*Physics of Galaxies, Spring 2015*

# Active Galactic Nuclei

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# – Content –

- Introduction
  - A little background
  - Classes of AGN
  - Redshift distribution
  - Key questions
- The Nucleus
  - Milky Way nucleus
  - Black hole basics
  - Reverberation mapping > black hole mass
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- AGN spectra
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  - Seyfert 1s vs Seyfert 2s
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  - Unification of Seyfert-galaxies
  - Basic structure and ideas
  - Disclaimer
- Evolution of AGN
  - How do AGN form?
  - Can mergers form an AGN?
- Open questions

# Our Milky Way – an ordinary galaxy?

- Galaxy: gravitational assembly of stars, gas, dust and dark matter.
- What makes a galaxy ordinary

  and what makes us name a galaxy as “non-ordinary”?
- Milky Way: ordinary or non-ordinary?
  - Fermi bubbles: radio jets from the center?
  - Super-massive black hole.

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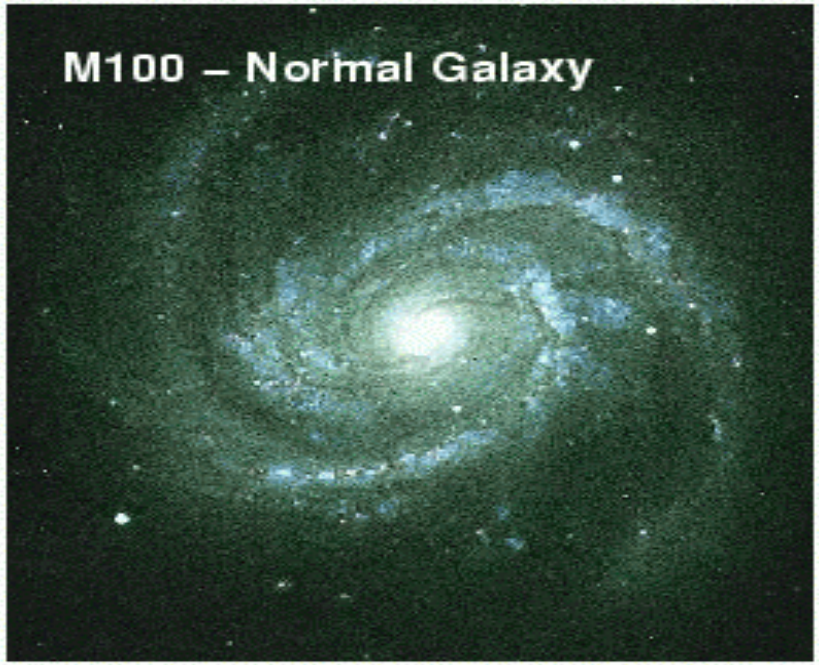
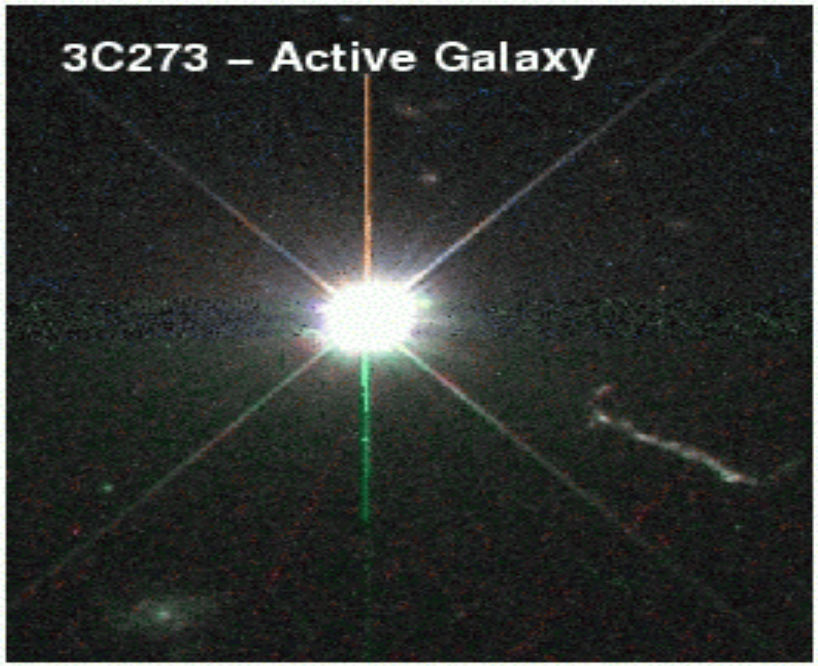
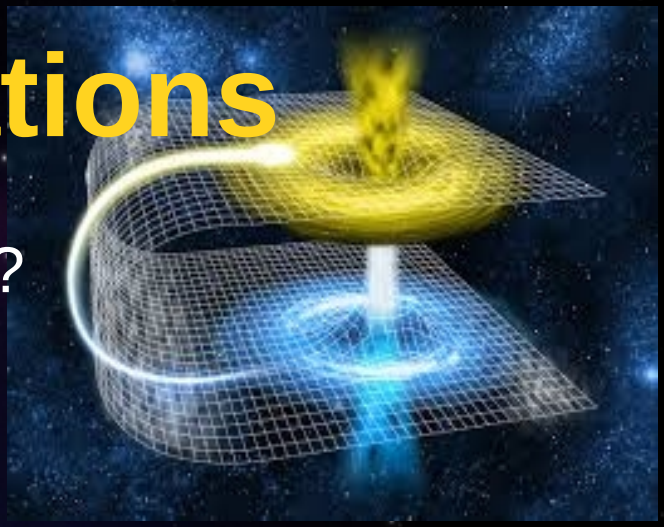
# Active Versus Normal Galaxies


**An Active Galactic Nucleus (AGN) has excessive and extreme luminosity from its nucleus (strongest: 10^41 W)**

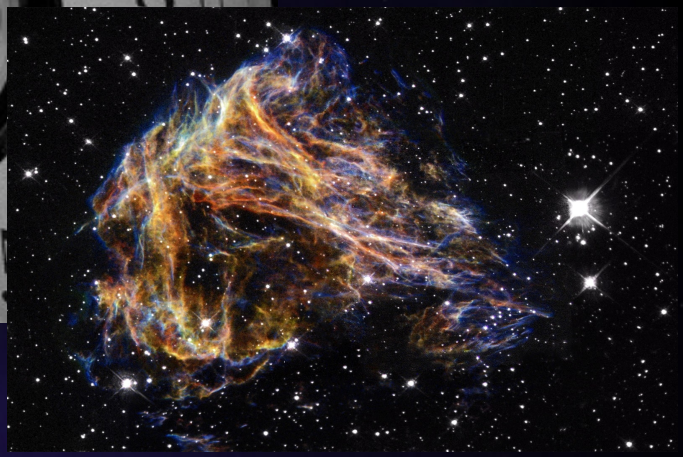
# Historical speculations



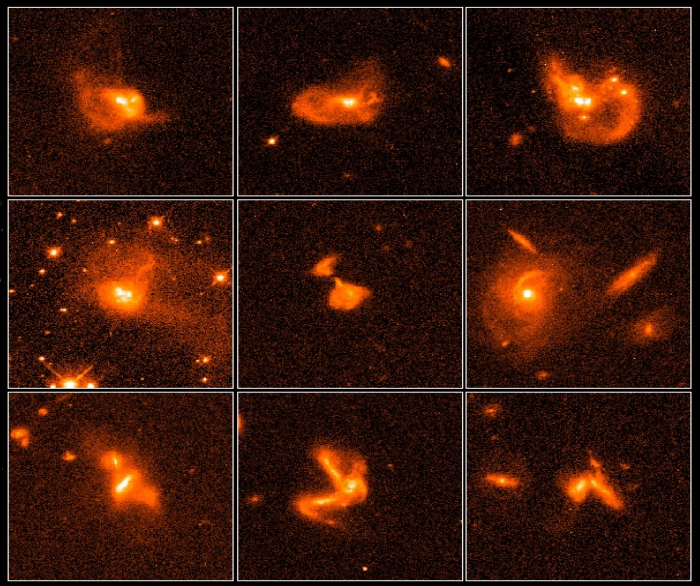
An assembly of stars?

Giant supernova explosions?

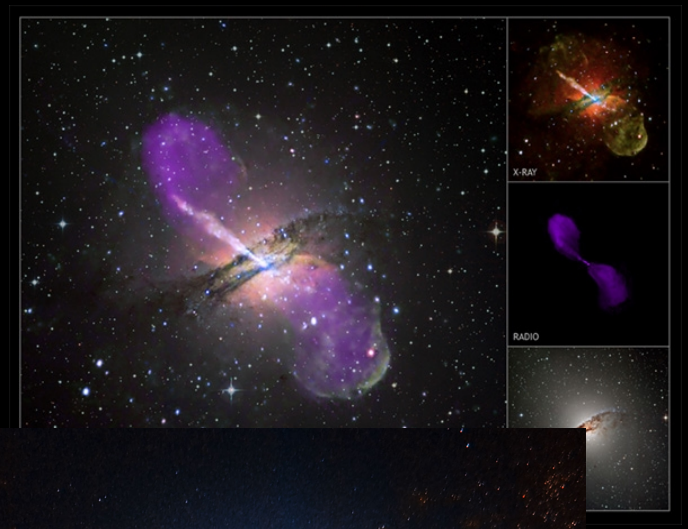
Wormholes? Time-traveling machines?

