Galaxies, part 2

Sterrenstelsels en Kosmos deel 4

Active galaxies

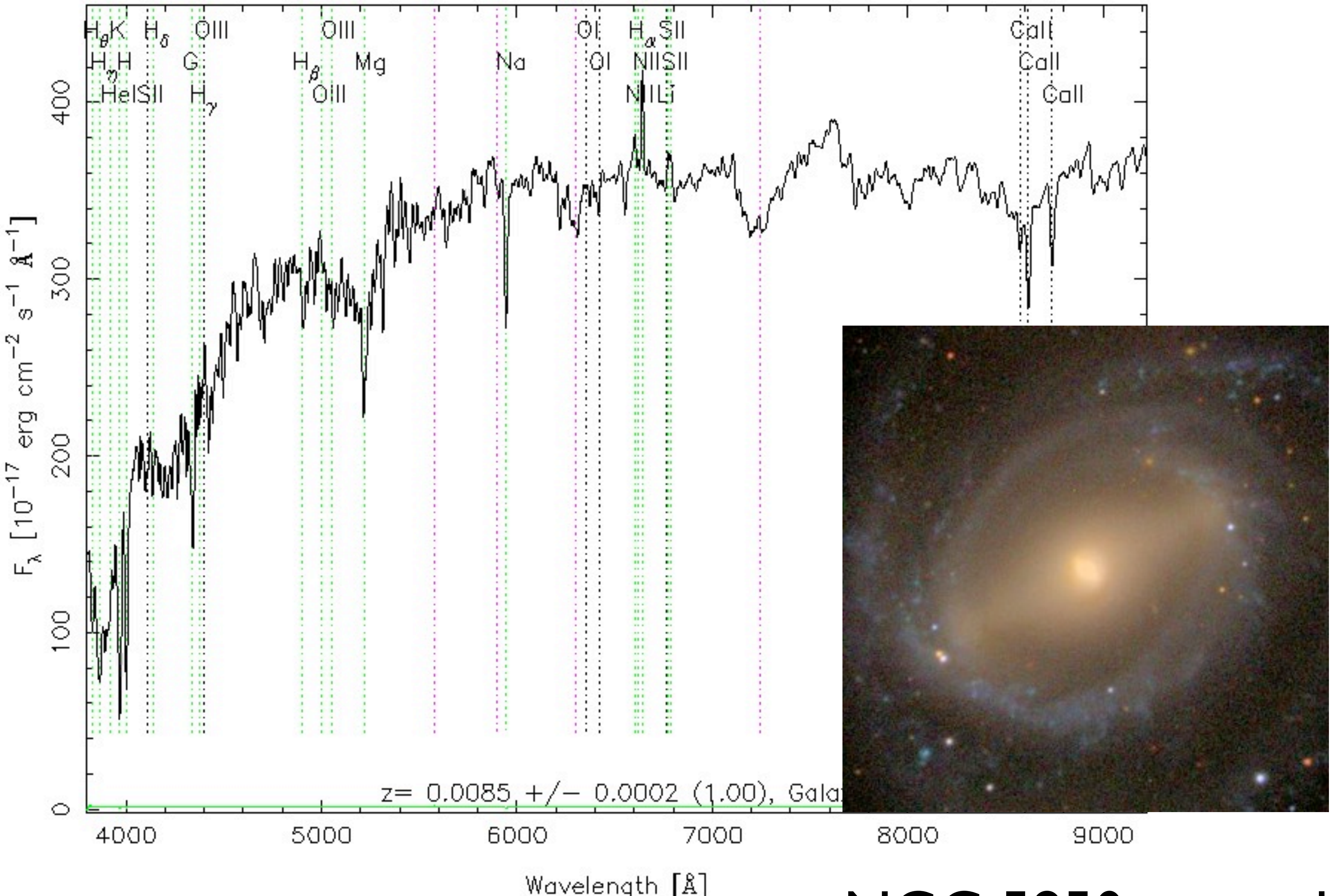
or, “flashlights on the sky”

- Not all galaxies are dull, boring ellipticals or pleasantly star-forming spirals

- Some are active! Or at least their nuclei (centers) are...

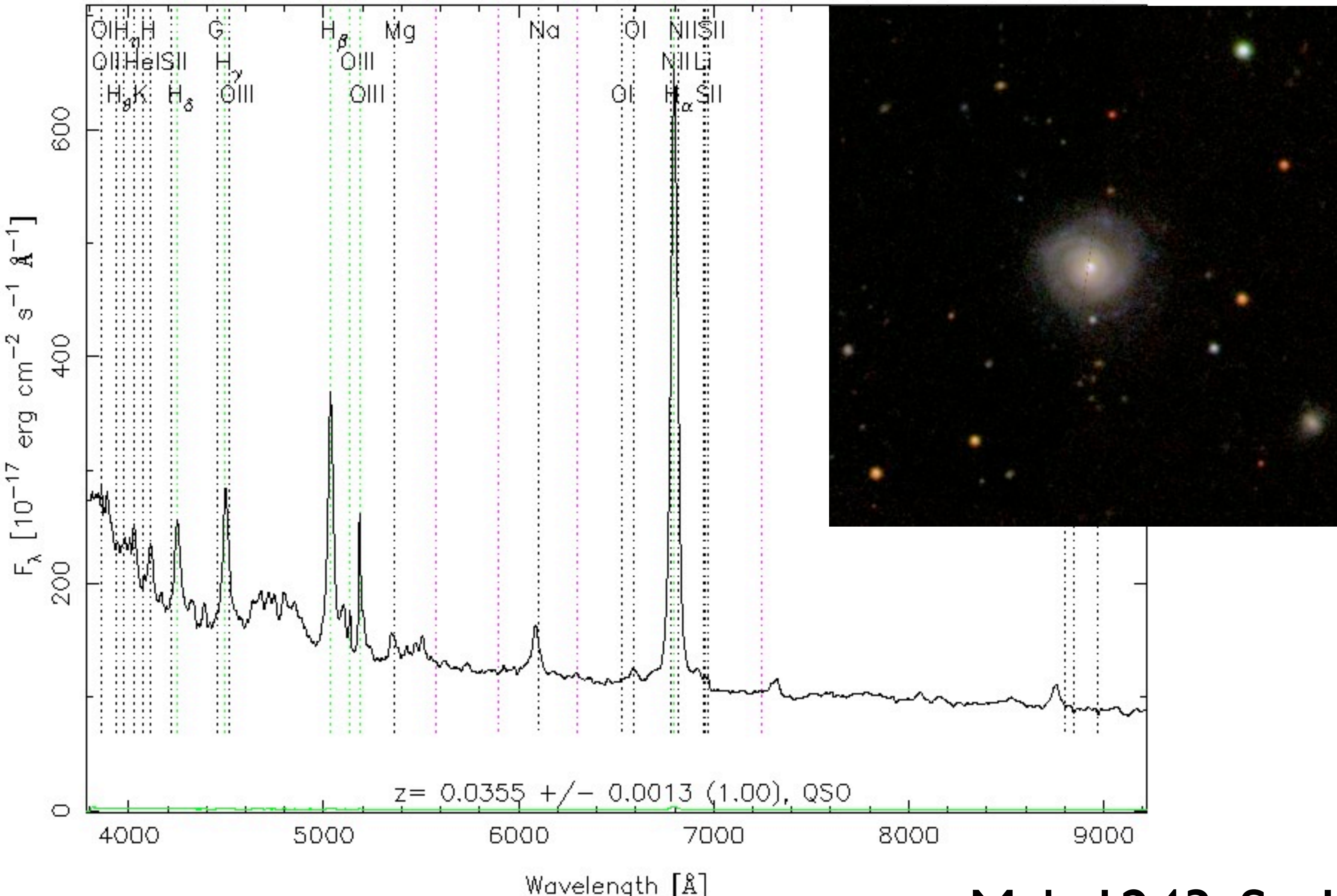
Seyfert galaxies

- At the beginning of the 20th century, Edward Fath was using the telescopes at Lick Observatory to take spectra of "spiral nebulae" (spiral galaxies)
- He noticed that the spectrum of NGC 1068 had *both* emission and absorption lines
- In 1941 Carl Seyfert noted that the emission lines were too broad compared to normal spirals, which have spectra like this...



NGC 5850: normal

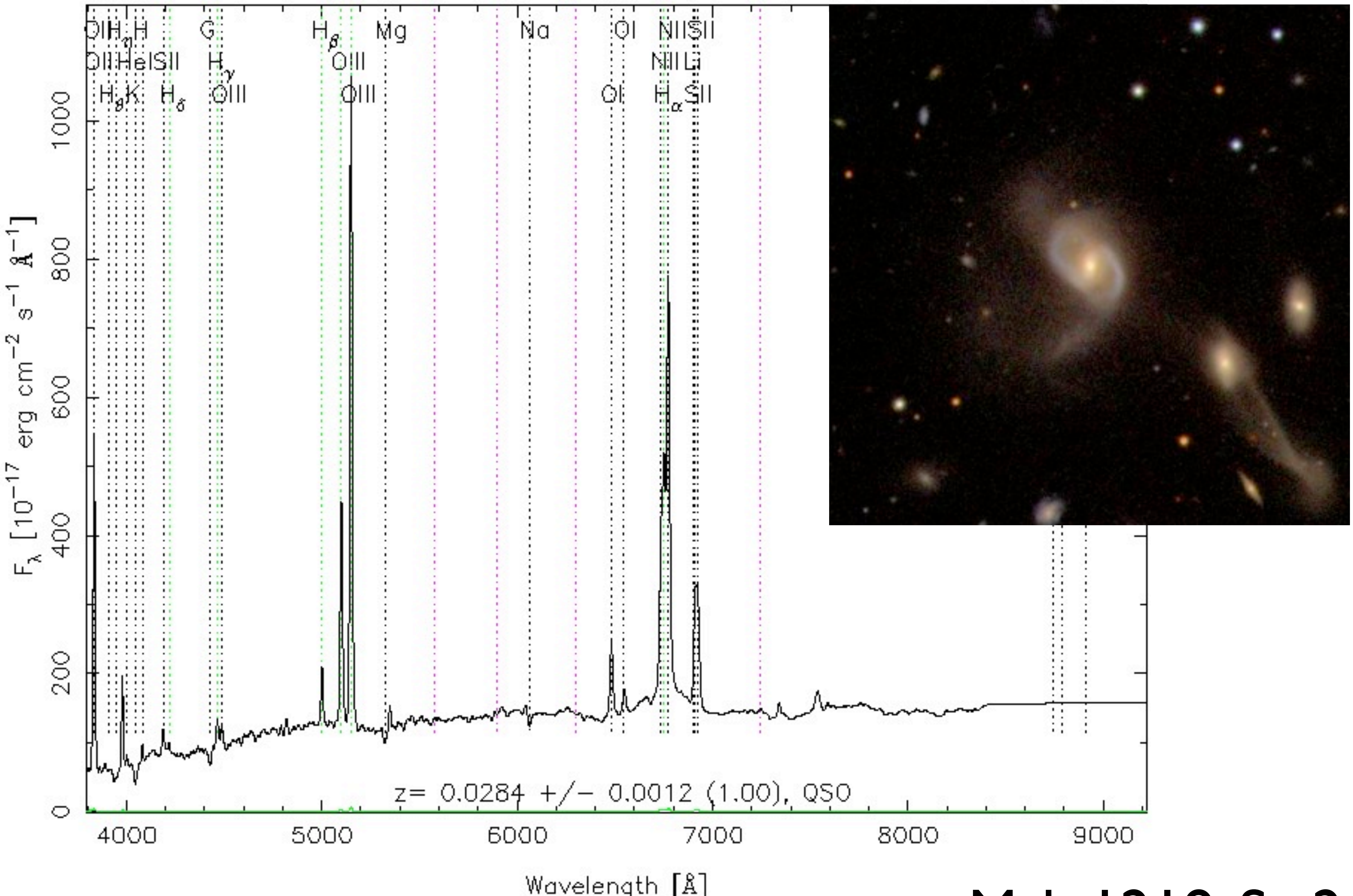
- ...but the spectra of galaxies like NGC 1068 instead look like this...


OI Hη H
OII HeI SII
Hθ K Hδ
G
Hγ
OIII
Hβ
OIII
OIII
Mg
Na
OI
OI
NII SII
NII Li
Hα SII
600
400
200
0
Fλ [10⁻¹⁷ erg cm⁻² s⁻¹ Å⁻¹]
z= 0.0355 +/- 0.0013 (1.00), QSO
4000
5000
6000
7000
8000
9000
Wavelength [Å]

Mrk 1243: Sy 1

- This "Seyfert 1"-type spectrum has three notable features:
    - <u>Broad</u> emission lines: fast motions (1000-5000 km/s!)
    - <u>Narrow</u> emission lines: slower (but still fast!) motions (~500 km/s)
        - both produced by *highly-ionized gas*, requiring a <u>strong energy source</u>
    - A strong continuum that completely (or at least nearly) drowns out the <u>absorption lines of the stars</u>

- Some galaxies only have the narrow high-ionization emission lines and are called "Seyfert 2" galaxies...


OII H H
OII HeI SII
H K H G
H OIII
H OIII
OIII Mg
Na
OI NII SII
NII Li
OI H SII
z= 0.0284 +/- 0.0012 (1.00), QSO
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
Wavelength [Å]
0
200
400
600
800
1000
4000
5000
6000
7000
8000
9000

Mrk 1218: Sy 2

- Nearly *all* Seyfert galaxies are spirals (and usually early-type Sa-Sb spirals) and often have nearby companions

- The nuclei of Seyfert galaxies are typically dominated by *synchrotron radiation*

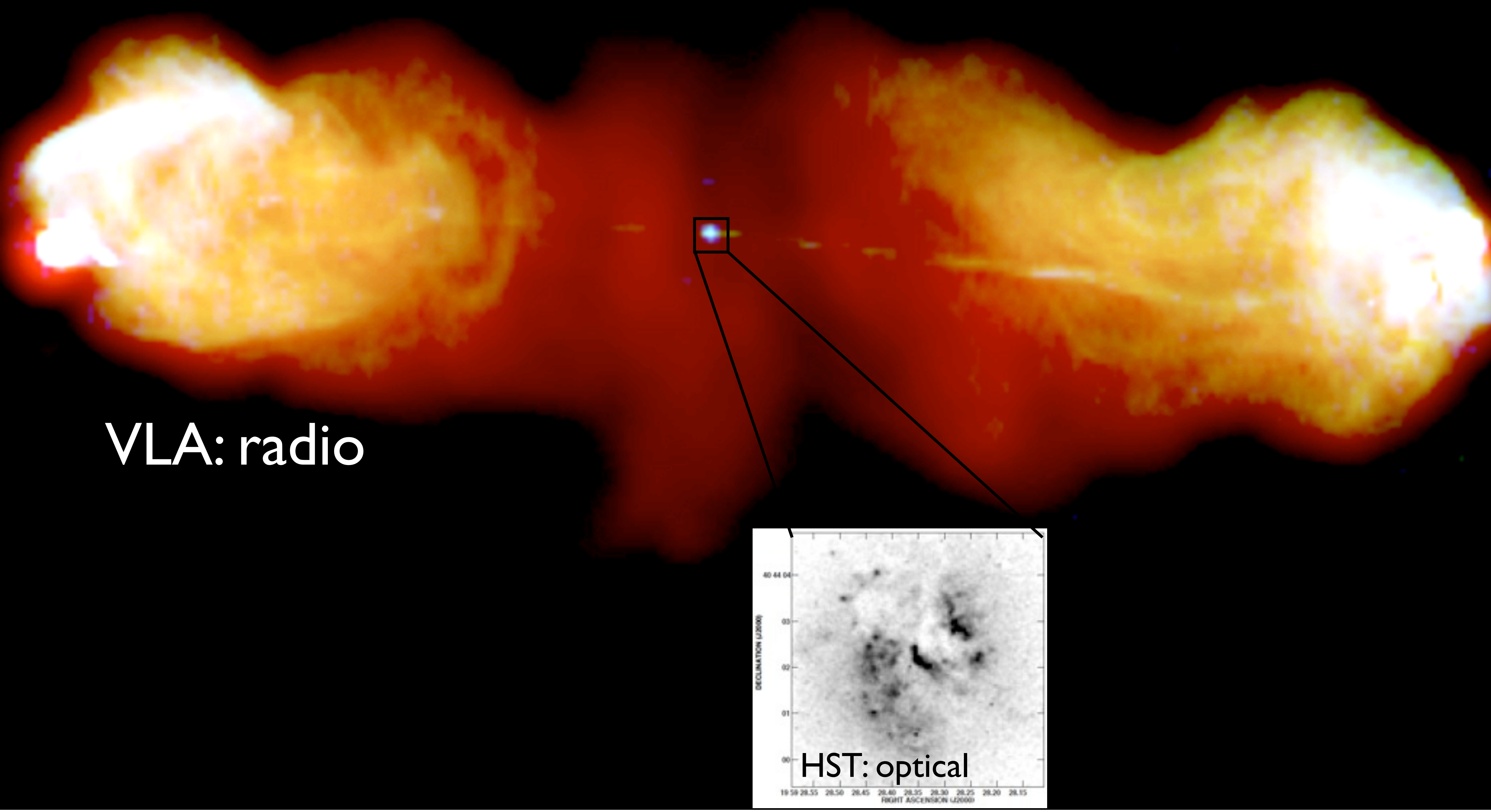
    - However, Seyfert galaxies are (typically) *radio-quiet* --- that is, they are faint at radio wavelengths

Radio galaxies

- After WWII, radio astronomers started scanning the sky and discovered extremely bright radio sources... but the spatial resolution of the early single-dish radio telescopes was poor, so it took quite a while to locate the *optical counterparts* of these objects

- One of the brightest radio sources in the sky is *Cygnus A* (the brightest radio source in the constellation of the Swan)
    - In 1953 it was found to be a *double* source
    - We now know it to be a *radio galaxy* at a distance of ~200 Mpc consisting of a central source (an amorphous but giant elliptical-like galaxy), two *jets*, and two *radio lobes*
        - note however that only *one* jet appears to be "on" currently---in fact, only one jet seems to on at a time in *any* radio galaxy

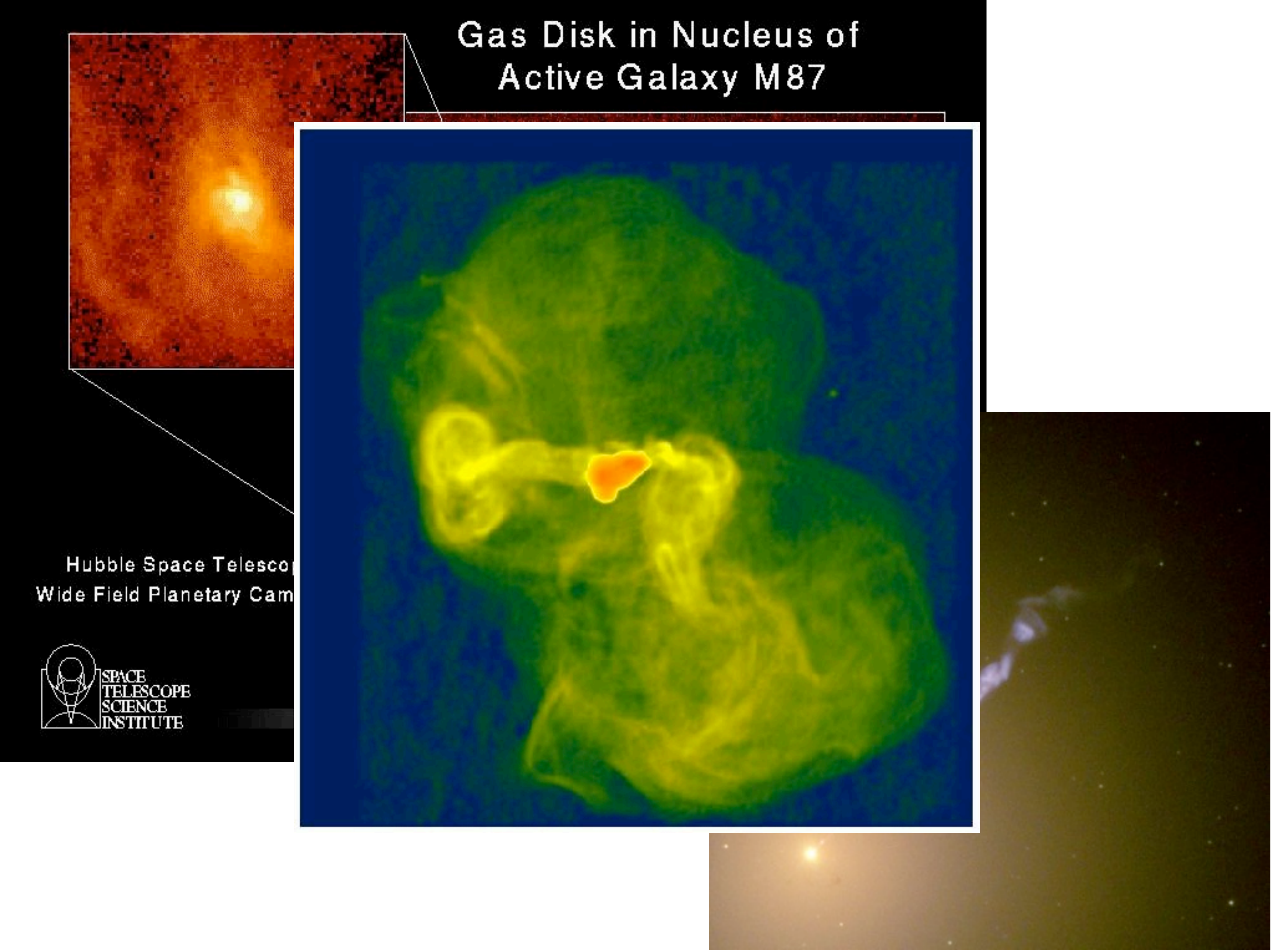
Cygnus A

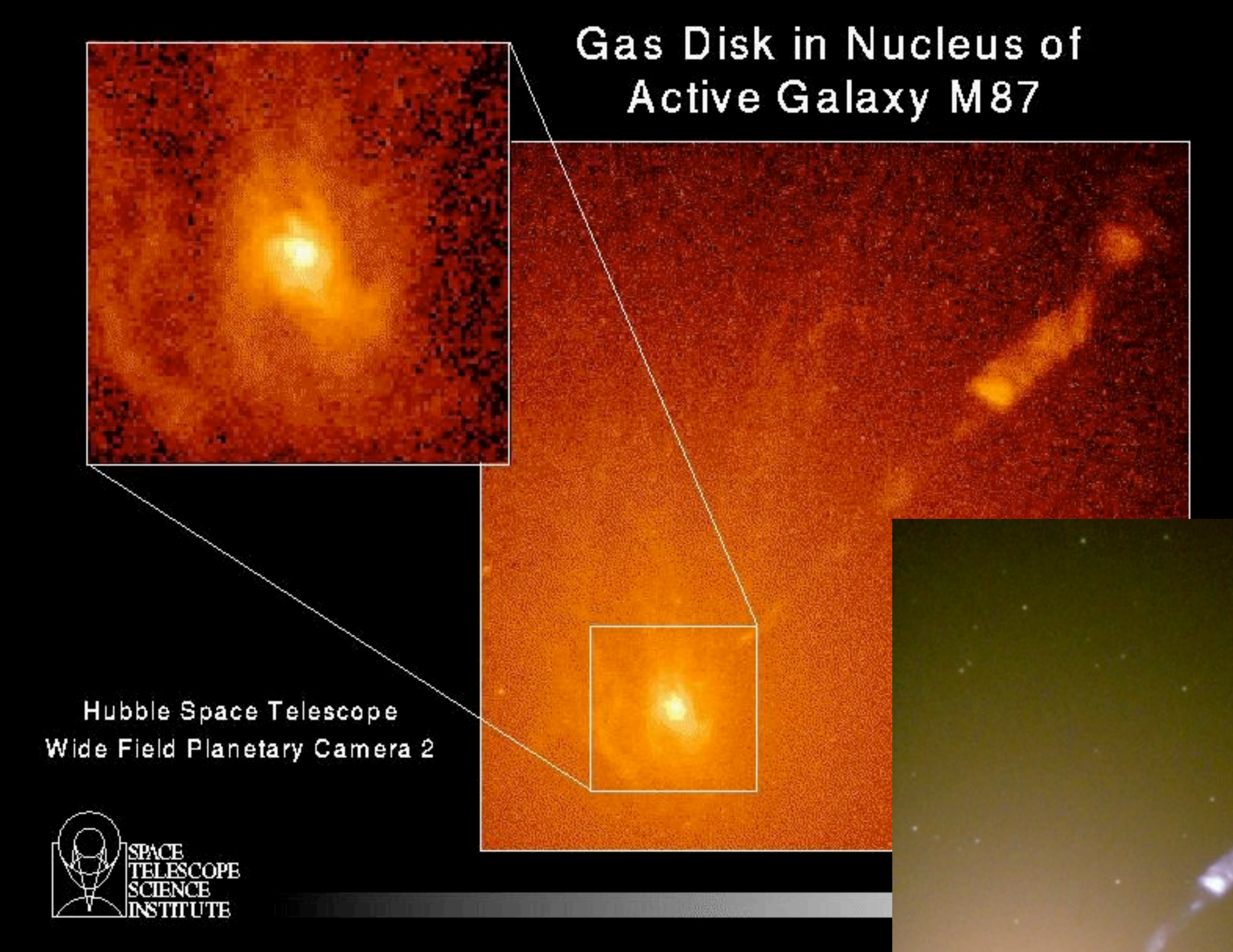


- The lobes span more than 100 kpc from one to another and have a radio luminosity of 10^{45} erg/s, more than *a million times brighter* in the radio than normal galaxies

- Radio galaxies are (usually) hosted by *elliptical* galaxies, unlike Seyfert galaxies

- In fact, the (second) brightest galaxy in the Virgo cluster, Messier 87 (NGC 4486) is also the brightest radio source in Virgo, and is thus also called Virgo A...


