# The Co-Evolution of Black Holes and their Host Galaxies


Dr. Vardha N. Bennert

Assistant Professor

California Polytechnic State University San Luis Obispo


Astronomy Club CalPoly SLO

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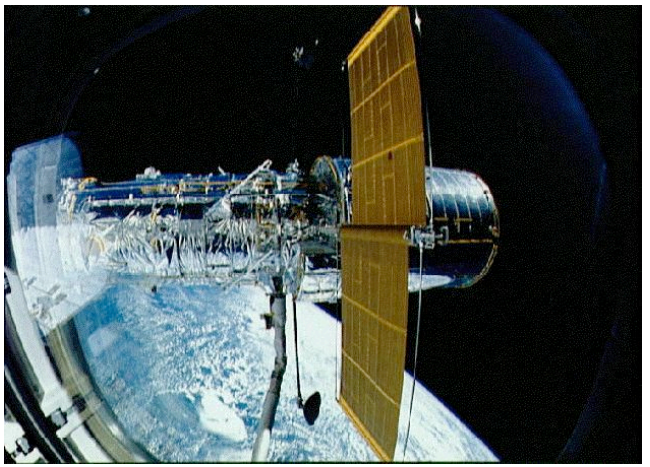


NSF

NASA

The co-evolution of black holes and their host galaxies

