SUPERMASSIVE BHS & ACTIVE GALACTIC NUCLEI

Lecture 9, Introduction to Black Hole Astrophysics (PHYS480)

Hsiang-Yi Karen Yang, NTHU, 4/27/2021

ANNOUNCEMENTS

- Slides for each lecture will be posted on iLMS before the class. Feel free to download in advance and take notes!
- HW4 is due today. The solutions will be posted on iLMS next week.
- Please search for black hole news for the oral presentation and paste the news link here:

https://docs.google.com/spreadsheets/d/1_aYyMj1wf_uGheZ7zp_hvthmy4mdmPwIxFDdZOMG-nc/edit?usp=sharing

- For the oral presentations, I will compile the scores and comments from the audience and send to you after the presentation
- Please start forming a team of 3 people for the final report. Choose a team leader and enter your names on iLMS -> 小組專區

FINAL TEAM REPORT (30%)

- Each team will choose any black-hole-related topics, do research and gather information, study, discuss, brainstorm, and ***write a 3-5 page research proposal*** （中英皆可）
- The research proposal will include background introduction to the topic, what unknown question to be solved, and proposed methods used to answer the question
- This is a great opportunity to practice scientific writing – how to structure an article, convey your thoughts in a clear and logical manner, convince people (to give you money) to do this ***important*** and interesting science
- The report will be ***due on 6/11 (Friday) at 5pm through iLMS***
- ***On Week 16 (6/15), the proposals will be evaluated by panels formed by other teams***
- Grades will take into account scores/comments from the instructor, panels, and your team members
- Please start gathering ideas and discuss strategies with your team members.
- For ideas, please pay attention to the "***Open Questions***" part of the lectures

PLEASE PROVIDE YOUR FEEDBACK!

- Your feedback and comments would be valuable for improvements of this course!
- Link to the course evaluation form:

  https://qrgo.page.link/9f6cE
- Or scan the QR code here:

PREVIOUS LECTURE…

- Measuring BH masses
  - Four methods: (1) dynamical mass from stellar motions, (2) using stellar/gas motions (velocity dispersions) near the center of galaxies, (3) ***reverberation mapping***, (4) gravitational waves
  - Big open question – whether ***IMBHs of*** $10^2 - 10^5\ M_{sun}$ exist or not and what is their distribution? The origin of ***ULXs***?
- Measuring BH spins
  - Three methods: (1) ***continuum fitting method*** (use thermal black-body spectrum to fit for the ISCO and obtain spin), (2) ***X-ray line fitting method*** (use skewed Fe line in X-ray to measure the gravitational redshift effect and determine ISCO and spin), (3) gravitational waves
  - Open question – what are the spin distributions for smbhs and SMBHs and what can we learn about BH formation/growth?

THIS LECTURE

- Overview of active galactic nuclei (AGN)
- Brief overview of radiative processes
- The different faces of AGN in the EM spectrum
- AGN unification
- Open questions

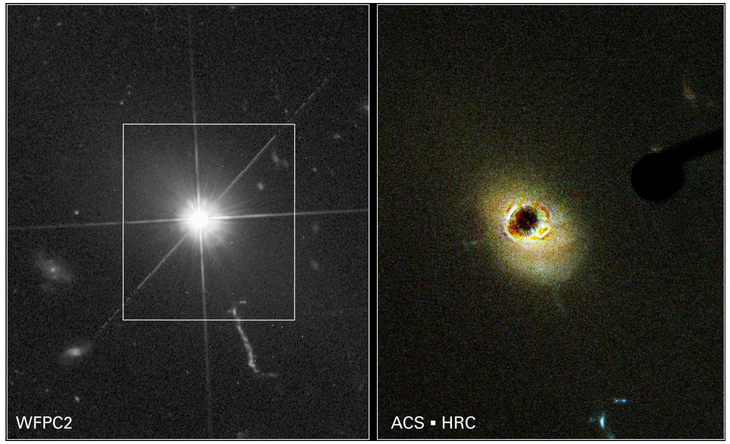
An **active galactic nucleus** (AGN) is a compact region at the center of a **galaxy** that has a much higher than normal luminosity over at least some portion of the electromagnetic spectrum with characteristics indicating that the luminosity is not produced by stars.

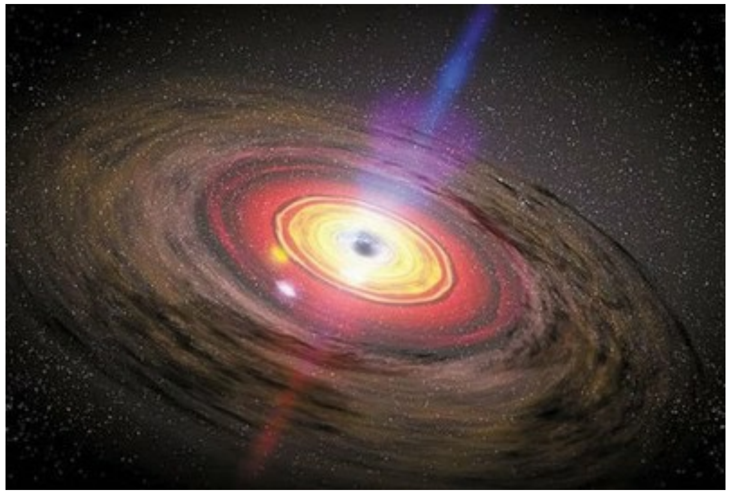
en.wikipedia.org › wiki › Active_galactic_nucleus ▾

Active galactic nucleus - Wikipedia

ACTIVE GALACTIC NUCLEI (活躍星系核)

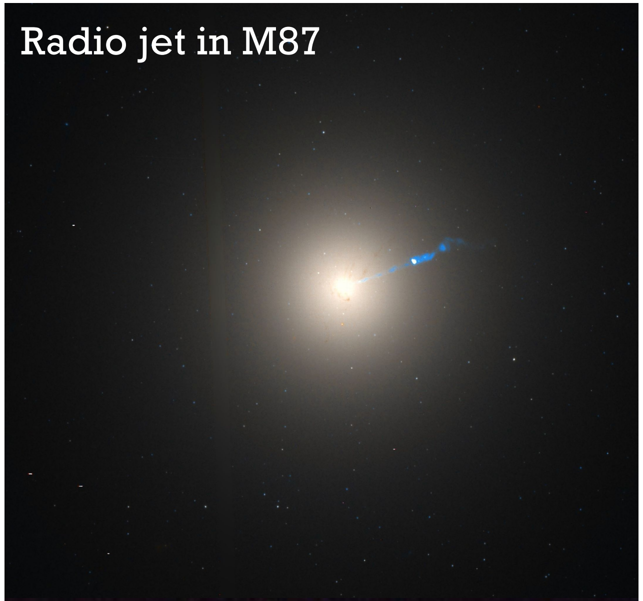
- First discovered quasar – 3C 273 (Lecture 5)
- Characterized by ***extreme luminosity*** and ***fast variability***
- Linked to SMBH accretion because
  - Accretion disks could efficiently turn gravitational energy into radiation
  - Fast variability infers that the emission originates from a compact region
- ***AGN = actively accreting SMBHs***
- While all massive galaxies host a SMBH at the center, only about ***1-10% are AGN***





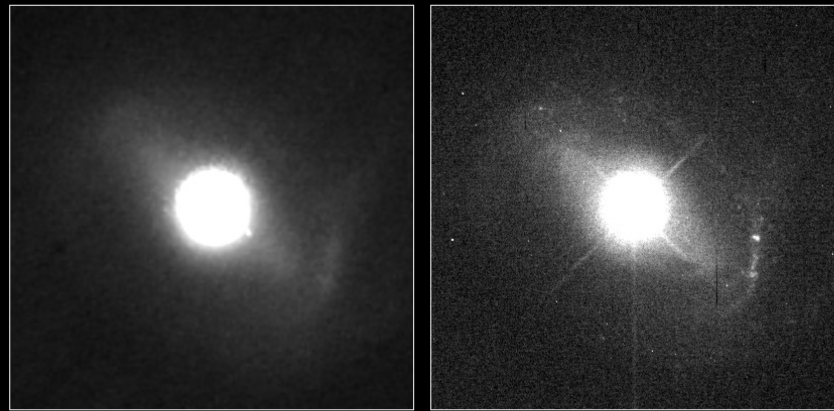
SMBH IS RESPONSIBLE FOR ALL THESE WEIRD PHENOMENA!

- SMBHs are only confirmed in the 90's
- In 1918, first SMBH ***jets*** in M87 were observed in radio
  - Heber Curtis: "curious straight ray ... apparently connected with the nucleus by a thin line of matter."
- In 1944, Carl Seyfert found a class of weird galaxies with unusually bright nucleus – ***Seyfert galaxies***
  - Similar to quasars but somewhat less luminous
  - Quasars outshine their host galaxies but Seyfert galaxies don't
- In the 60's-80's, ***quasars*** were found
- All of the above are different ***types*** of active galactic nuclei (AGN), i.e., actively accreting SMBHs!



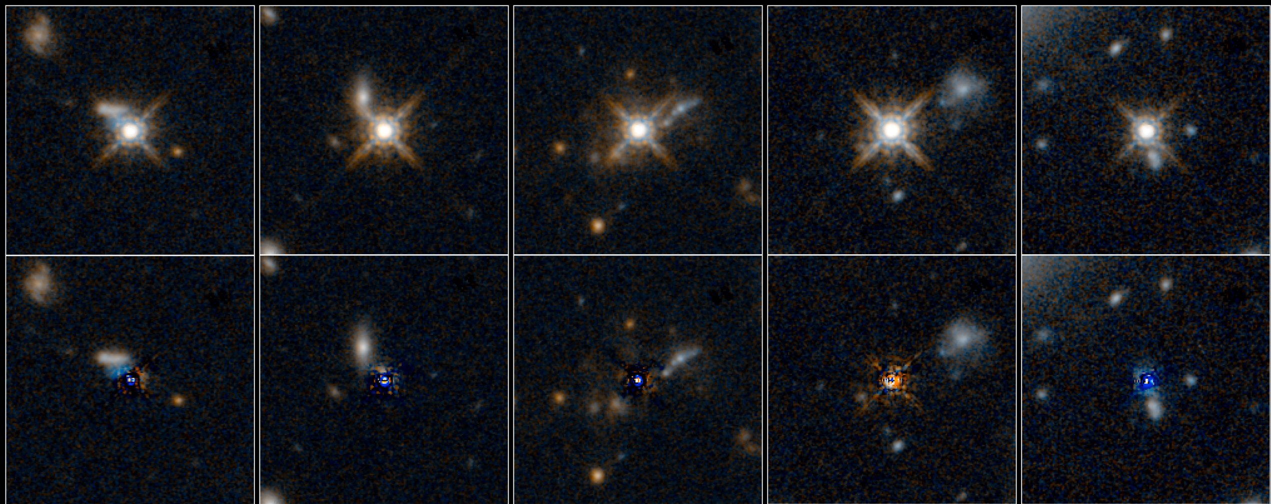
QUASARS & THEIR HOST GALAXIES

QSO 1229+204



Ground Based | **Hubble Space Telescope**

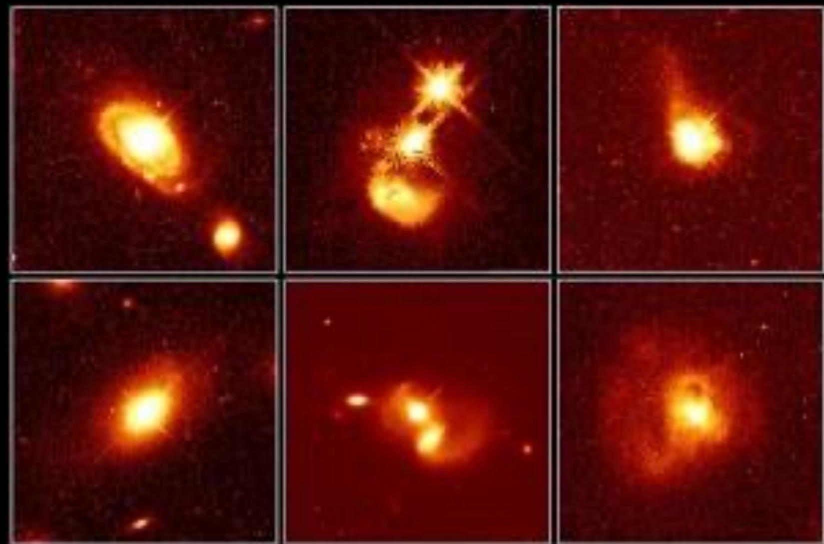
Canada-France-Hawaii Telescope | Wide Field Planetary Camera



