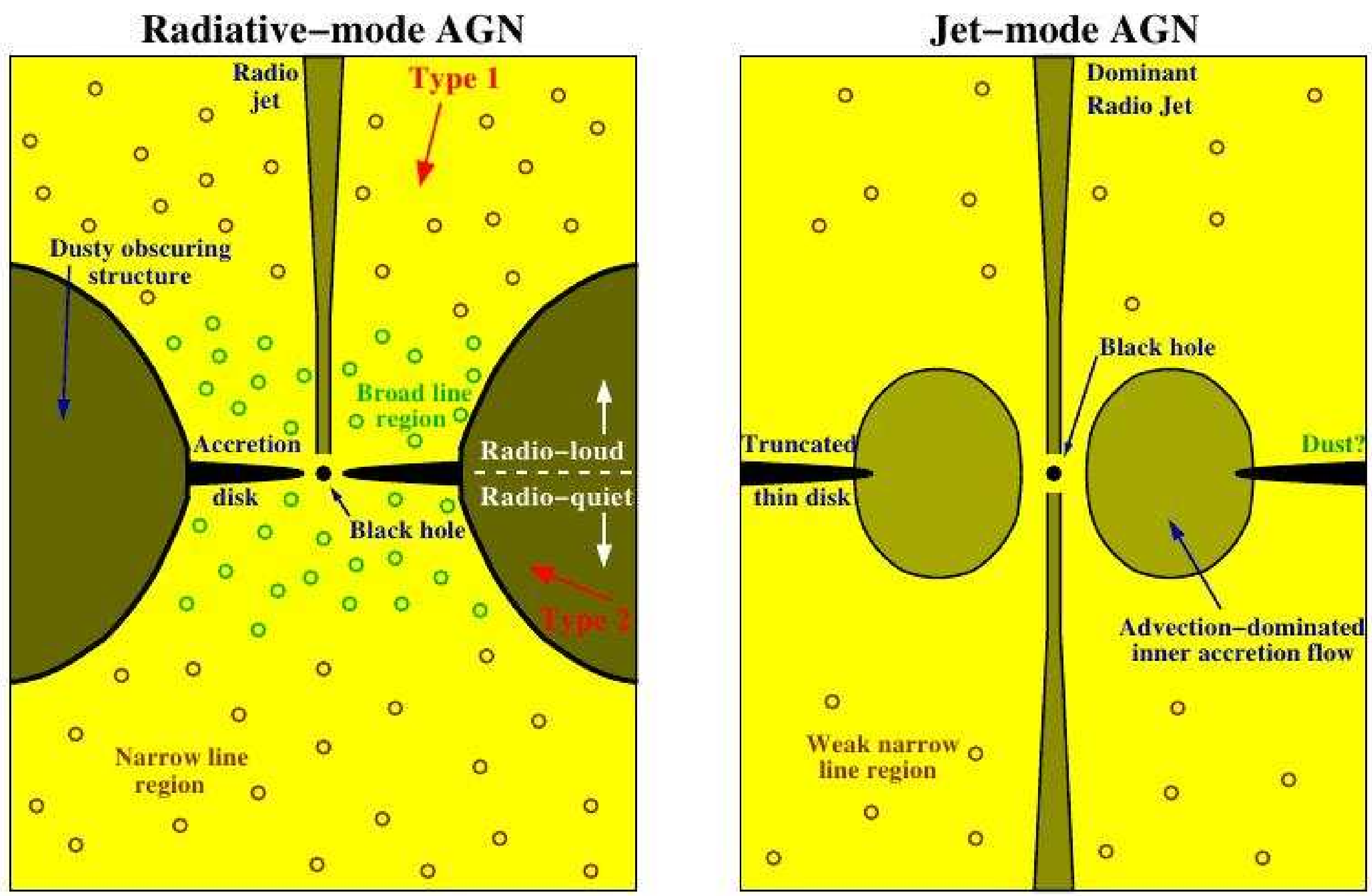

- supermassive BH ($M \sim 10^7 - 10^9 M_\odot$), spinning, and surrounded by an accretion disk

- BH jets:
  $v_{\rm jets} \sim 0.9 - 0.995\, c$
  $c = 3 \times 10^8$ m s$^{-1}$, speed of light



# Unification scheme of the AGN

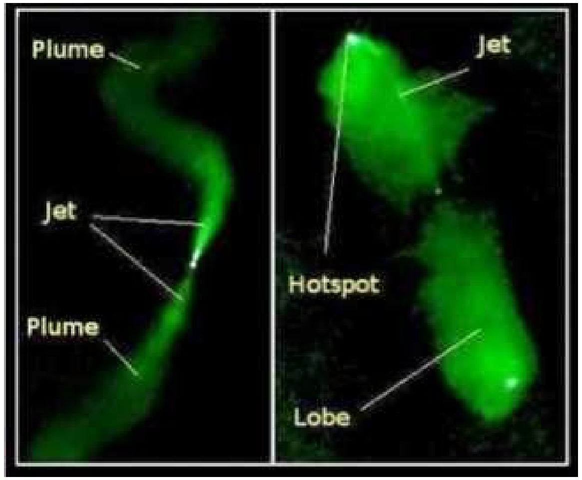





- Schematic drawings of the central engines of radiative-mode and jet-mode AGN (Hackman & Best 2014)

# Unification scheme of the AGN






- Radio dichotomy: Radio galaxies present either strong emission or weak emission (radio loud and radio quiet)
- study of dichotomy is important for elucidation of mechanisms that produce the activity at the center of galaxies (STAR project at the Institute of Space Science)