# Intro I: Galaxies

http://www.ifa.hawaii.edu/users/tully/outreach/movie.html

# Hubble Ultra Deep Field

Deepest image of Universe
ever taken

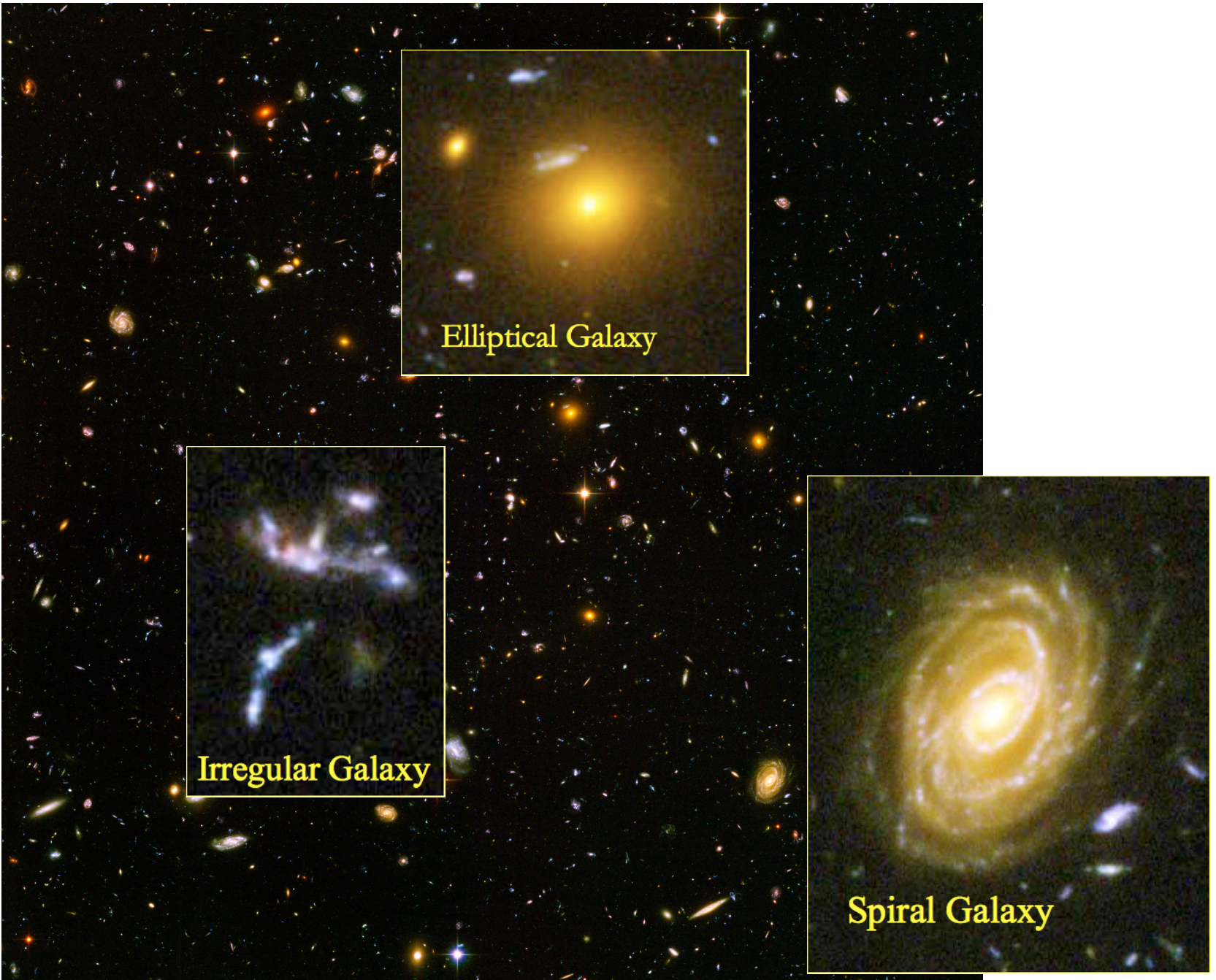
11 days with Hubble

Almost every blob: galaxy
~10,000 galaxies

Tiny size!

Extrapolate:
>100 bio. galaxies
in Universe!

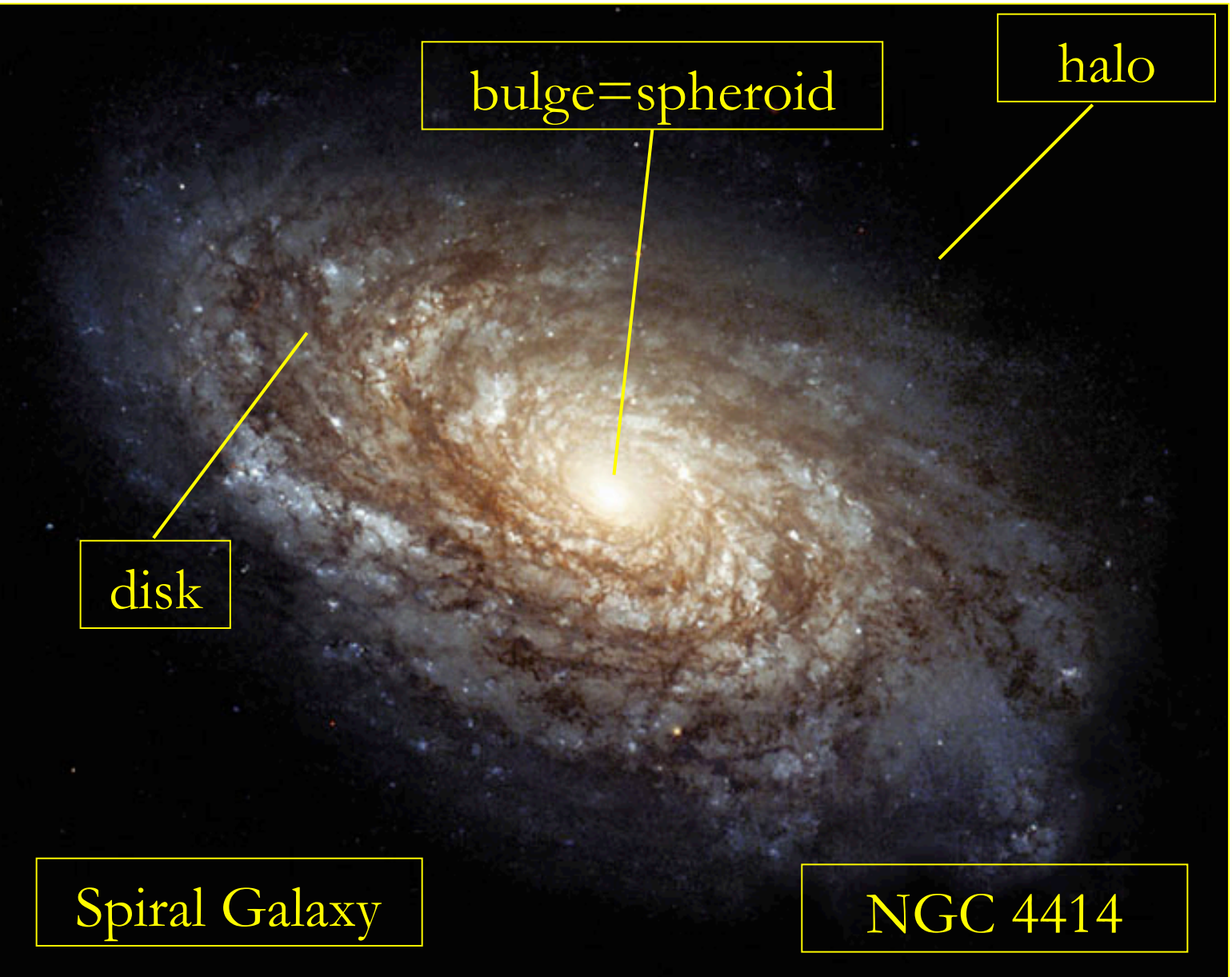
# Galaxies come in different shapes and sizes