Gas Disk in Nucleus of
Active Galaxy M87
SPACE
TELESCOPE
SCIENCE
INSTITUTE


Gas Disk in Nucleus of
Active Galaxy M87
Hubble Space Telescope
Wide Field Planetary Camera 2
SPACE
TELESCOPE
SCIENCE
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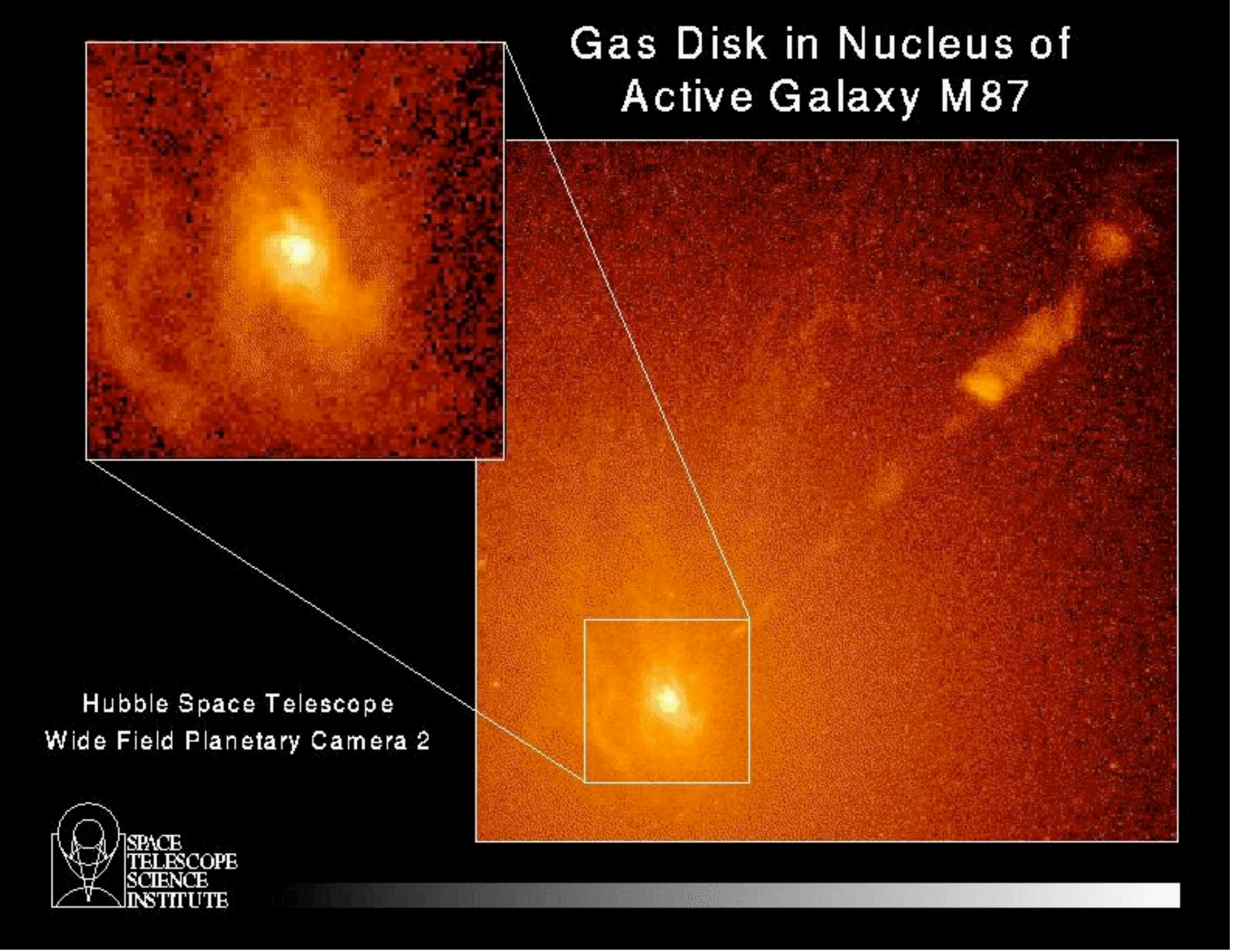
Gas Disk in Nucleus of
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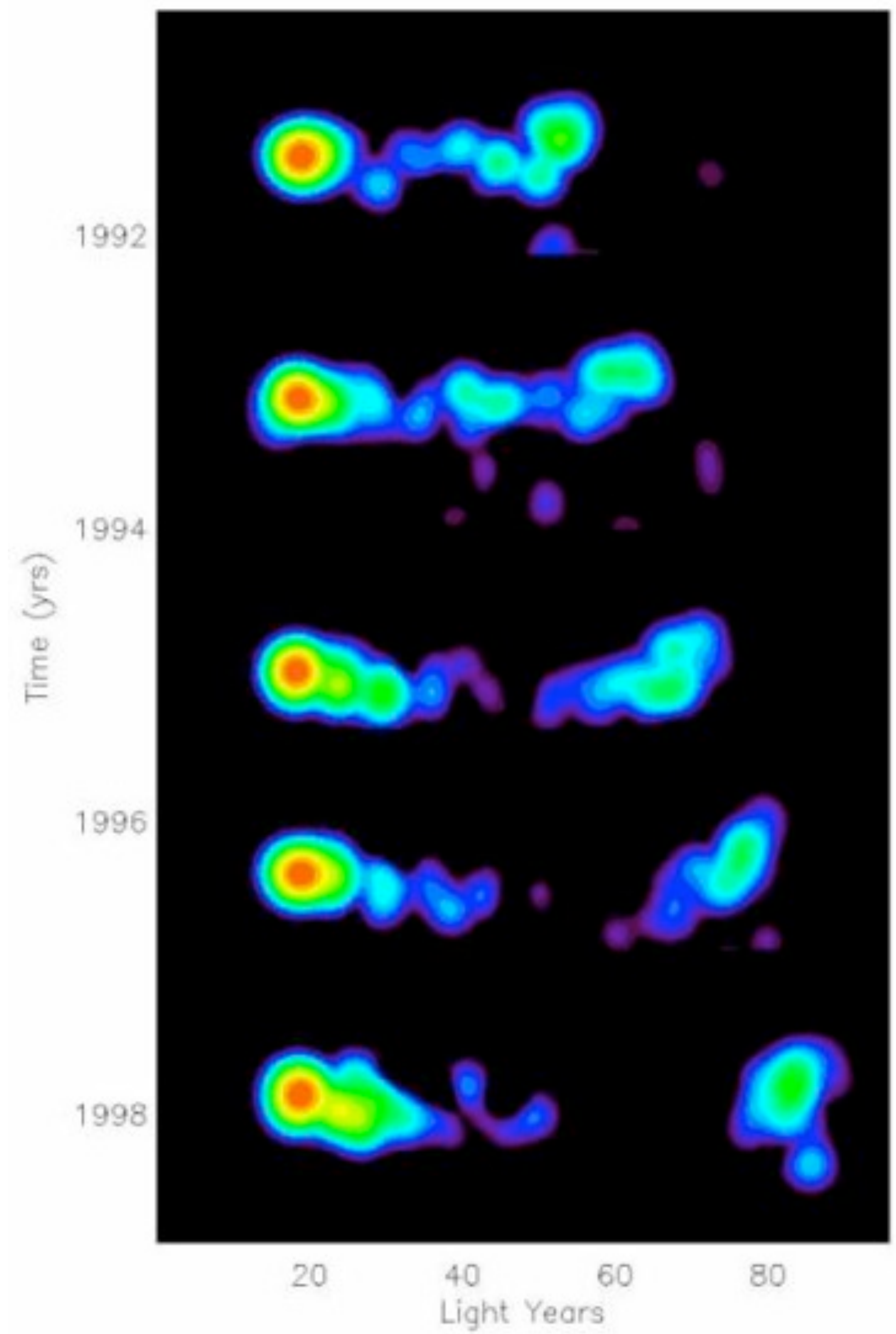
- In fact, in M87, we can see the jet in the *optical*, not just the radio
    - The jet has the spectrum of synchrotron radiation, which might tell us something about its origin
- We also see a disk of gas at the center of M87, apparently at the base of the jet
    - We'll return to this tantalizing hint soon!

A tangent: “superluminal motions”

- High-resolution radio imaging has revealed that jets in radio galaxies appear to expand *faster than the speed of light!* That is, the proper motion of the components move apart from each other at a rate that appears to violate special relativity.



A time sequence of the motion of the jet in 3C279: note that the jet *appears* to move ~30 light years in ~7 years of real time!

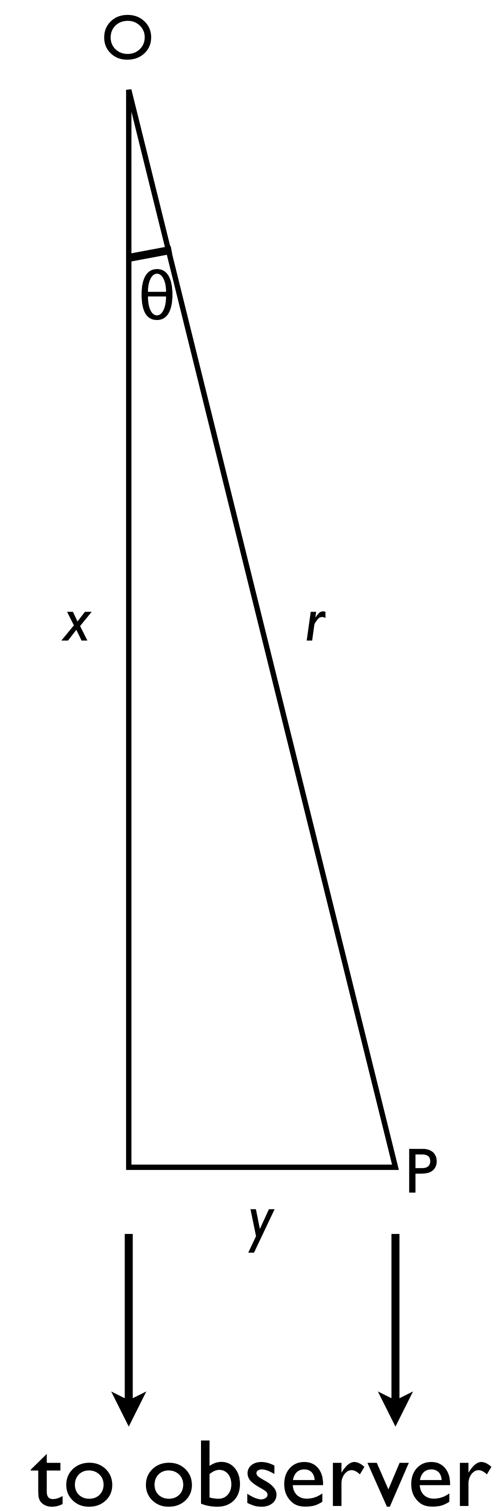
- In 3C279, the components appear to move between 4.8*c* and 7.5*c*!

- How might this come about?
- Imagine that the jet components are actually moving *towards* you *as well as* along the plane of the sky
- Suppose an object is moving along the line *OP*, over a distance *r,* with velocity *v*
- Then, in terms of *r*, we can write *x* and *y* as

$$x = r\cos\theta$$
$$y = r\sin\theta$$

- The time for the object to move the distance *r* is

$$t = r/v$$



- However, a photon emitted at *P* travels a shorter path than one emitted at *O* before reaching the observer, by the distance *x*

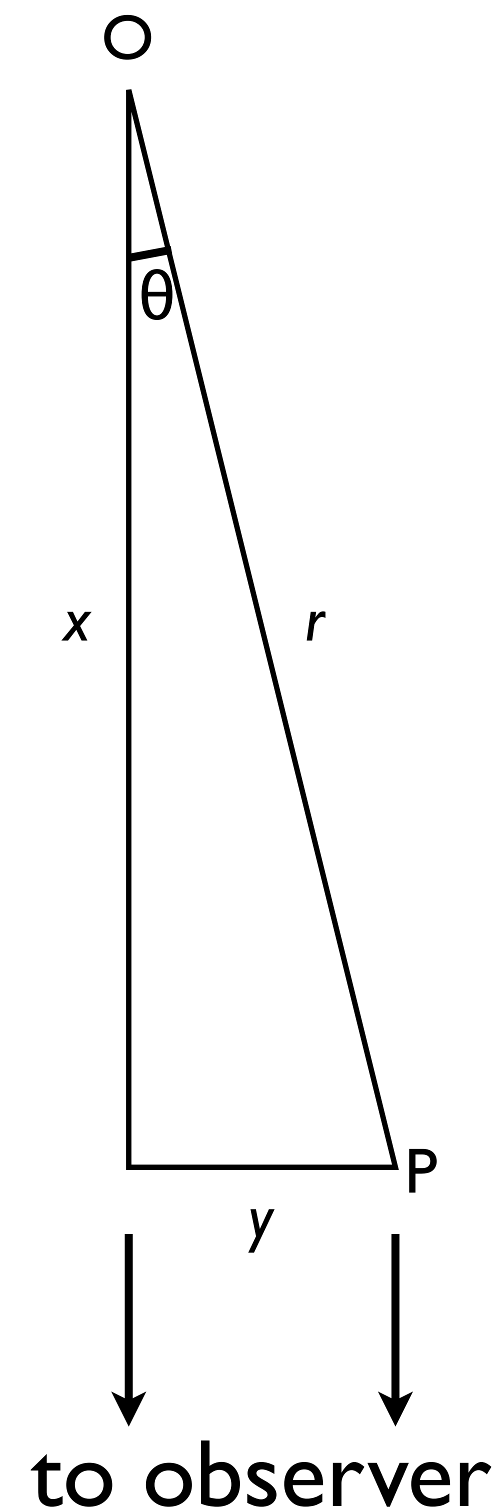
- So the photon emitted at *P* takes *x/c* less time than the one emitted at *O*, so the *apparent time* the object takes to move from *O* to *P*, *from the standpoint of the observer*, is $t_{\rm app} = t - x/c$

- Substituting in our equations for *t* and *x*, we have

$$
\begin{aligned}
t_{\rm app} &= (r/v) - (r/c)\cos\theta \\
&= (r/v)(1 - \beta\cos\theta)
\end{aligned}
$$

where

$$\beta = v/c$$



- The *apparent velocity,* v_{app}, across the sky is then

$$v_{\rm app} = \frac{y}{t_{\rm app}} = \frac{r\cos\theta}{(r/v)(1-\beta\cos\theta)}$$

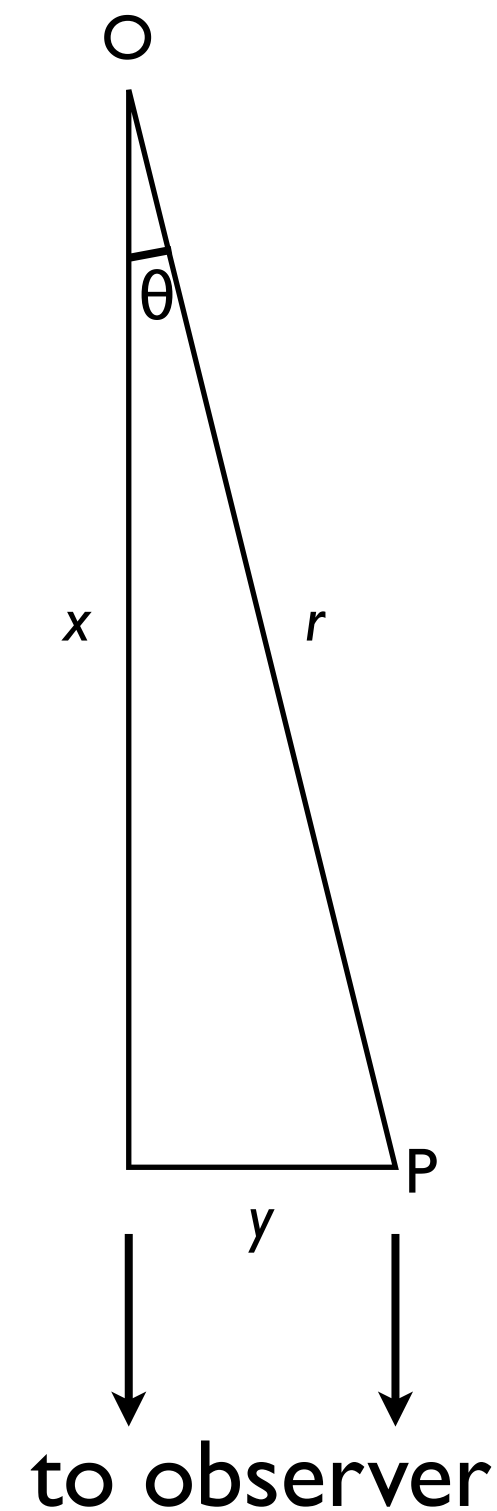
- Eliminating *r* gives

$$v_{\rm app} = \frac{v\cos\theta}{1-\beta\cos\theta}$$

- Now, if $v \ll c$, then $\beta \approx 0$, and $v_{app} \approx v\sin\theta$, as expected; but if $v \approx c$, then $\beta \rightarrow 1$ and clearly v_{app} can be *very* large, even (significantly) exceeding *c*!

- In fact, by taking the derivative of v_{app}/v with respect to θ, and setting this equal to 0, we find that the *maximum value* of v_{app}/v is

$$\left(\frac{v_{\rm app}}{v}\right)_{\rm max} = \frac{1}{(1-\beta^2)^{1/2}}$$



Quasars

- Not all strong radio sources were found to be associated with identifiable (elliptical) galaxies
- Some, like 3C273, when they were finally optically identified, looked like faint stars
- These were called "quasi-stellar radio sources" or *quasars*