- radio loud galaxies: FR I and FR II, two morphological types, according to where the most of the luminosity is radiated
- radio power division at $L_{178MHz} \sim 10^{25}$ W Hz$^{-1}$ sr$^{-1}$ (Fanaroff & Riley 1974)
- FR I: edge darkened, with extended twin lobe structure
  FR II: edge brightened, with bright hot spots

# Radio dichotomy of AGN



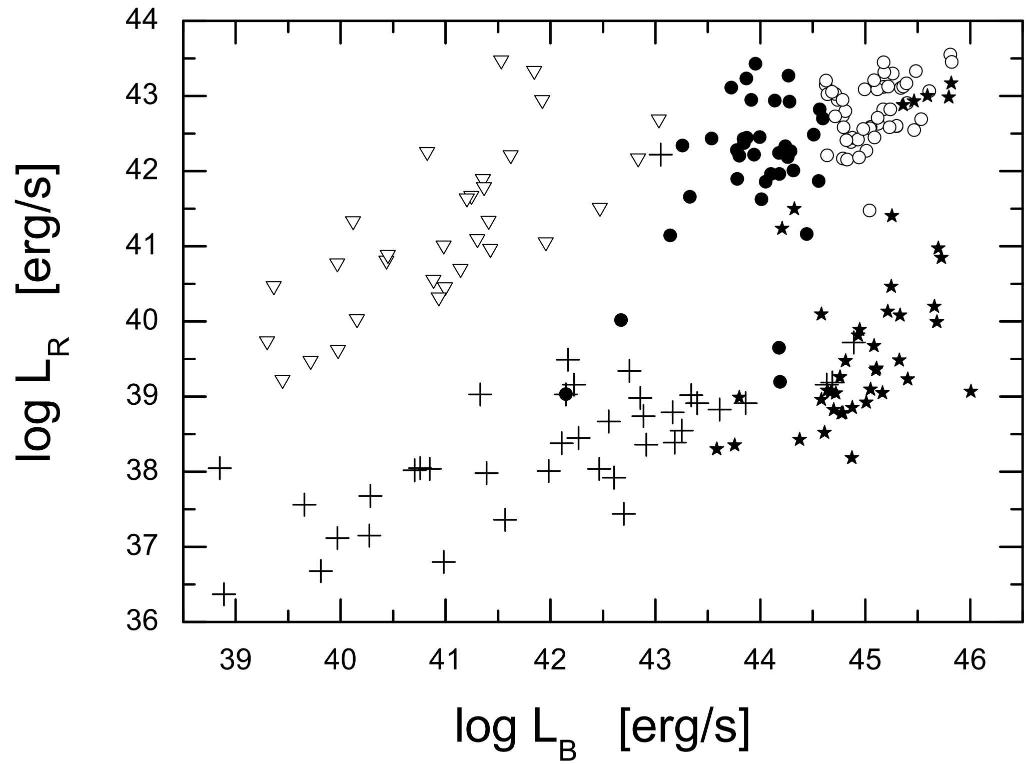
- radio dichotomy = bimodal separation of AGN based on radio loudness parameter
- radio loudness – ratio of the luminosities in radio and optic:

$$\mathcal{R} = \frac{L_{\rm radio,5GHz}}{L_{\rm optic,B}}$$

- it gives two branches: radio-loud and radio-quiet galaxies (e.g., Sikora et al. 2007)
- radio dichotomy in AGN as a result of rapidly and, respectively, slowly rotating black holes questioned (e.g., Broderick & Fender 2011)
- Sikora+ sample: 199 AGN from Véron-Cetty & Véron catalog, no blazars, no narrow-line region galaxies
- estimate black hole mass from the emission of the broad-line region

# Radio dichotomy of AGN

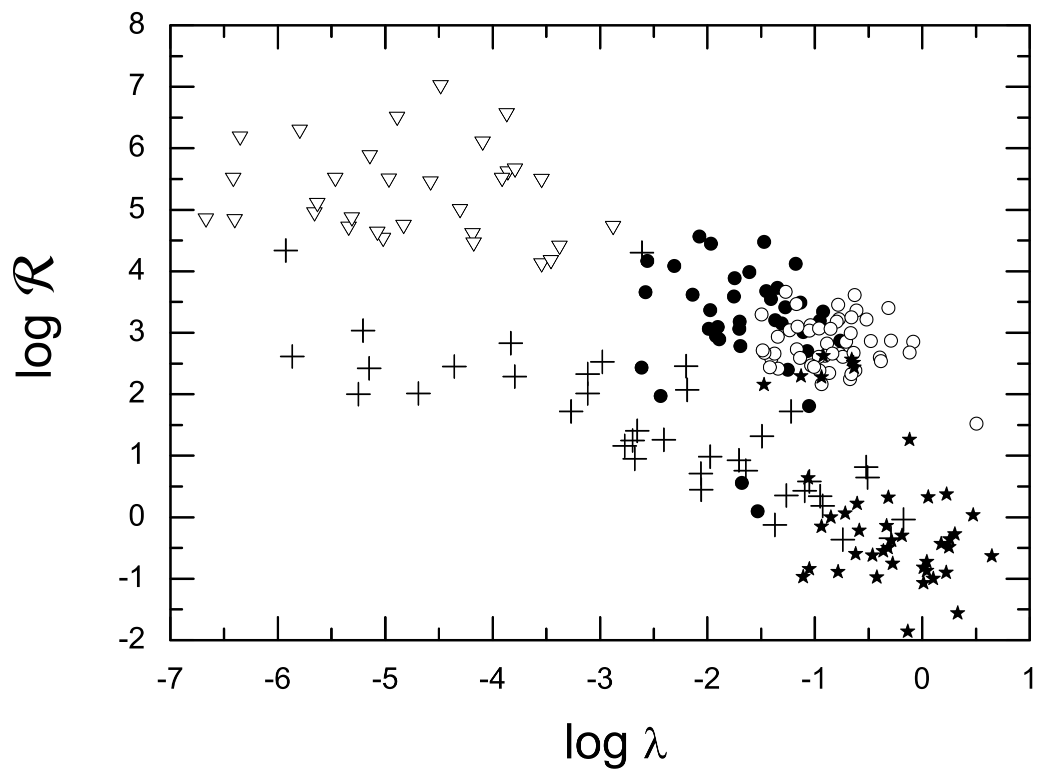





- Total radio luminosity vs. B-band luminosity for 199 AGN (Sikora et al. 2007)