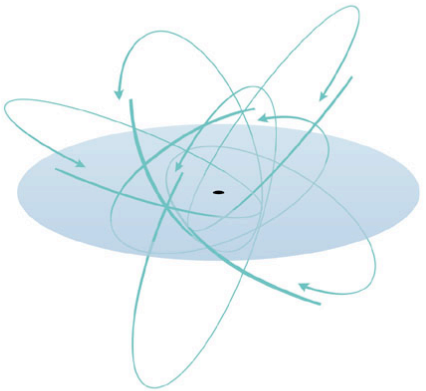


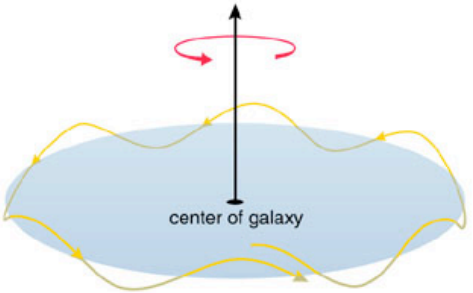
# Spiral galaxies

Gas & dust: starformation

Most common in local Universe

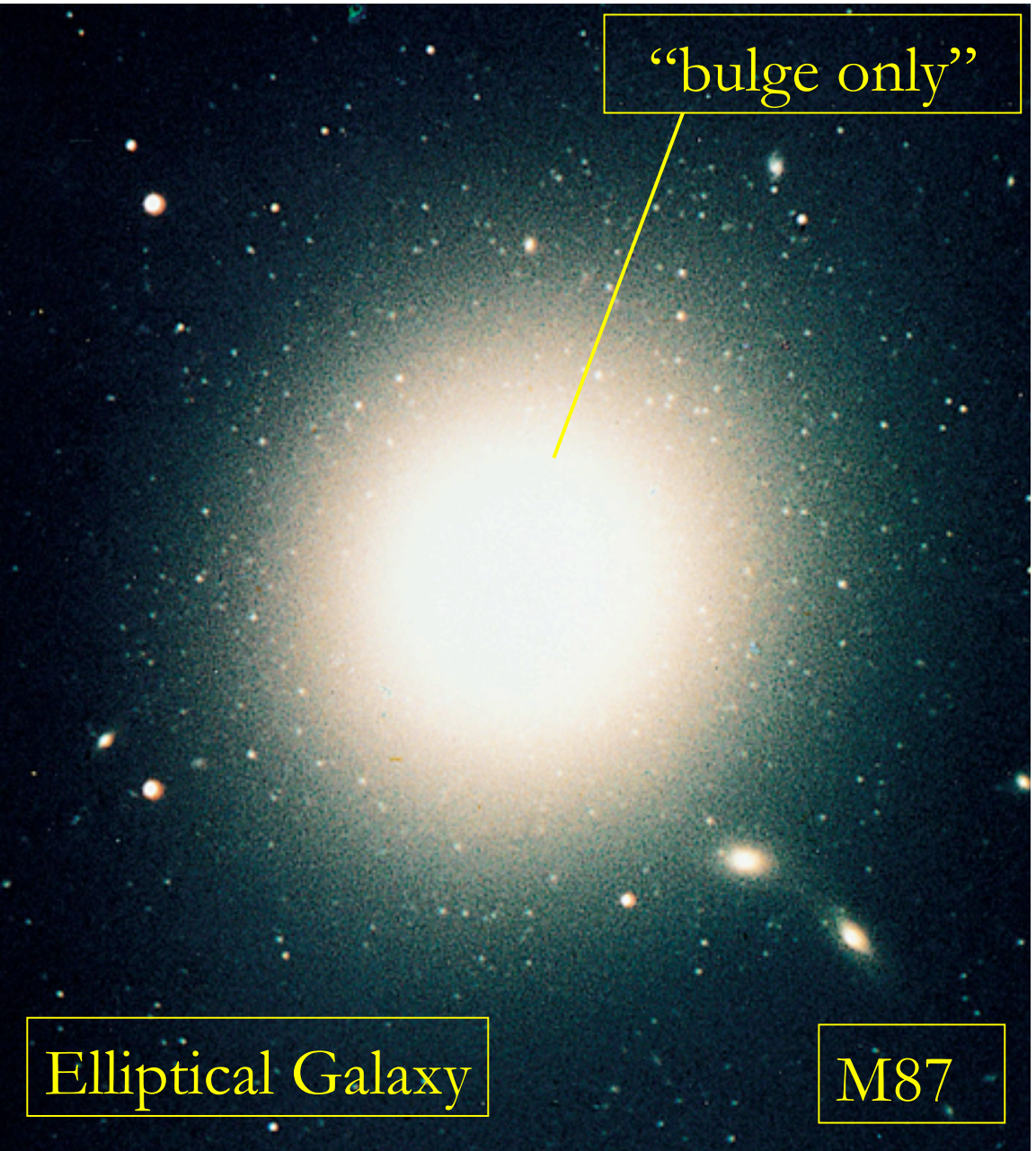