Quasars

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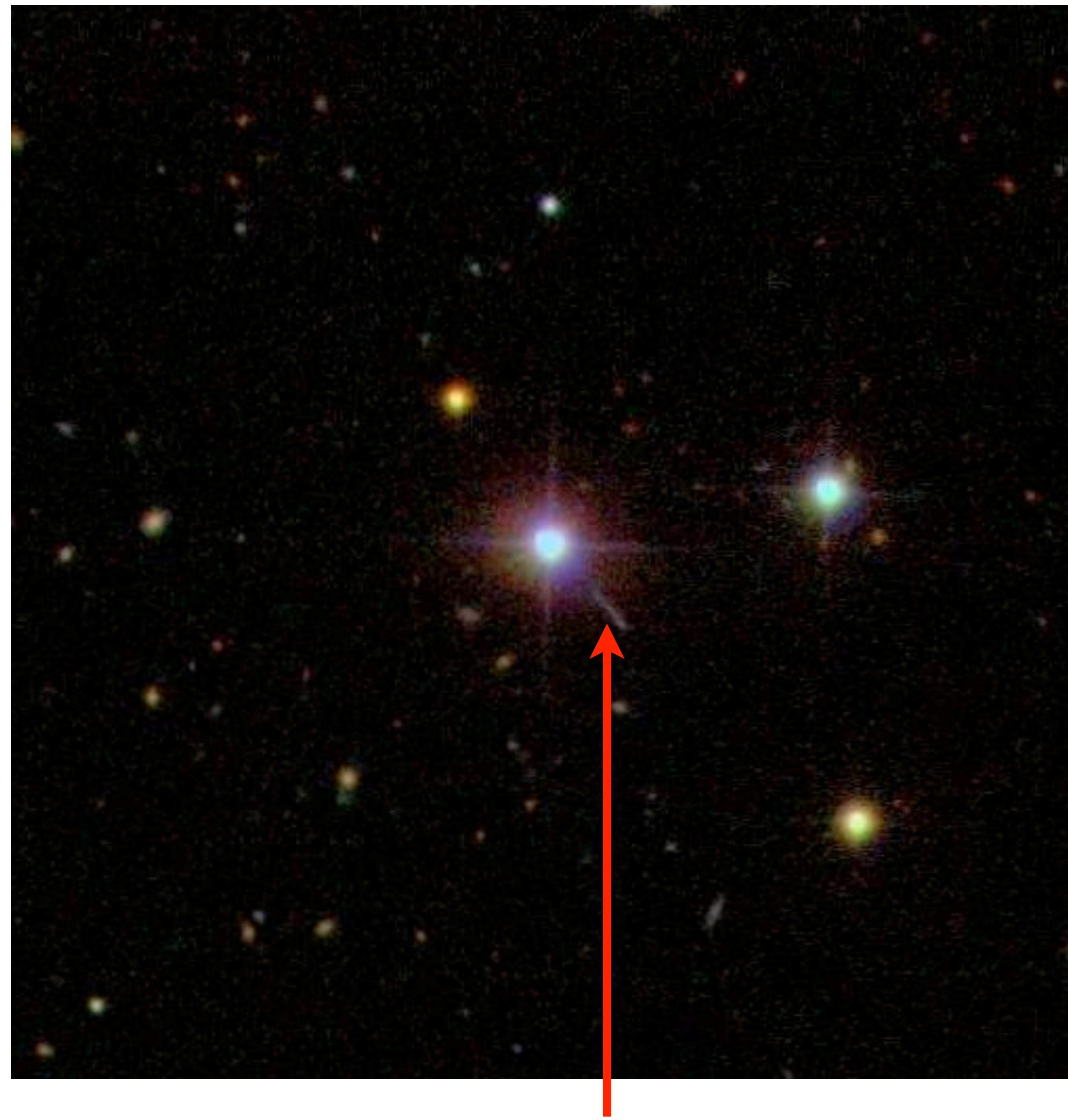
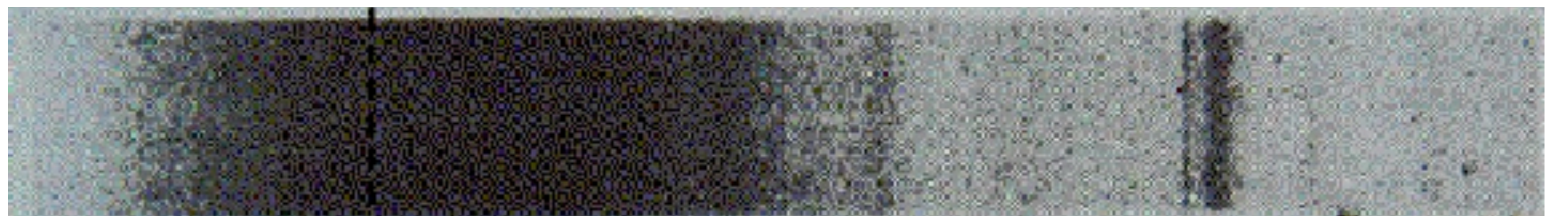
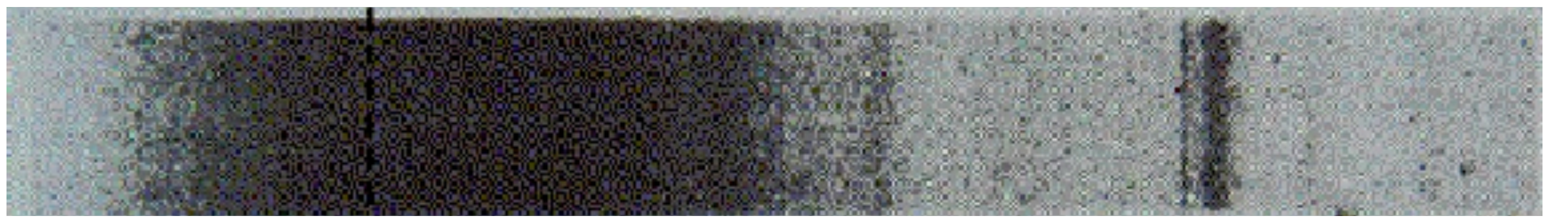
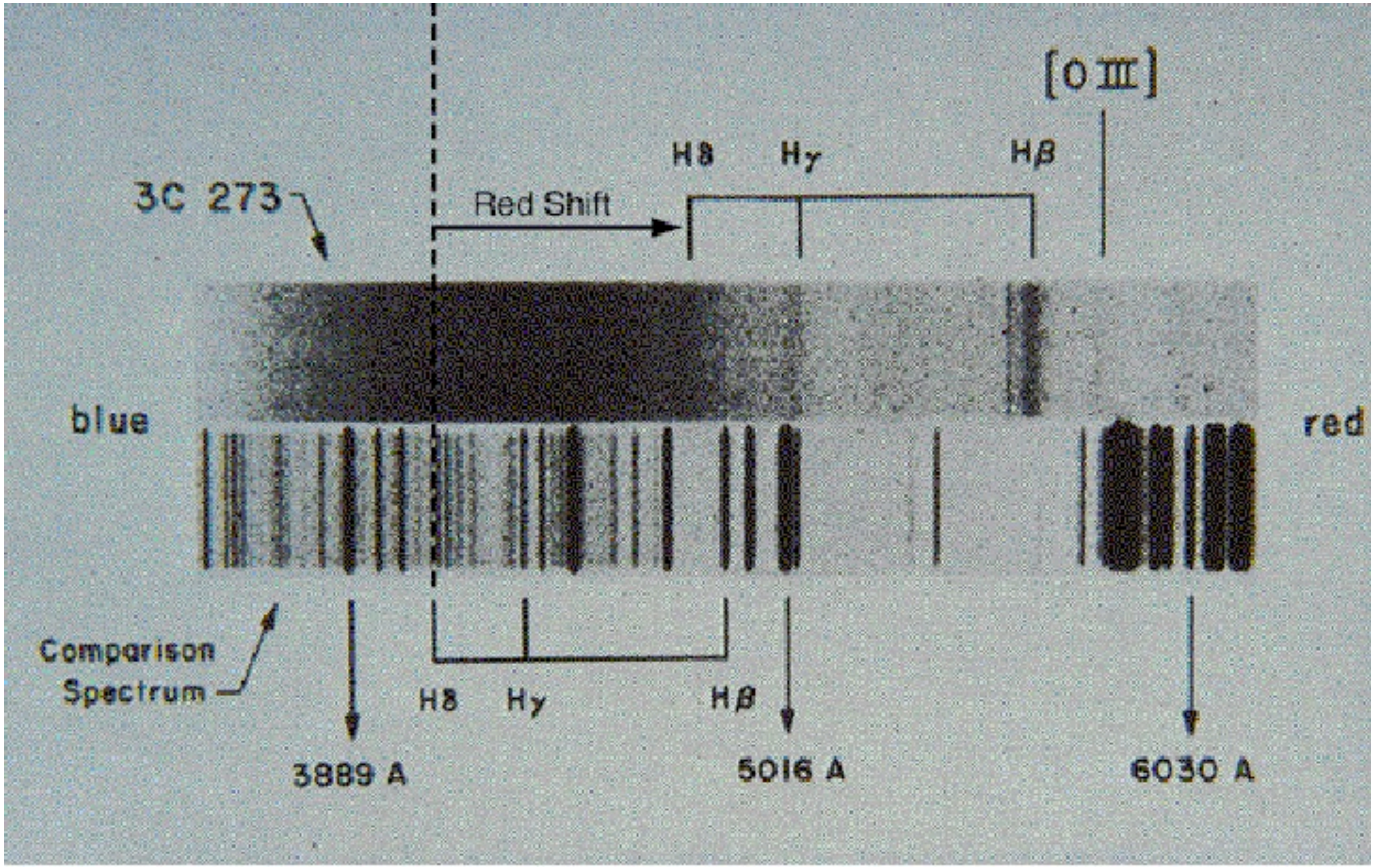


note jet!





- In the words of Allan Sandage, "The spectrum was exceedingly strange"



- In the words of Allan Sandage, "The spectrum was exceedingly strange"
- In 1963, Maarten Schmidt realized that the pattern of emission lines in 3C273 was that of *hydrogen severely redshifted*, to z=0.158!

An important aside: redshift

- The light emitted by a source moving towards or away from us will be *Doppler shifted* in wavelength by an amount related to its speed relative to us
  - If an object is emitting light and moving toward us, we see the peaks of the light waves closer together than the object does, so the light is *blueshifted*
  - If the object is moving away from us, we see the peaks farther apart than the object does, so the light is *redshifted*

- We measure the redshift as

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}} = \frac{\Delta\lambda}{\lambda_{\text{emitted}}}$$

- For an object moving significantly more slowly than the speed of light (*v*«*c*), the redshift is directly related to the ratio of the object's velocity to the speed of light:

$$z = \frac{\Delta\lambda}{\lambda_{\text{emitted}}} = \frac{v}{c}$$

  where *v* here is the *radial velocity* of the object

- At higher speeds ($v \sim c$), the redshift is related to the radial velocity through

$$1 + z = \sqrt{\frac{1 + (v/c)}{1 - (v/c)}}$$

- So for 3C273, z=0.158 means that this quasar is moving away from us at 14.6% the speed of light!

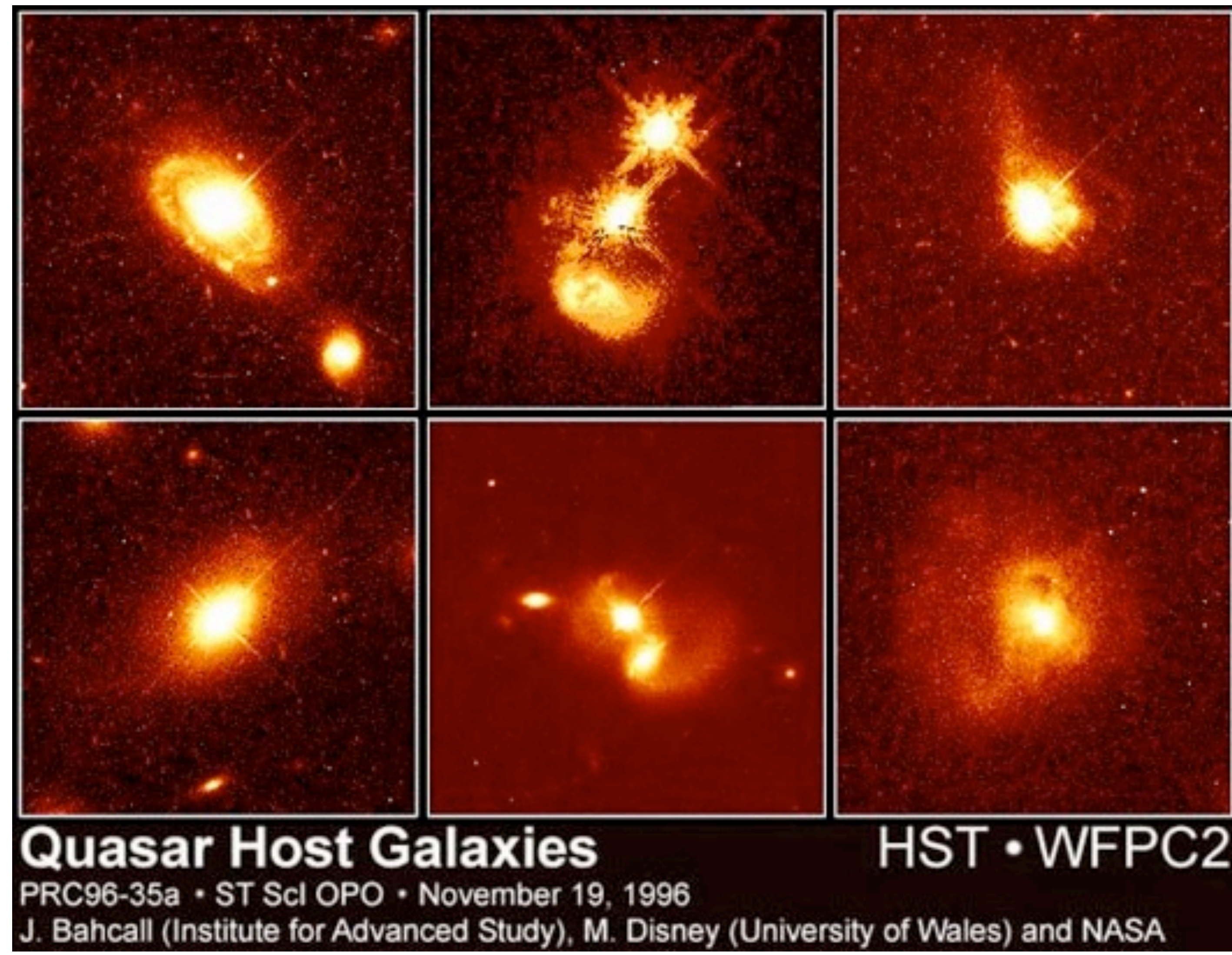
- Using Hubble's law (which we'll see shortly!), this implies that 3C273 is about 630 Mpc away from us, or m-M=39.3

- The *apparent* visual magnitude of 3C273 is V=12.8, so its *absolute* magnitude is M_V=-26.5

  - This is *very, very bright* --- about 7 magnitudes (nearly 10^3 times) brighter than *the entire Milky Way!*

- In fact, quasars are among the most distant objects known in the Universe
  - The highest redshift quasar currently known has z=6.42! That corresponds to a time when the Universe was only 1.2 Gyr old...

- When the *Hubble Space Telescope* was finally available, it was possible to remove the contribution of the point-like quasar from the image and see the underlying, "host" galaxy
  - Nearly all are *peculiar* elliptical galaxies, and most look like they're involved in a merger



A unified scheme?

- Are these objects related?
- An interesting observation is that the light (both in the optical and X-rays) of Seyfert 1s and quasars can vary by a few percent in brightness *over timescales of hours*!
- This implies that the emitting region must be **small**: $R_{\max} = c\Delta t \approx 10\,\mathrm{AU}$

- They are very bright---and all this radiation comes from a volume significantly smaller than our Solar System!

- And the emitter *must* therefore be very massive:

  - Remember that light can exert pressure on matter, so it can impart a force

$$F_{\rm rad} = \frac{L}{4\pi R^2}\frac{\sigma}{c}$$

where σ is the Stefan-Boltzmann constant

- This force needs to be balanced by gravity:

$$\frac{L}{4\pi R^2}\frac{\sigma}{c} = \frac{GMm}{R^2}$$

- Solving for the mass *M* we find

$$M = \frac{L}{4\pi}\frac{\sigma}{cGm}$$

- If the mass of the emitter is less than this, the system will be driven apart by radiation. So if quasars (AGN in general) aren't wildly out of equilibrium, their luminosity places a *lower limit on their mass*, called the *Eddington limit*

- For a typical quasar, this implies a mass of ~few x 10^8 $M_\odot$
- OK, we then have a
  - very bright
  - very small
  - very massive
- object ... which leads us to believe that a **supermassive black hole** is the emitter

- Wait a minute! A black hole doesn't emit light! How do we get such high luminosities?
- The answer: an *accretion disk*
  - There's no surface for a particle to strike, so something is required to release the gravitational potential energy of particles brought in from far away

- Matter spirals in towards the black hole through a disk in which its rest energy can be released as viscosity converts kinetic energy into heat (and therefore radiation)

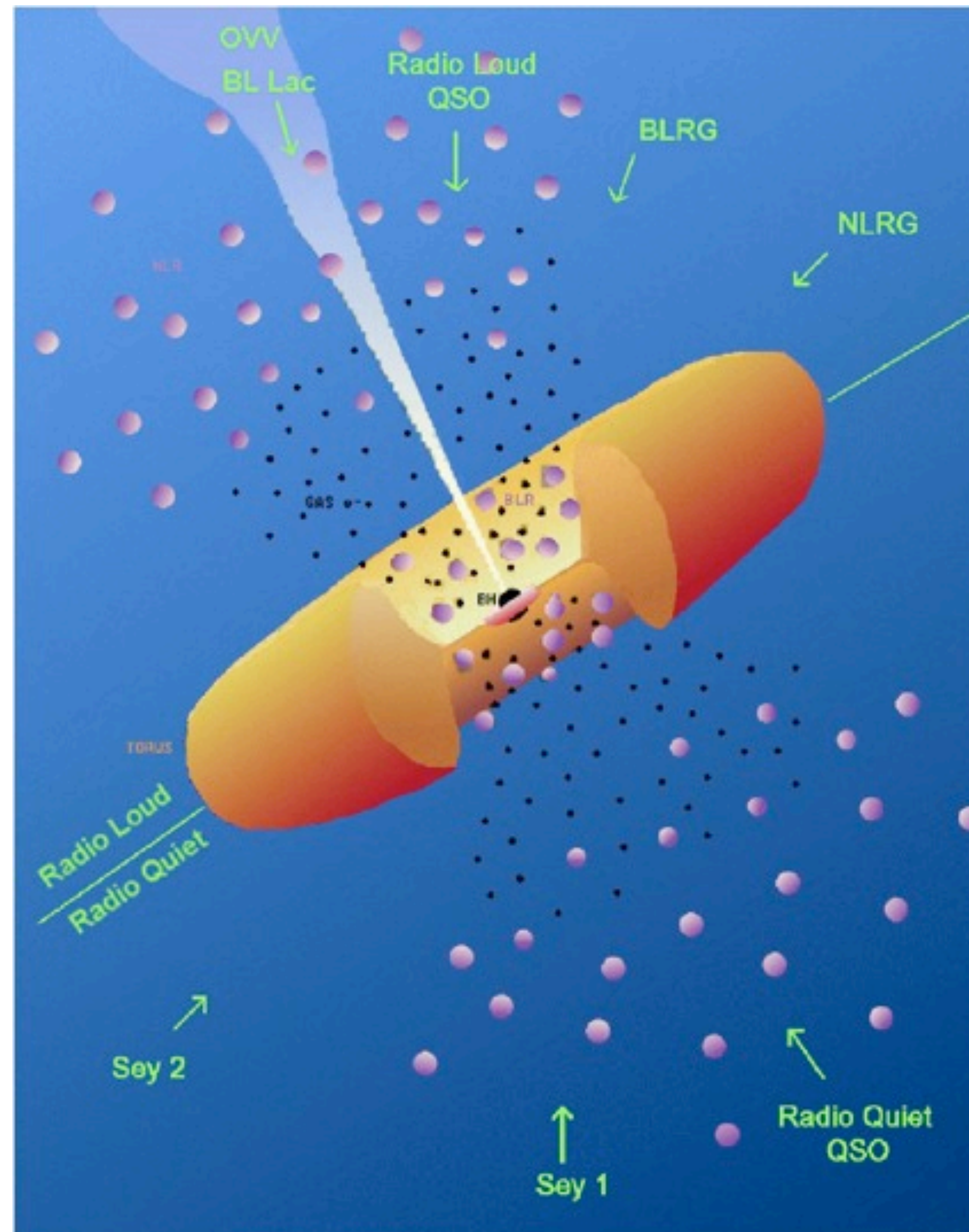
- If the rate of accreting mass into the disk and black hole is $\dot{M}$, then the accretion luminosity can be written

$$L_{\rm disk} = \eta \dot{M} c^2$$

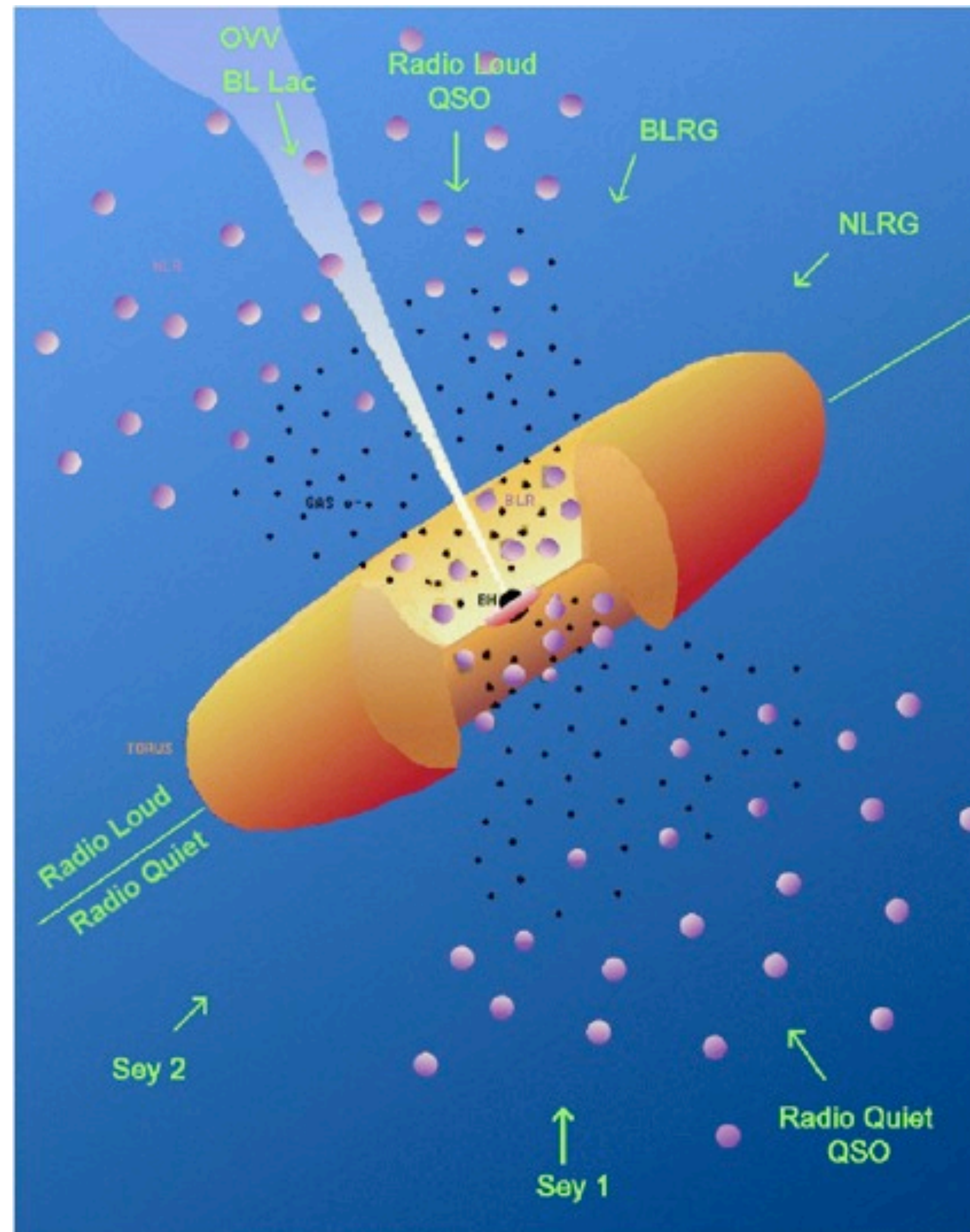
  where η is the efficiency of the process. For black holes, $0.06 \leq \eta \leq 0.42$, depending on whether the black hole is rotating (high value) or not

Why are there so many *kinds* of AGN?