Quasars in Interacting Galaxies
Hubble Space Telescope ▪ WFC3/IR

NASA and ESA

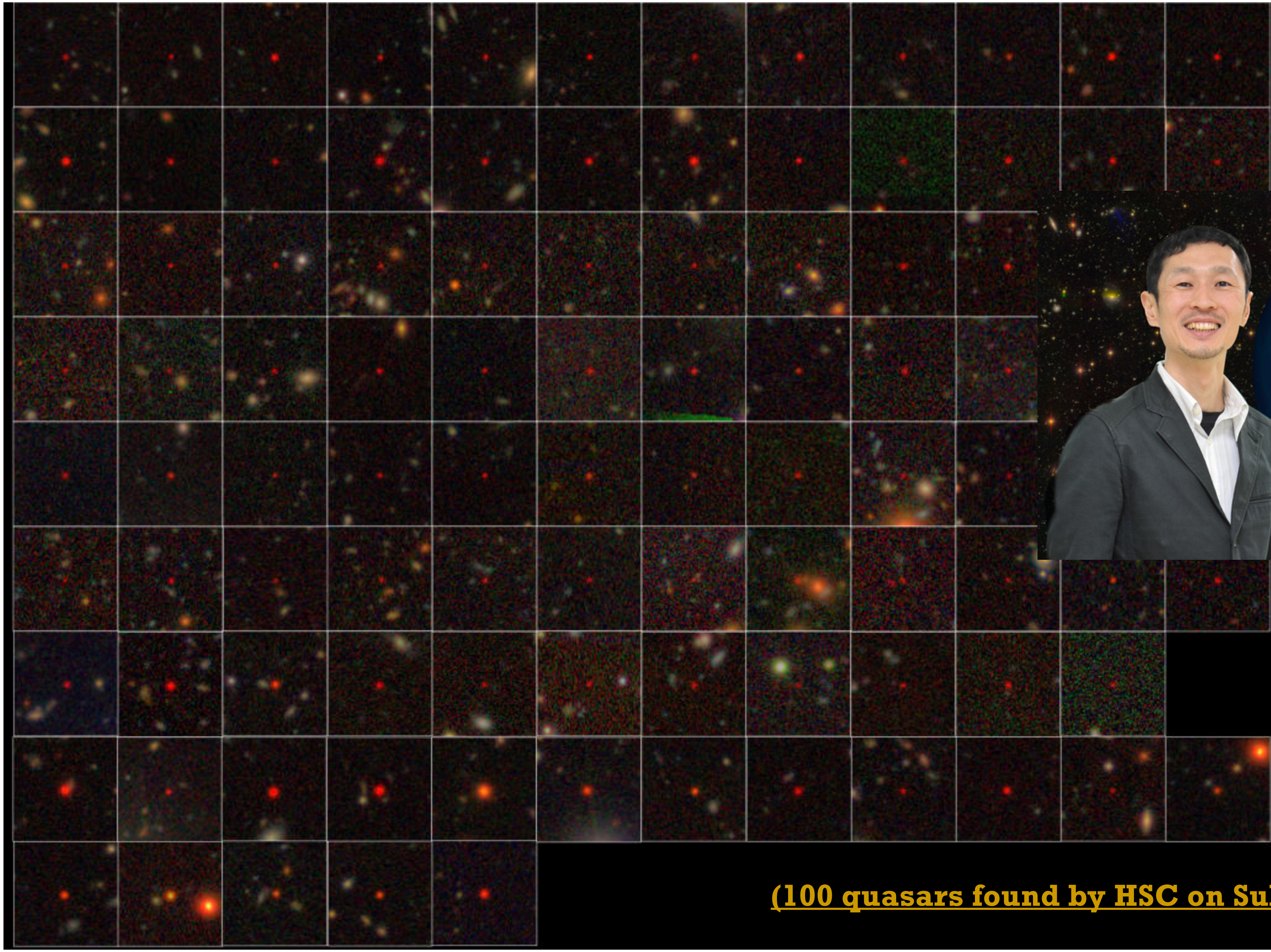
STScI-PRC15-20a

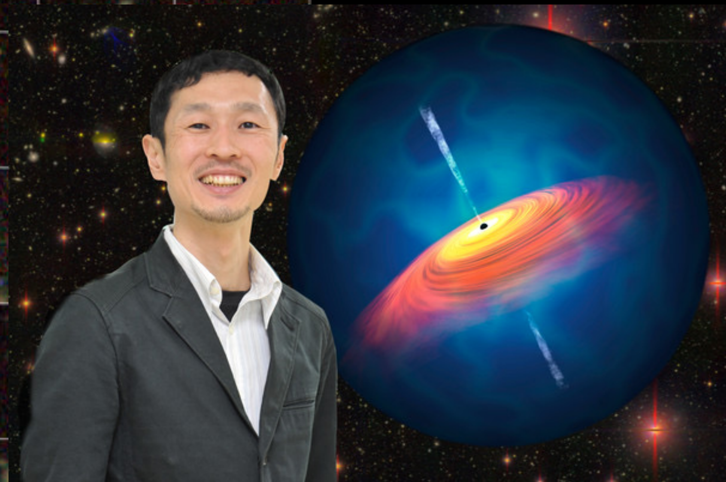


Quasar Host Galaxies HST • WFPC2

PRC96-35a • ST ScI OPO • November 19, 1996

J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

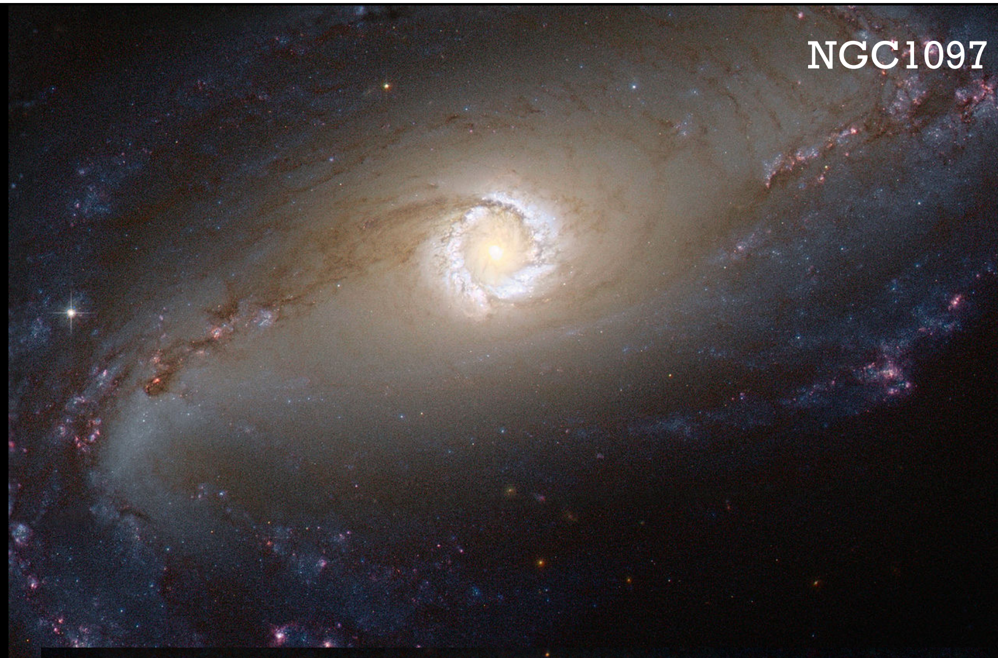


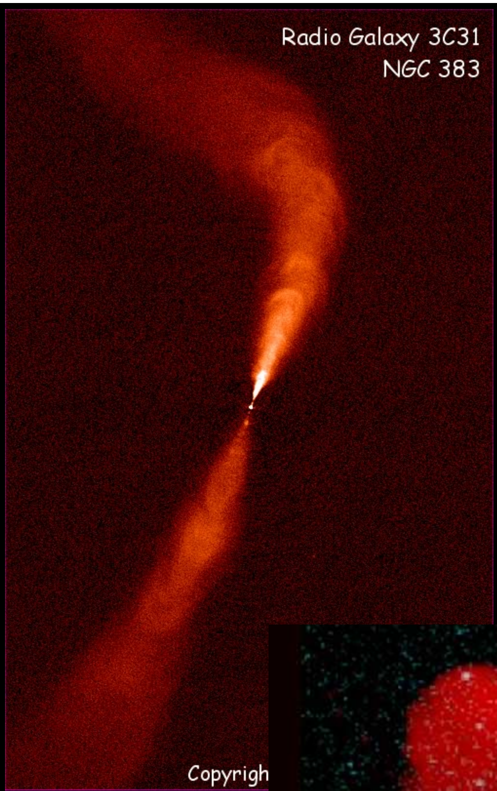


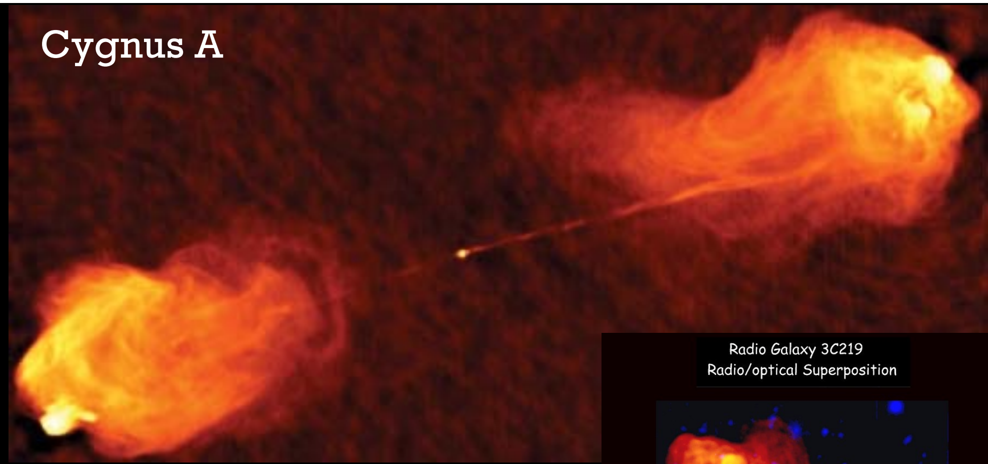
QUASARS

(100 quasars found by HSC on Subaru, 13 billion lyr away)