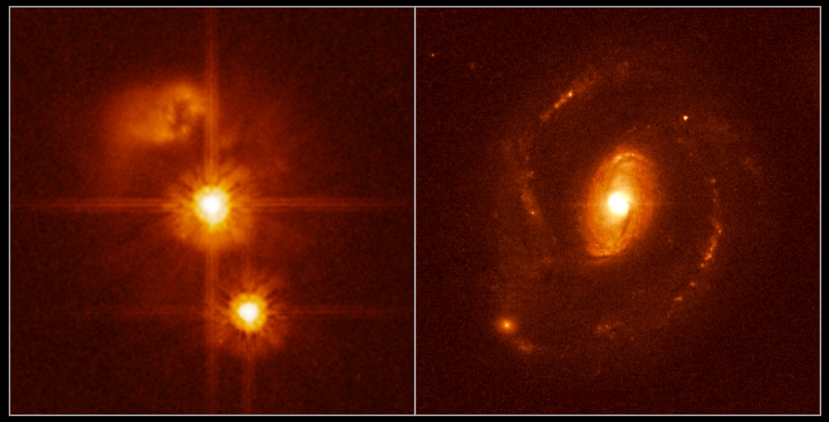


# AGN captured on image



**Ultraluminous Infrared Galaxies** **HST** • WFPC2
NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center), H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)



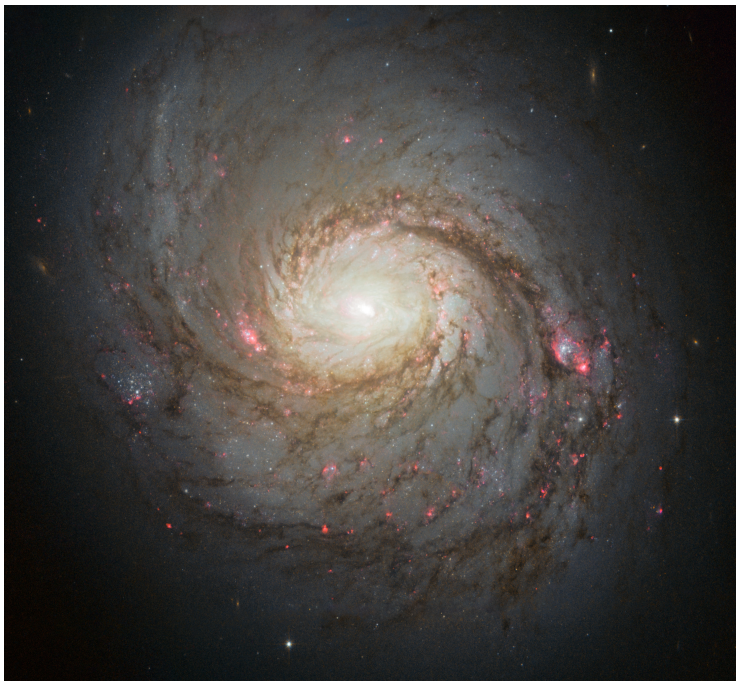
**Warning:** *Many classes are overlapping in properties and their nomenclature often varies.*

# Typical classes of AGN

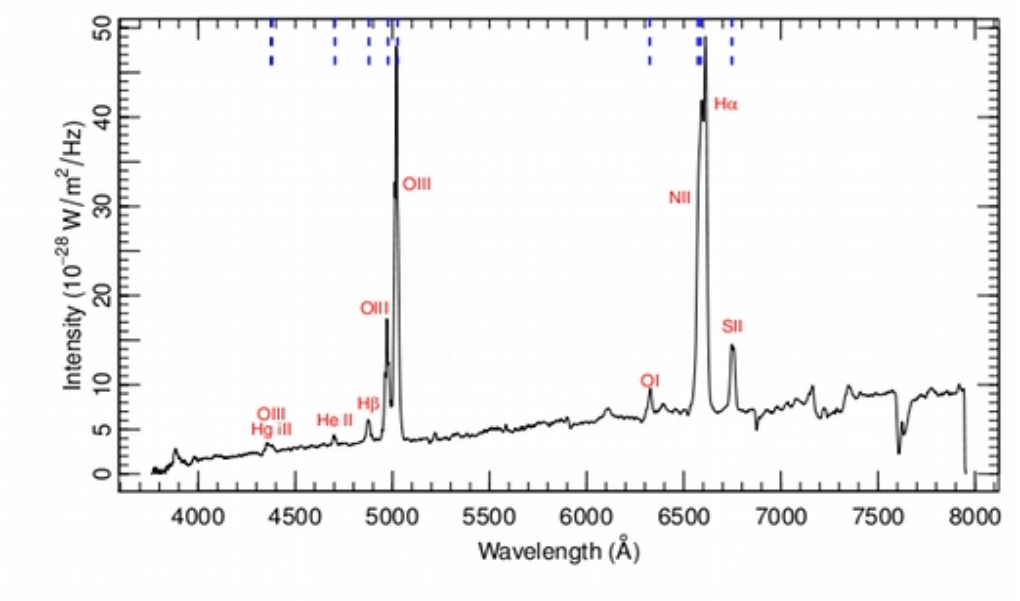
- Radio-quiet ones:
  - Seyfert galaxies.
  - Quasars (90% radio-quiet)
  - LINERs
- Radio-loud ones:
  - Radio-loud quasars
  - Blazars
  - BL Lac
  - OVV
  - Radio galaxies

# Seyfert-galaxies

- Radio-quiet.
- Optically identifiable. First discovered in 1908 due to strong emission lines in optical spectrum.
- Many reside in spiral or lenticular galaxies. Seyferts are weaker AGN.
- Seyfert galaxies are the “weaker” AGN identifiable by optical spectra.



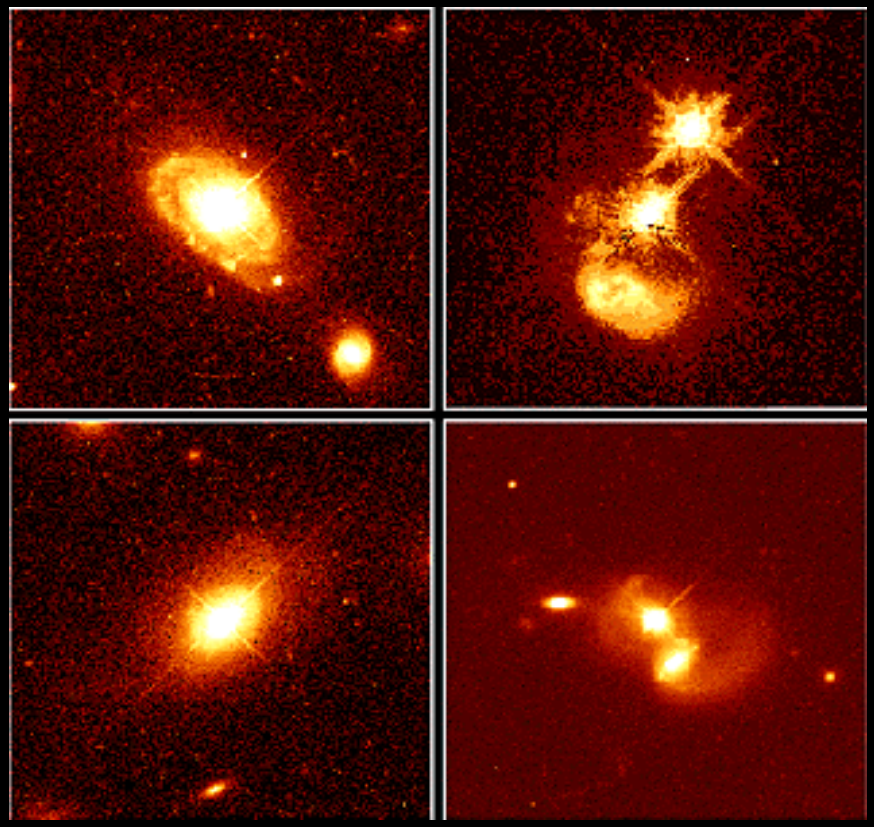
NGC 1068




NGC 1068 spectrum

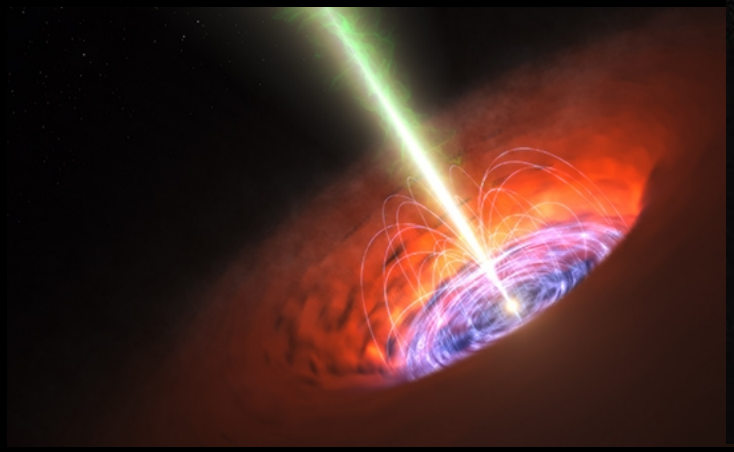
# “Quasars” or “QSOs”: the most powerful of all AGN