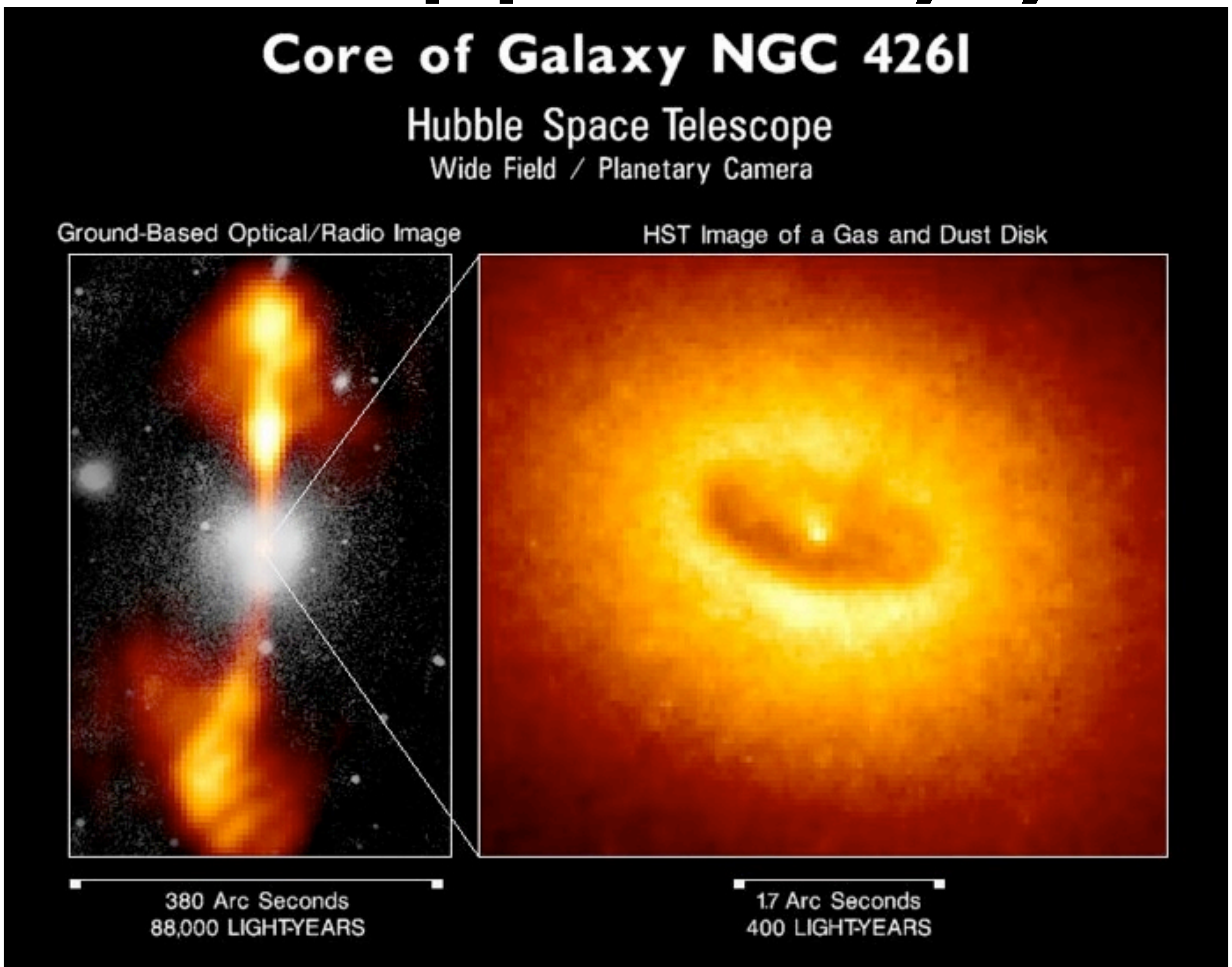
- It's now thought that the *broad lines* of quasars and Seyfert 1 galaxies come from dense, hot clouds near the SMBH (the "broad line region"), while the *narrow lines* seen in Seyfert 2 galaxies (and others) come from cooler, lower-density clouds outside of the *obscuring torus*



- Then the different kinds of AGN depend on the *viewing angle* of the SMBH
  - QSOs: close to the jet axis, perpendicular to the disk and torus
  - Seyfert 1: slightly off-axis
  - Seyfert 2: very close to the torus
  - Radio-loud objects: the jet side
  - Radio-quiet objects: the non-jet side

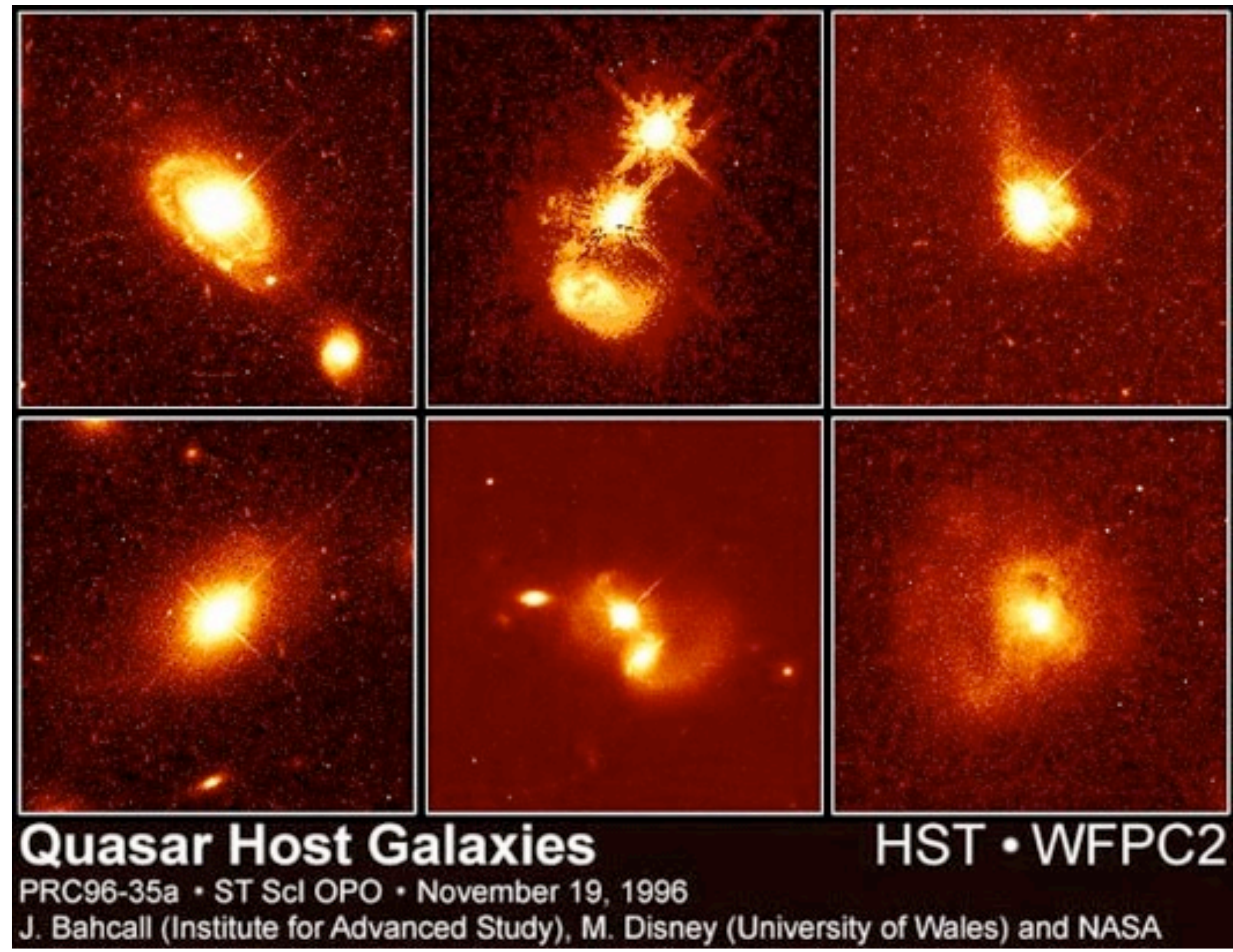


Do we actually observe this? Apparently yes!



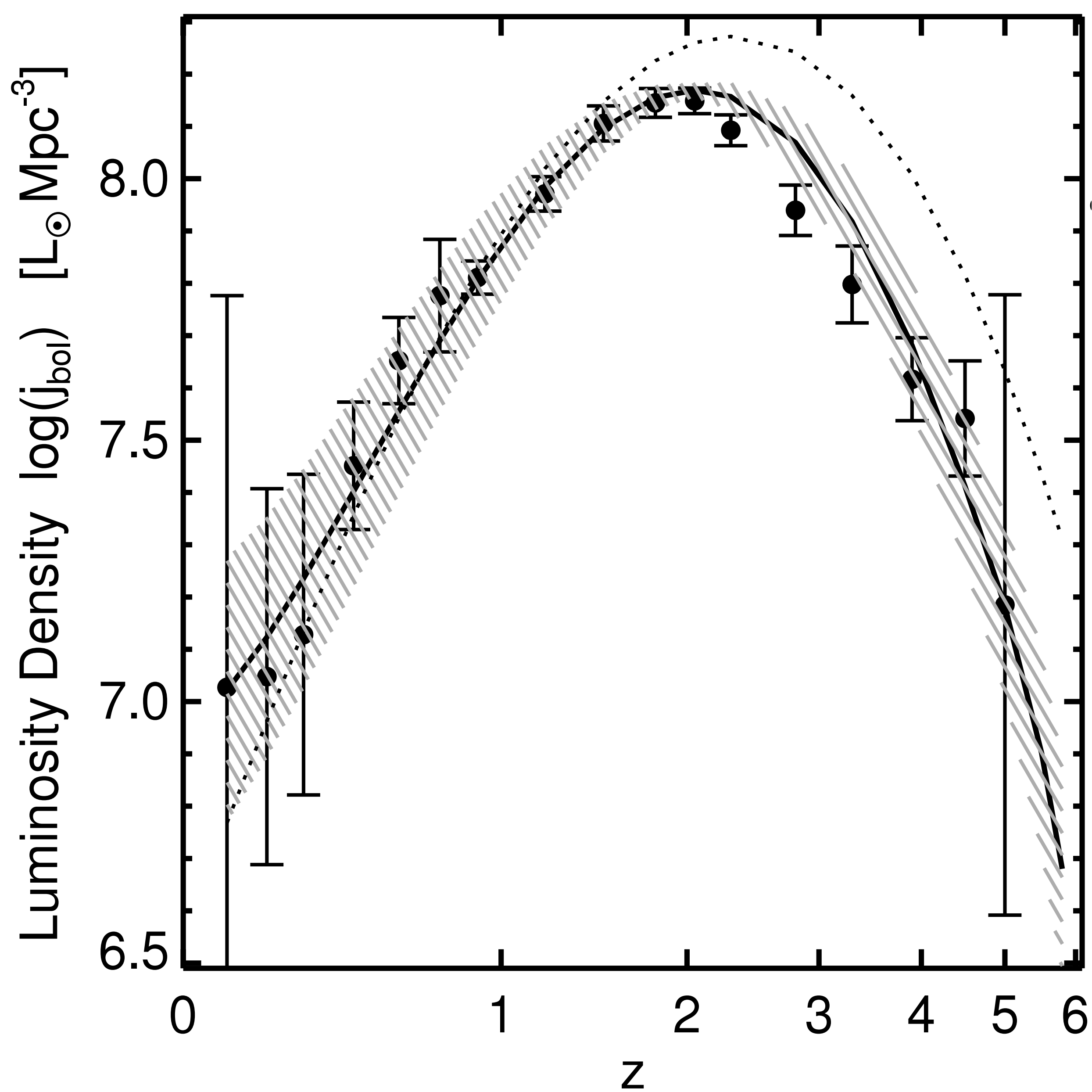
What triggers the activity?

- As we discussed earlier, the activity appears to be triggered by *gravitational interactions*, like galaxy mergers
    - Note that this is even true for the Seyfert galaxies, which typically have nearby companions



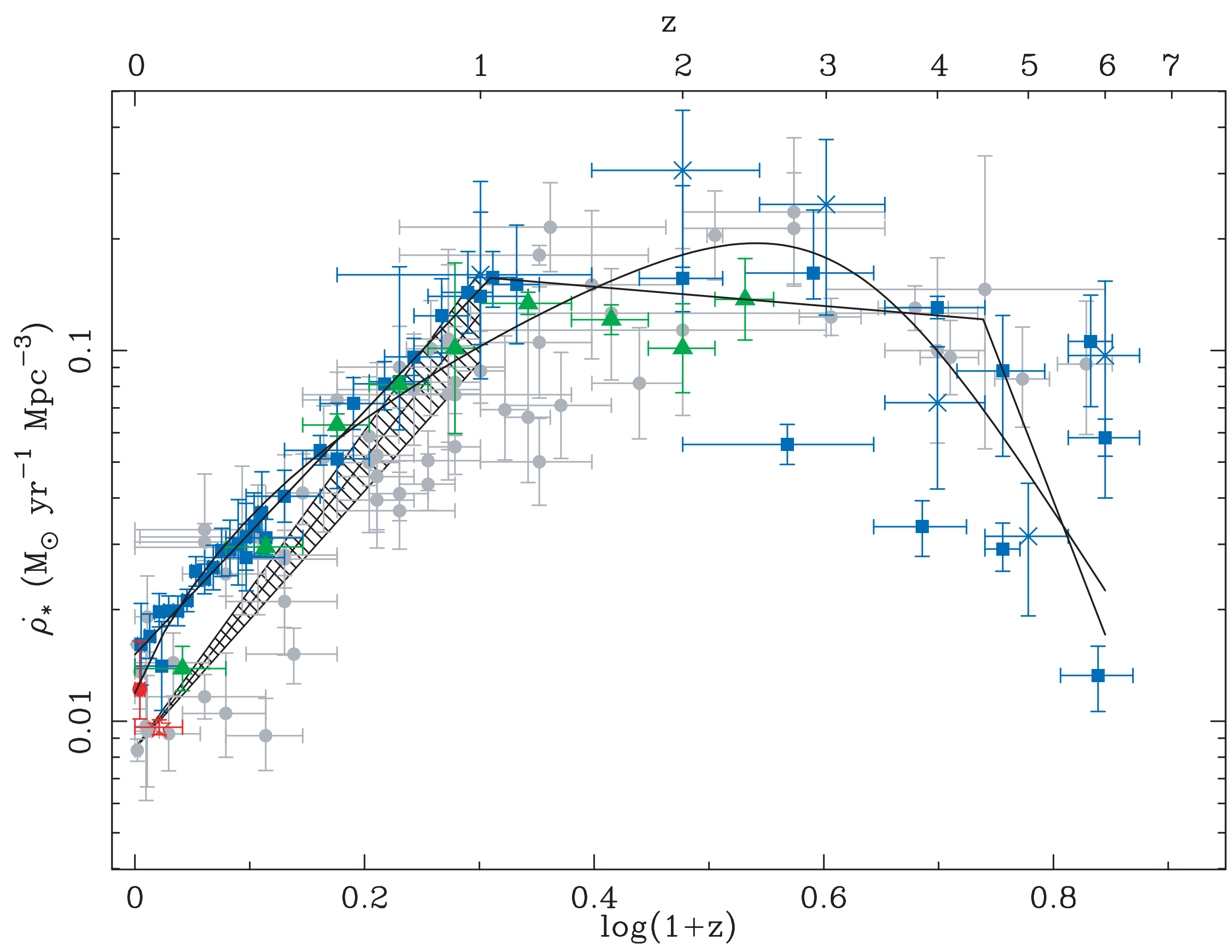
When were quasars most active?

- We can ask when quasars were putting out the most energy
- This occurs at $z\sim2$, when the Universe was only ~25% of its current age (i.e., about 10 Gyr ago)



- This is also the epoch at which the *cosmic star formation rate* peaks!

- This coincidence suggests that *quasars are an intrinsic part of galaxy evolution*

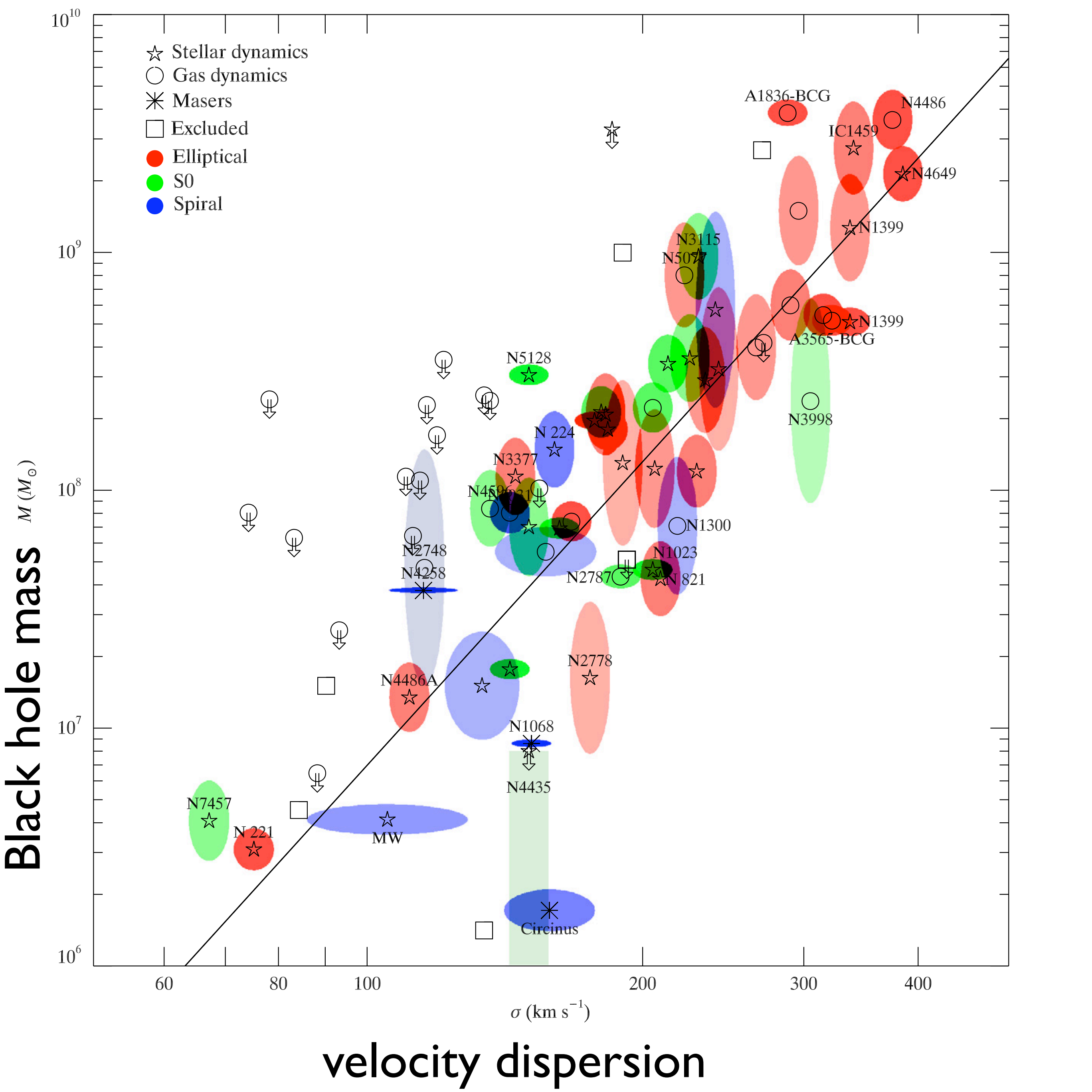


Black hole masses

- In fact, it suggests that every galaxy likely hosts a (supermassive) black hole
- We can measure the masses of these black holes in several different ways:
  - Stellar dynamics
  - Gas dynamics
  - Maser motions
  - Reverberation mapping

- The most recent compilations of black hole masses in galaxies suggest that *all* galaxies have black holes, and that the BH masses are correlated with the luminosity or velocity dispersion (i.e., mass) of their host galaxy:

$$M_{\rm BH} \propto \sigma^4$$



- This means that there is a tight coupling between *black hole mass* and *galaxy mass*!
  - Why?

An introduction to galaxy formation

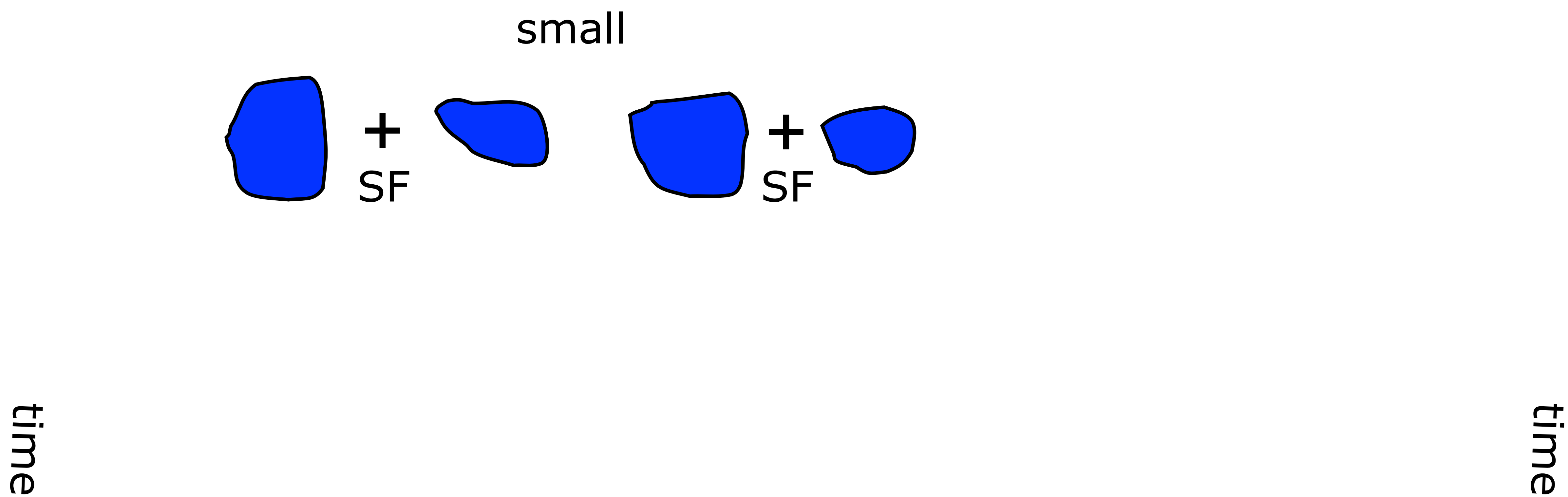
or, "why do galaxies have the shapes they do, and did they always have their current shapes?"