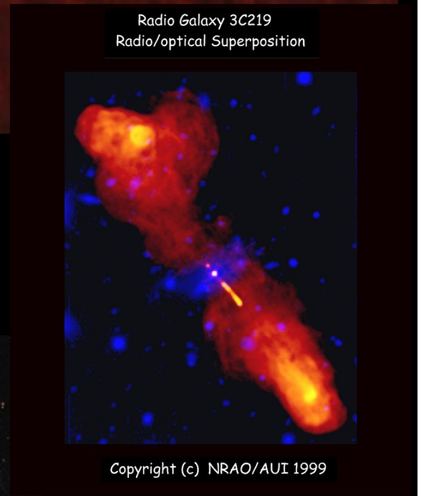
SEYFERT GALAXIES

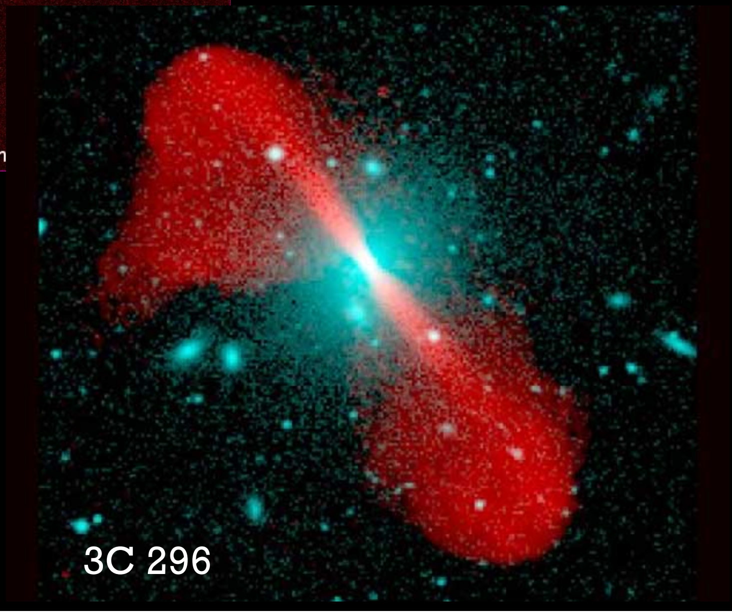


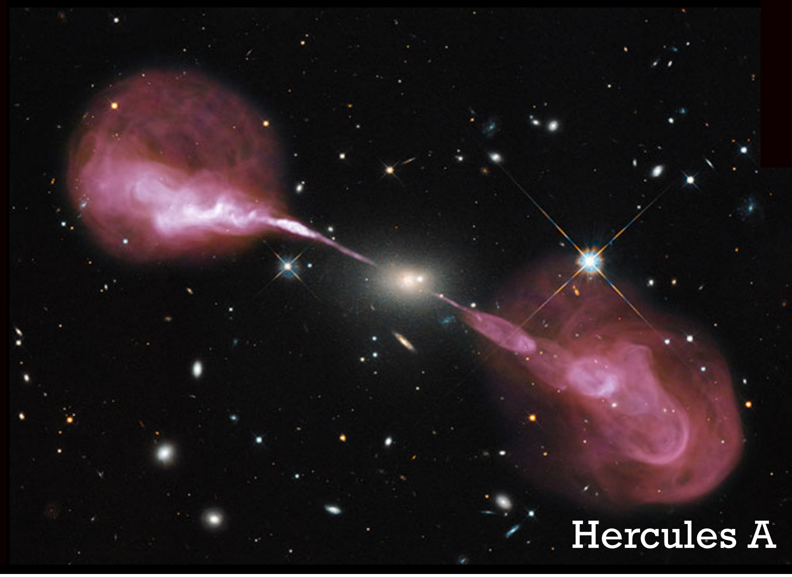


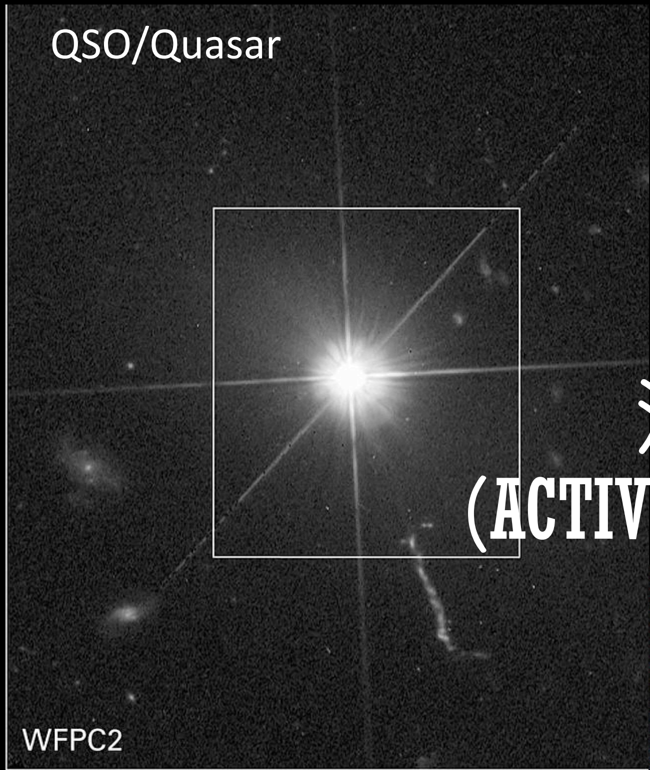


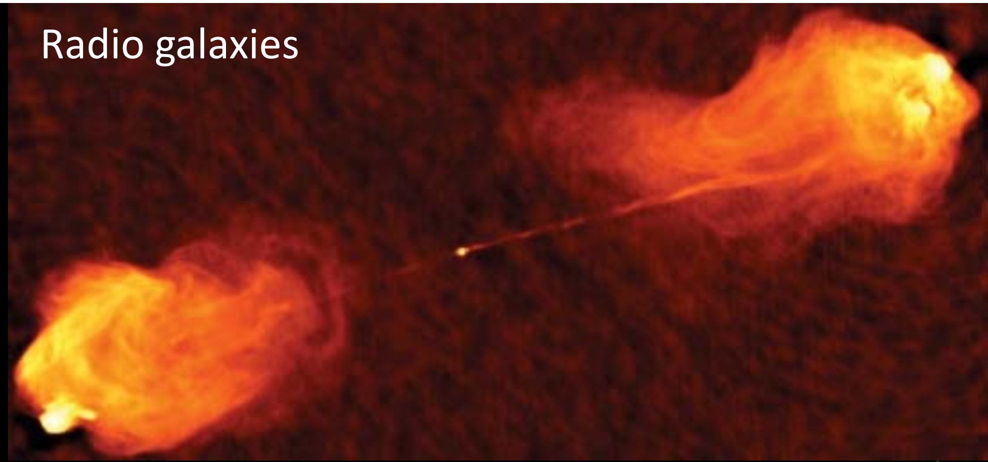
RADIO GALAXIES





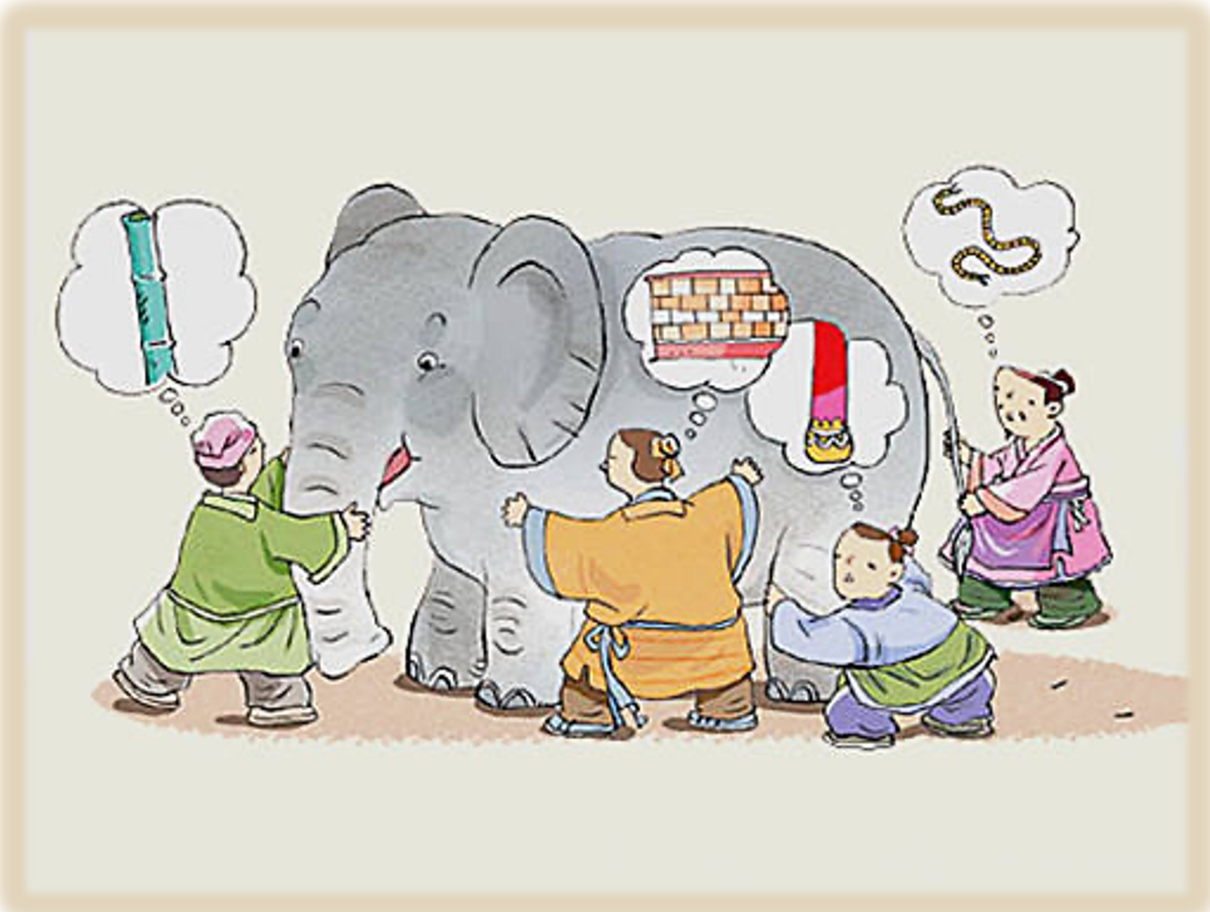






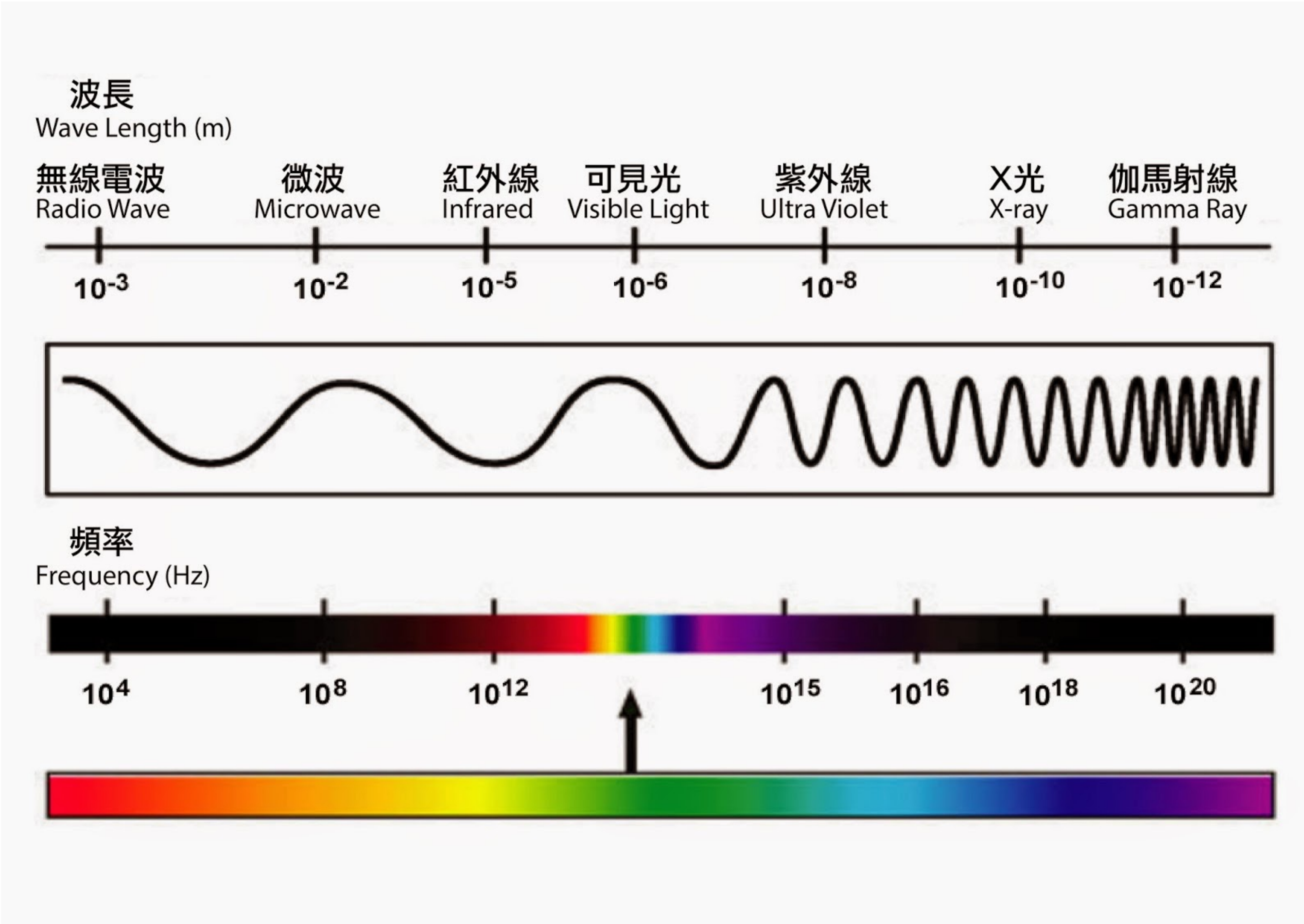
活躍星系核 (ACTIVE GALACTIC NUCLEI)

THE DIFFERENT FACES OF AGN



BRIEF OVERVIEW OF RADIATIVE PROCESSES

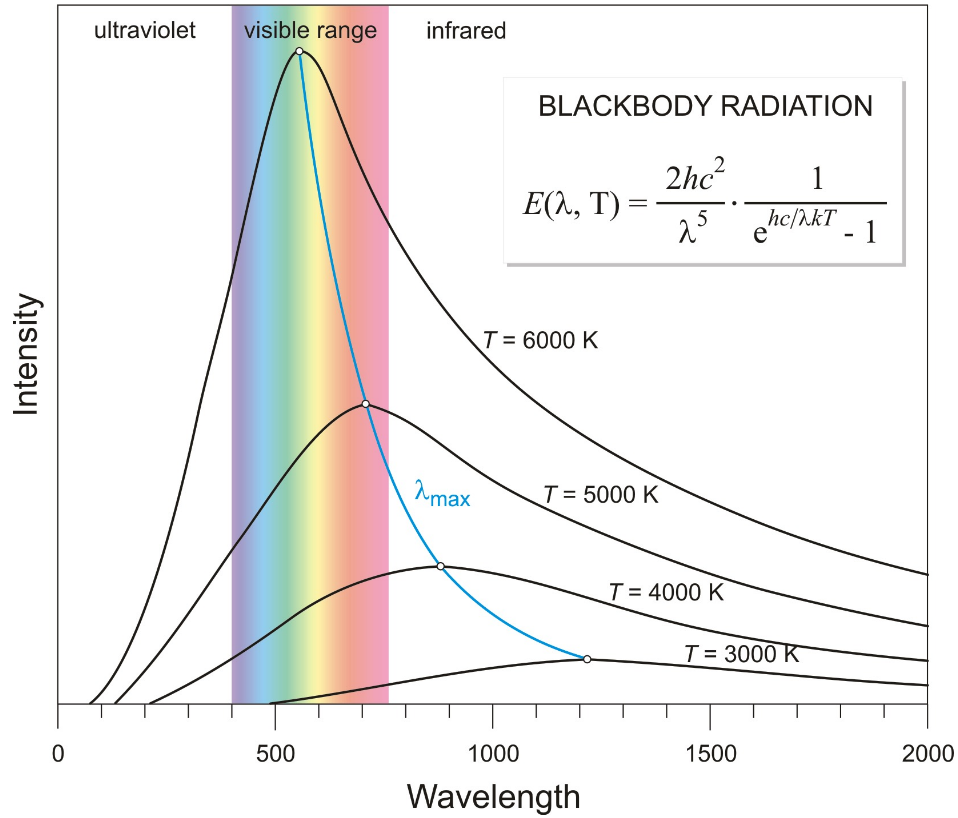
THE ELECTROMAGNETIC SPECTRUM



BLACK-BODY RADIATION

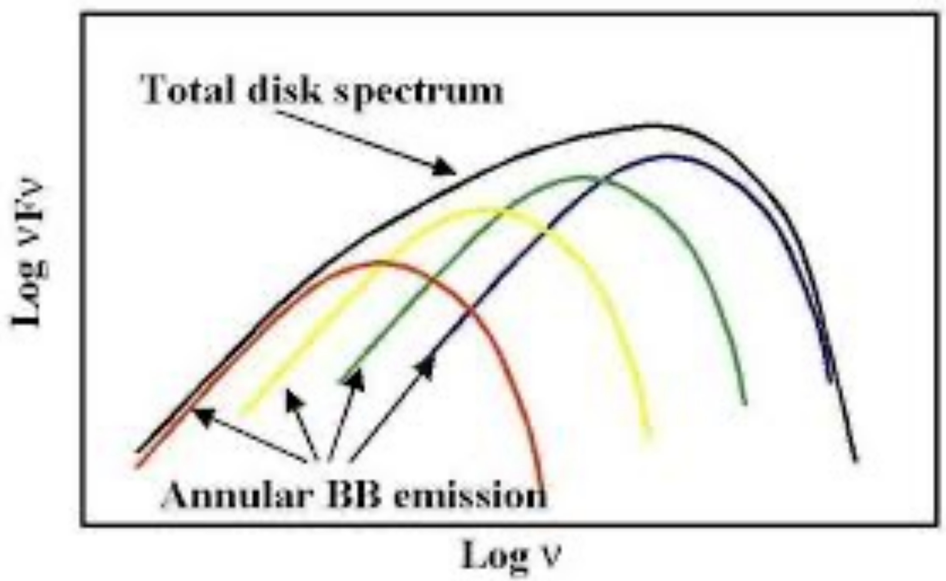
- ***Thermal*** electromagnetic radiation of a black body (opaque, non-reflective) in thermal equilibrium with its environment
- The spectrum can be described by the Planck's law
- The temperature is related to the peak wavelength of the spectrum by the Wien's law:

$$\lambda_{peak} T = 2.898 \times 10^{-3} m\ K$$



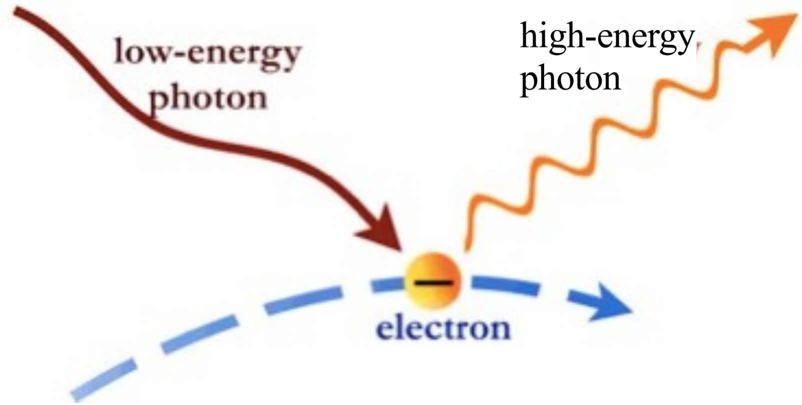
BLACK-BODY RADIATION

- For highly accreting BHs, thin disks are composed of accreted materials with T(r) ~ $r^{-3/4}$, with spectrum described by ***superposed black body*** radiation
- The high-energy end can be used to find R_{ISCO} and infer BH spin – the "***continuum fitting method***"



NONTHERMAL EMISSION MECHANISMS OFTEN SEEN IN ASTROPHYSICS

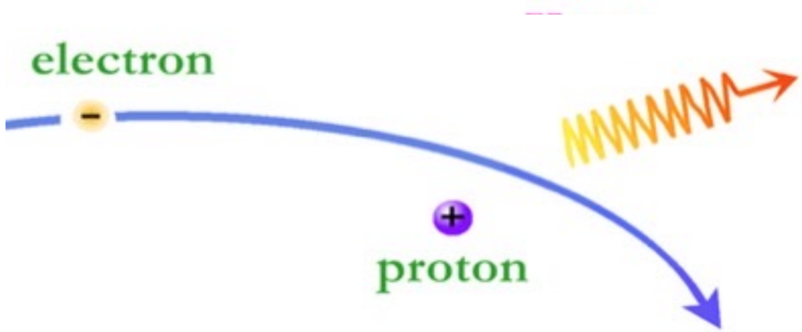
- ***Compton scattering*** – scattering of a photon by a charged particle, resulting in decrease in photon energy
- When the photon gains energy from hot/high-energy charged particles -- ***Inverse Compton scattering***
- Examples: interactions between photons emitted by accretion disks and the hot corona (see later slides)



The process of Inverse Compton scattering

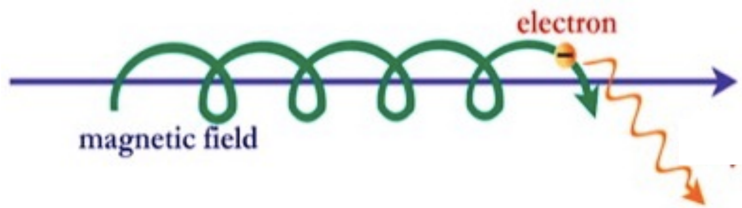
NONTHERMAL EMISSION MECHANISMS OFTEN SEEN IN ASTROPHYSICS

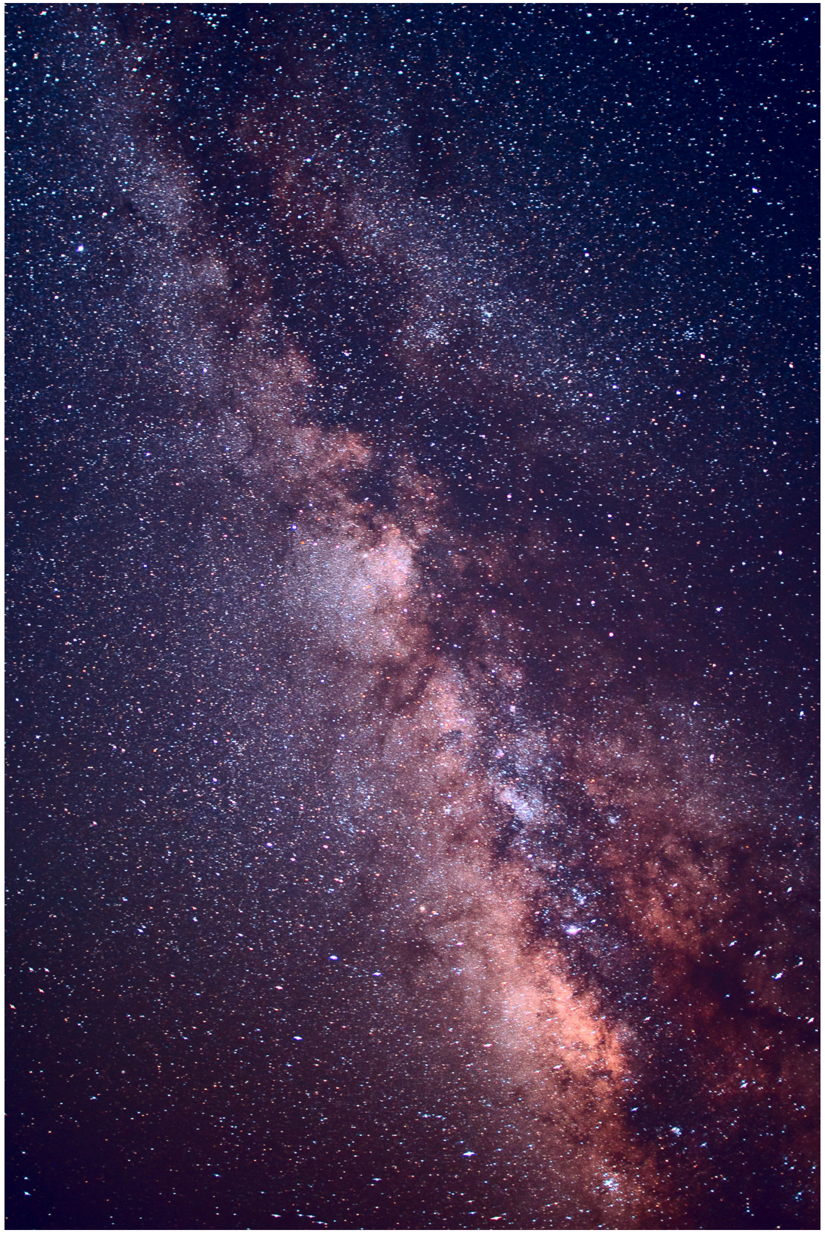
- ***Bremsstrahlung emission*** ("braking radiation") – radiation produced by a decelerated charged particle when deflected by another charged particle
- Also called "***free-free emission***" because it is produced by free electrons
- Often observed in ***hot, ionized*** medium
- Examples: emission from the hot corona or thick accretion disks, gas in galaxy clusters



NONTHERMAL EMISSION MECHANISMS OFTEN SEEN IN ASTROPHYSICS

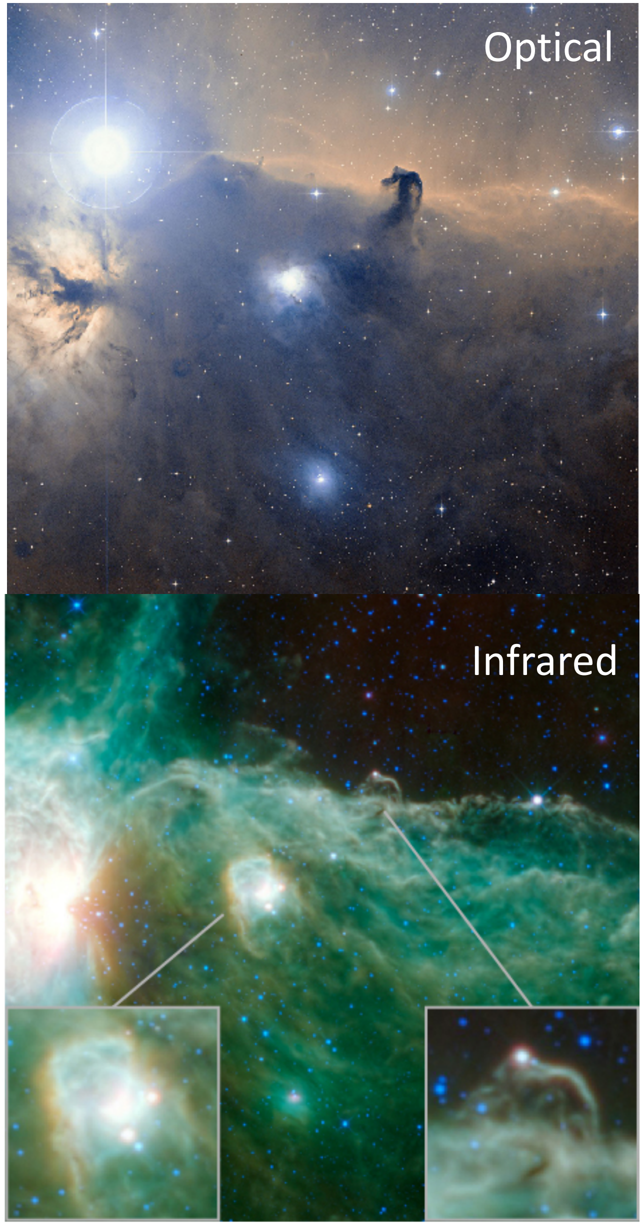
- ***Synchrotron radiation*** – radiation emitted when a ***relativistic*** charged particles are accelerated radially
- ***Cyclotron radiation*** – same but for a non-relativistic charged particle
- Often seen when charged particles gyrate around magnetic field lines
- Examples: relativistic jets from BHs





OBSCURATION OF LIGHT BY DUST

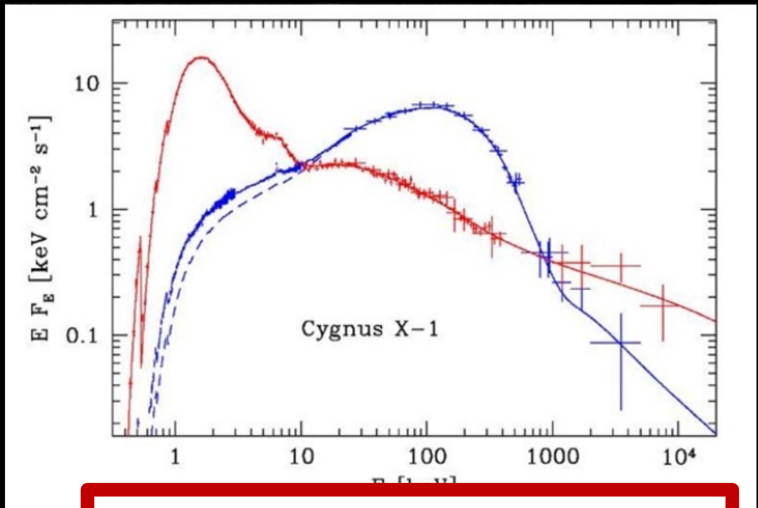
- Astrophysical ***dust*** is composed of ***solid*** particles in space with typical sizes in the ***~μm*** range
- Dust is synthesized at outer layers of stars and then ejected into space via supernova explosions
- ***Extinction* (消光)** = scattering + absorption
- Light with short wavelengths (e.g., UV photons) would be blocked, while light with longer wavelengths (e.g., infrared/radio) could penetrate



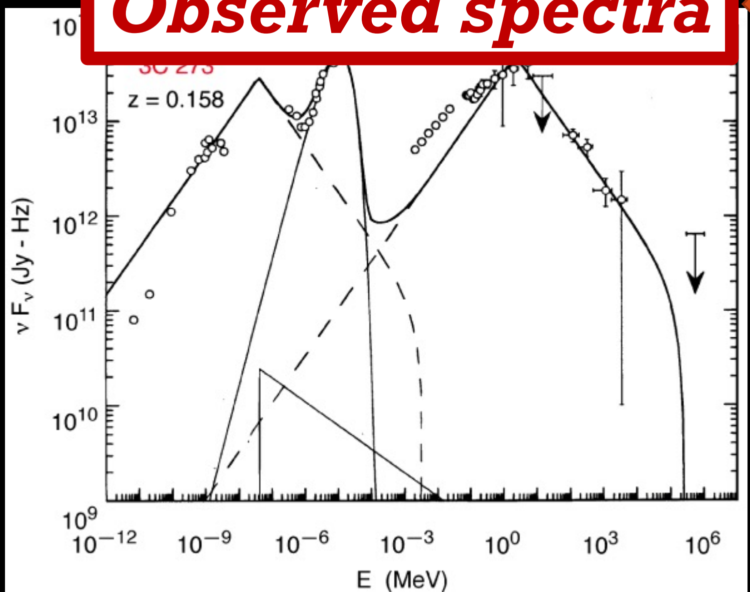
EMISSION BY DUST

- After absorbing the UV/optical photons, the dust can be heat up to T~10-500 K and re-radiate this heat at ***infrared*** wavelengths
- Examples
  - Horsehead Nebula in Orion (left figure)
  - Dust near the center of galaxies blocking light from near the SMBH accretion disks (see later slides)