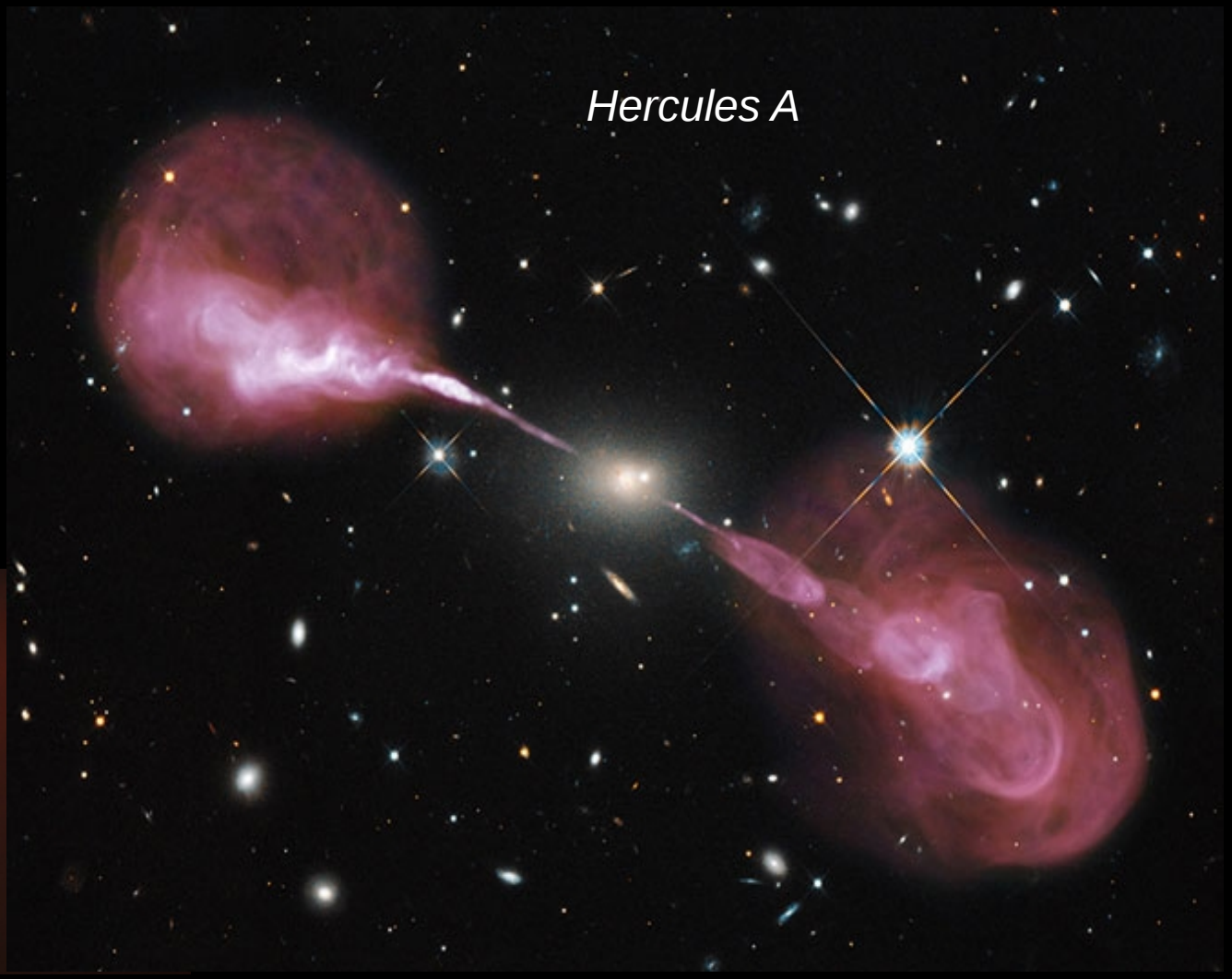
- First quasar discovered 1963, Maarten Schmidt. Confused with a star. (“QUAsi StellAr RAdio source”)
- Seen at large distances.
- Strongest optically bright quasar, absolute magnitude M_r ~ -32.2
- 10% are radio-loud: radio-jets, radio blobs and/or radio cores.
- Often difficult to see host galaxy.



# Radio-galaxies

- Bright at radio wavelengths.
- Often in giant elliptical hosts.
- Typical features: lobes, jets, radio core, diffuse radio.
- Classification system: Fanaroff-Riley

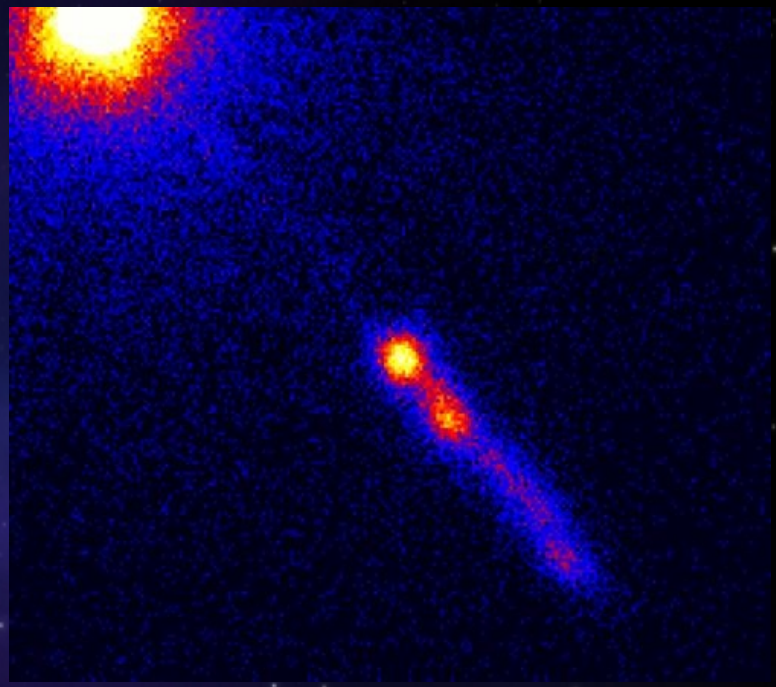




# Blazars

- Highly variable quasar
- Some of them (BL Lac): no optical emission
- Others (OVV quasars): radio-loud quasars with jet along our line of sight.

*3c 273 as observed with Hubble*

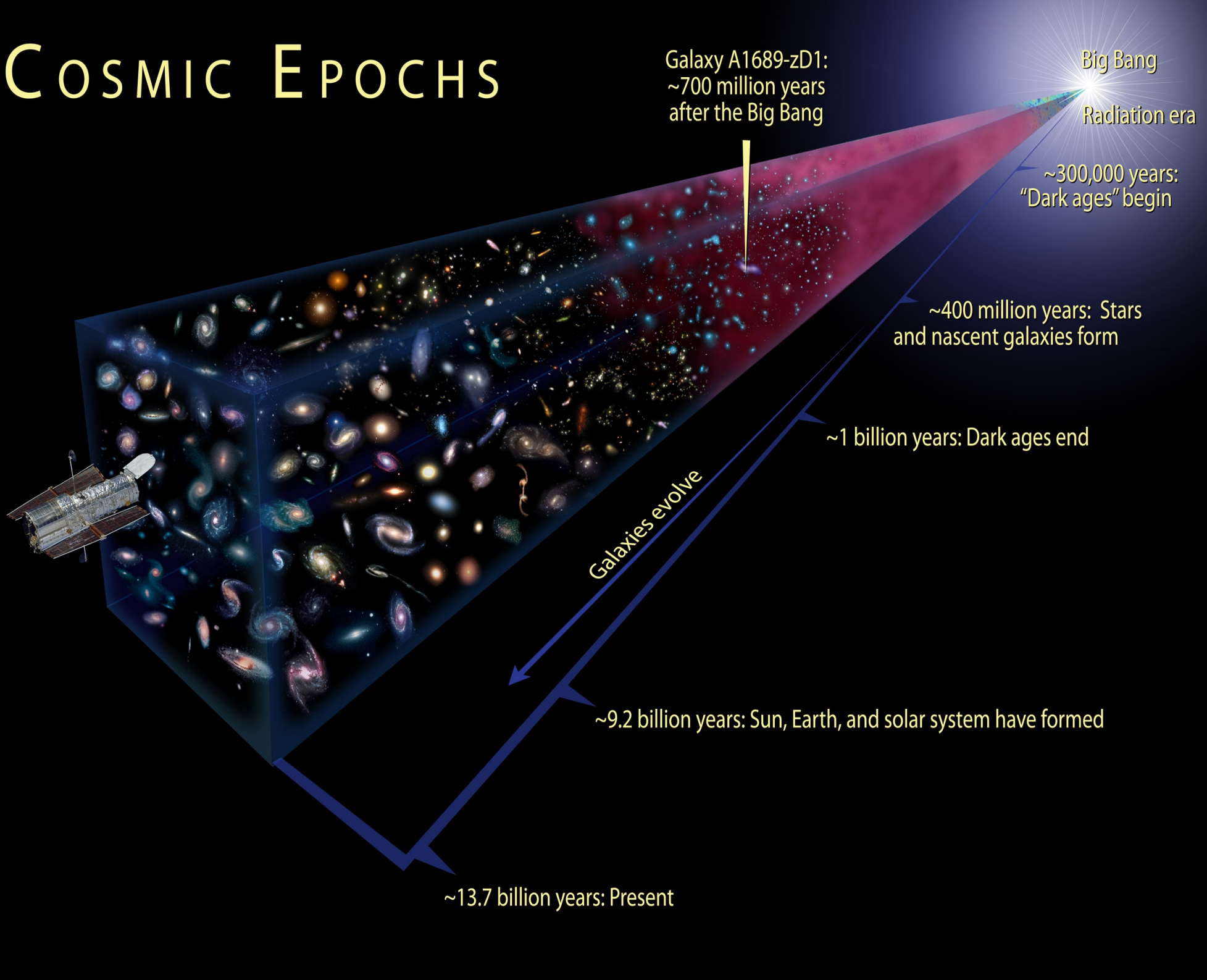


*3c 273 as observed with Chandra x-ray*

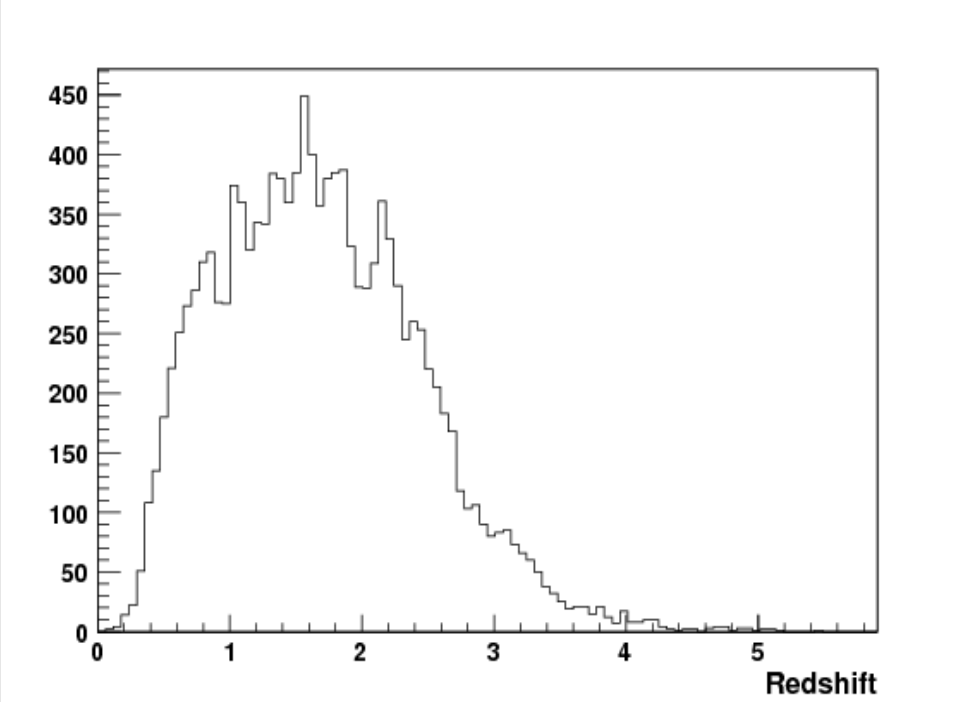
# LINERs

- “Low-ionization nuclear emission-line regions”
- Many morphologies
- Weak highly ionized emission-lines (weak [OIII], [OII],...)
- Are they AGN?