Two extreme galaxy formation models

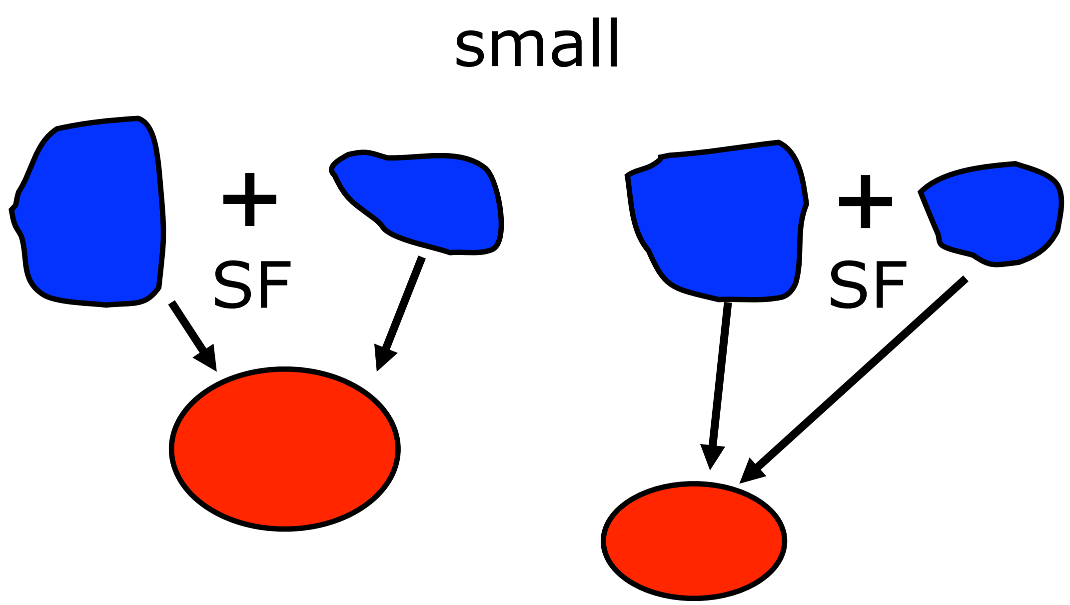
time

time

Two extreme galaxy formation models



Two extreme galaxy formation models

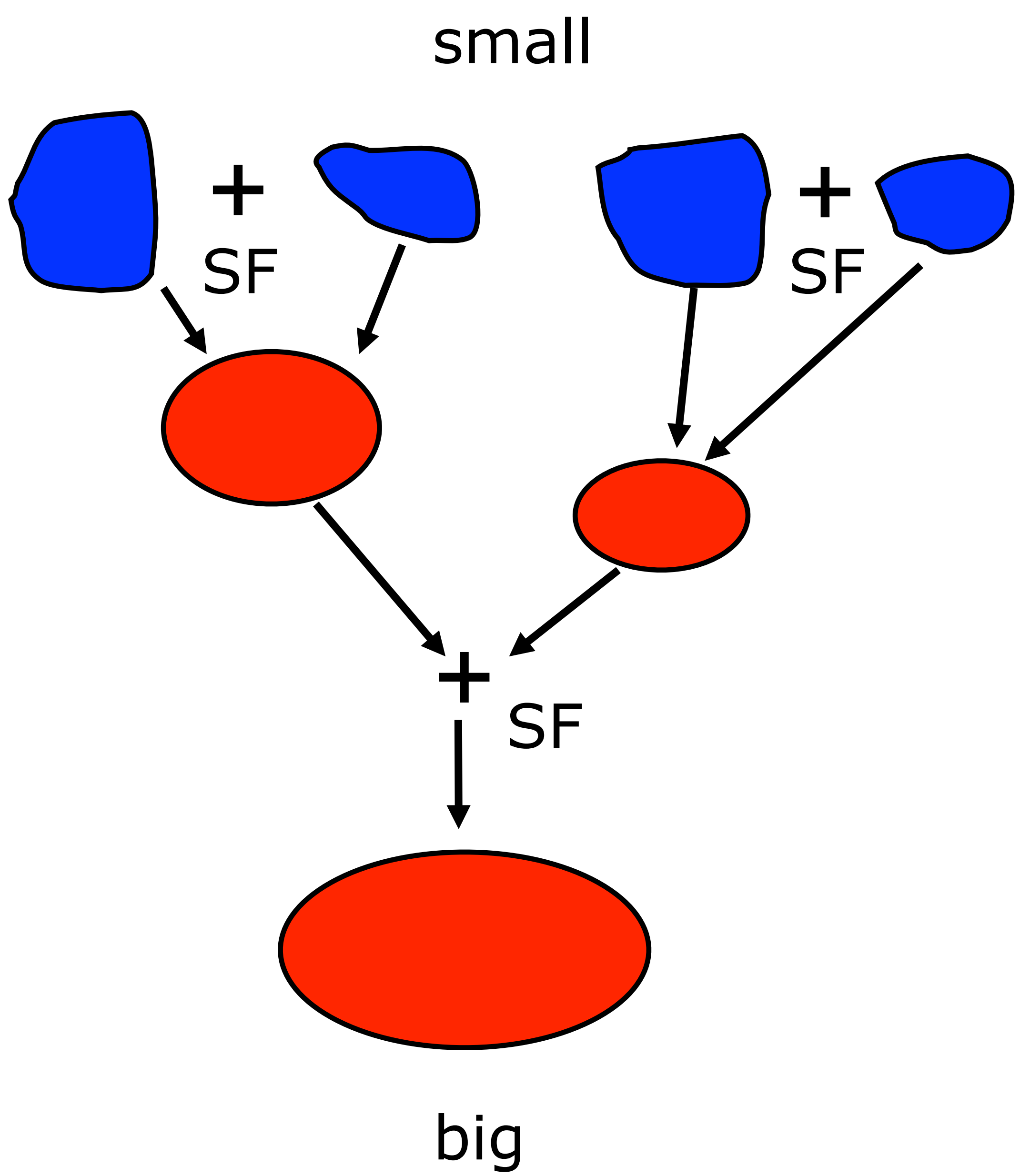


time

time

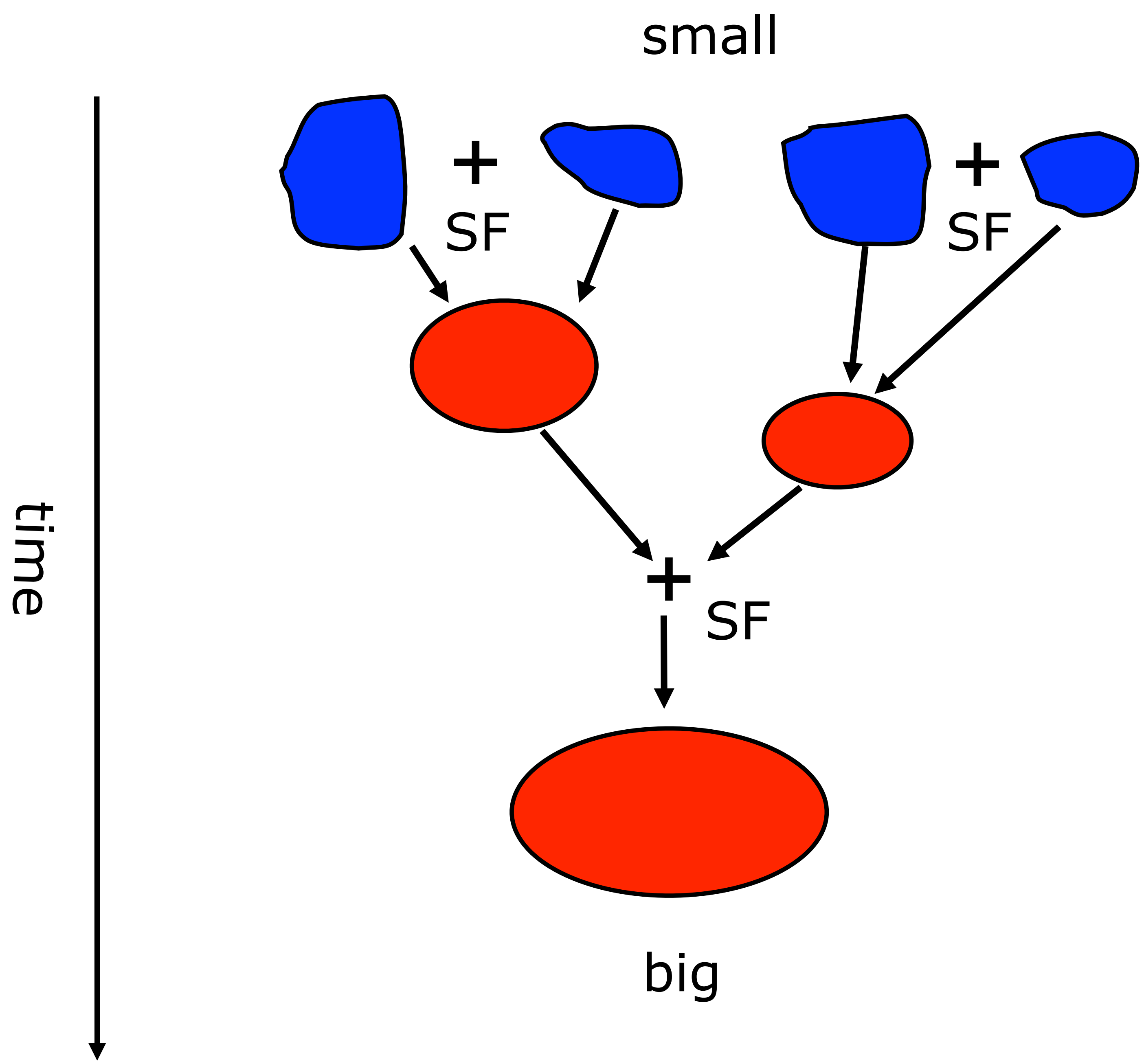
Two extreme galaxy formation models

time



time

Two extreme galaxy formation models



time

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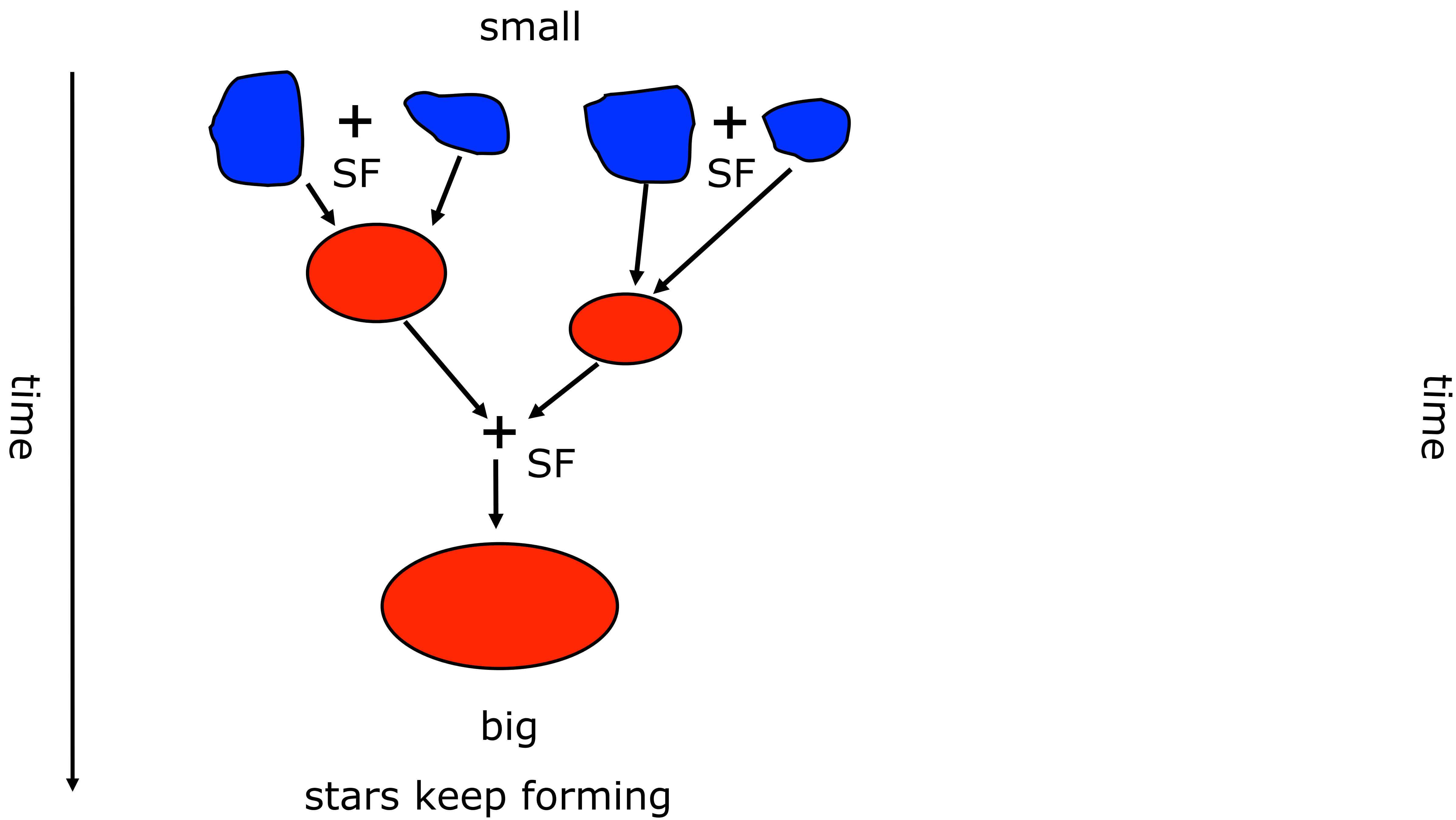

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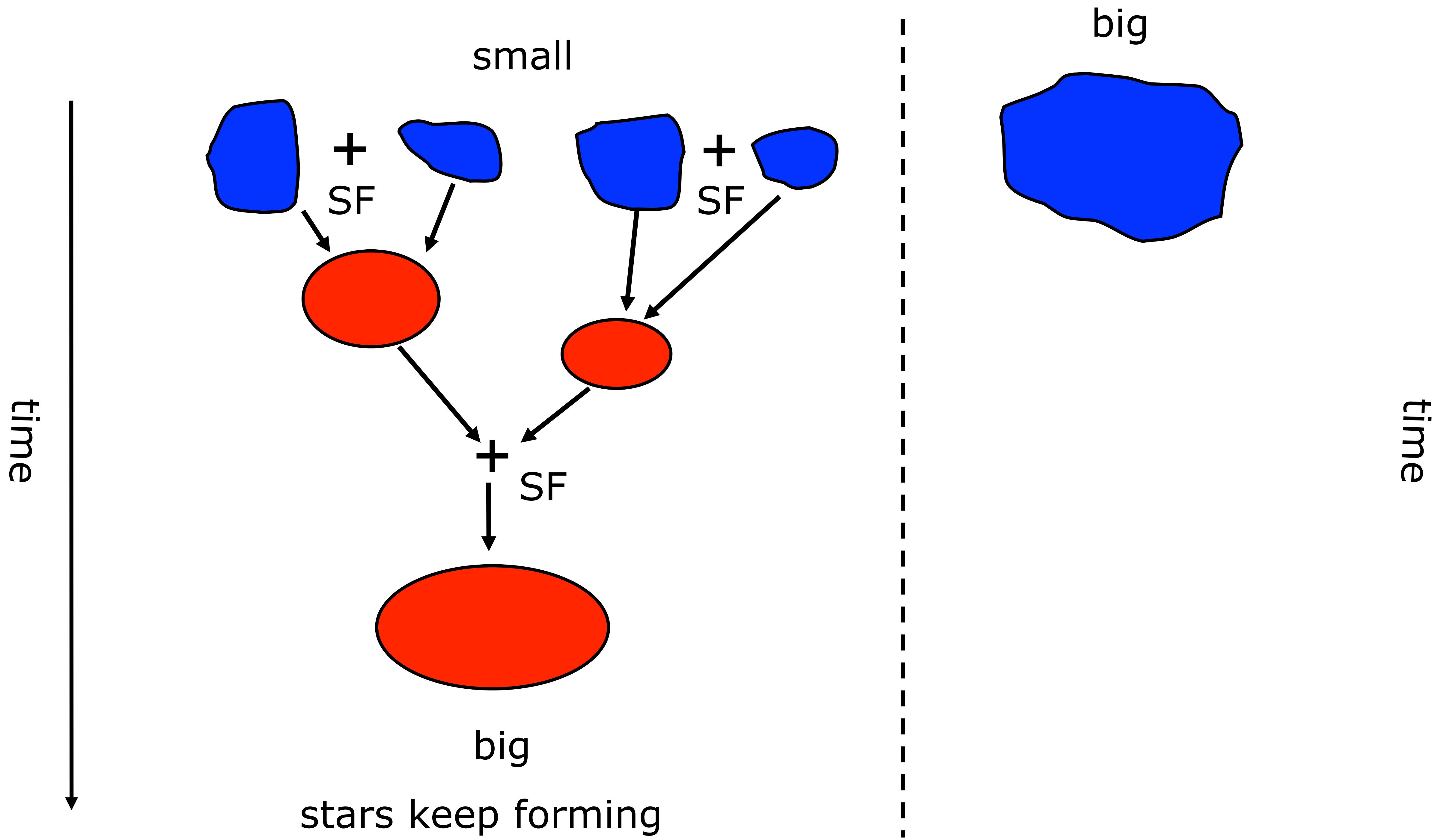

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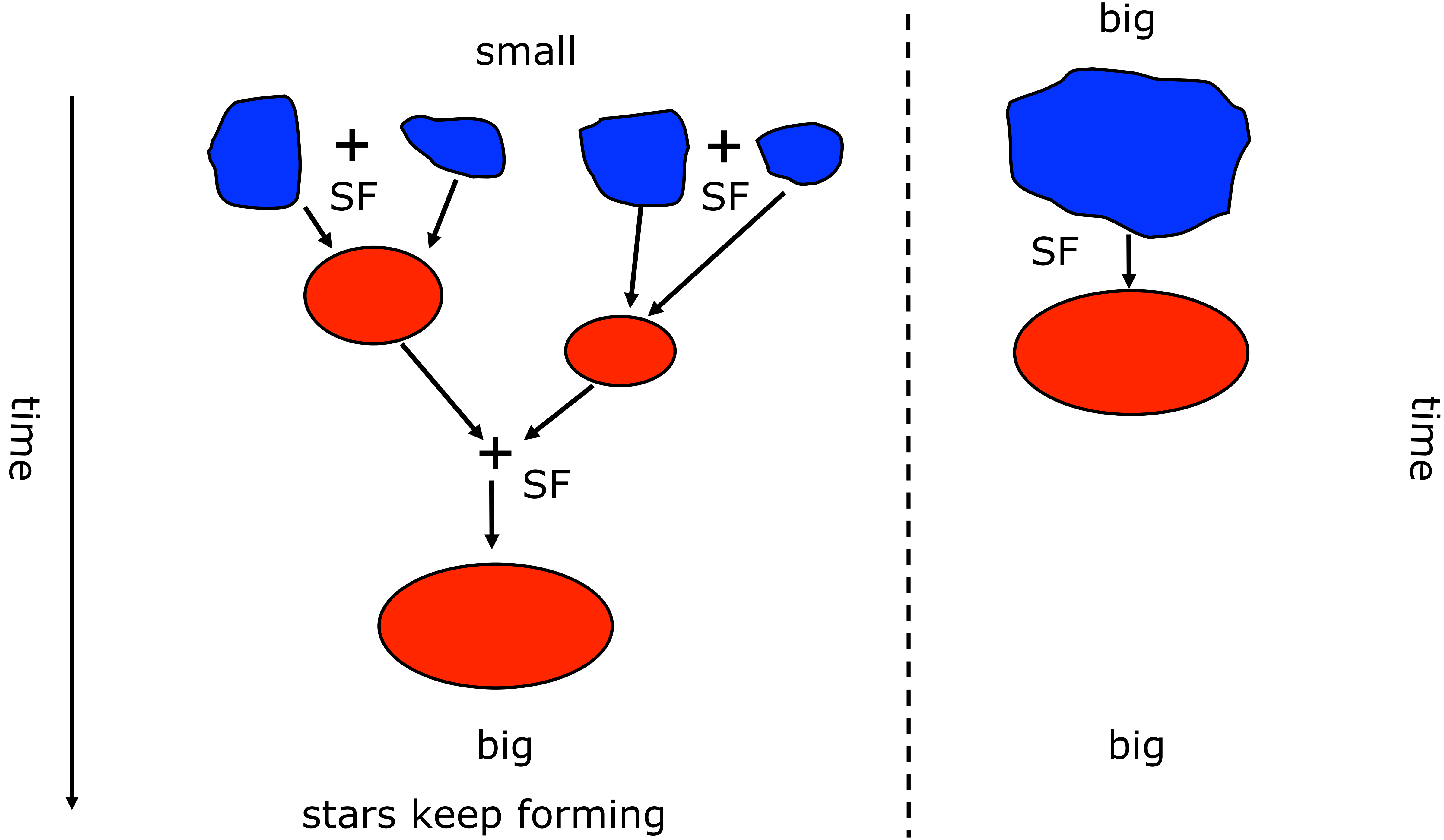

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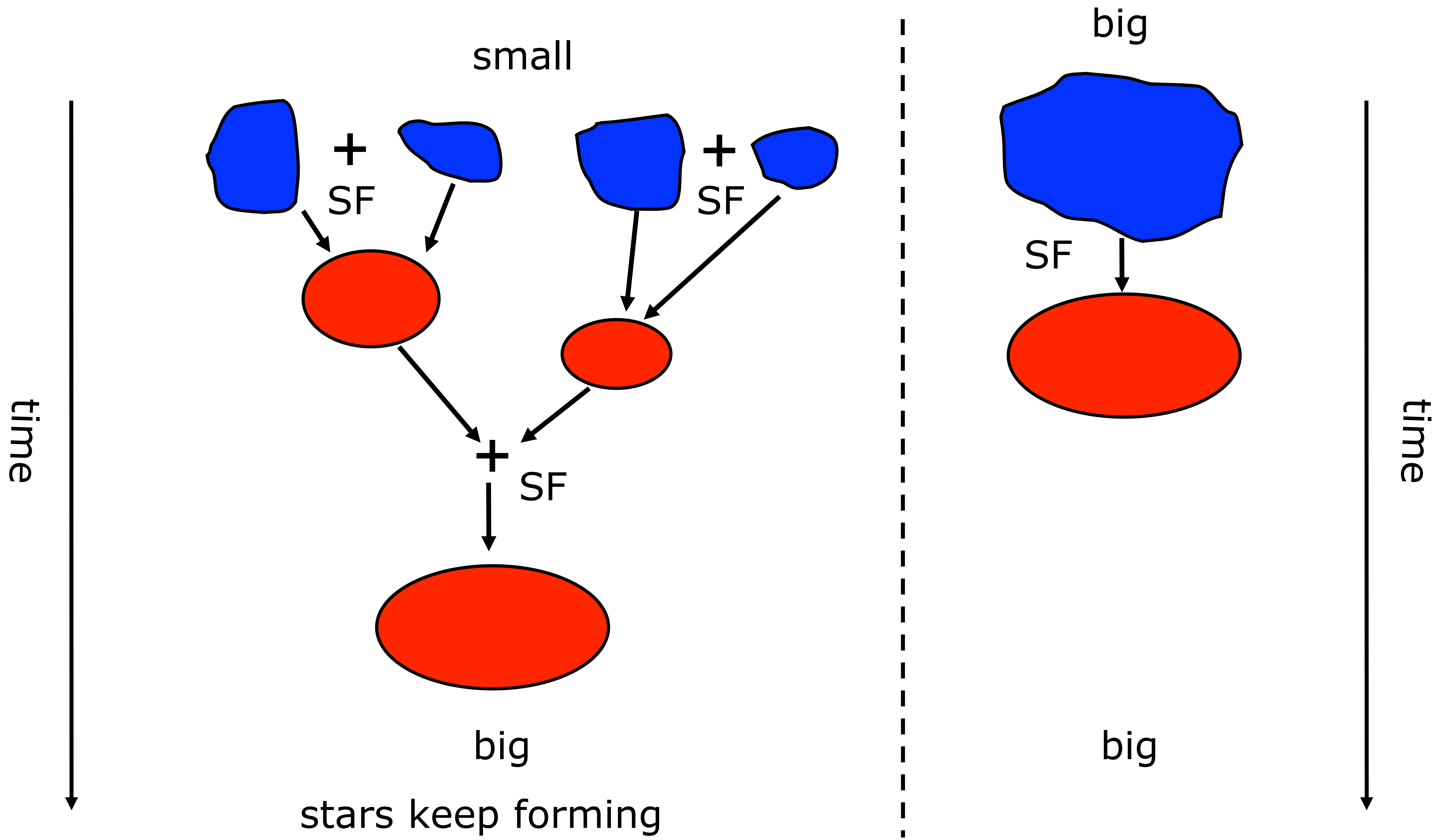