DECIPHERING THE SPECTRUM OF AGN

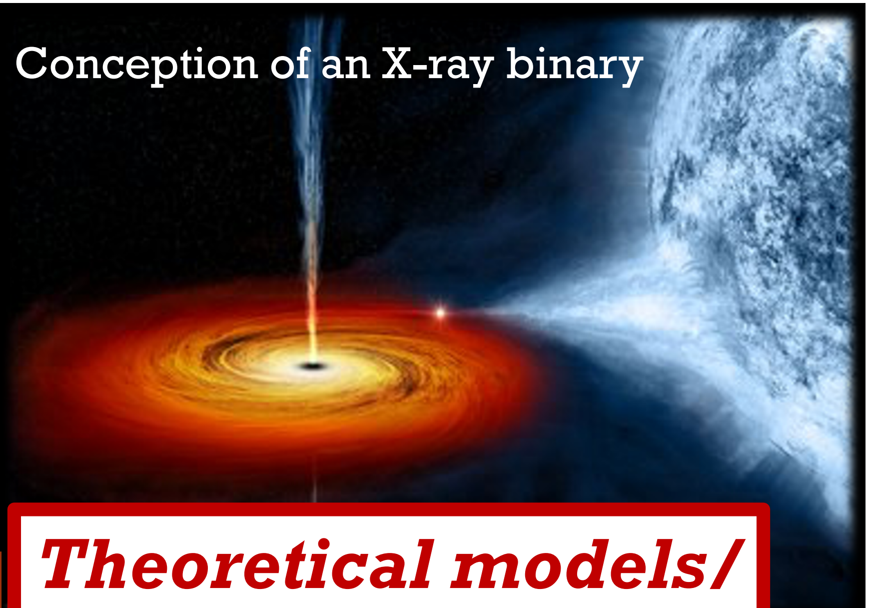


Observed spectra

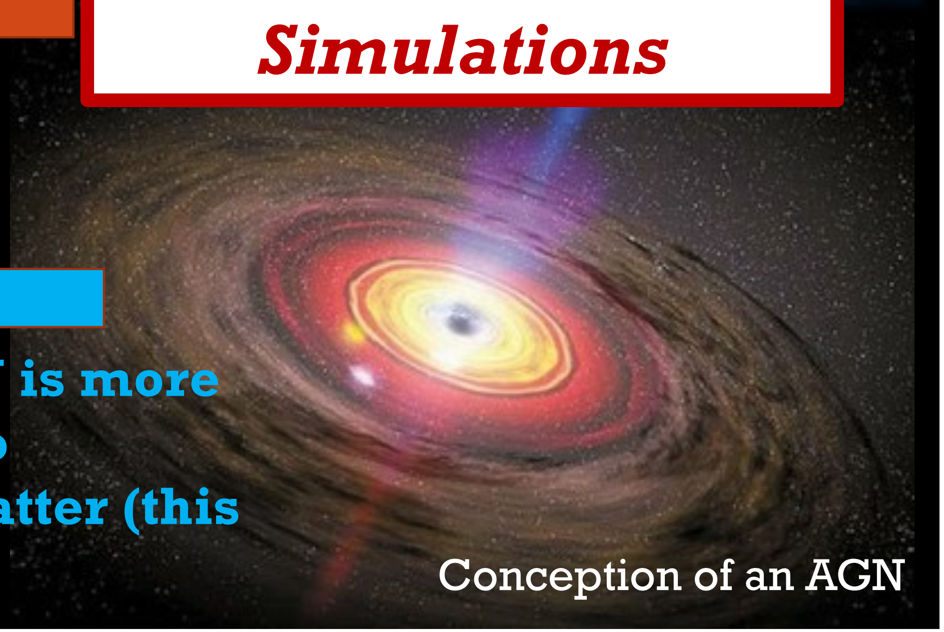


*****State transition of X-ray binaries (Lecture 9)***

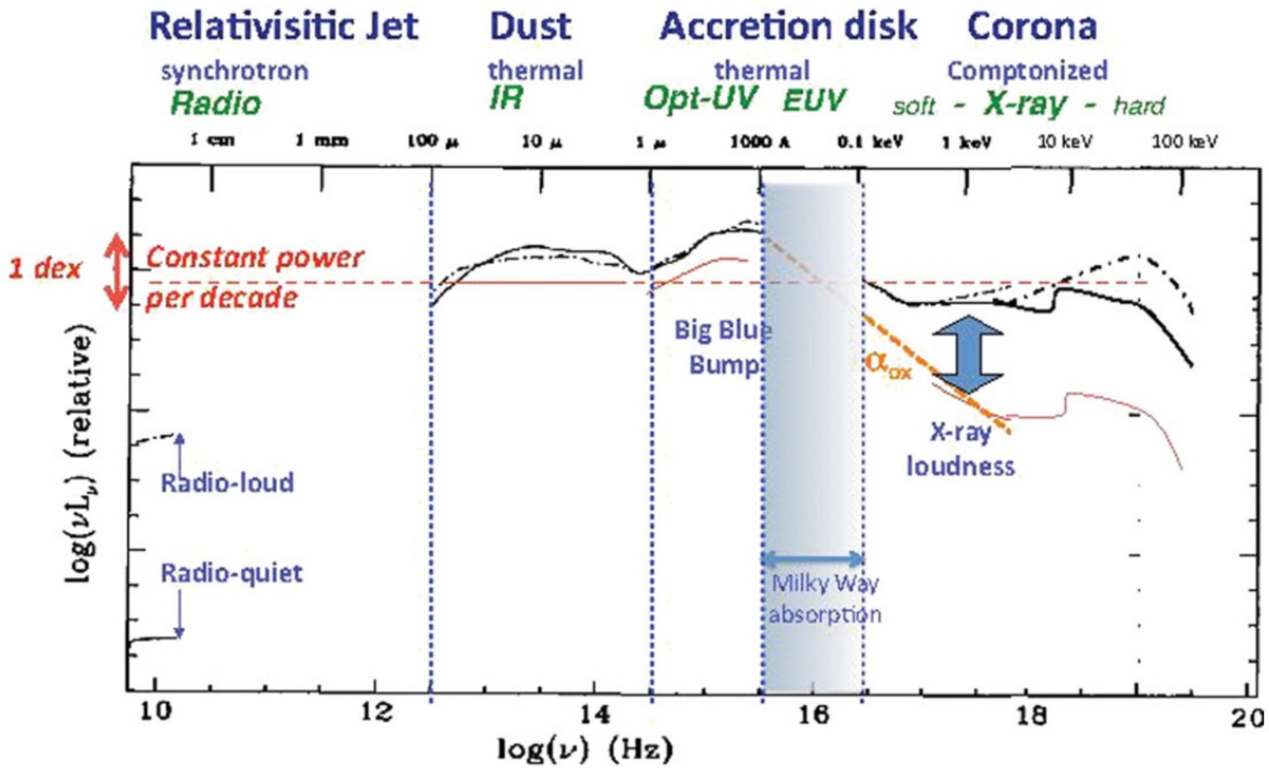
Theoretical models/ Simulations



Spectra of AGN is more complex due to intervening matter (this lecture)

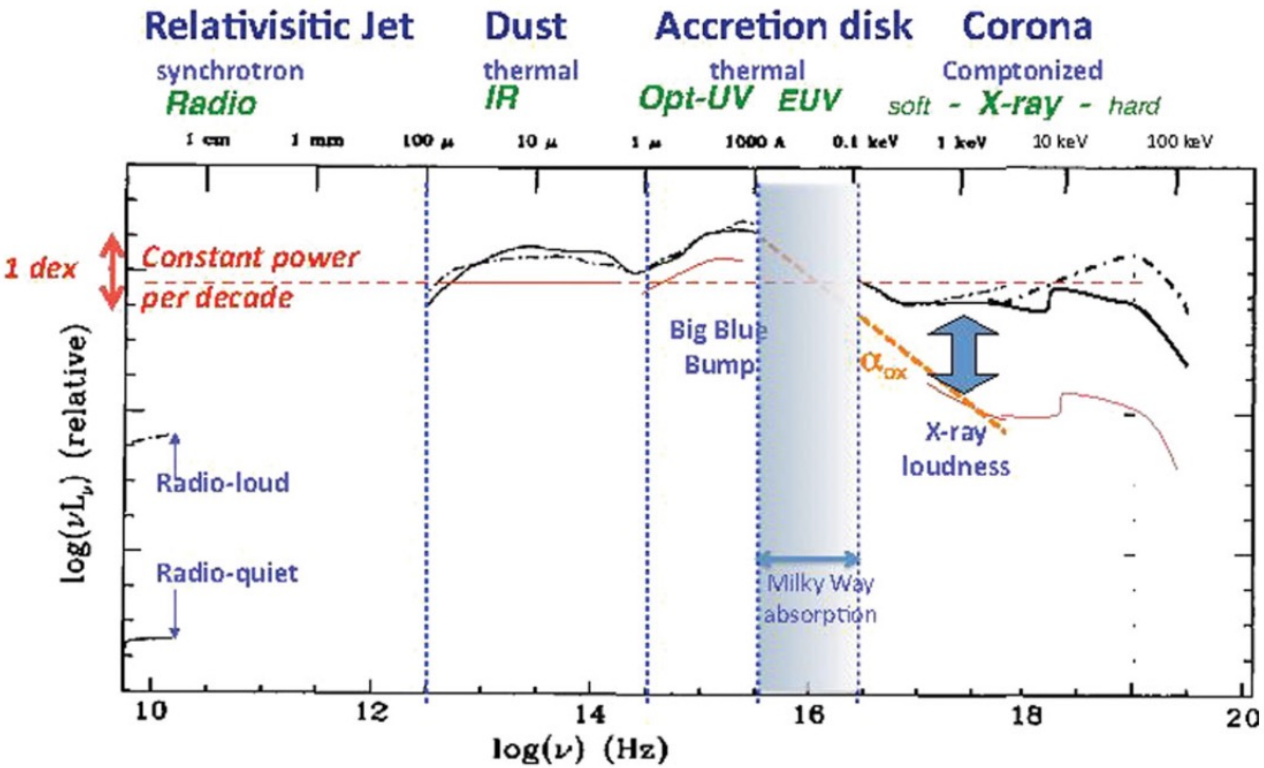


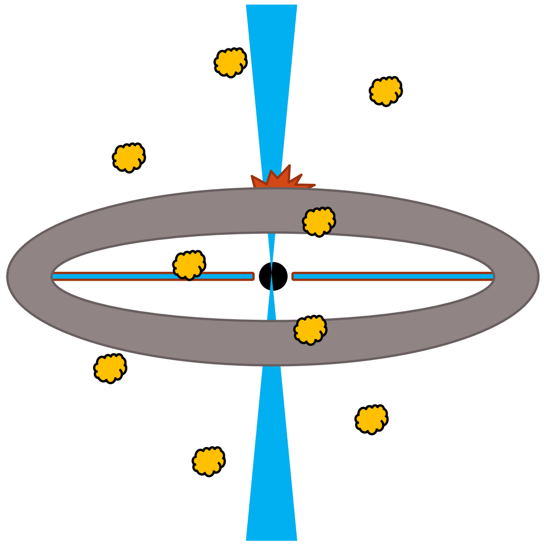
SCHEMATIC AGN SPECTRUM



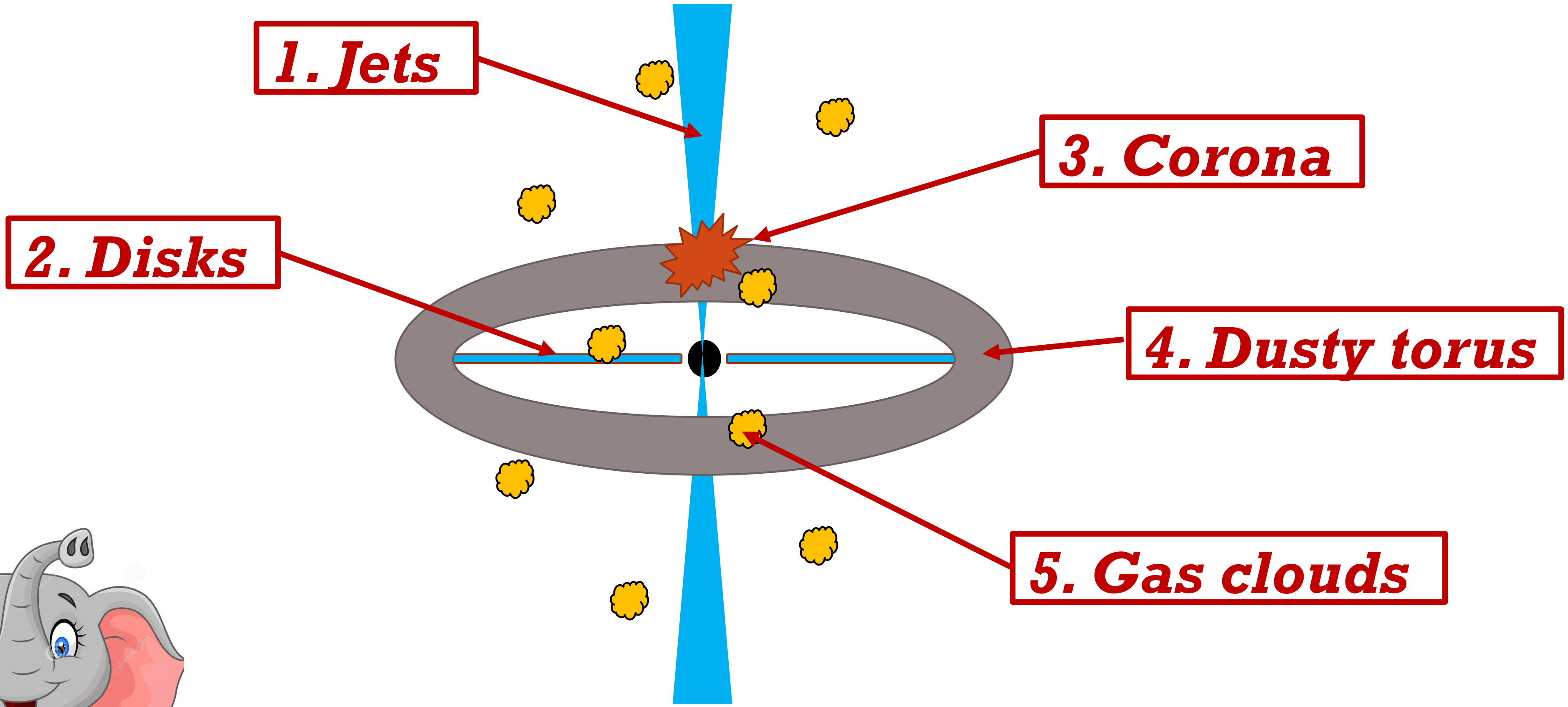
- This is the representative spectrum for ***actively accreting*** SMBHs with radiatively efficient thin/slim disks (not thick disks)
- Different wavelengths trace different components of an AGN
- Different types of AGN can have different dominant components
- Emission comes from (1) intrinsic emission, (2) reprocessed emission, and (3) intervening stuff in the neighborhood