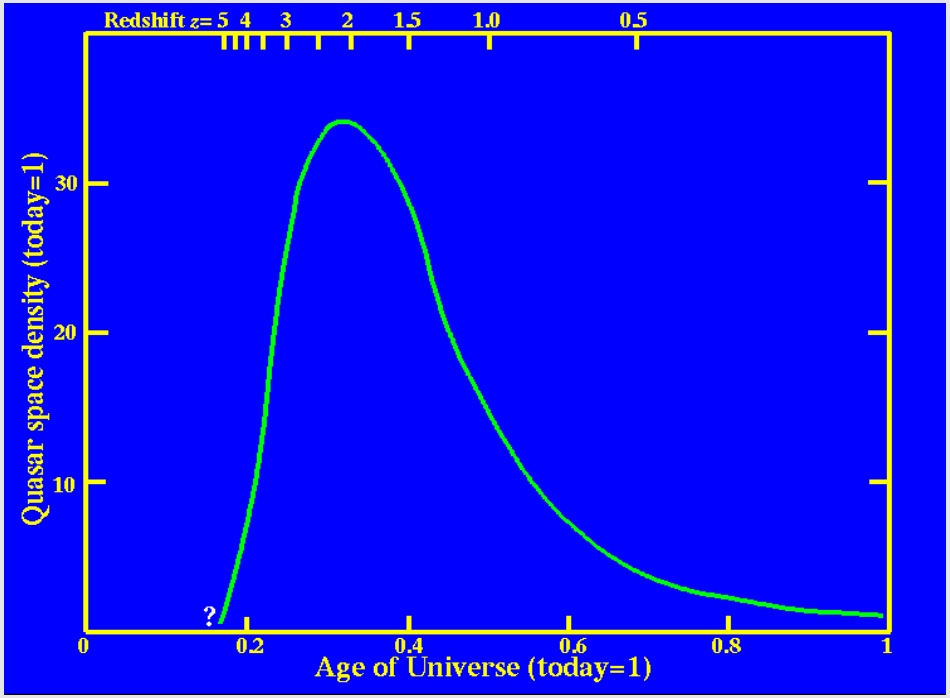
# Cosmic Epochs



# Quasar distribution




Variable quasars from Stripe 82 in DR10



# – Key questions –

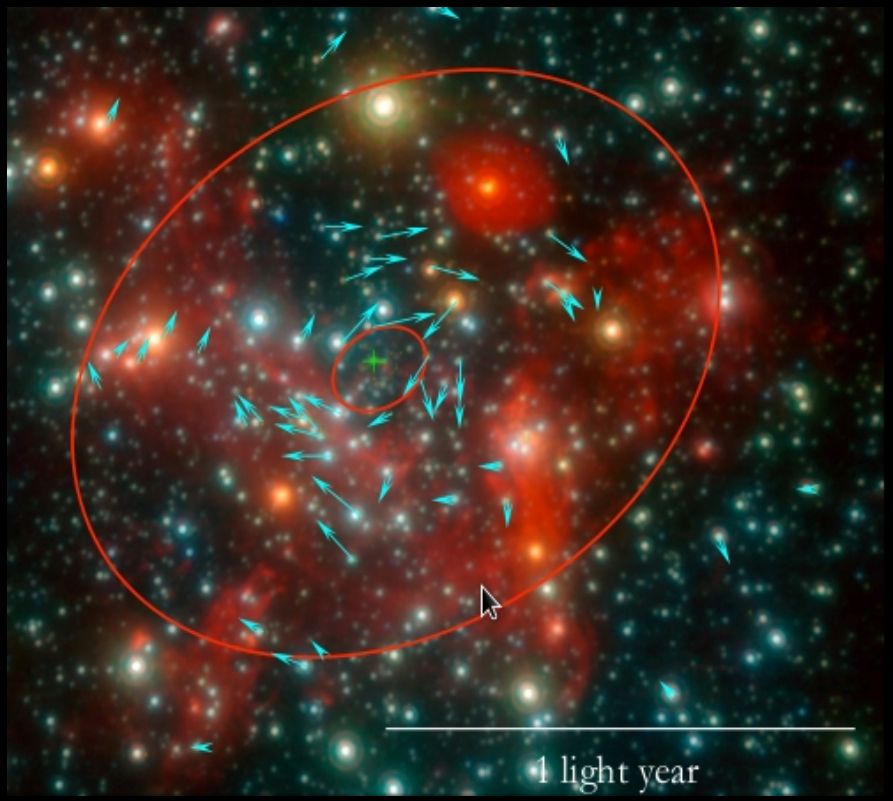
**How do AGN and quasars form and feed?**

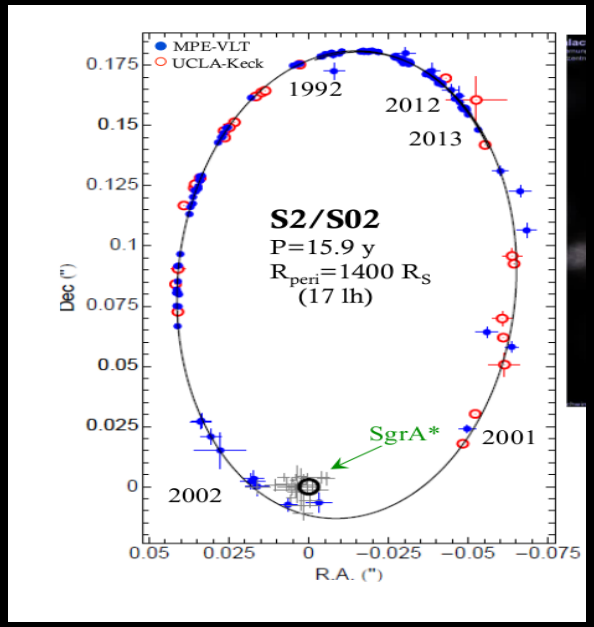
**Why are there no luminous quasars today? Where did they all disappear?**

**What is the physics of an AGN?**

# The Milky Way nucleus

- Sgr A* ~ flat radio source spectrum
- Three different types of emission:
  - Steady emission (synchotron). No blue bump in the spectral energy distribution (SED).
  - Variable emission: X-ray flares and variable IR-emission.
- What is in Sgr A*?
- Proper motions of s-stars.

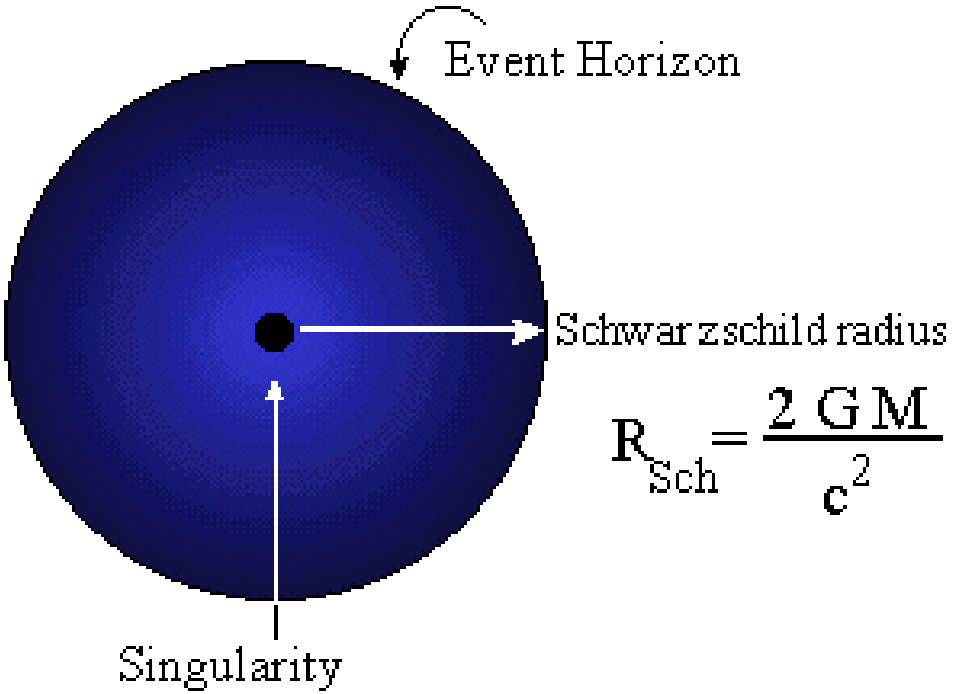



The invisible object has a mass of 4 million solar masses.