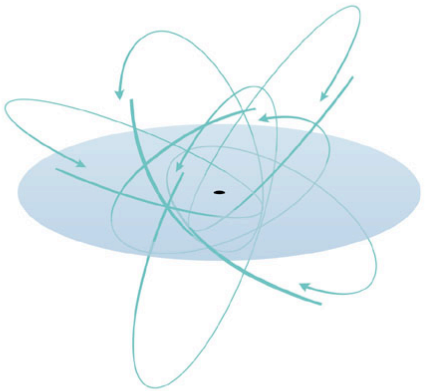





# Elliptical galaxies

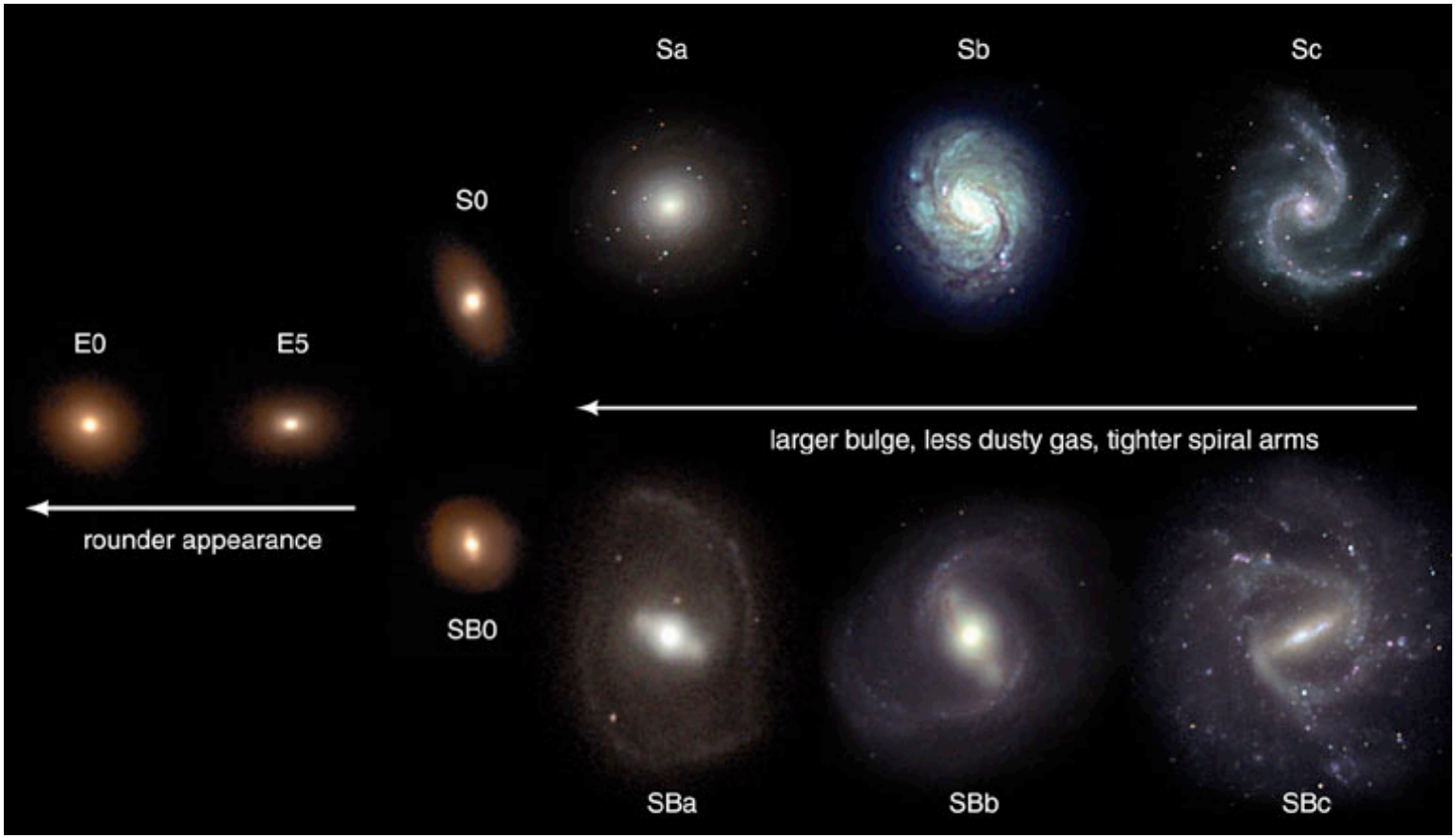
Little gas/dust: no starformation



# Hubble's tuning fork

Edwin Hubble
(1889–1953)