SCHEMATIC AGN SPECTRUM

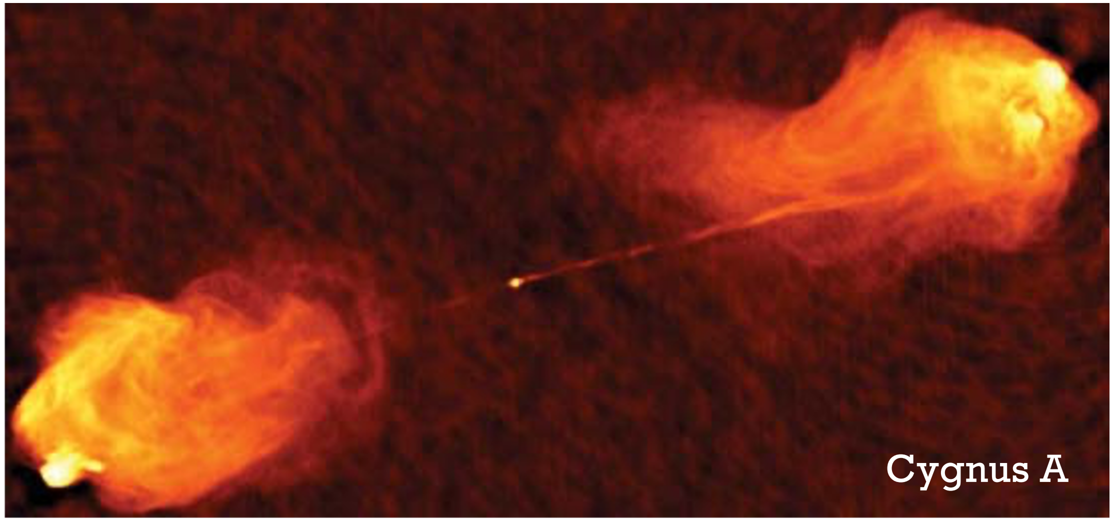




This is typically unresolvable -> why connections between theories and observations are often ambiguous!


1. Jets
2. Disks
3. Corona
4. Dusty torus
5. Gas clouds

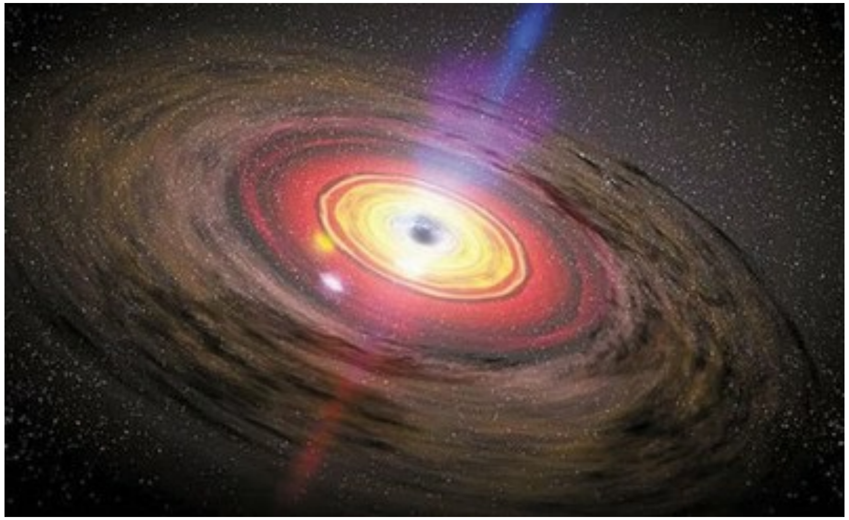
(1) JETS

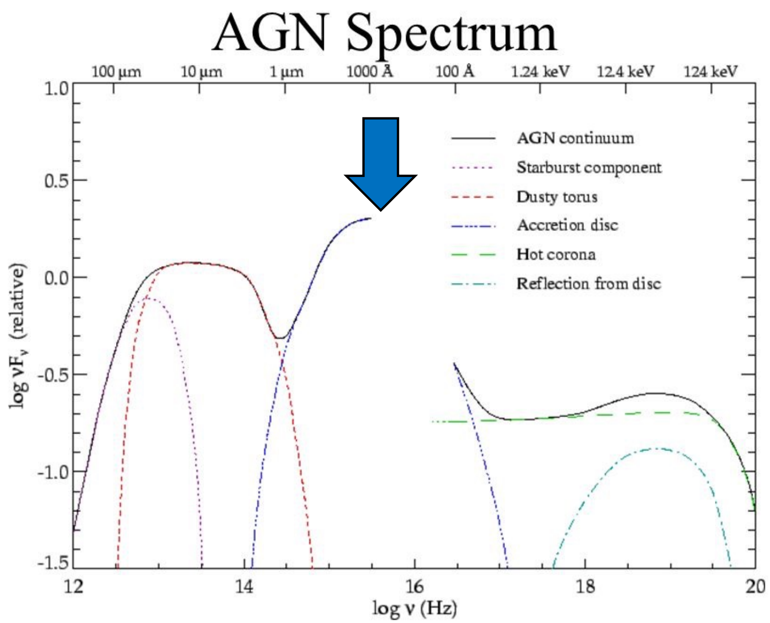


- Jets travel at relativistic speeds
- Typically observed in ***radio***
- Sometimes also seen in optical/X-ray/gamma-rays (harder to separate from other components)
- ***Radio-loud/radio-quiet*** AGN = AGN with/without jets
- ***Blazars*** -- one type of AGN when jets nearly align with the line of sight
- Not all AGN have jets: only ***~10% AGN are radio loud***
- We will discuss about jets in more detail in Lecture 12

(2) ACCRETION DISKS

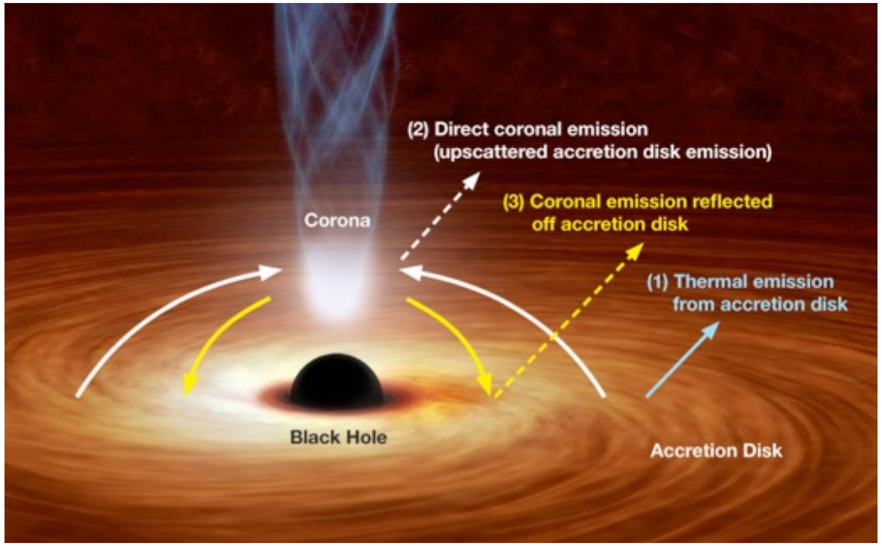
- Emission peaks in ***UV/optical***
  - Superposed black-body radiation with T~10^5K
  - Can be well described by the thin-disk model, suggesting highly accreting SMBHs
- Often called the "***big blue bump***" due to its spectral shape

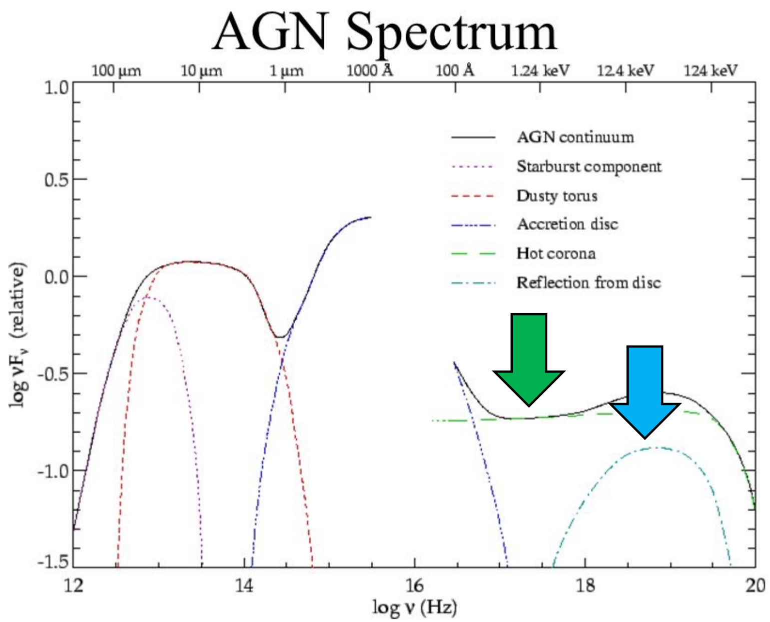




(3) CORONA

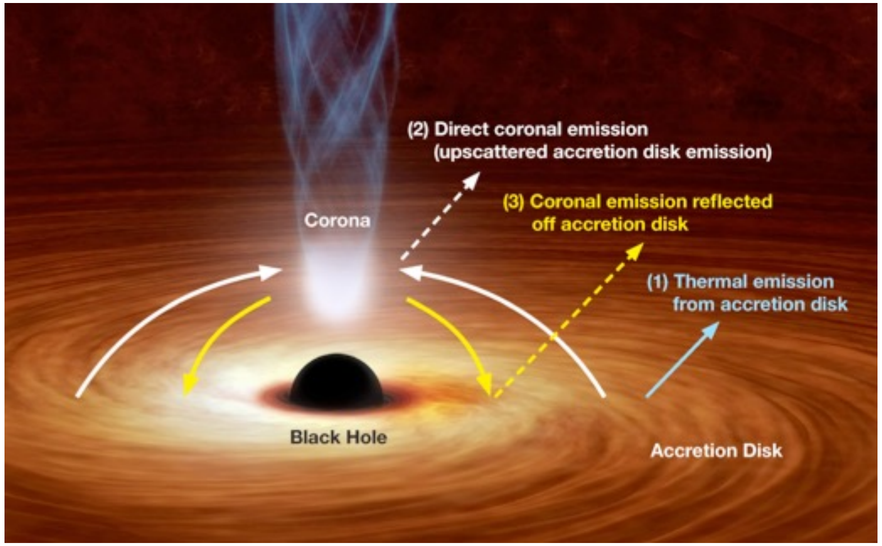
- Invoked to explain the ***X-ray*** emission of AGN
- Corona is very hot, T > 10^9K
- Shape, size, and origin of corona is still unknown
  - Not a part of the standard thin-disk model
  - But needed to explain the X-ray emission
  - Variability and Fe line suggest that the hot corona is a compact region close to the SMBH