# The nucleus

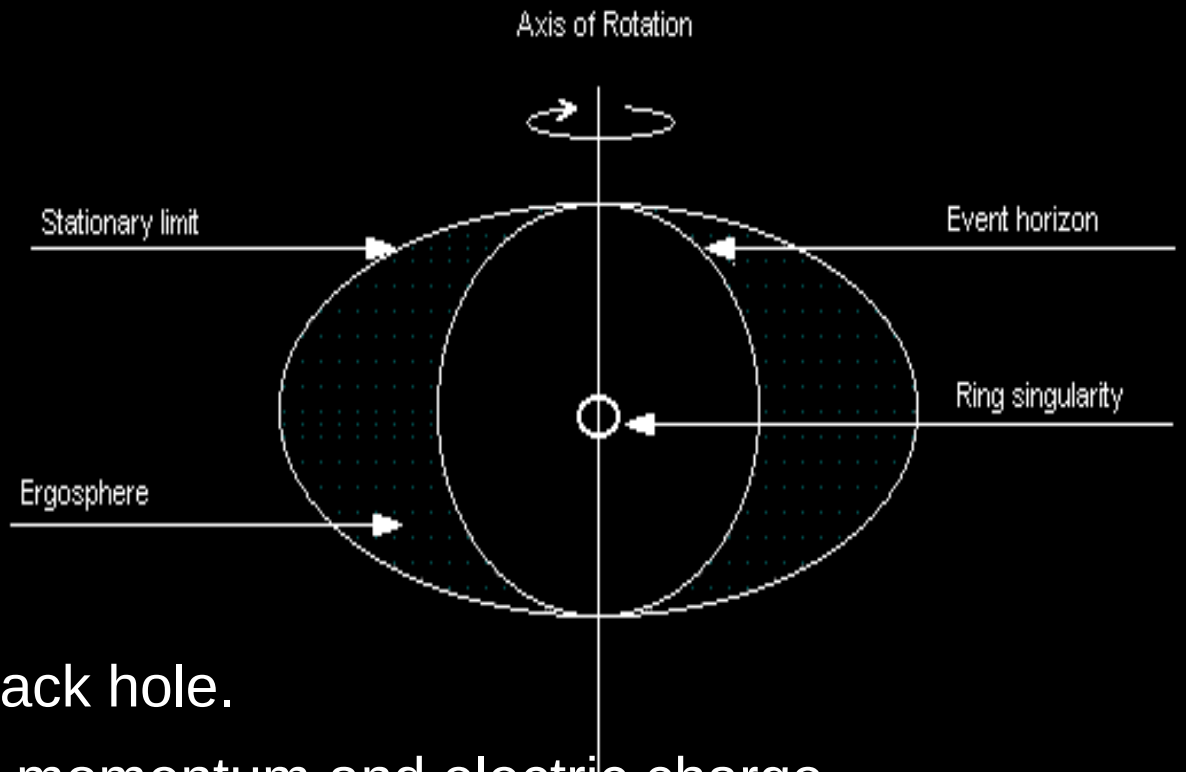
# Black hole basics



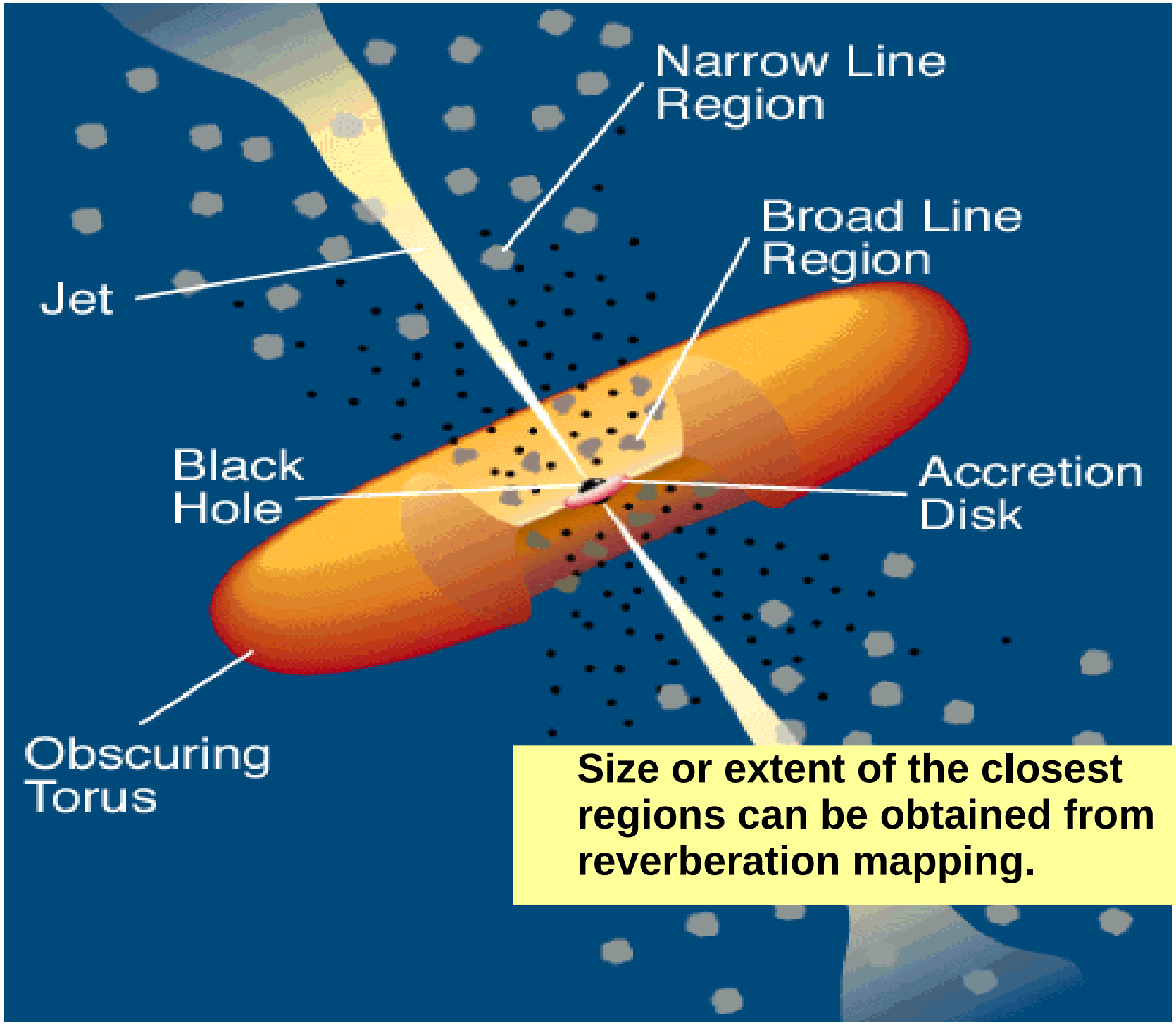

$$R_{Sch} = \frac{2GM}{c^2}$$

- Star collapsed within the Schwartzschild radius R_s;
- No light can escape from it.
- “Pointy” **singularity** (no volume, infinite density)
- **Event horizon** at R_s surrounds star.

# Rotating black hole

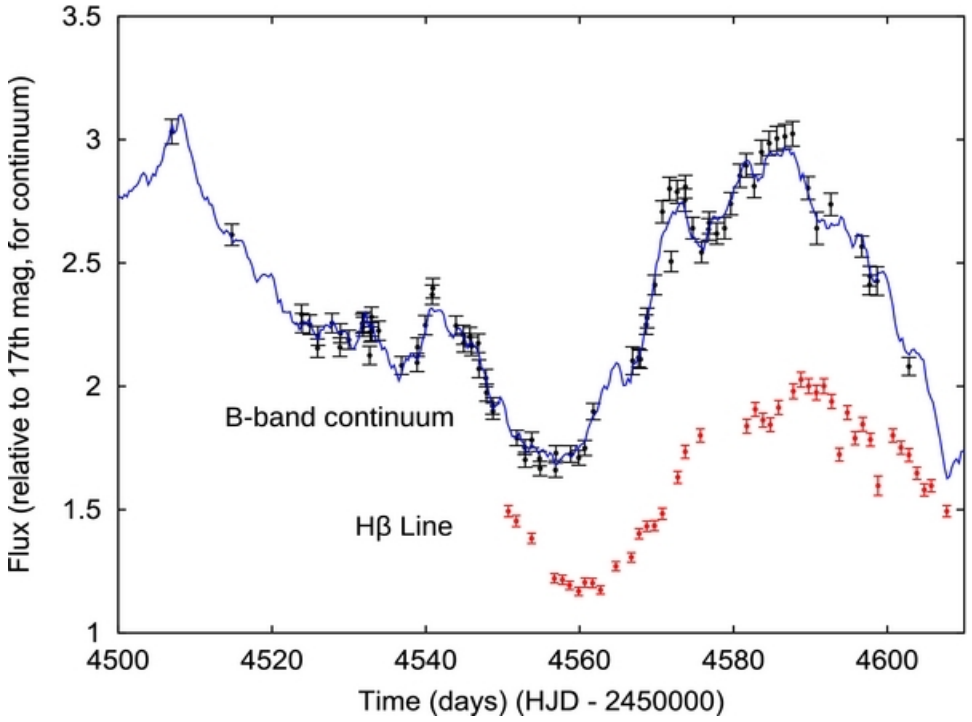



- All stars rotate, so will the black hole.
- Described by mass, angular momentum and electric charge.
- Singularity: flattened
- Event horizon: ellipsoid
- “Frame dragging” creates the **ergosphere**: region outside event horizon where all particles rotate in same direction as the black hole.
- Infinite time of evaporation, unless Hawking radiation exists.




**Size or extent of the closest regions can be obtained from reverberation mapping.**

# Reverberation mapping 1




- Light-curves of a Seyfert-1 AGN
- Reverberation mapping uses the light-curves to determine the size of the line-emitting region.