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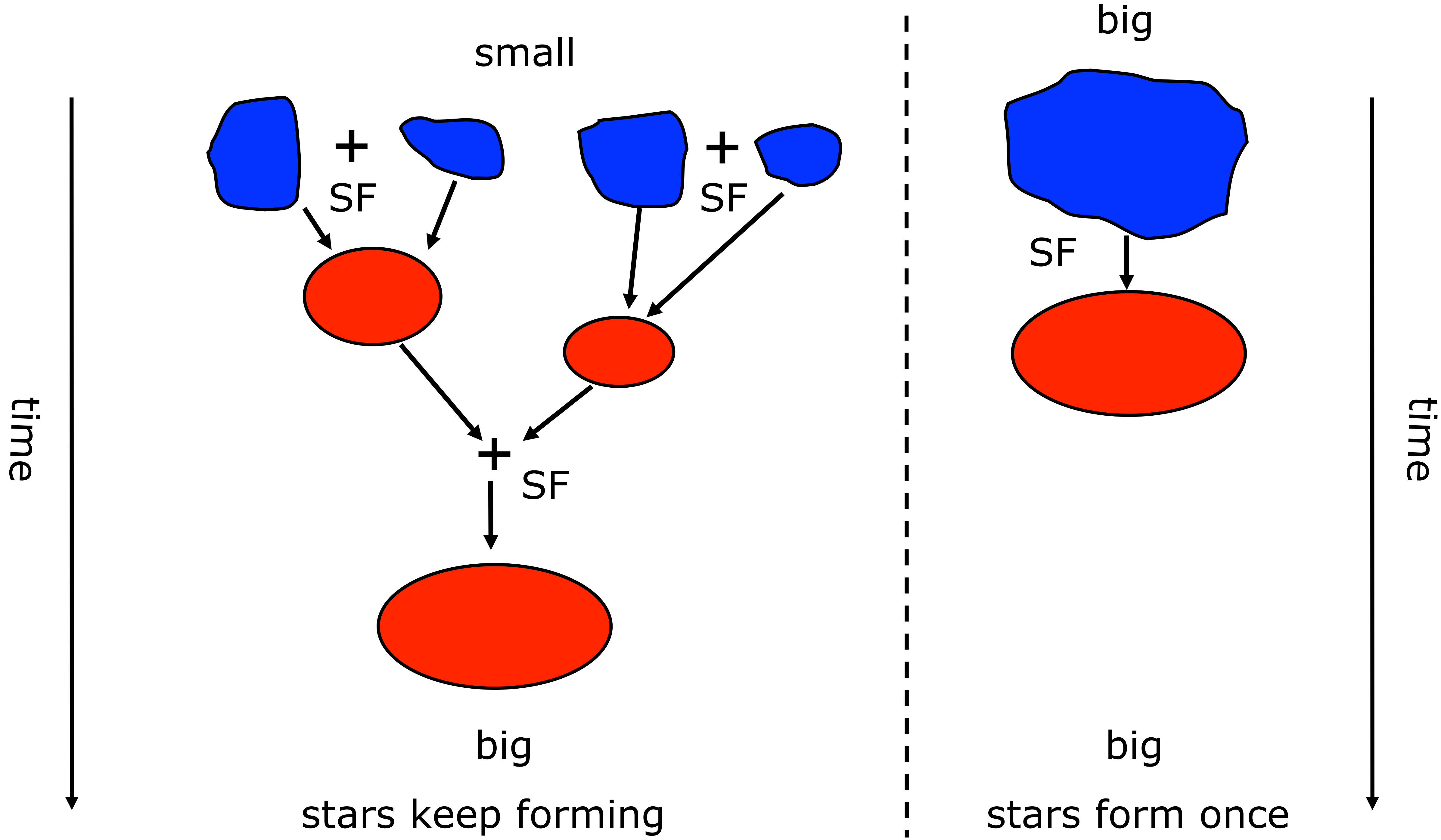
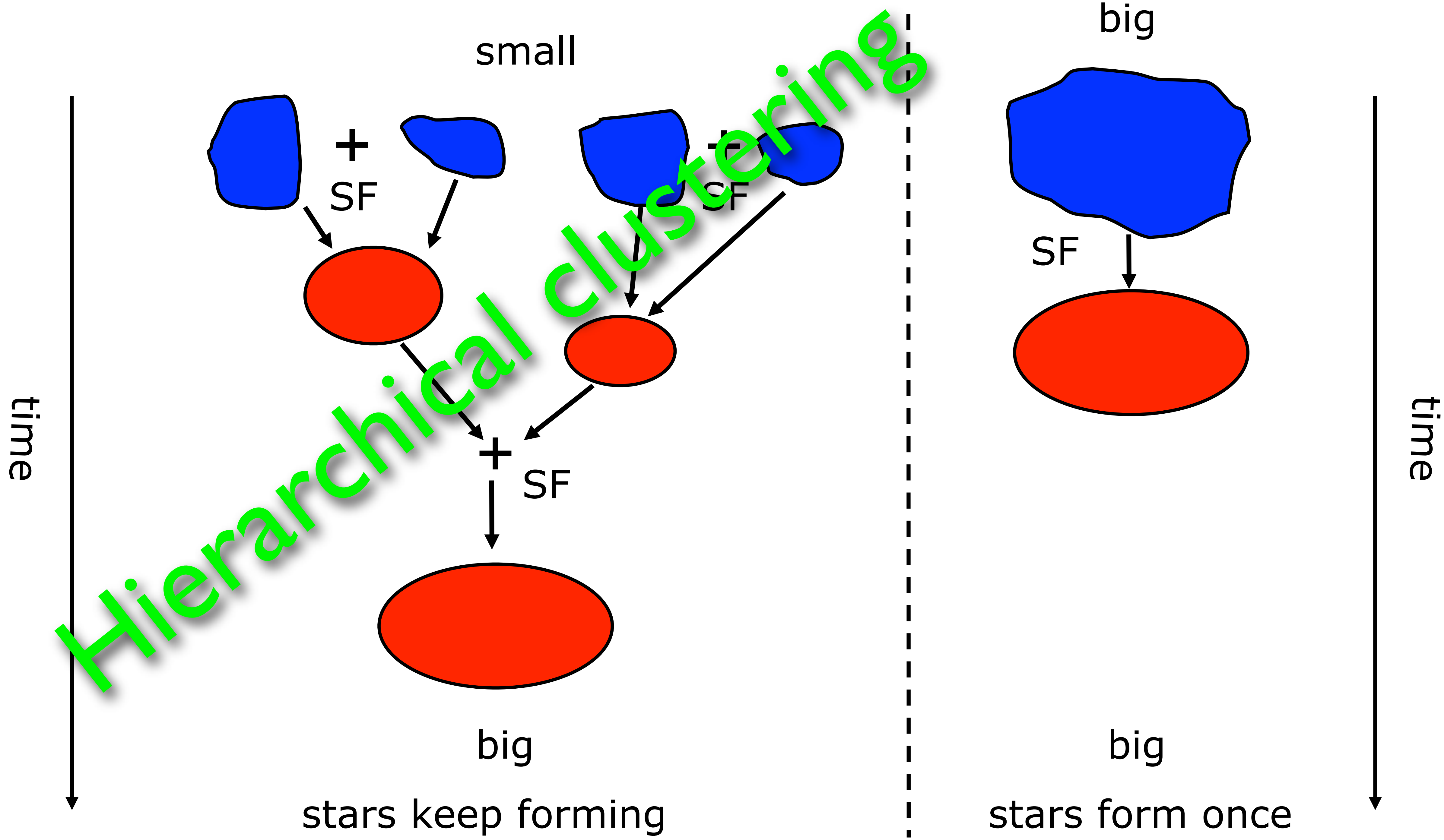
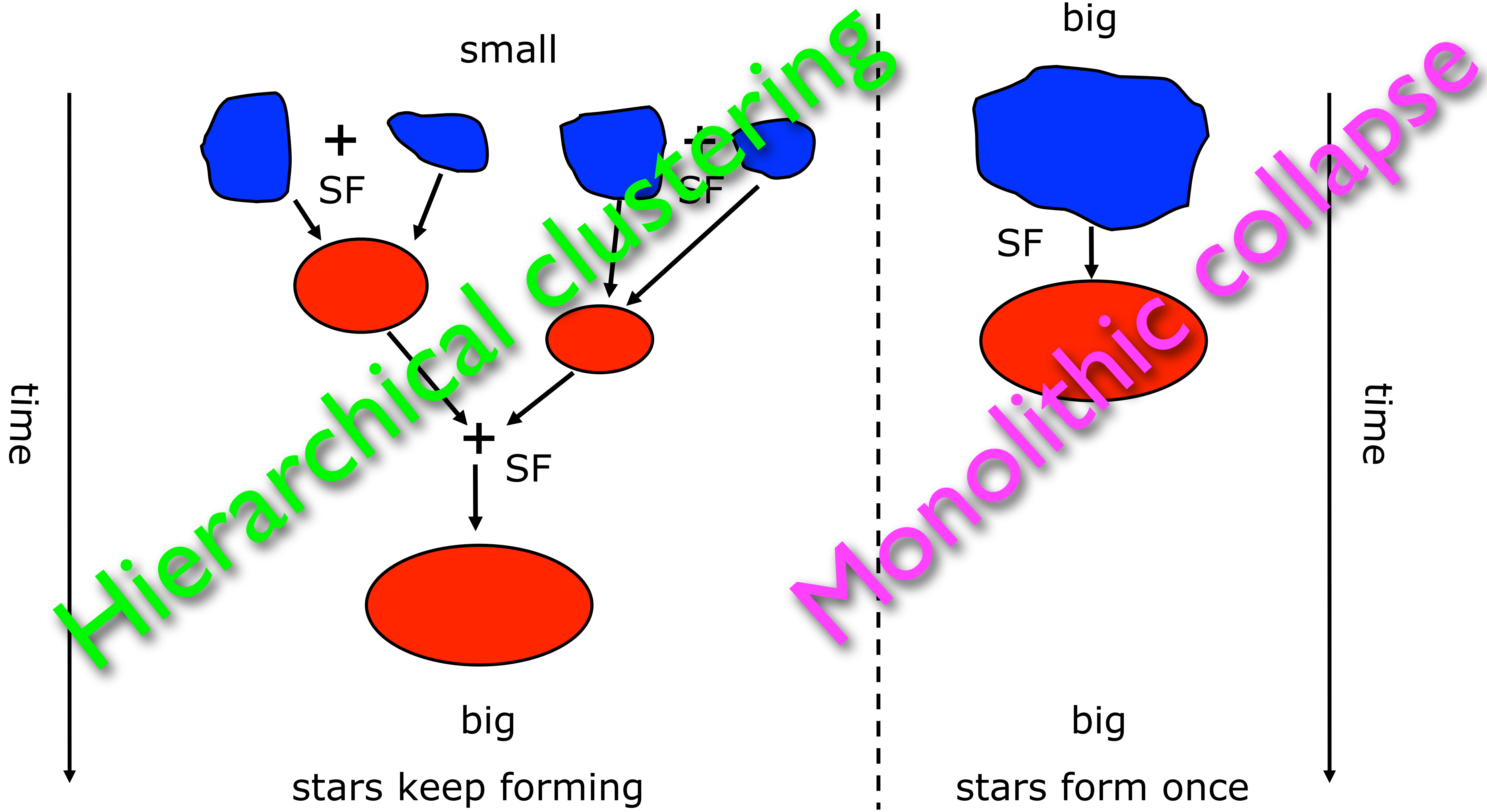


Two extreme galaxy formation models



Two extreme galaxy formation models



Model 1: Monolithic collapse

- In 1962, Olin Eggen, Donald Lynden-Bell, and Allan Sandage noticed that the (stellar) *halo* of the Milky Way has very little angular momentum and low metallicity, while its *disk* is strongly rotating and has high metallicity

- This led them to propose the following picture, now referred to as the “ELS” collapse model:
  - The galaxy forms out of **one** “protogalactic” cloud of gas
  - As the gas starts to collapse under its own gravity, stars begin to form with low metallicity on orbits following this collapse --- i.e., on highly radial, not circular, orbits; these are the *halo* stars

- These stars began to die and released their newly-formed metals to the collapsing gas, enriching the gas further
- As the gas cloud is assumed to have *some* angular momentum at the beginning, these further, more metal-rich generations of stars begin to get more angular momentum (because ang. mom. must be conserved without some process to remove it) and therefore begin to form a *disk*

- This is a **top-down** formation model, where the biggest structures form first

- How long does this take?
    - It turns out that *free-fall collapse* of a (homogeneous) sphere always takes an amount of time proportional to the inverse square-root of the initial density:

$$t_{ff} \propto \frac{1}{\sqrt{G\rho_0}}$$

    - note that this basically true even if the initial cloud isn't *quite* homogeneous

- Assuming the initial gas cloud has a mass of $5\times10^{11}\ M_\odot$ and an initial radius of ~50 kpc and was initially homogenous, we find

$$t_{ff} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2} = 200\,\mathrm{Myr}$$

  - It would be somewhat faster than this if the initial cloud was already centrally concentrated, so the old but metal-rich stars in the bulge could be explained if this were the case

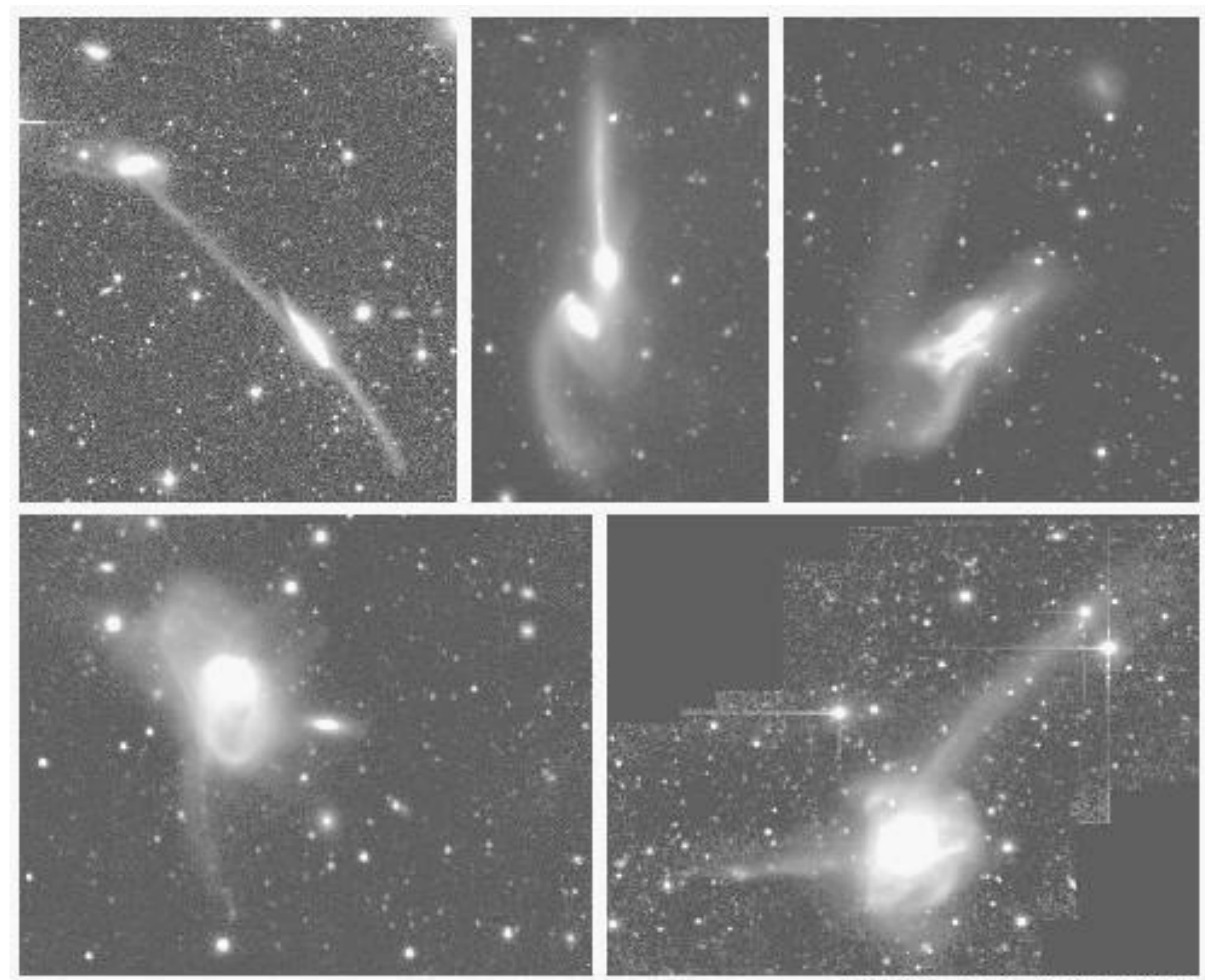
- Problems with the ELS model:
  - In the ELS model, all halo stars and globular clusters should have the same general direction of motion... but ~1/2 of outer halo stars are moving in the opposite direction ("retrograde")
  - The age spread in globular cluster and halo stars is ~2 Gyr, 10x longer than the ELS estimate

- The inner globular clusters are metal-richer and older than the outer metal-poor but younger globular clusters
    - Plus the inner clusters seem to be associated with the disk, not the halo, in terms of their distributions and motions

Model 2: Hierarchical clustering

- When we look around us in the Universe, we notice that many galaxies appear to be undergoing *gravitational interactions* or even *mergers*

- Interestingly, these interactions often involve significant star formation



Hibbard & van Gorkom 1996, AJ. 111. 655

- What happens when two galaxies collide?
- Their stars do not collide! The distances between stars in a galaxy are far too big --- the chances of even a single direct stellar collision is very small
- Instead, gravitational drag --- **dynamical friction** --- causes the galaxies to slow down and become one object

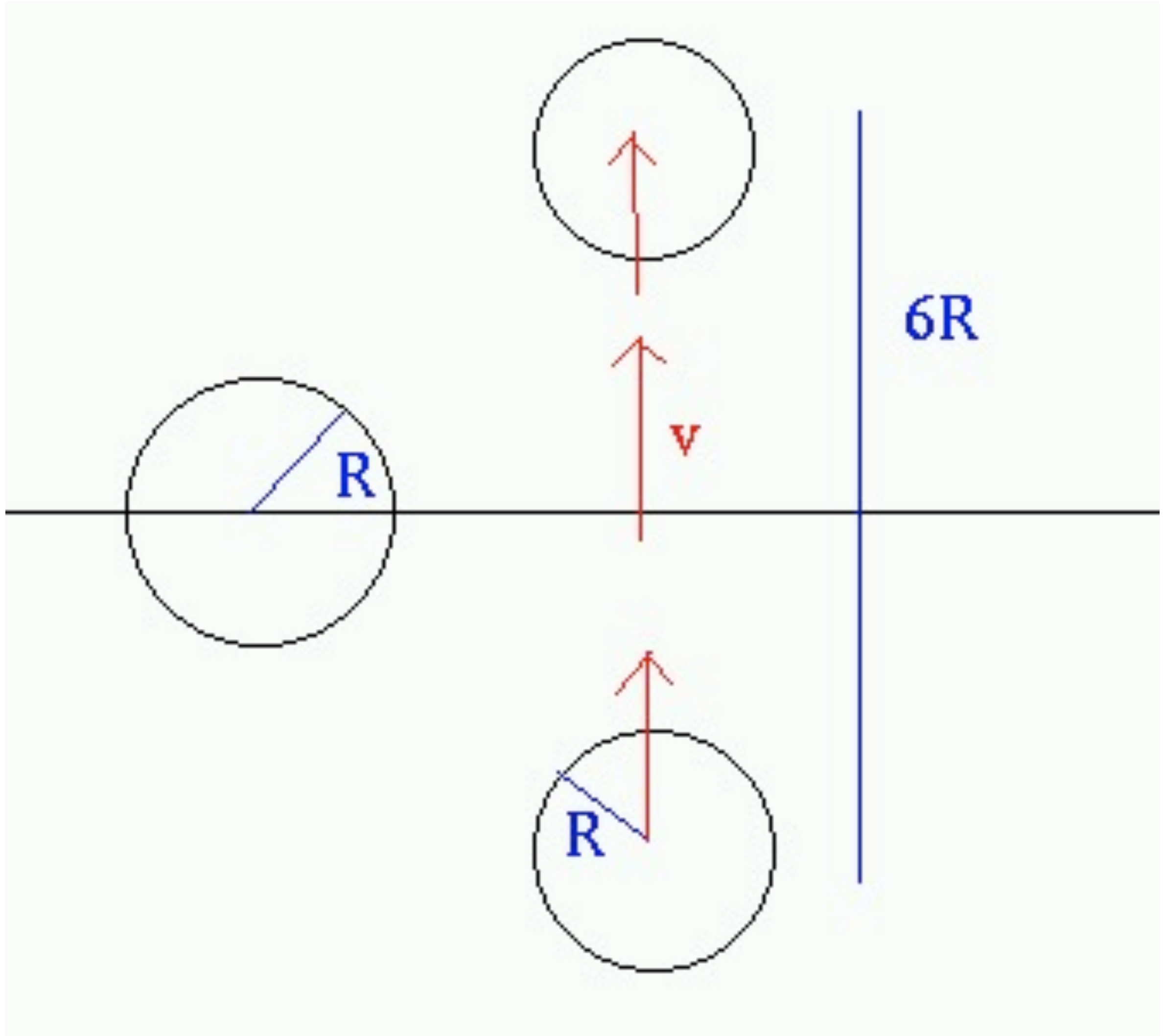
- How long does this take?