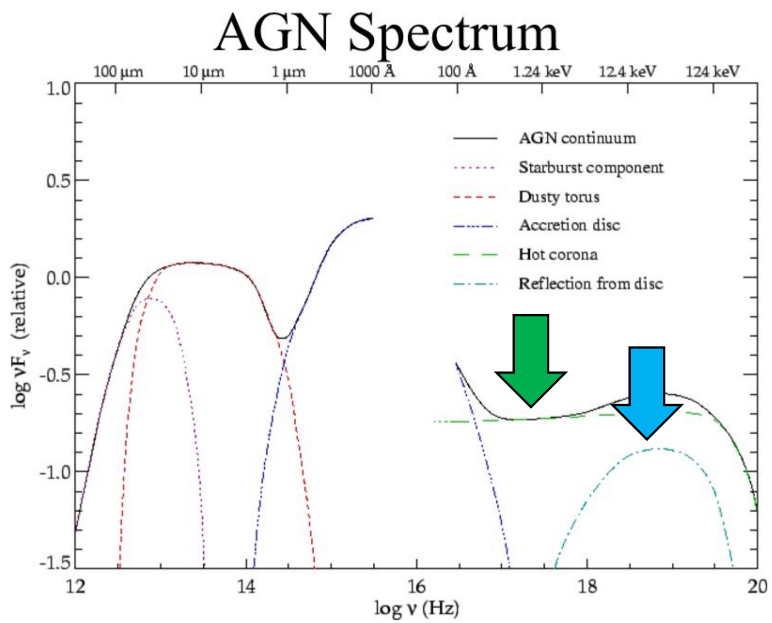


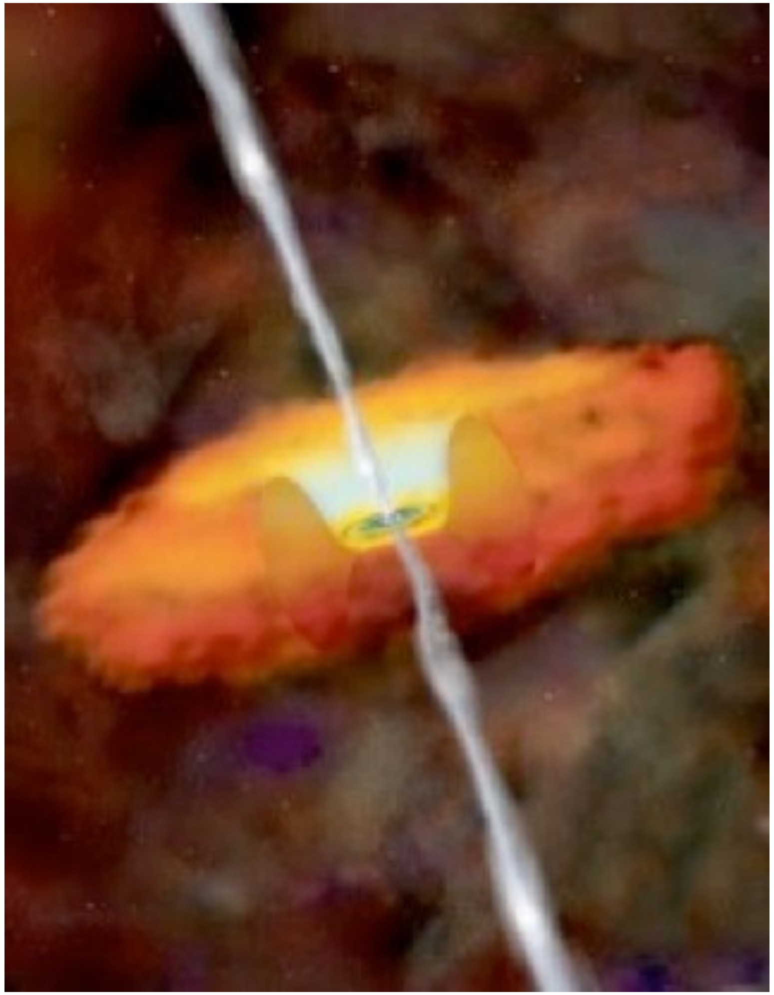


(3) CORONA

- ***Direct corona emission*** comes from reprocessed disk emission -> ***soft X-rays***
  - This is from the Inverse Compton scattering of the UV photons by hot electrons in the corona
- Coronal emission ***reflected*** off accretion disk -> ***hard X-rays***
  - Often called the "***Compton hump***"
  - The Fe line at 6.7 keV used to measure spin is also part of this reflection





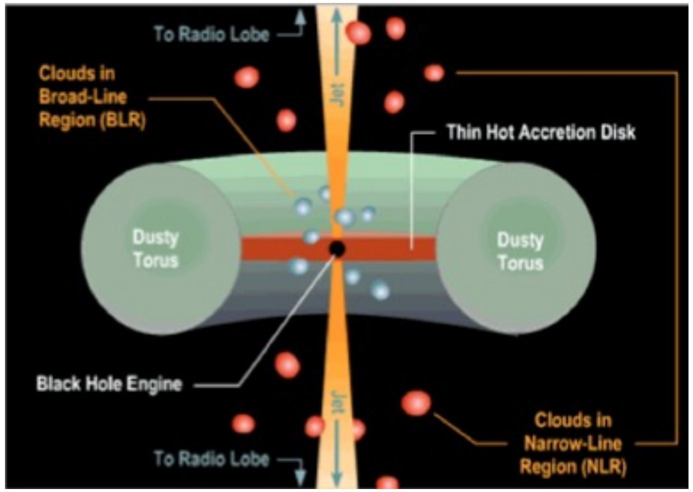


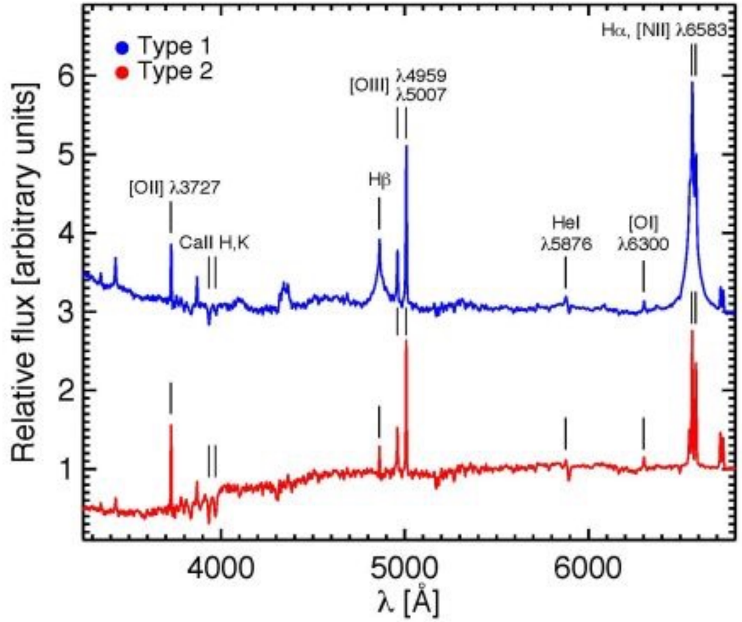
(4) DUSTY TORUS

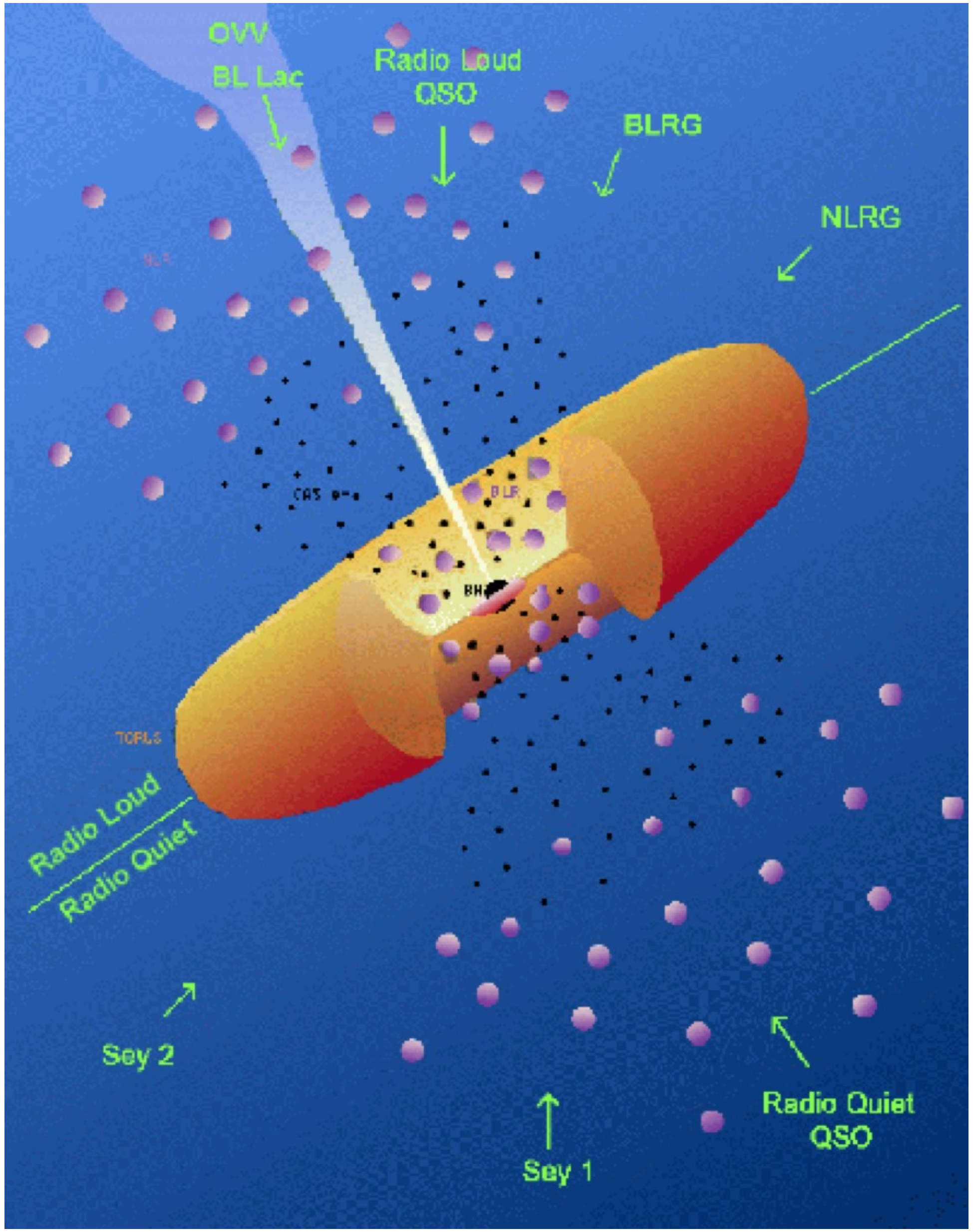
- Responsible for the ***infrared*** emission of AGN
- Dust can reprocess UV emission from the disks and re-emit into infrared radiation
- Dusty torus could block light from regions close to the accretion disk
- ***Type-1/type-2*** AGN: unobscured/obscured AGN

(5) GAS CLOUDS

- Responsible for the ***optical emission lines*** in the AGN spectrum
- Broad/narrow lines originate from fast/slowly moving clouds due to Doppler shift
- ***Broad line region (BLR)***
  - Closer to the SMBH (scale <pc) (1pc = 3.26 light-years)
  - Velocity of clouds ~ 1000-10000 km/s
  - The velocity dispersion and time delay can be used to measure BH masses – reverberation mapping
  - Often absent in type-2 AGN -> likely blocked by the dusty torus
- ***Narrow line region (NLR)***
  - Further from the SMBH (up to kpc scale)
  - Velocity of clouds ~ 100-500 km/s
  - Seen in both type-1 and type-2 AGN





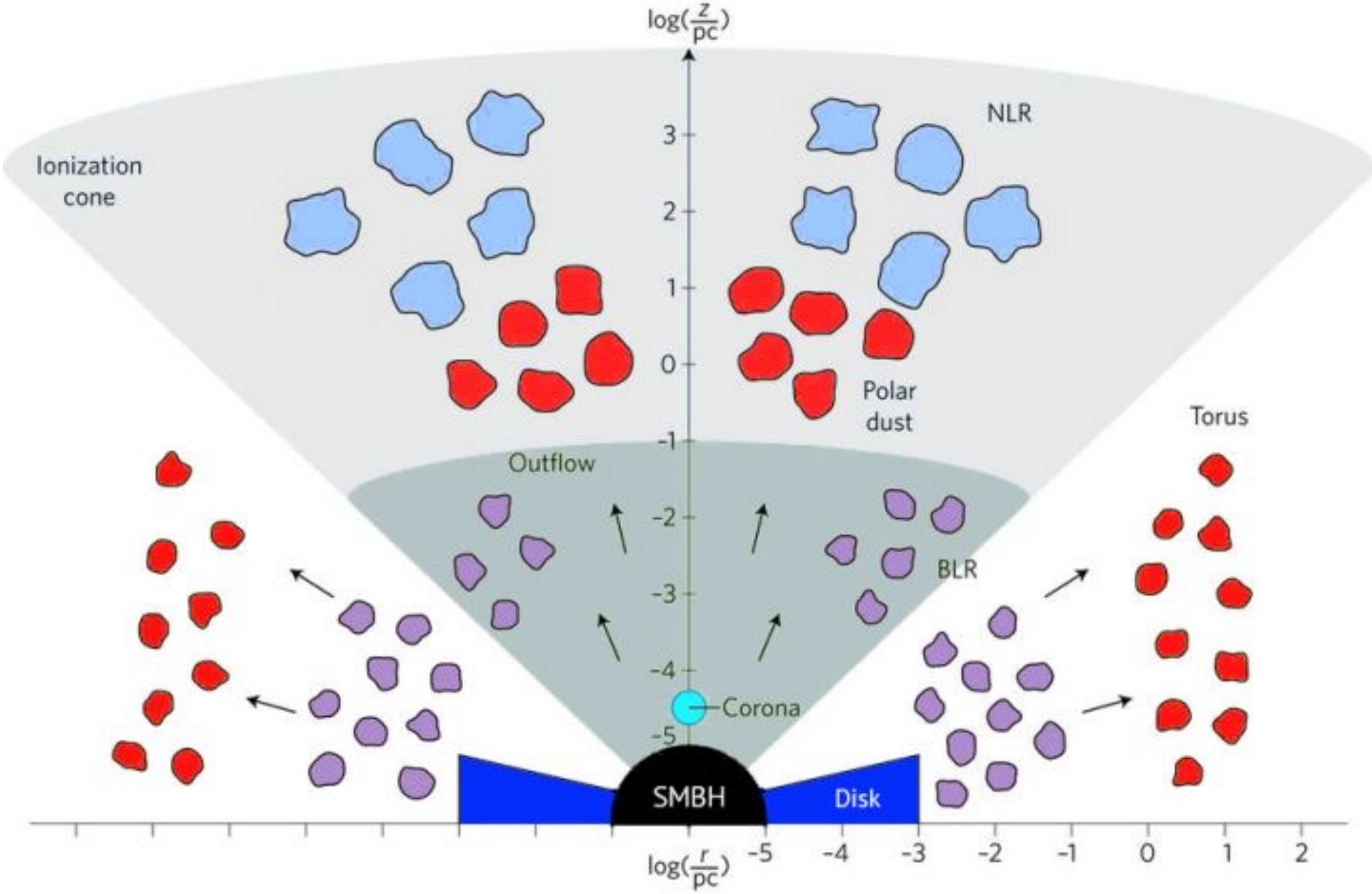


AGN UNIFICATION

- The different types of AGN can be largely explained by our viewing angle relative to the ***orientation*** of the disk, rather than their intrinsic differences

***The AGN terminology is often confusing, since the names sometimes reflect how they were discovered or initially classified, rather than their real physical differences*

NOTE THE LARGE RANGE OF SCALES INVOLVED!