- Some radio-quiet AGN, have variable continuum and broad-line region fluxes.
- Changes the continuum are followed by the changes in emission-lines.
- Changes in fluxes can happen in hours or years in the broad-line region (BLR). Too slow to be observed in the narrow-line region (NLR).
- Can be used to constrain size of the emitting gas region >> R.
- Dispersion σ of a Doppler-broadened line in the BLR appears to vary with

  σ prop. R^(-1/2)

# Reverberation mapping 2

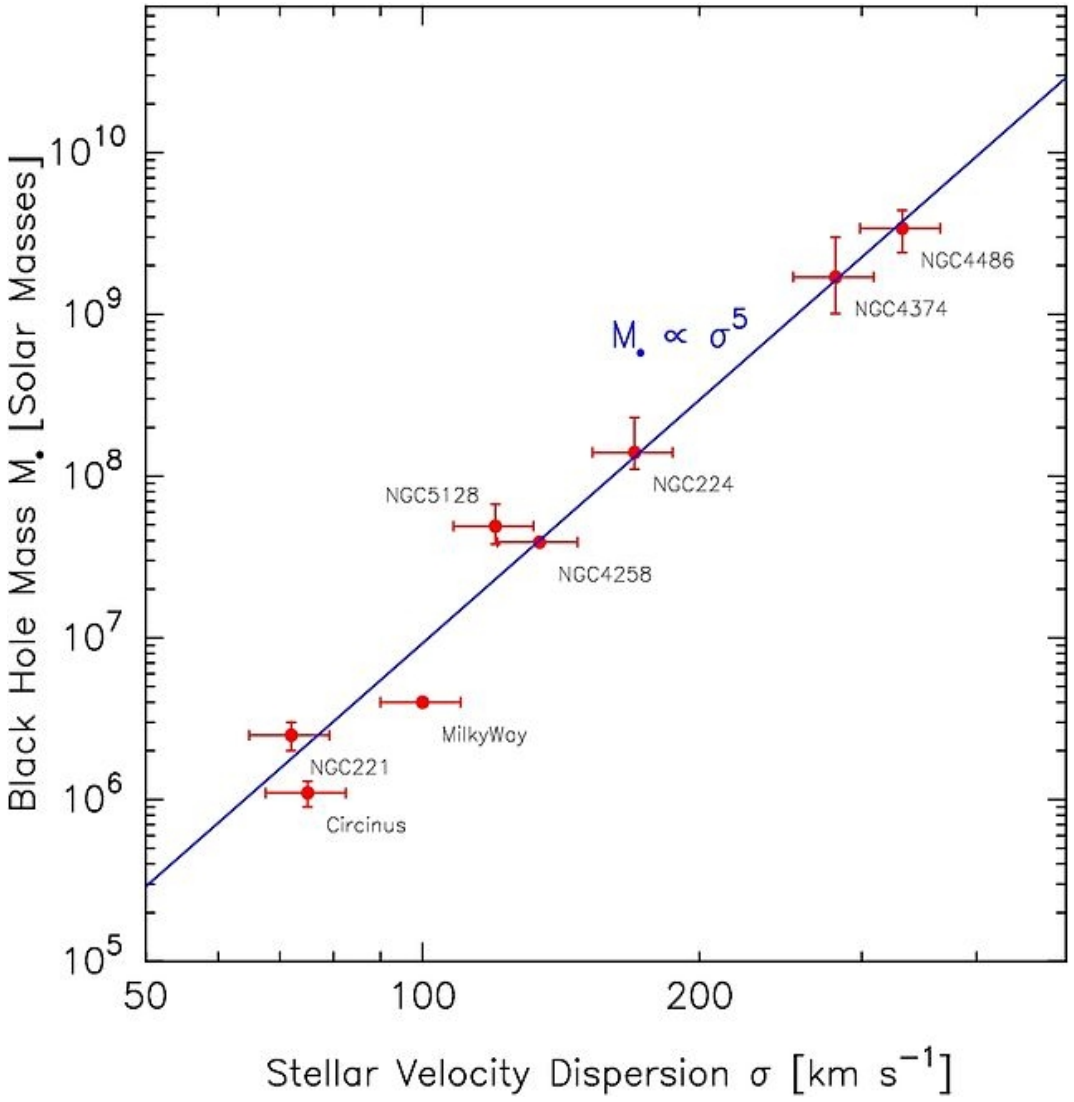
- Assume
  - System is virialised
  - Individual clouds move in own Keplerian orbits

$$M_{BH} = f(R_{BLR}) g_r \frac{R_{BLR} v^2}{G}$$

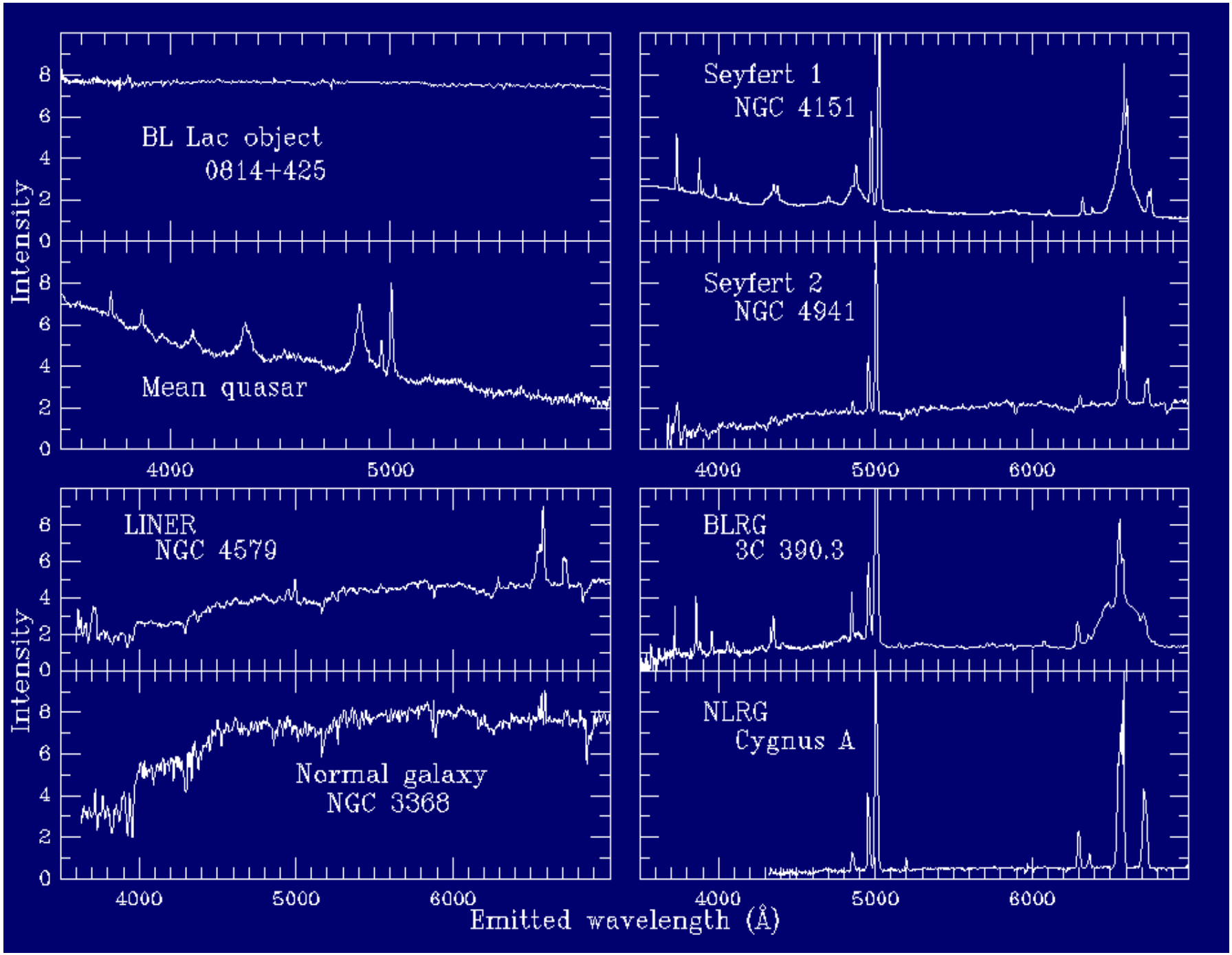
- Estimate the mass of the black hole!
- M ~ 10^6 to 10^10 M_sun

# M - σ relation

- There is a relation between the stellar velocity dispersion σ of bulge and the super-massive black hole mass.
- Co-evolution of SMBH and the host galaxy?
- Proof of feedback from AGN?



# AGN spectra

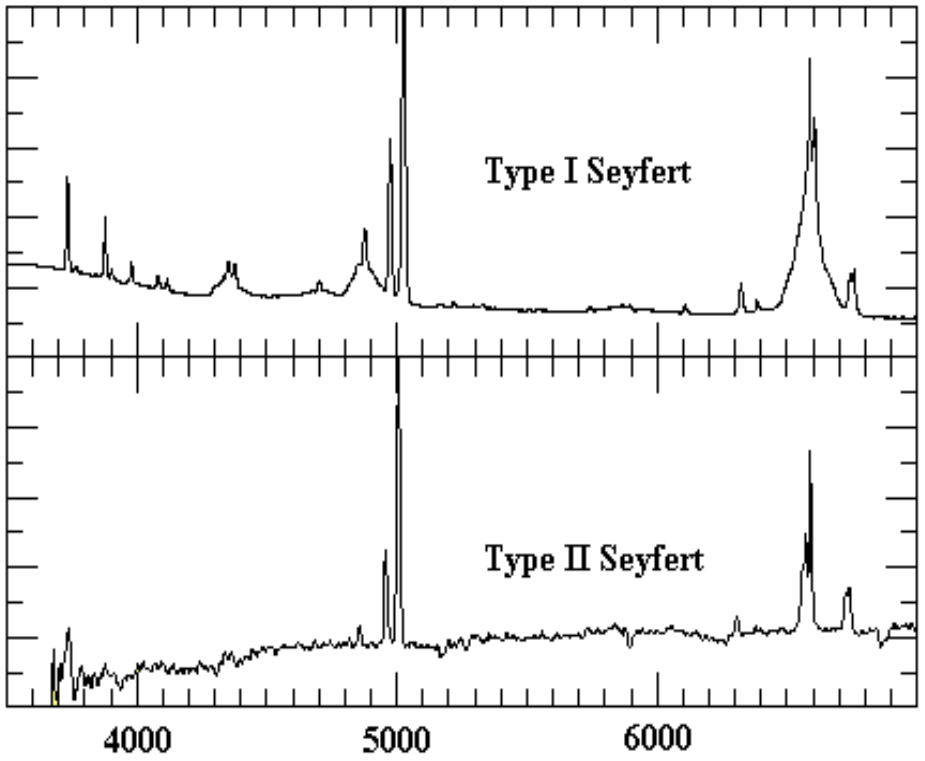

BL Lac object
0814+425
Mean quasar
Seyfert 1
NGC 4151
Seyfert 2
NGC 4941
LINER
NGC 4579
Normal galaxy
NGC 3368
BLRG
3C 390.3
NLRG
Cygnus A
Intensity
Emitted wavelength (Å)
0
2
4
6
8
4000
5000
6000