# Radio dichotomy of AGN

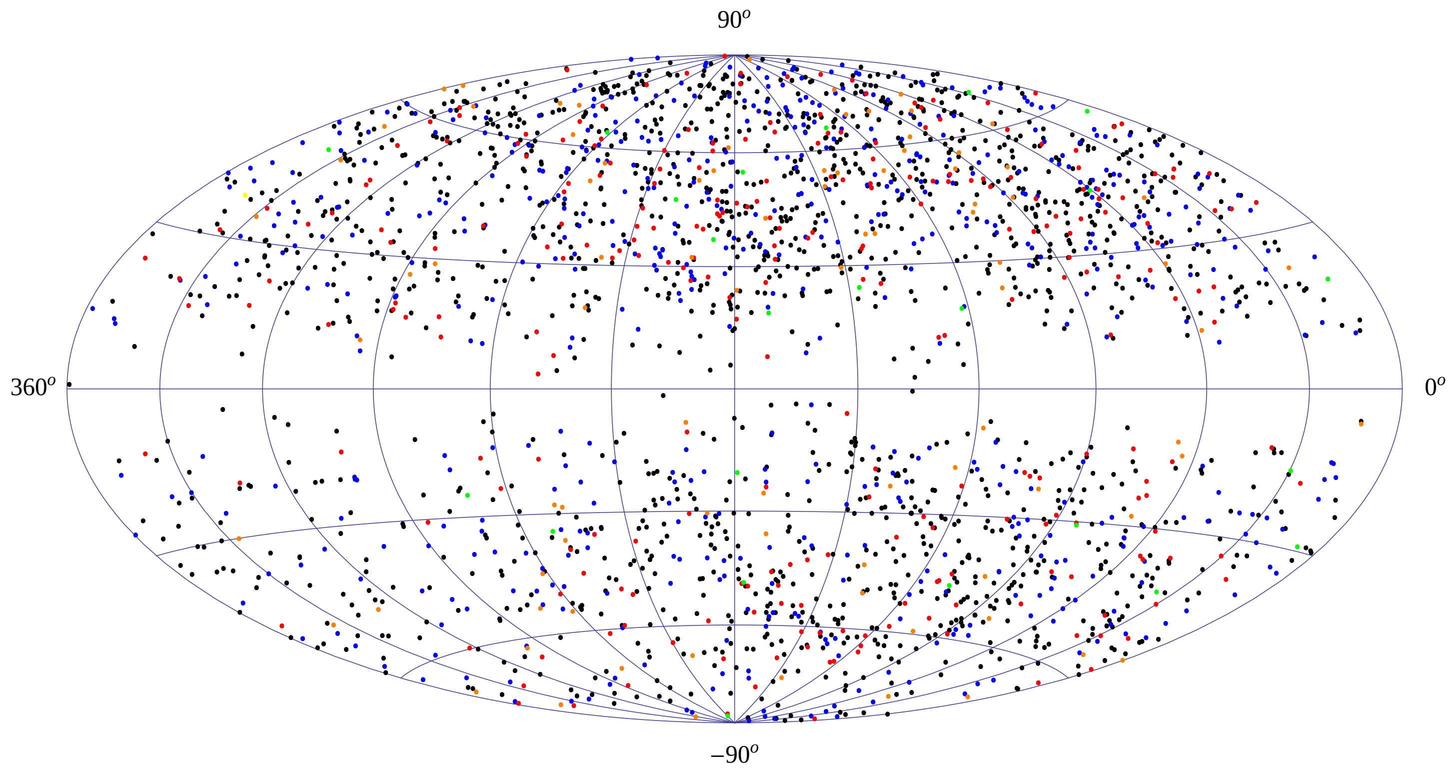





- Radio loudness parameter vs. accretion rate in Eddington units for 199 AGN (Sikora et al. 2007)