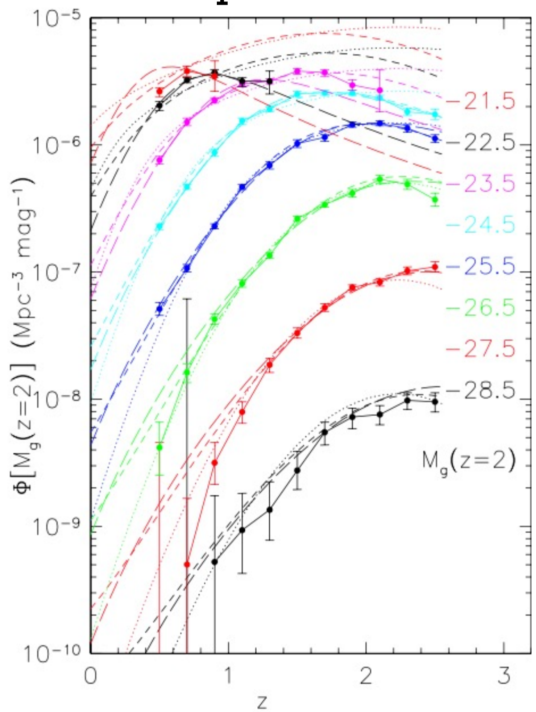
OPEN QUESTIONS

SO…WHAT TRIGGERS THE AGN??

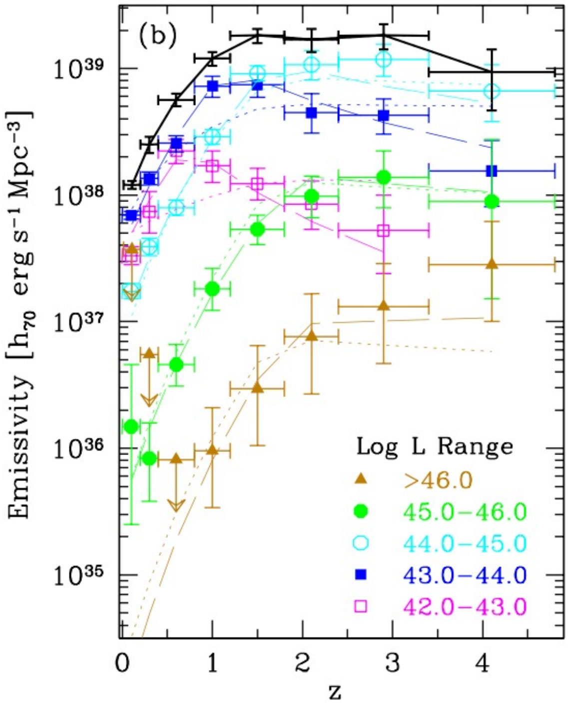
- Only ~1-10% of the SMBHs are AGNs. What factors determine whether they are actively accreting or not? How are AGNs triggered?
- Do AGNs preferentially live in certain type of galaxies?

HINT #1: THE "DOWNSIZING" OF AGN

Optical AGN



X-ray AGN

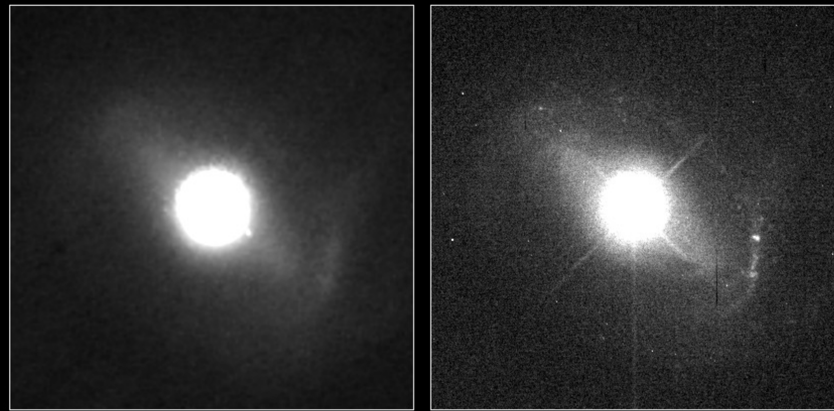


early universe

- More luminous AGN (especially quasars) at higher redshifts
- Trends opposite to the hierarchical build-up of galaxies as well as SMBH masses
- Consistent with ***more galaxy interactions*** and ***more gas supply*** in the early universe

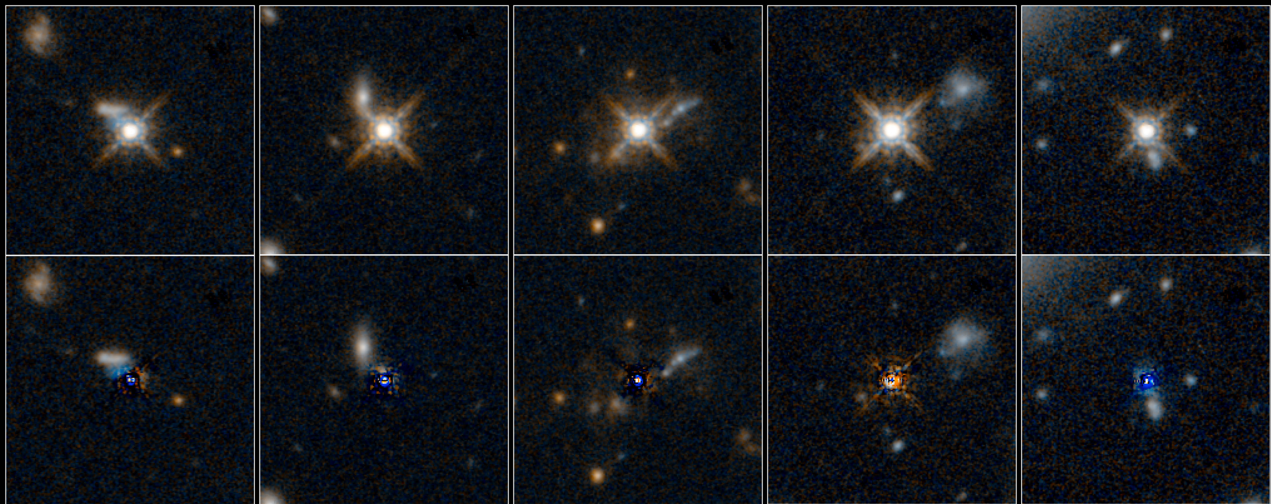
HINT #2: QUASARS TEND TO BE FOUND IN MERGING GALAXIES

QSO 1229+204



Ground Based
Canada-France-Hawaii Telescope

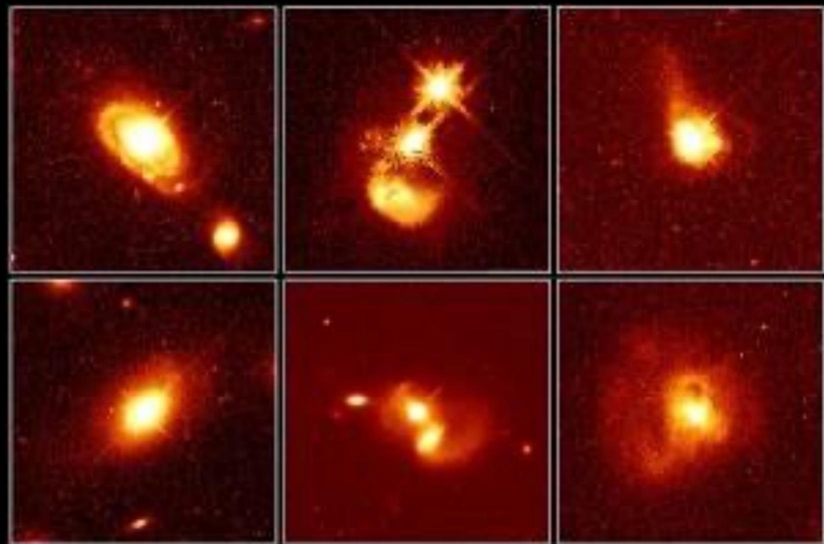
Hubble Space Telescope
Wide Field Planetary Camera



Quasars in Interacting Galaxies
Hubble Space Telescope ▪ WFC3/IR

NASA and ESA

STScI-PRC15-20a

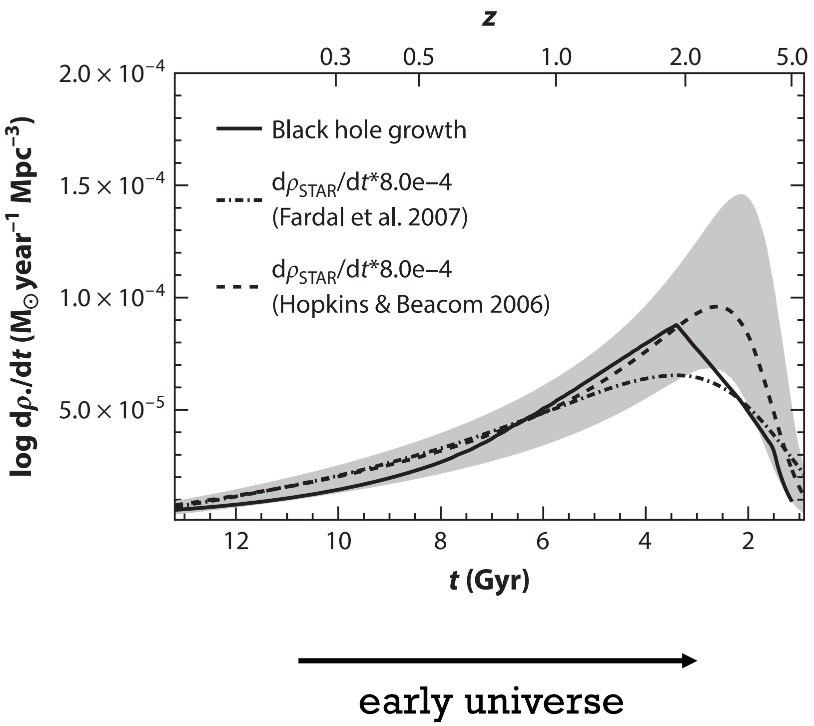


Quasar Host Galaxies HST • WFPC2
PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

ARE AGNS TRIGGERED BY GALAXY MERGERS?

- Expectation: Yes, because galaxy interactions would perturb gas, provide torque, enhance angular momentum transport and trigger accretion onto the SMBH
- Method: see if the host galaxies of AGNs are preferentially merging galaxies
- For ***quasars***, the answer is ***yes***
- But for the majority of the AGN population (especially ones at z~2-3), the observational evidence have been null or controversial
- It means that ***most AGNs are not necessarily triggered by mergers***, but there're still other factors that determine the onset of accretion activity!

ANOTHER CLUE: SMBH AND STARS IN GALAXIES GROW TOGETHER!!



- Left figure shows the growth rate of SMBHs vs. (renormalized) growth rates of stars within galaxies
- The shapes of the curves are remarkably similar, both peaking at z~2-3
- This suggests that ***SMBHs and galaxies grow together!***
- Likely explanation: they grow and AGNs shine as long as there is ***abundant gas supply***

SOME OTHER OPEN QUESTIONS

- What is the structure and origin of the corona and how it depends on mass accretion rates?
- What is the composition, geometry, and morphology of the obscuring dust? How is it formed?
- What are the connections among different types of AGN, e.g., are there any evolution sequences?
- Are AGNs scaled-up versions of X-ray binaries?
- Why do some AGN have jets and others do not? (Lecture 12)
- How do the radiation and jets of AGN influence galaxy formation? (Lecture 13)
- How do SMBHs form and grow? (Lecture 14)

SUMMARY

- ***Active galactic nuclei (AGN) = actively accreting SMBHs***
- Observationally they have many different faces – ***quasars, Seyfert galaxies, radio galaxies***, etc, are all different types of AGN
- Radiative processes: thermal & non-thermal (Compton, Bremsstrahlung, synchrotron)
- The spectrum of AGN at different wavelengths comes from different components
  - ***Jets*** – radio, optical, X-ray, gamma-rays
  - ***Accretion disk*** – UV/optical
  - ***Corona*** (hot gas with unknown origin) – soft and hard X-ray
  - ***Dusty torus*** – infrared
  - ***Gas clouds*** – broad and narrow emission lines
- AGN ***unification*** – we see different types of AGN due to the viewing angle
- Only ***~1-10%*** SMBHs are AGNs. While quasars are preferentially found in merging galaxies, most AGNs are triggered as long as there is abundant gas supply

PRESENTATIONS 4/27

- Astronomers discover most distant quasar by Wen-Chi Cheng 鄭文淇

https://qrgo.page.link/jKGmQ

- Mysterious Gamma-ray Heartbeat by Chian-You Huang 黃千祐

https://qrgo.page.link/YcsN9

- Cygnus X-1 contains a 21 Msun black hole by Chih-Teng Ling 凌志騰

https://qrgo.page.link/Vyau1