# What forms the spectrum?

- What ionizes the gas: shocks, ionizing photons?
- Static or variable central source? Isotropic/ anisotropic illumination?
- Gas density, temperature and geometry.
- Time-scales ionization vs recombination.
- Dynamical time scales; infall motions, outflow motions.
- Jets?
- Collision history/future?

## Seyfert-1

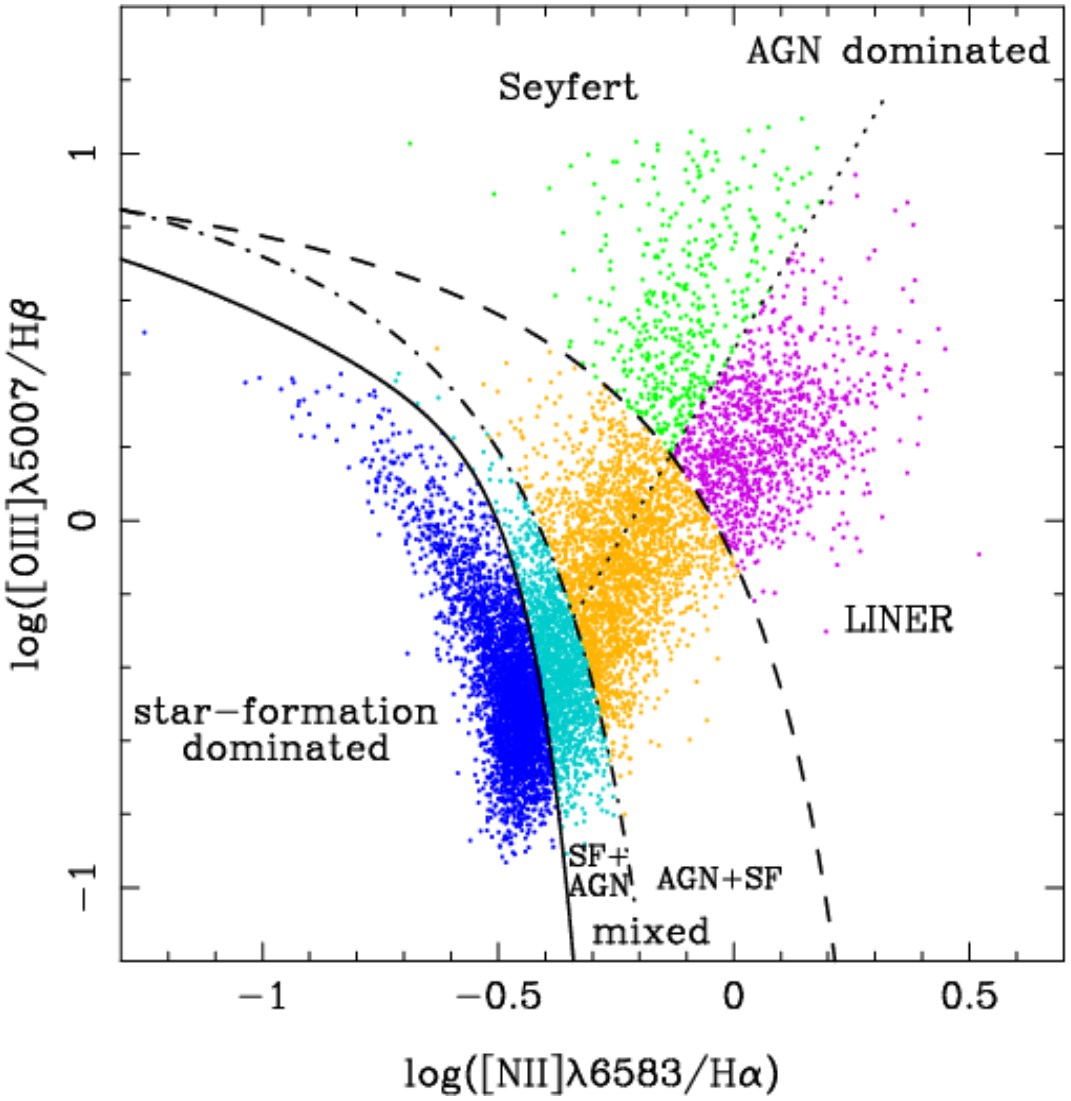
- Broad Balmer lines
- Featureless non-stellar power-law continuum.
- Wide range of ionized states: [OI] 6300, [OII]3727,3730, [OIII]4363,4960,5007,[NII]6583, [SII]6718,6733,...




## Seyfert-2

- Narrow Balmer lines
- Weak continuum.
- Wide range of ionized states: [OI] 6300, [OII]3727,3730, [OIII]4363,4960,5007,[NII]6583, [SII]6718,6733,...

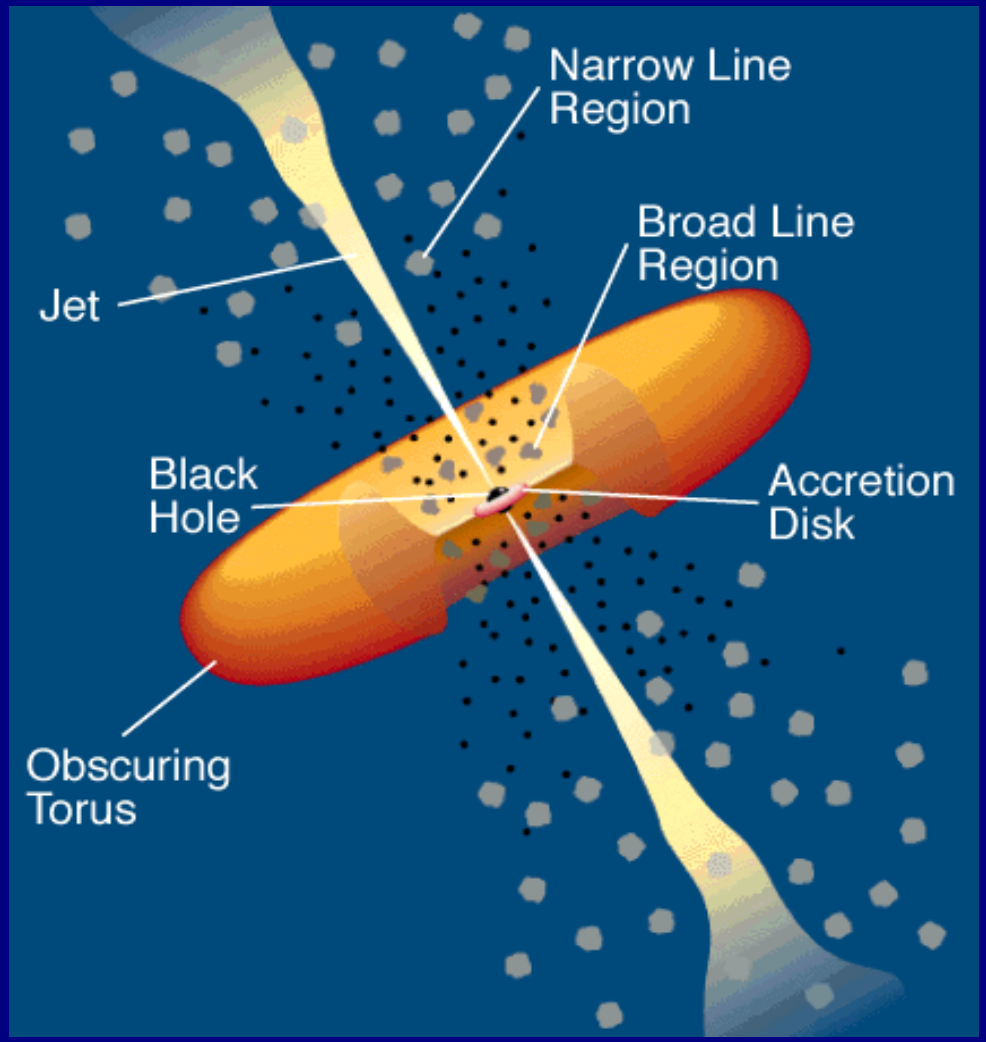
# Baldwin-Phillips-Terlevich (BPT) diagram




- Uses the presence of strong forbidden lines to separate AGN from star-forming galaxies.
- Assumes AGN to have the central photoionizing source, and LINERs to be a mix of photoionization and shocks.
- Useful for classification of AGN.

# The Unification Theory

# Unification Paradigm 1




- Seyfert-1 galaxies are observed face-on (right into accretion disk), "**unobscured**".
- Seyfert-2 galaxies are observed edge-on and thus we observe only the narrow-line region, "**obscured**".