# Radio dichotomy of AGN

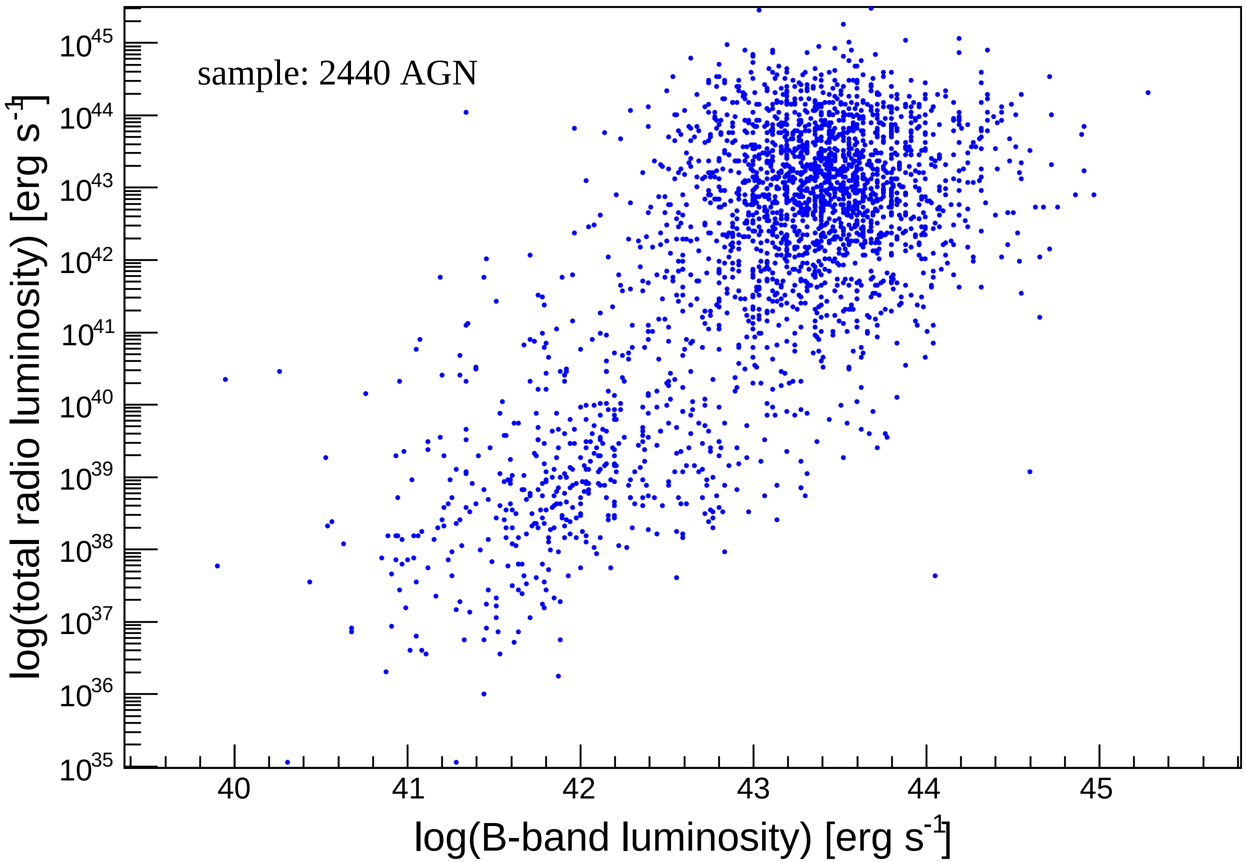





- Aitoff projection in galactic coordinates of our sample of 2,440 AGN
- Black, Blue, Red, Orange, and Green correspond to redshifts between 0, 0.7, 0.9, 1.5, 2.4

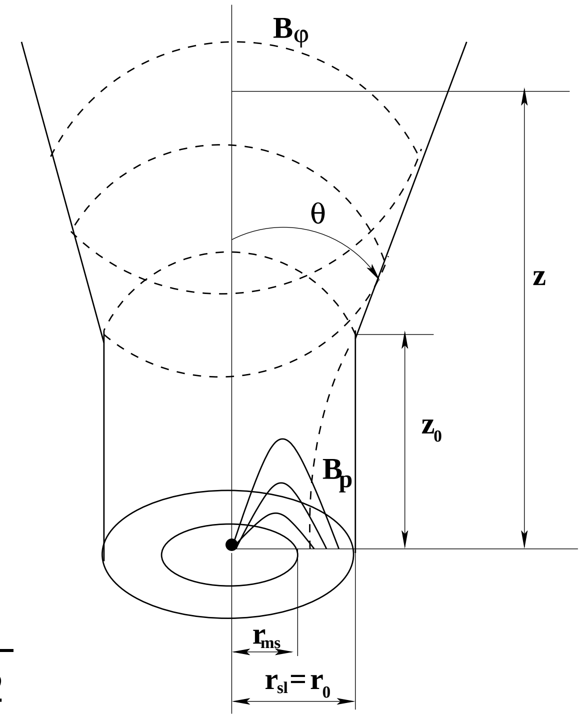
# Radio dichotomy of AGN






- Radio luminosity vs. B-band luminosity for our sample of 2,440 AGN

- equations which describe the synchrotron self-absorbed emission of a non-thermal particle distribution ($\sim E^{-\mathrm{p}}$) obtained from acceleration at shocks (Duţan & Caramete 2015)




- observed radio flux from a flat spectrum core times squared distance:

$$D_{\mathrm{s}}^2 F_{\mathrm{obs}} \sim M_{\mathrm{BH}}^{\frac{2p+3}{2(p+4)}} \left(\frac{B_{\mathrm{H}}}{B_{\mathrm{H}}^{\mathrm{max}}}\right)^{\frac{2p+3}{p+4}}$$

- launching area of the jet:

$$(S)_{z=0} = 2\pi r_{\mathrm{g}}^2 \int_{r_{\mathrm{ms}*}}^{r_{\mathrm{sl}*}} r_* \sqrt{\frac{1+r_*^{-2}a_*^2+2r_*^{-3}a_*^2}{1-r_*^{-1}+r_*^{-2}a_*^2}}\, dr_*$$

- maximum BH magnetic field:

$$B_{\mathrm{H}}^{\mathrm{max}} \simeq 0.56\times 10^4 \left(\frac{M}{10^9 M_\odot}\right)^{-1/2} \text{ gauss},$$