- Let's imagine that the "passing time" is the time it would take for a galaxy to pass another by three diameters,

$$t_{\rm pass} = 6R/v$$

- So if a galaxy has a radius of ~20 kpc and passes another at ~350 km/s (typical of intermediate density regions), then

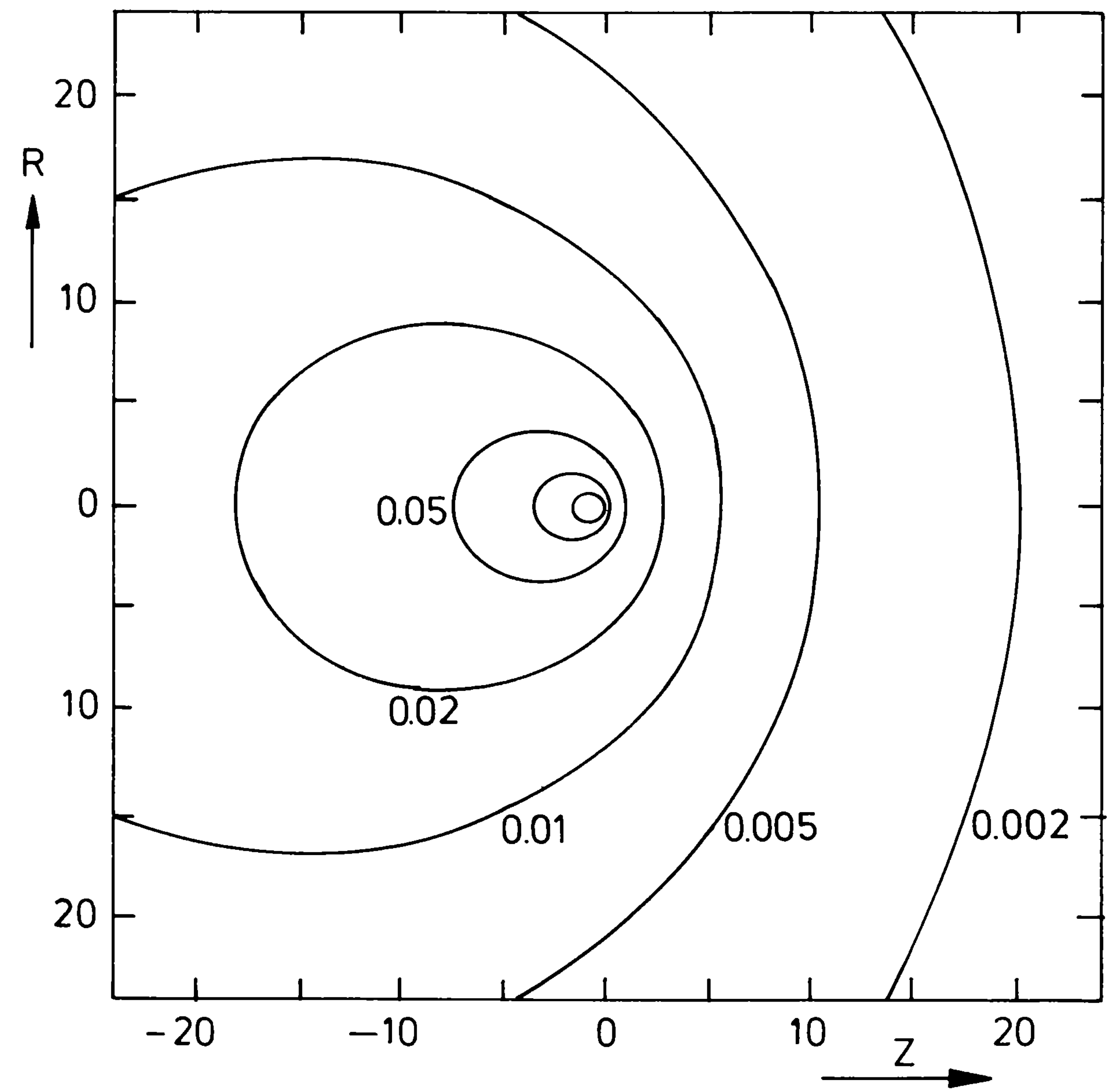
$$t_{\rm pass} \sim 350\,{\rm Myr}$$



- Dynamical friction is caused by the *wake* of particles resulting from the motion of an object moving through a "sea" of other particles

- Imagine an object of mass *M* moving through an infinite "sea" of particles with constant density ρ, and each particle has mass *m*«*M* so that our object is not deflected as it moves through the medium

- As *M* moves forward, objects are pulled into its path, causing a high-density wake to trail *M*, opposing its motion --- thus transferring kinetic energy from *M* to the medium



- Using dimensional analysis, only the mass *M*, speed v_M, and density ρ can contribute to the dynamical friction force:

$$f_d \sim C\frac{G^2M^2\rho}{v_M^2}$$

- where *C* is not a constant but a function that depends on the ratio (v_M/σ) of the medium
  - for $v_M \sim 3\sigma$, $C \sim 23$ for the LMC, 76 for globular clusters, and 160 for elliptical galaxies

- With a little bit of algebra, we can figure out how long it takes for a small galaxy (or a globular cluster) with mass *M* takes to merge with a larger one, assuming a flat rotation curve with (outer) velocity *v* for the big galaxy and an initial distance *r*:

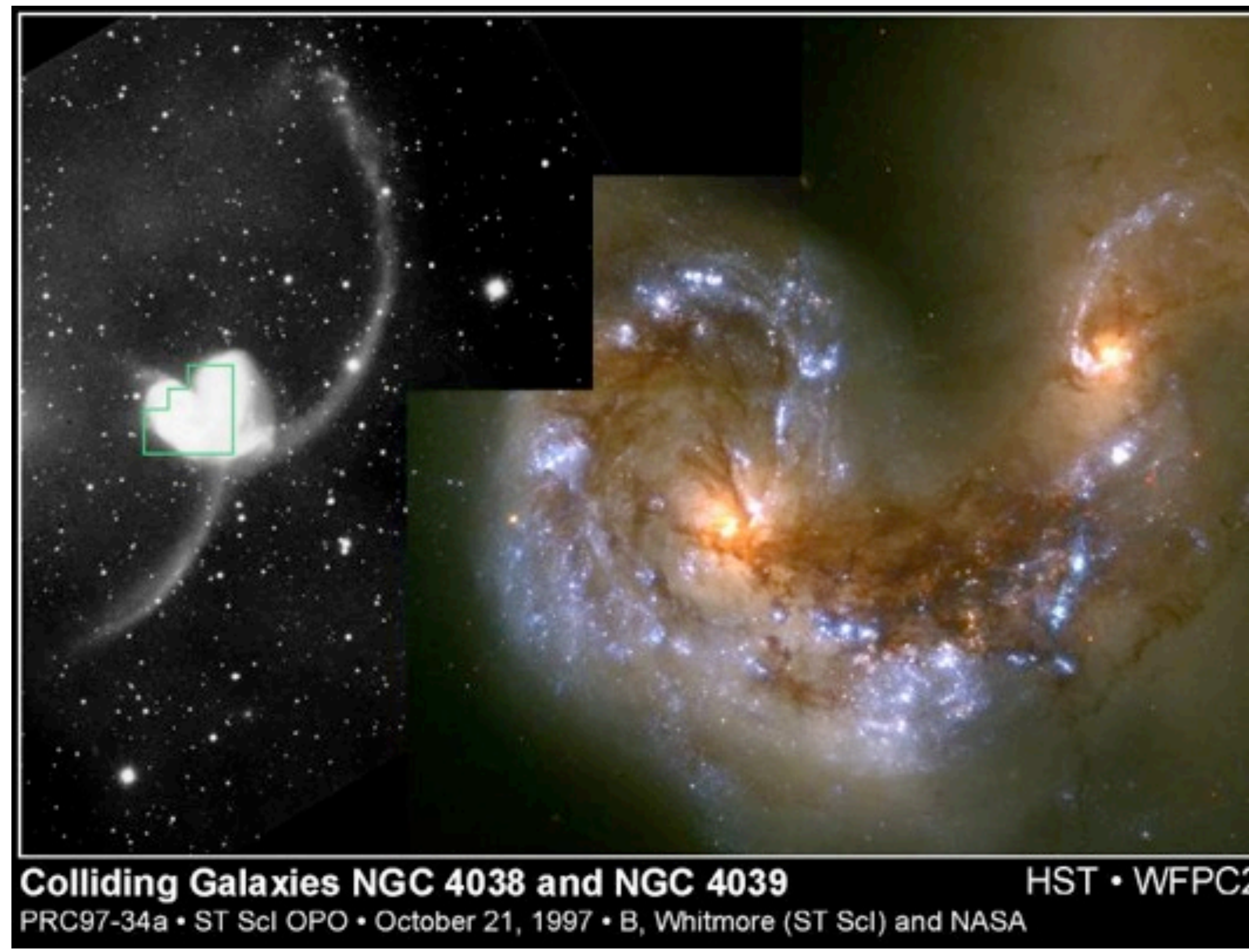
$$t_M \sim \frac{2\pi v r^2}{CGM}$$

- This formula implies that the Large Magellanic Cloud (LMC) will merge with the MW in ~1.7 Gyr
  - but this assumes a *circular* orbit; a calculation using an *elongated* orbit takes (sensibly) much longer
- The formula breaks down when the galaxies have similar masses and sizes, but detailed simulations show that it takes ~1 Gyr for a merger even in this case

An example: the MW-Andromeda merger

And what about the tails?

- Gravity acts to *radially stretch* anything passing near a massive object
- For example: the "Antennae" galaxies



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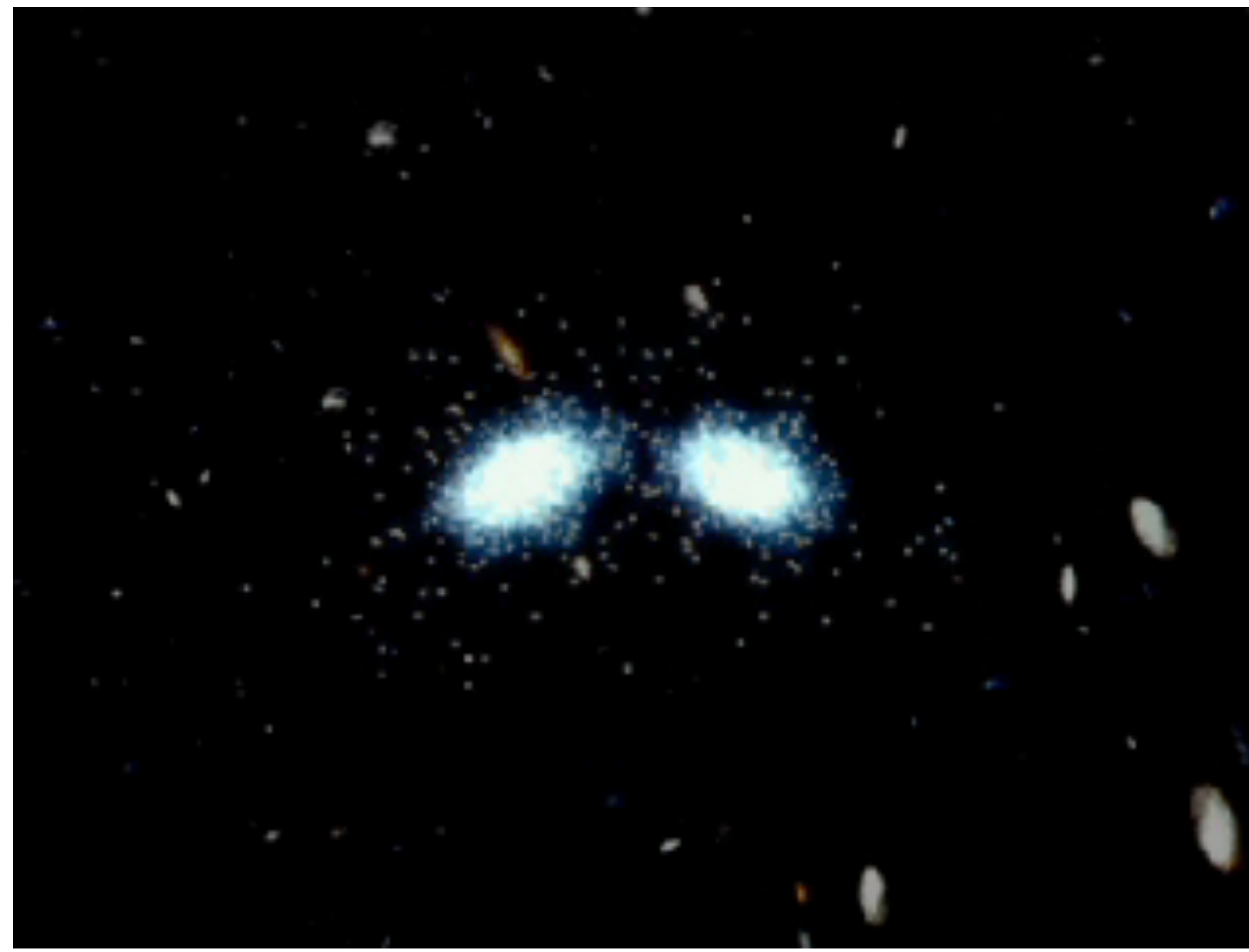

- However, not *all* encounters are so violent
- High-speed encounters can occur so rapidly that the stars don't have time to respond --- there is no dynamical friction in these encounters
  - In these encounters, the internal potential energy doesn't change, but the internal kinetic energy must decrease by an amount equal due to the increase to the total kinetic energy of the encounter (due to the Virial theorem)

- And how did this galaxy, “The Cartwheel,” come about?

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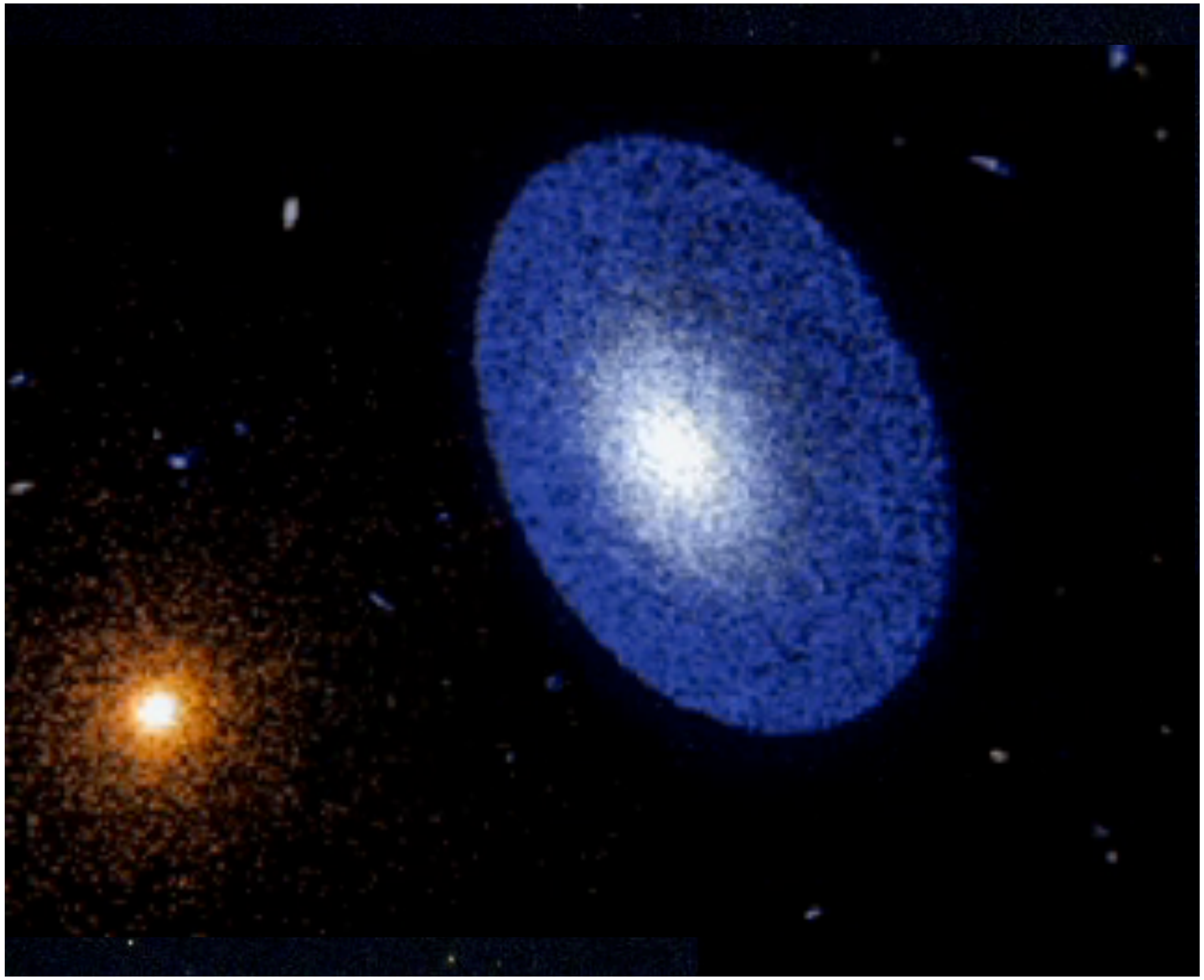

- In fact, if the speed of the encounter is much more than 3-5 times the internal speed of the galaxy, the encounter has little effect on the galaxies *if* the collision isn't head-on

Merger-driven galaxy evolution

violent relaxation	• destroys disks • produces spheroids • converts rotation into random motion
gas inflow	• sweeps cold gas into center • shuts off future star formation
starburst/ AGN	• depletes cold gas • fuels X-ray halo
environment	• encounters more frequent in high-density environments

- Merger products look a *lot* like elliptical galaxies
- Are there signs of merger-like effects in real elliptical galaxies?

- For example, tidal features are common in merger remnants

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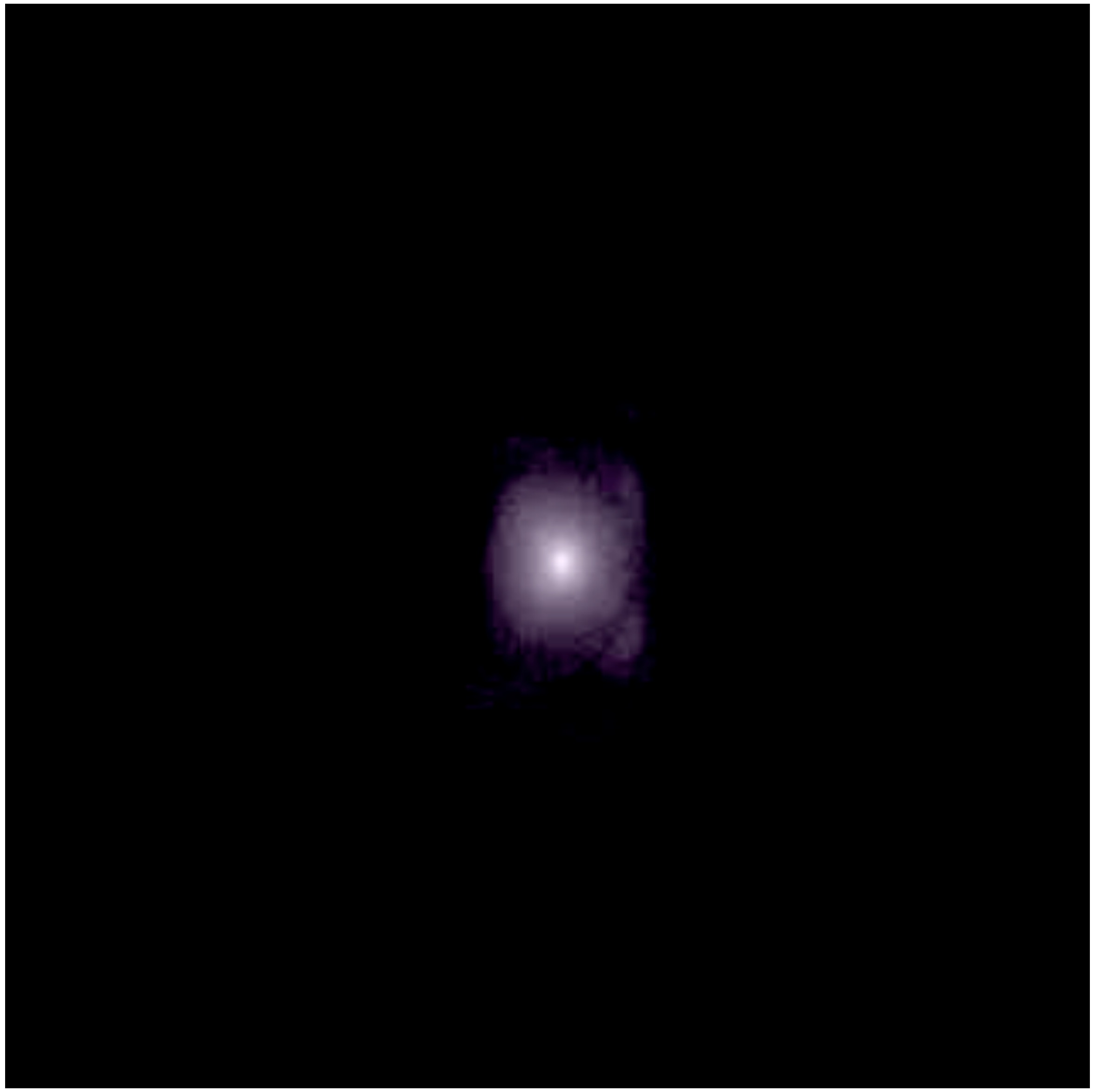
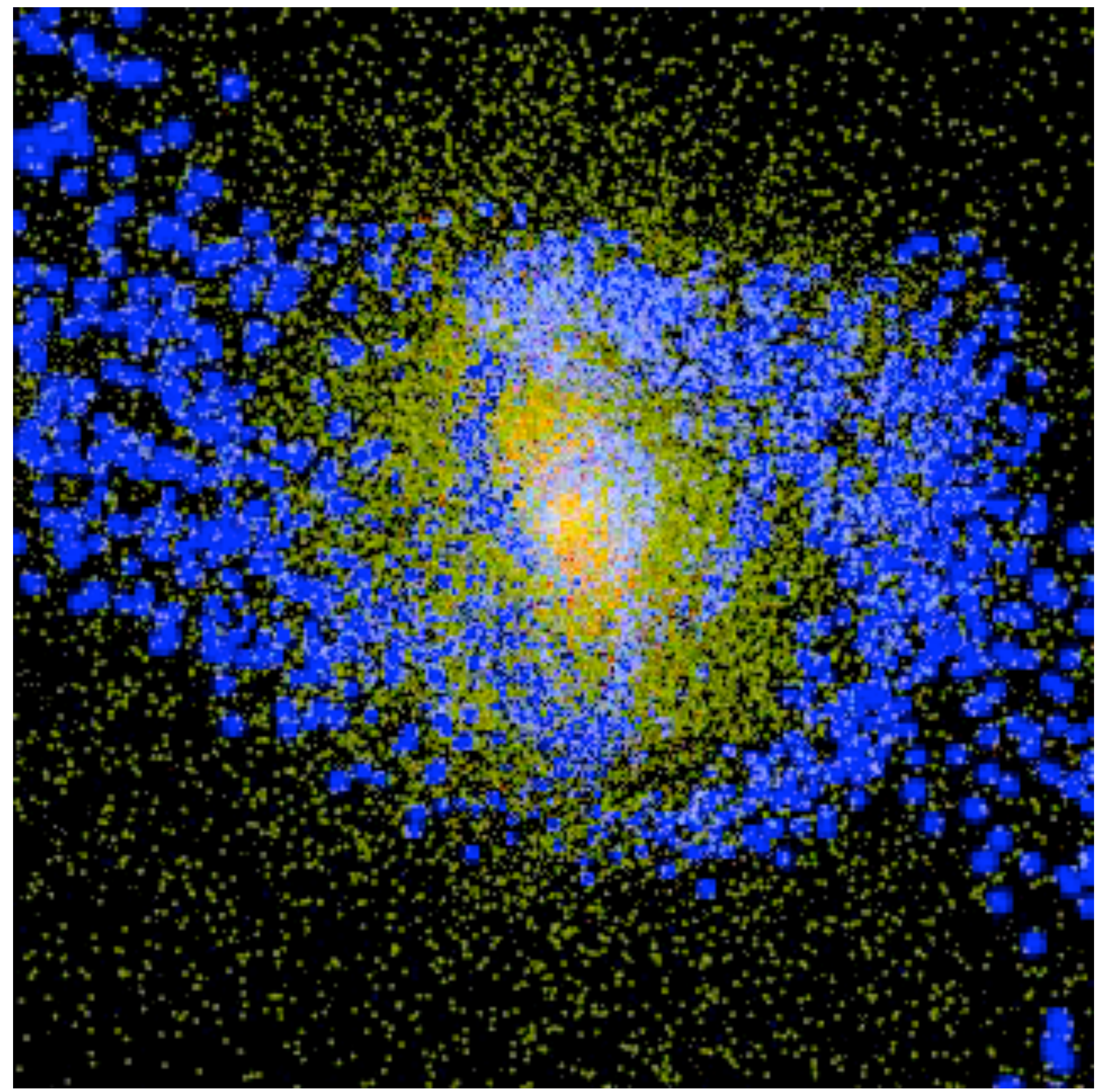
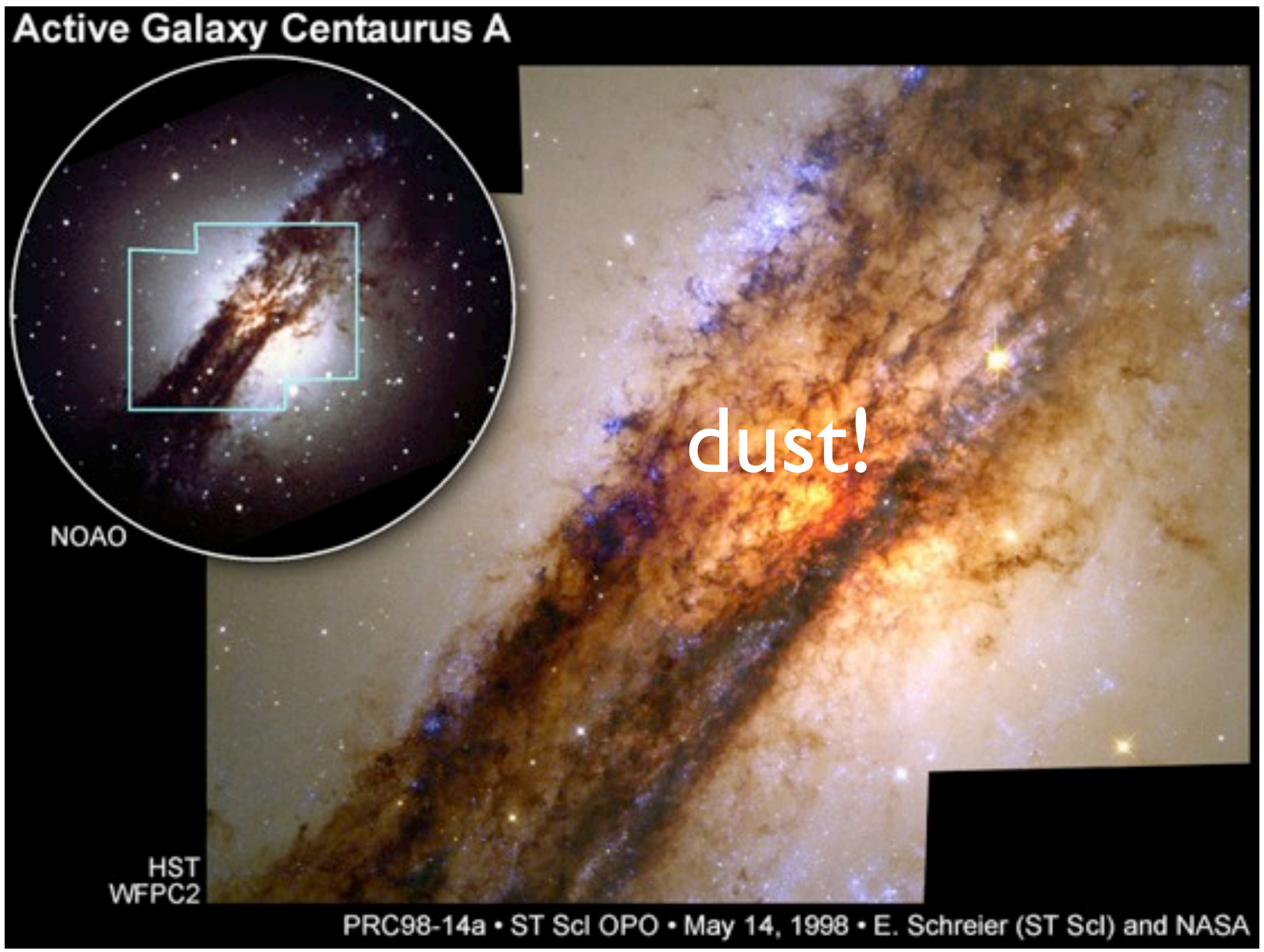