# Unification Paradigm 2

- Same basic structure for every AGN:
  - **SMBH**
  - **accretion disk/flow** >> photoionizing continuum radiation
  - **broad-line region (BLR):** Doppler-broadened Balmer lines, $H\alpha$, $H\beta$, $H\gamma$,... If not visible, it can be revealed via spectropolarimetry.
  - **dust torus (< 5 pc):** absorbs light and reemits NIR radiation. Hides the broad-line region and continuum radiation from certain angles
  - **narrow-line region:** strong forbidden emission, formed outside the torus, e.g. [OII], [OIII], [SII], [NII]-lines.
  - **the rest of the "host" galaxy**.

- Same basic structure for radio-loud objects (+ jet and radio core).
- Main idea: All AGN can be unified solely by the accretion rate, mass of the SMBH and the viewing angle.
- Most people also believe the torus covering factor might have an important role.

# Disclaimer

- There are lots of issues with these models.
- Nature of the host galaxy plays a significant role.
- AGN with too low accretion rates always might have narrow-lines.

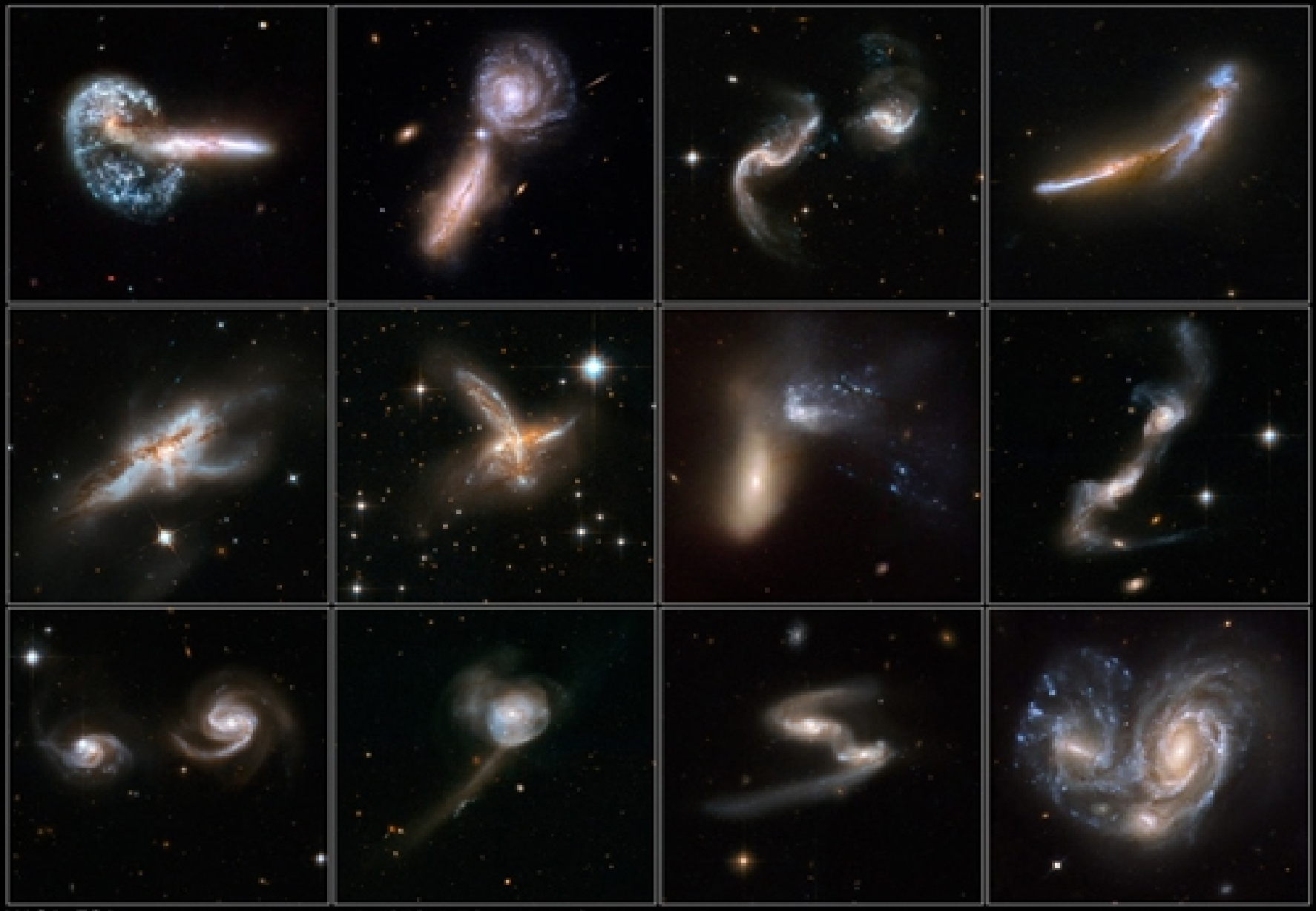
# Evolution of AGN

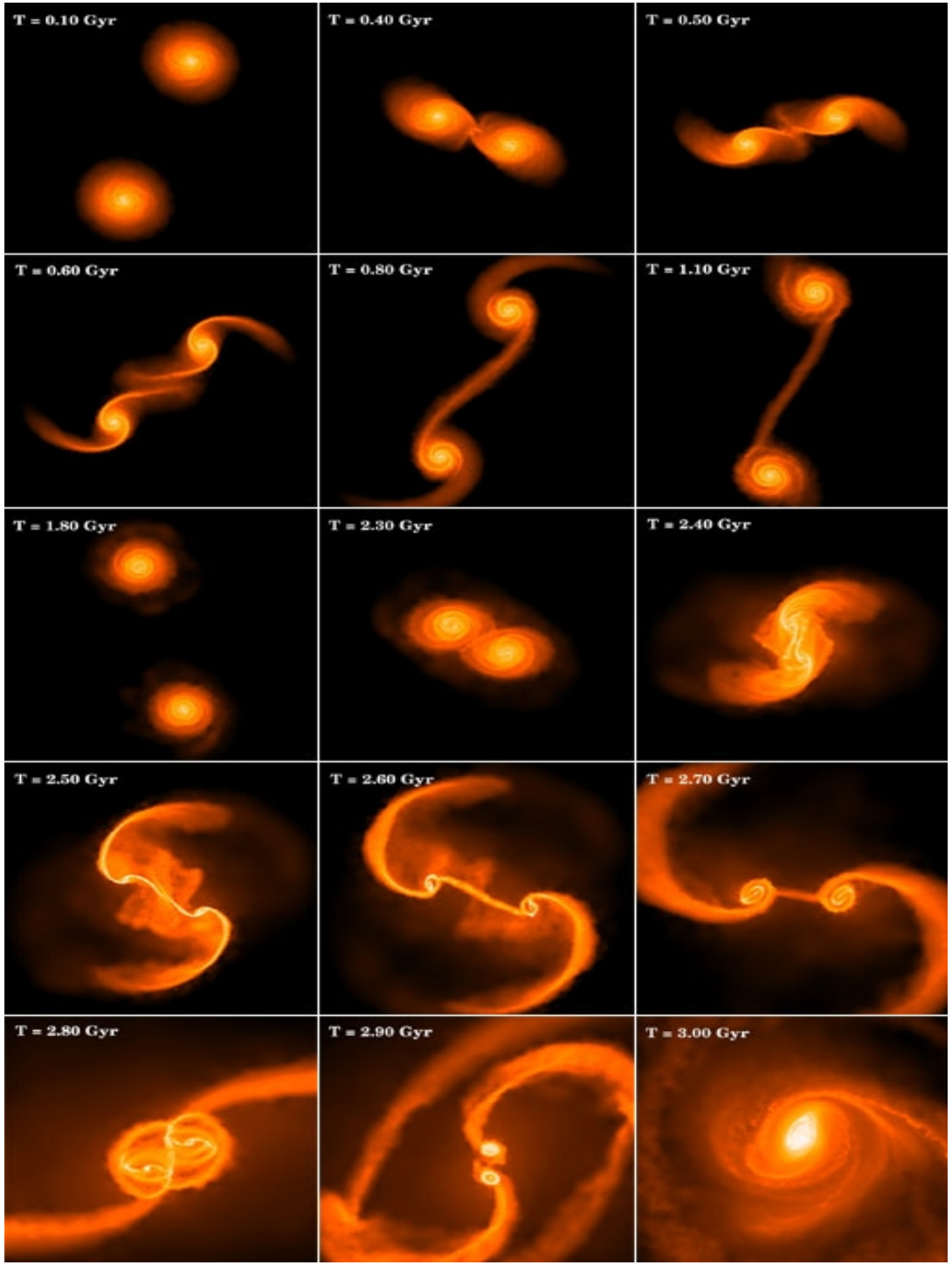
# Ideas about AGN formation

- From **primordial black hole** seeds at high redshifts
  - z > 10?
- **Direct collapse** into big dark matter halos?
- **Mergers**?
  - Half of all quasars show signs of interaction/mergers or a companion.
  - All kind of mergers, or a special type of mergers?
- Can strong **star-formation** trigger AGN?

*** Quasars are great probes of structure formation scenarios. ***

# Mergers, interactions or just accretion...?






How mergers can trigger a quasar.

# If merging... –

- ...is it true for all AGN?
- Different formation scenarios depending on AGN class?
- Can one class of AGN evolve into one another? E.g. radio-quiet into radio-loud.
- Classes explainable by Unification theory or by evolution?

# Open questions

- Where are all AGN today?
- Is AGN just an episode in a galaxy's life?
- How does the AGN produce all energy?
- Is it a black hole as predicted from General Relativity in the AGN center...or something else?
- What is the connection between star-formation in the galaxy and the AGN?

*And now the laboratory exercise...*

# Laboratory exercise

- Introduction to Sloan Digital Sky Survey
- Four exercises:
    1. Study of individual objects with Explore.
    2. Comparison between DR7 and DR12. Spectra of galaxies.
    3. Redshift distributions
    4. Your individual exercise.
- Individual reports.
- Last exercise requires an individual effort.

# Grading criteria

When grading the written report, the following is being assessed:

- Completeness of the solutions, physical reasoning and reporting.
- Writing skill.