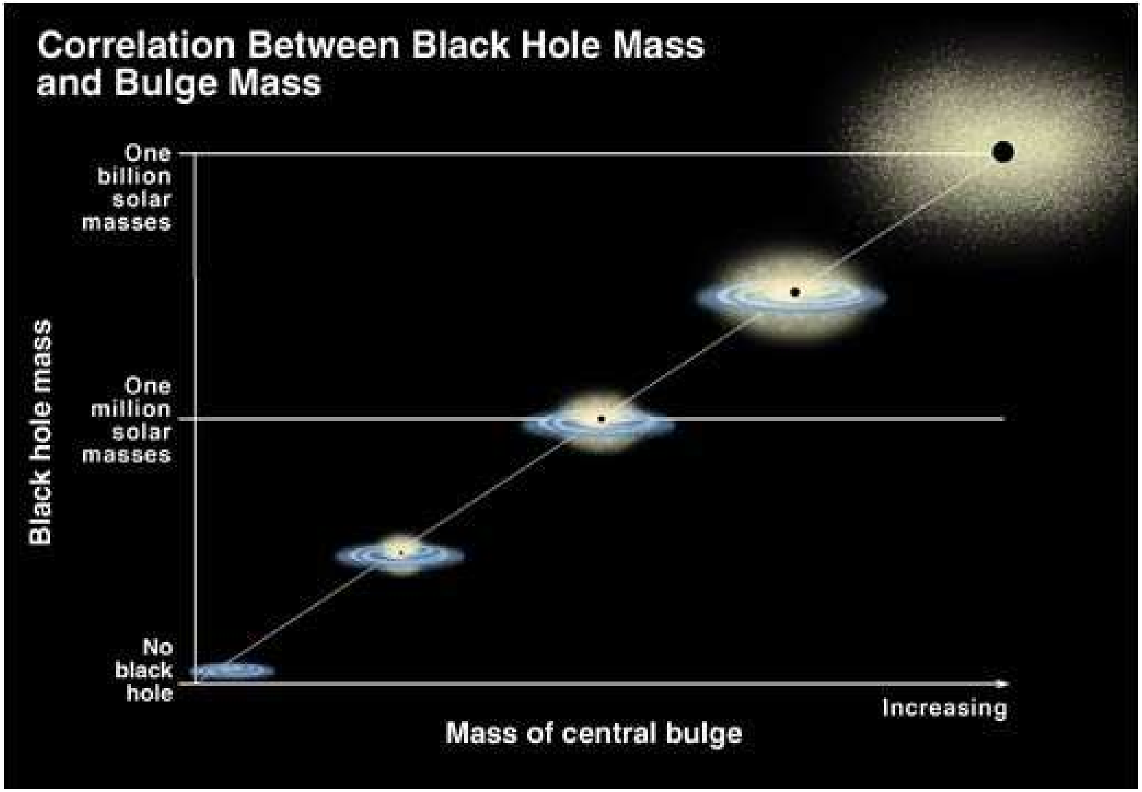
- from BLR (Broad Line Region): BLR size-luminosity relationship, gas produces Hα lines in optical

$$\frac{\mathcal{M}_{\rm BH}}{\mathcal{M}_\odot} = 4.8 \left[\frac{\lambda L_\lambda(5100\ \text{Å})}{10^{44} \text{ergs s}^{-1}}\right]^{0.7} \text{FWHM}^2_{\rm H\alpha}$$

# Determination of black hole mass



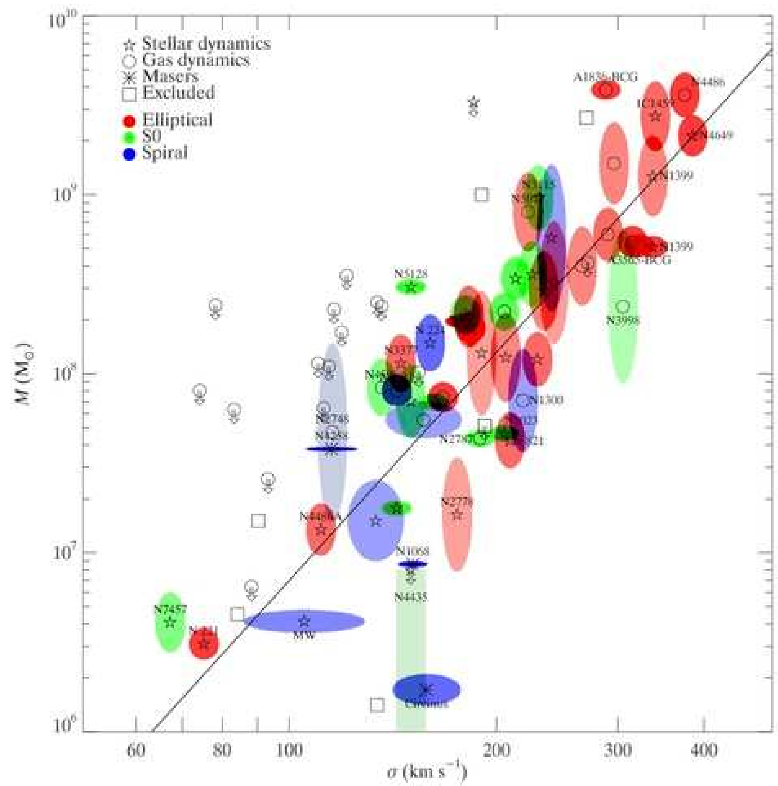
- measured directly through the dynamical modeling of the spatially resolved kinematics of stars and/or gas
- correlation between BH mass and galaxy bulge mass (e.g., Cordes & Brown)