- In simulations, only about half of the cold gas is actually driven into the center of the remnant

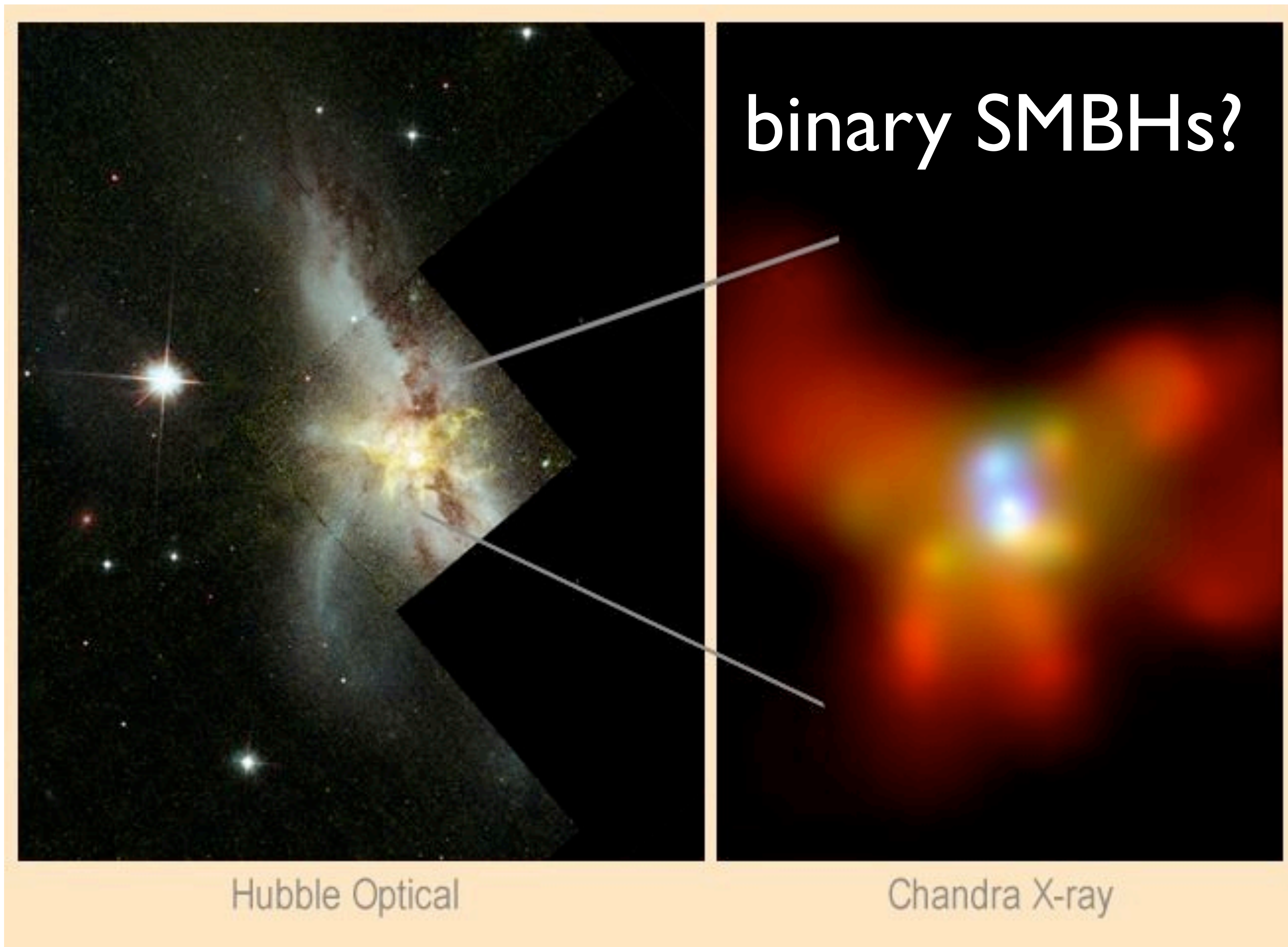
- The other half is thrown out into tails, which eventually rains down on the galaxy



Cen A (NGC 5128): a good candidate!

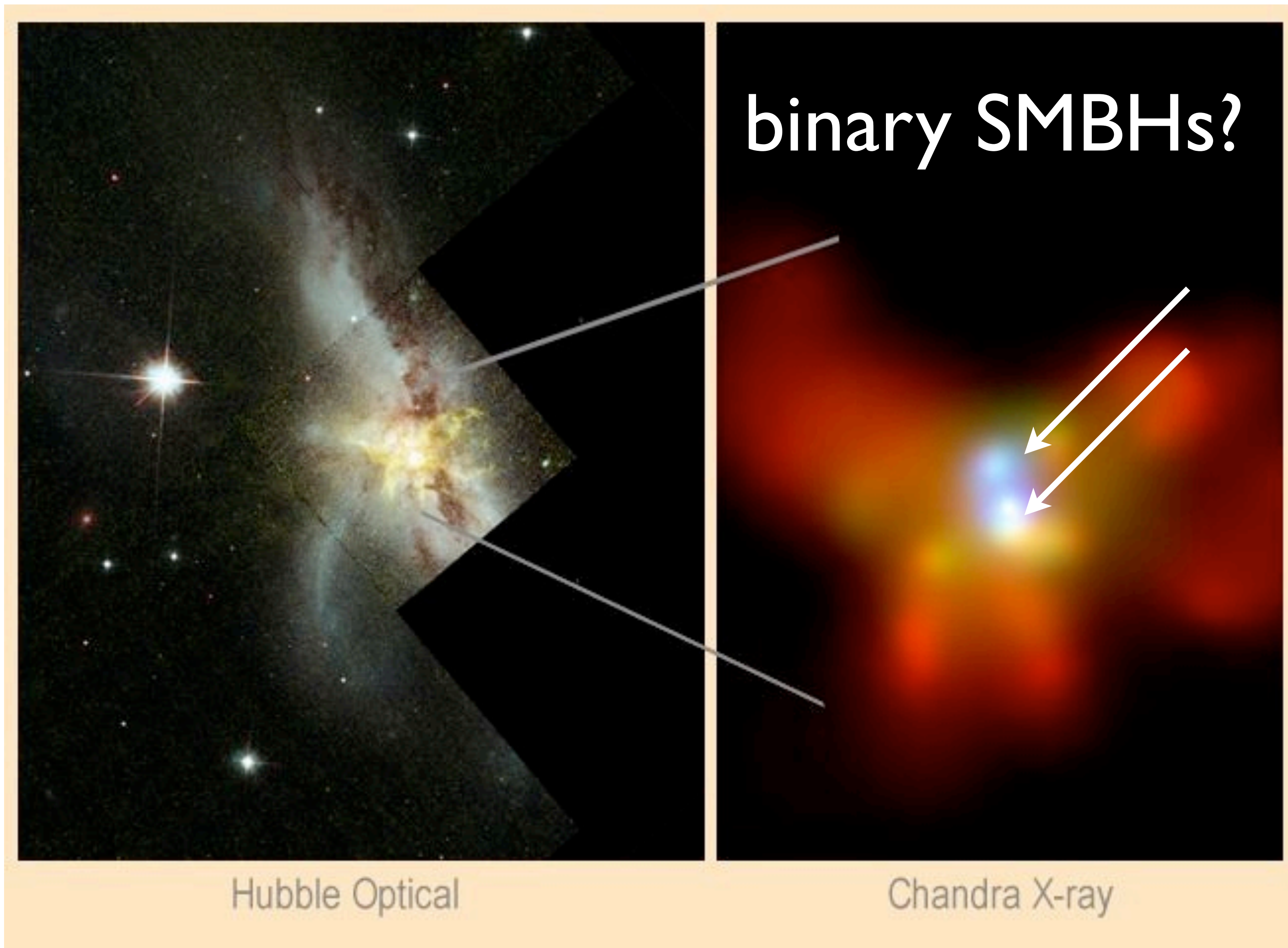


What about the black holes?



NGC 6240

What about the black holes?



NGC 6240

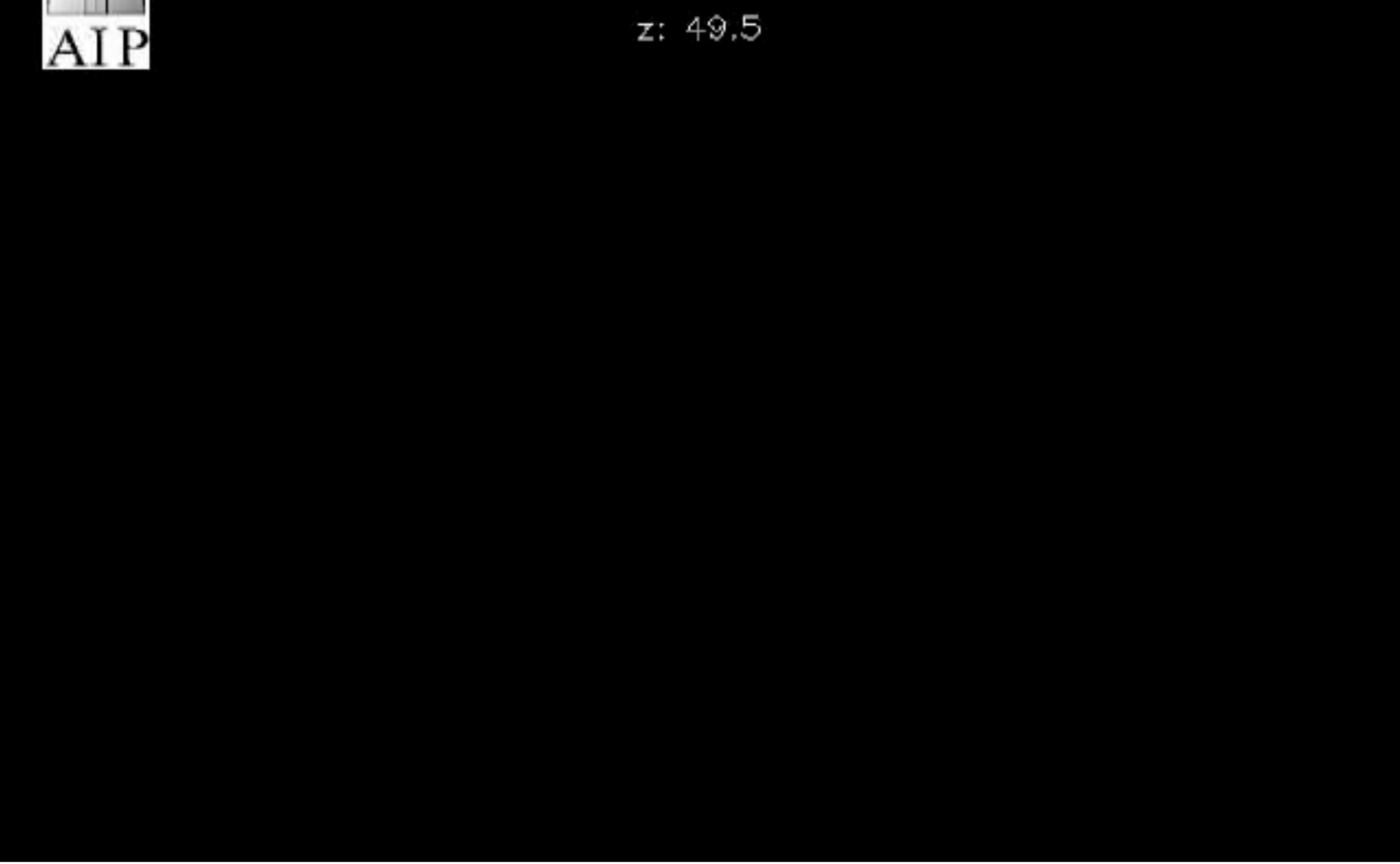
Dark matter & hierarchical clustering

- Theoretically, the fact that we think that dark matter is **cold** --- that is, it moves significantly more slowly than the speed of light --- means that **bottom-up** galaxy formation is the preferred scenario
  - This is because cold dark matter must cluster on scales smaller than galaxies, so that small objects are much more likely than big ones

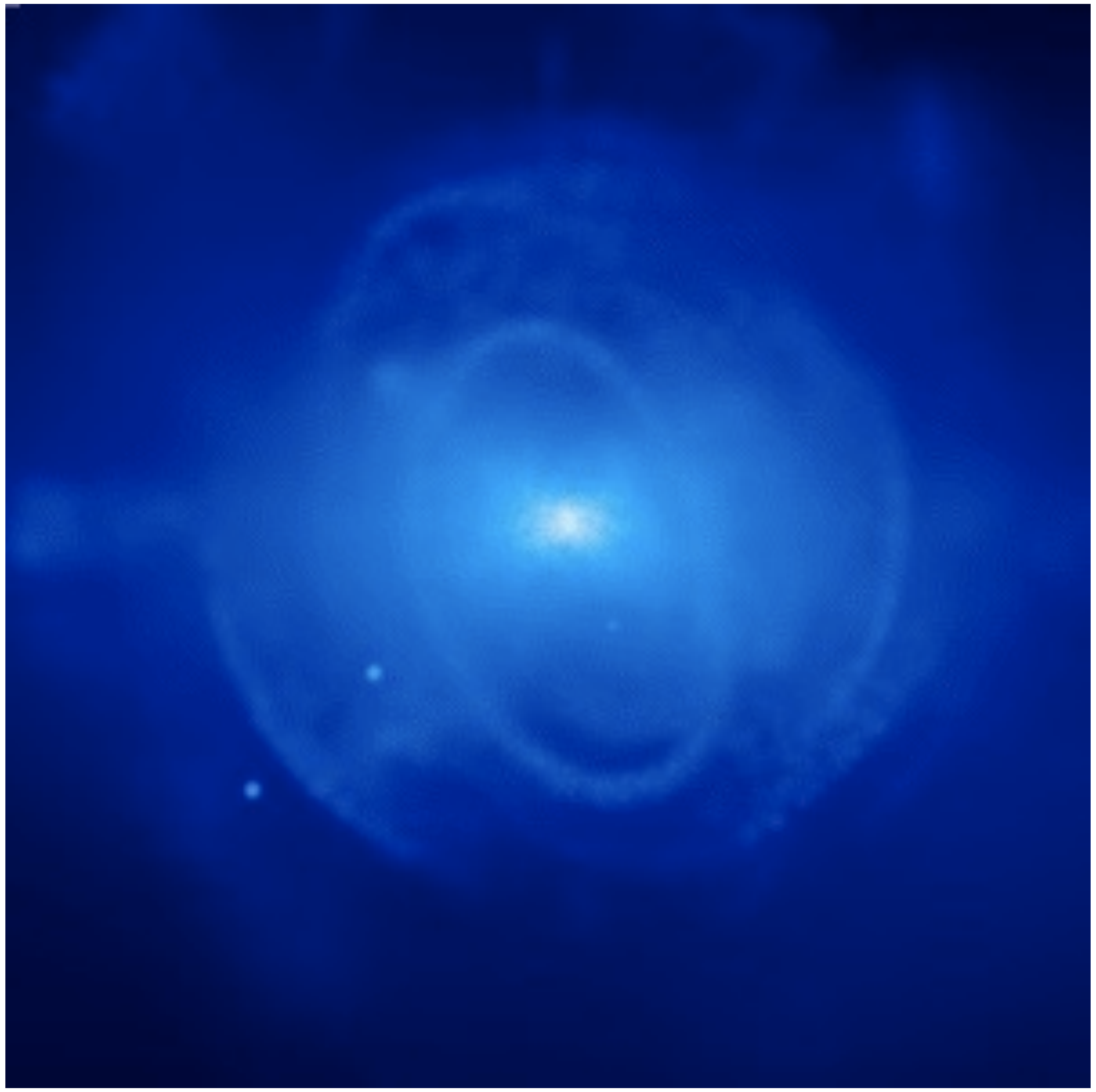
- This means that our preferred picture for the mass of the Universe drives us towards a merger-driven galaxy formation model

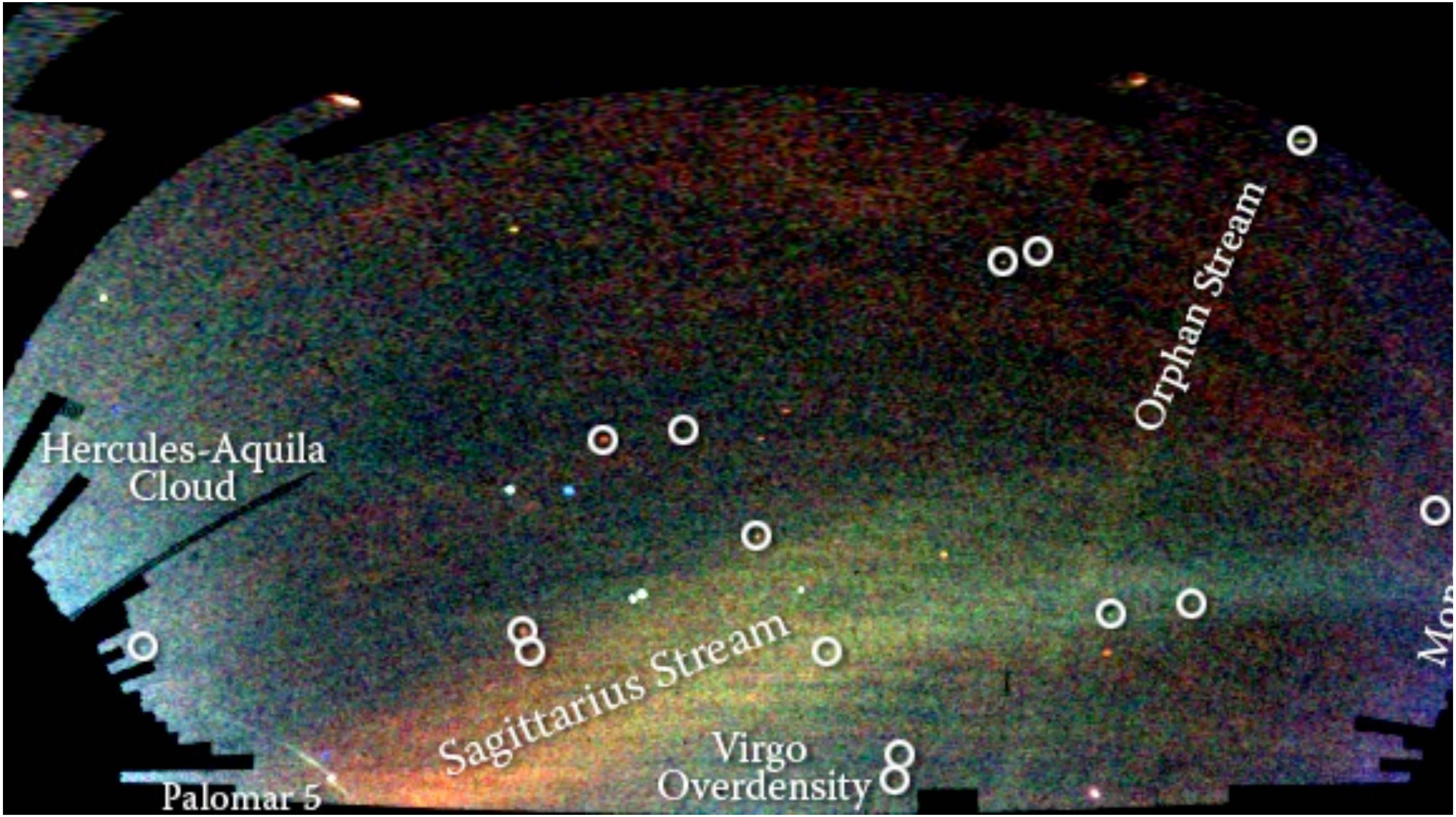
  - Note that if, instead, dark matter were **hot** --- that is, it moves near the speed of light, like, say, neutrinos --- then *top-down* scenarios like monolithic collapse are preferred, because the dark matter only clusters on very large scales, bigger than galaxies!

Disk galaxy formation in CDM



- One of the advantages of hierarchical formation of disk galaxies is that the complexity of the galactic halo arises from the mergers of smaller objects with the host





The "Field of Streams" in the MW halo

Elliptical galaxy formation in CDM

including SMBH feedback!

- This is ongoing work!
- We still don't really know how galaxy formation works, and we can't write down a compact system of equations that describe the process and the final product