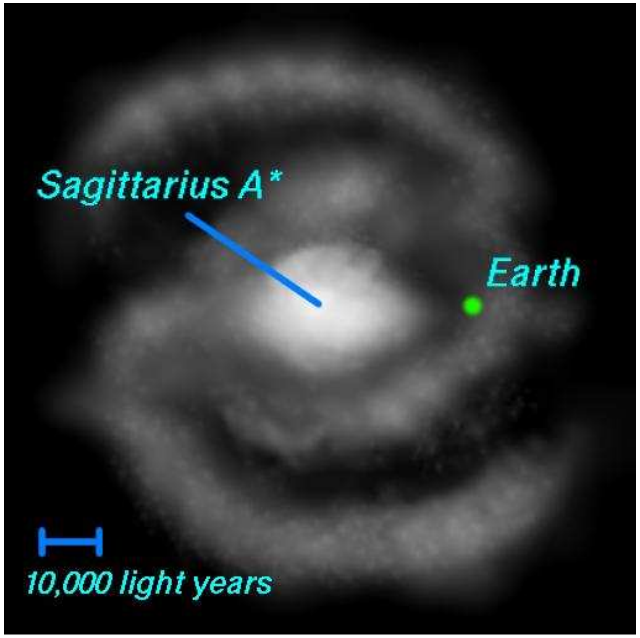


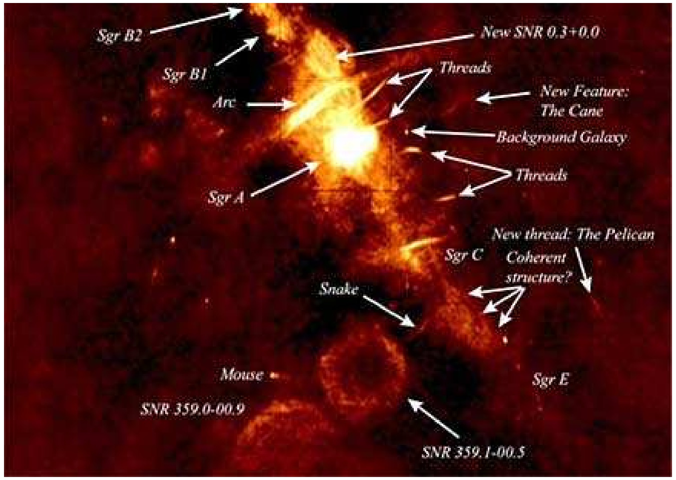
# Determination of black hole mass



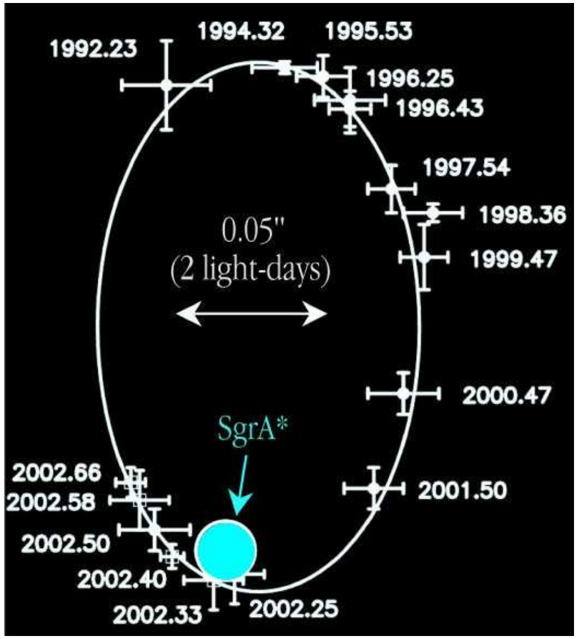
- measured directly through the dynamical modeling of the spatially resolved kinematics of stars and/or gas
- correlation between BH mass and host-galaxy bulge velocity dispersion (e.g., Gueltekin et al. 2009)





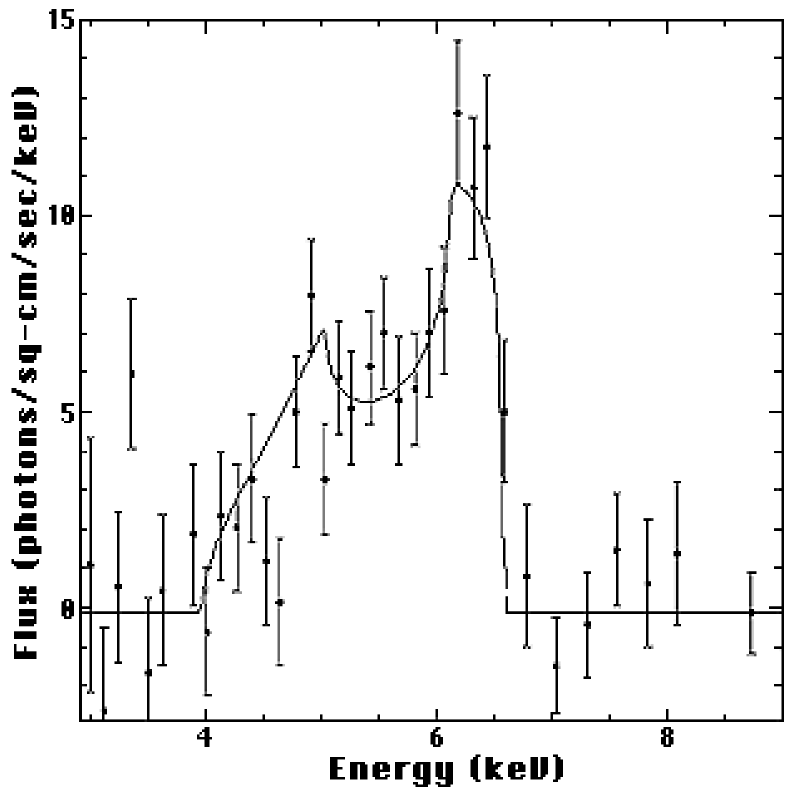

- Sgr A$^*$ = Galactic center
- BH mass was determined from the Keplerian motion of the stars around the BH $M \sim 10^6 M_\odot$



# Fe kα emission line



- Fe line: characteristic double-horned shape (Doppler effect)
- *X*-ray photons coming from close to the BH are gravitationally redshifted, introducing a characteristic distortion of the line
- gives an estimation for the BH spin (e.g., min 0.5 for Sgr A$^*$)



# Galaxy formation



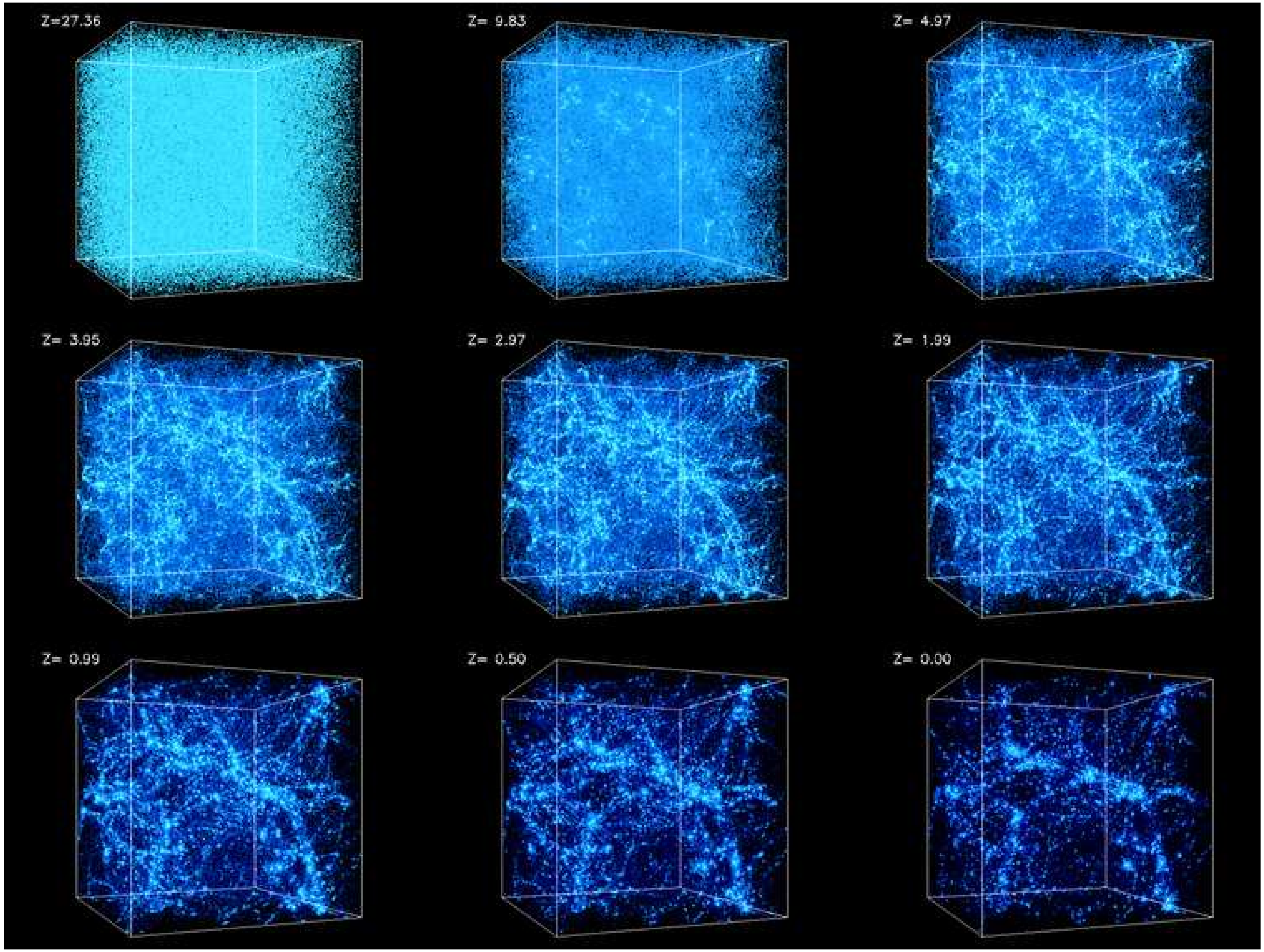



Image credit: http://cosmicweb.uchicago.edu

- spiral and elliptical galaxies started to form from protogalactic clouds

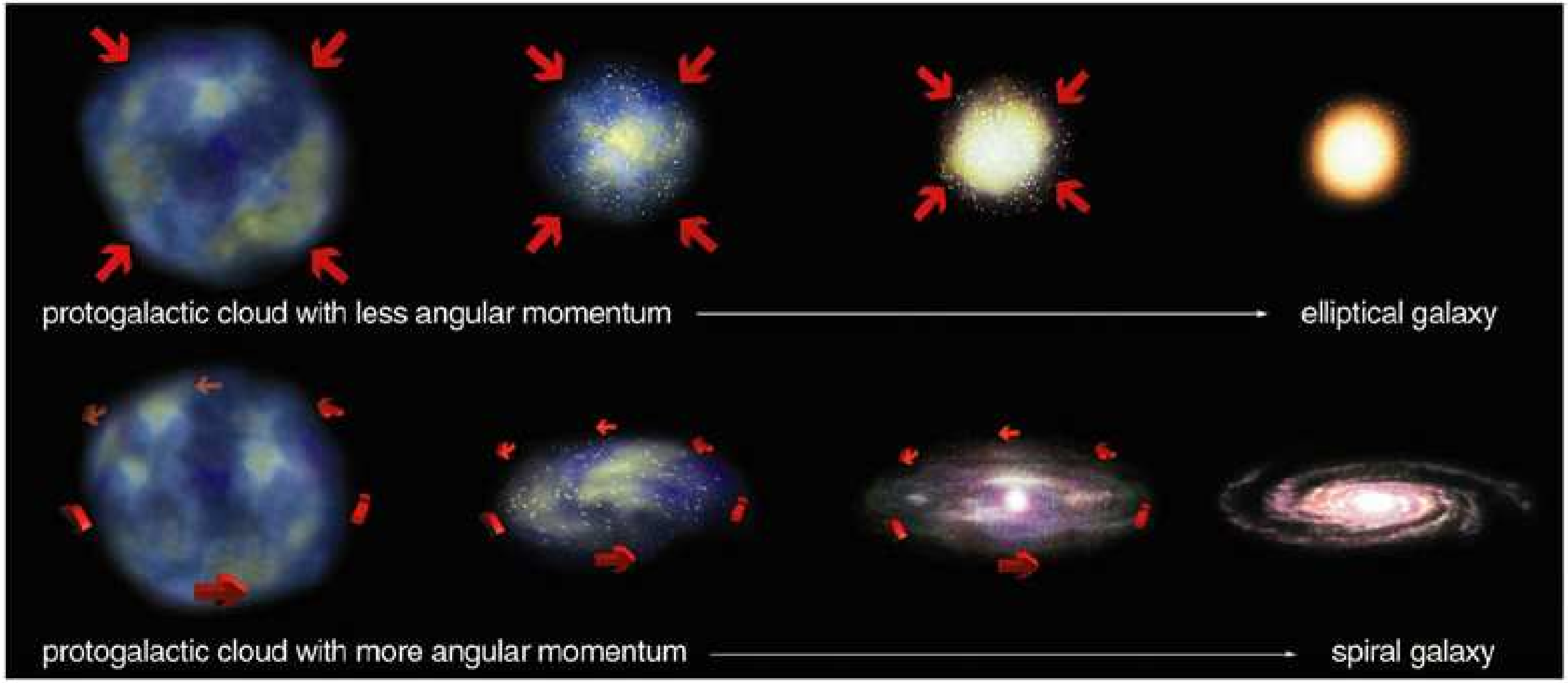



Image credit: Pearson Education, publishing as Addison Wesley

# Galaxy formation



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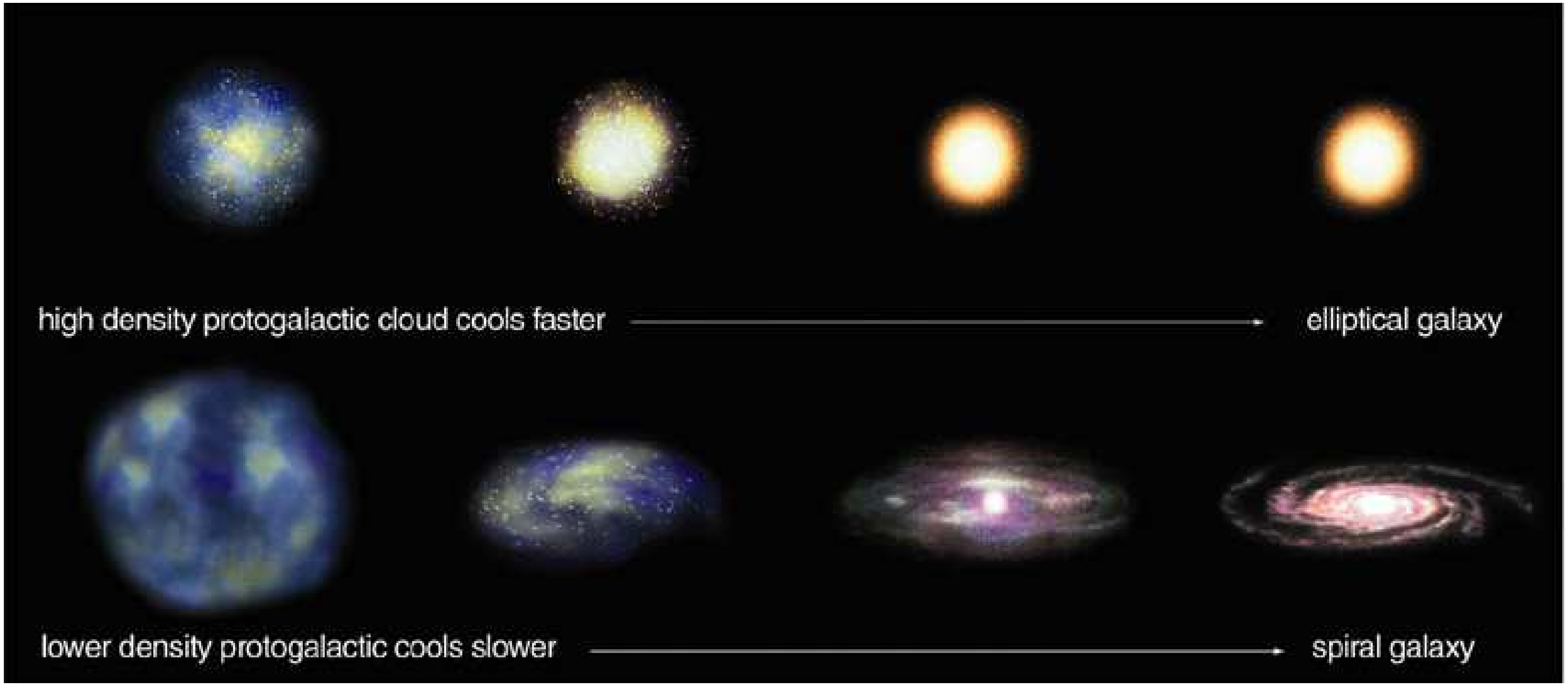


Image credit: Pearson Education, publishing as Addison Wesley

# AGN feedback



- AGN feedback invoked in both semi-analytic models and numerical simulations in order to reproduce the observed properties of massive galaxies
- AGN feedback is generally assumed to be negative: inhibiting star-formation and/or black hole growth
- AGN-driven outflows occur in galaxies with actively growing black holes and are responsible for the termination of star-formation and the migration of the galaxy from the blue star-forming main sequence to the red sequence