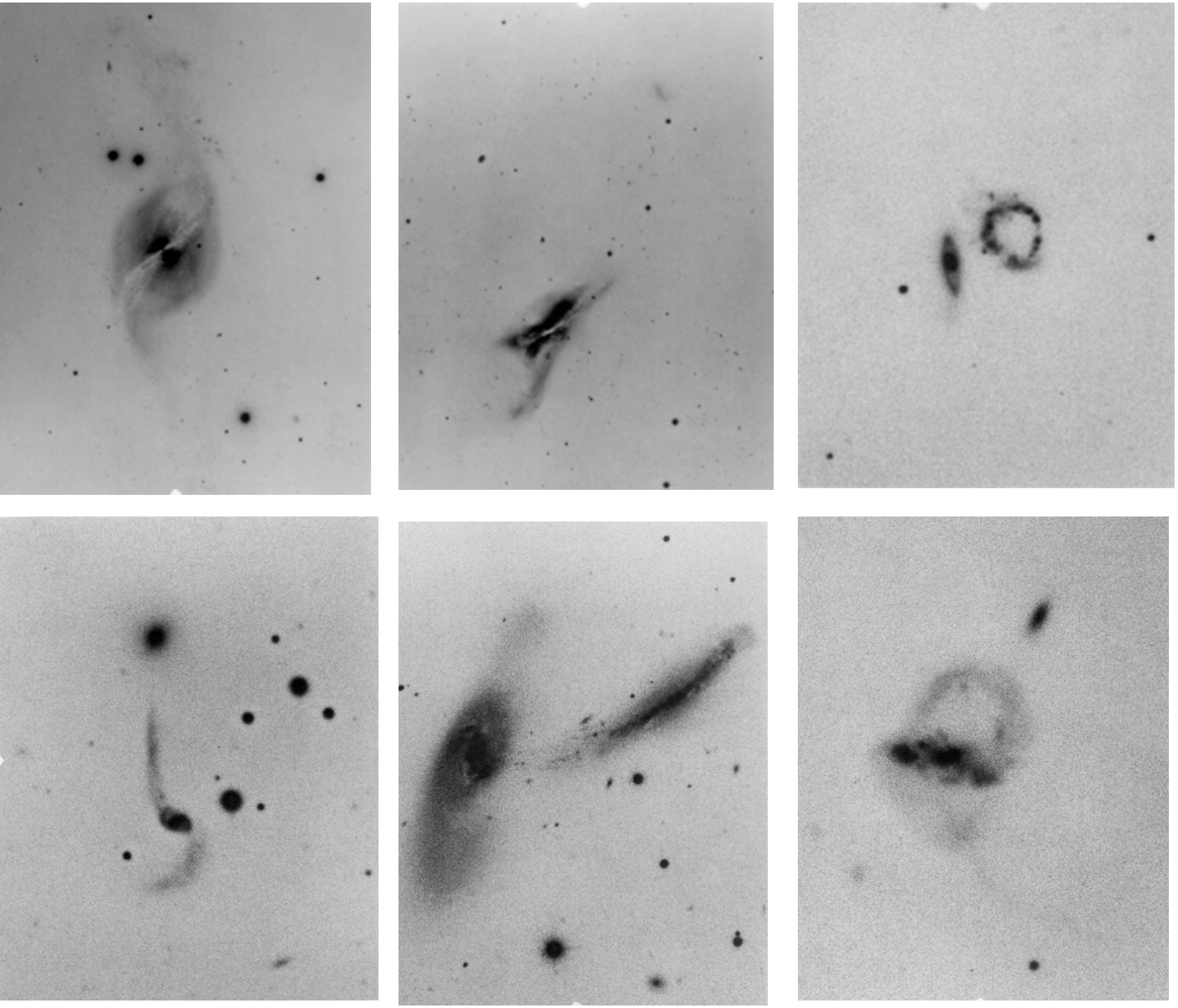



Spheroid
dominates

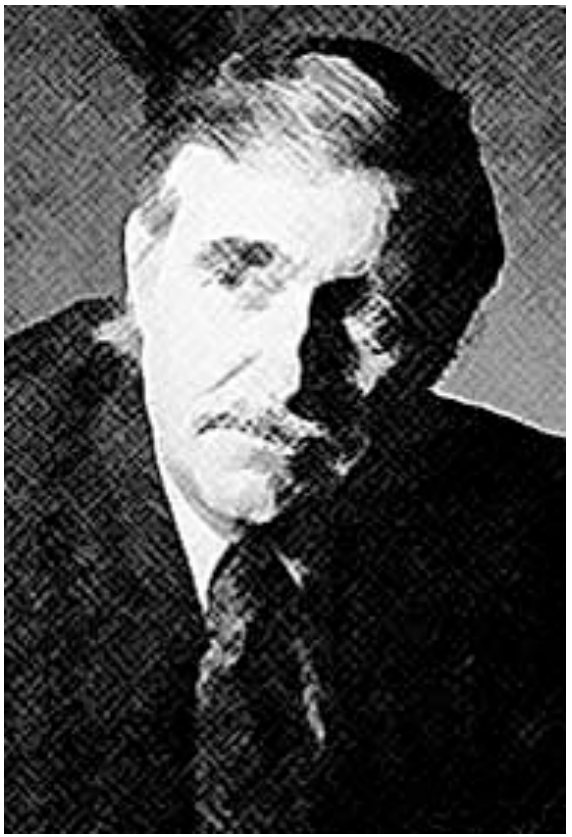
Disk
dominates

# Irregular galaxies

# Arp's *Atlas of Peculiar Galaxies* (1966)



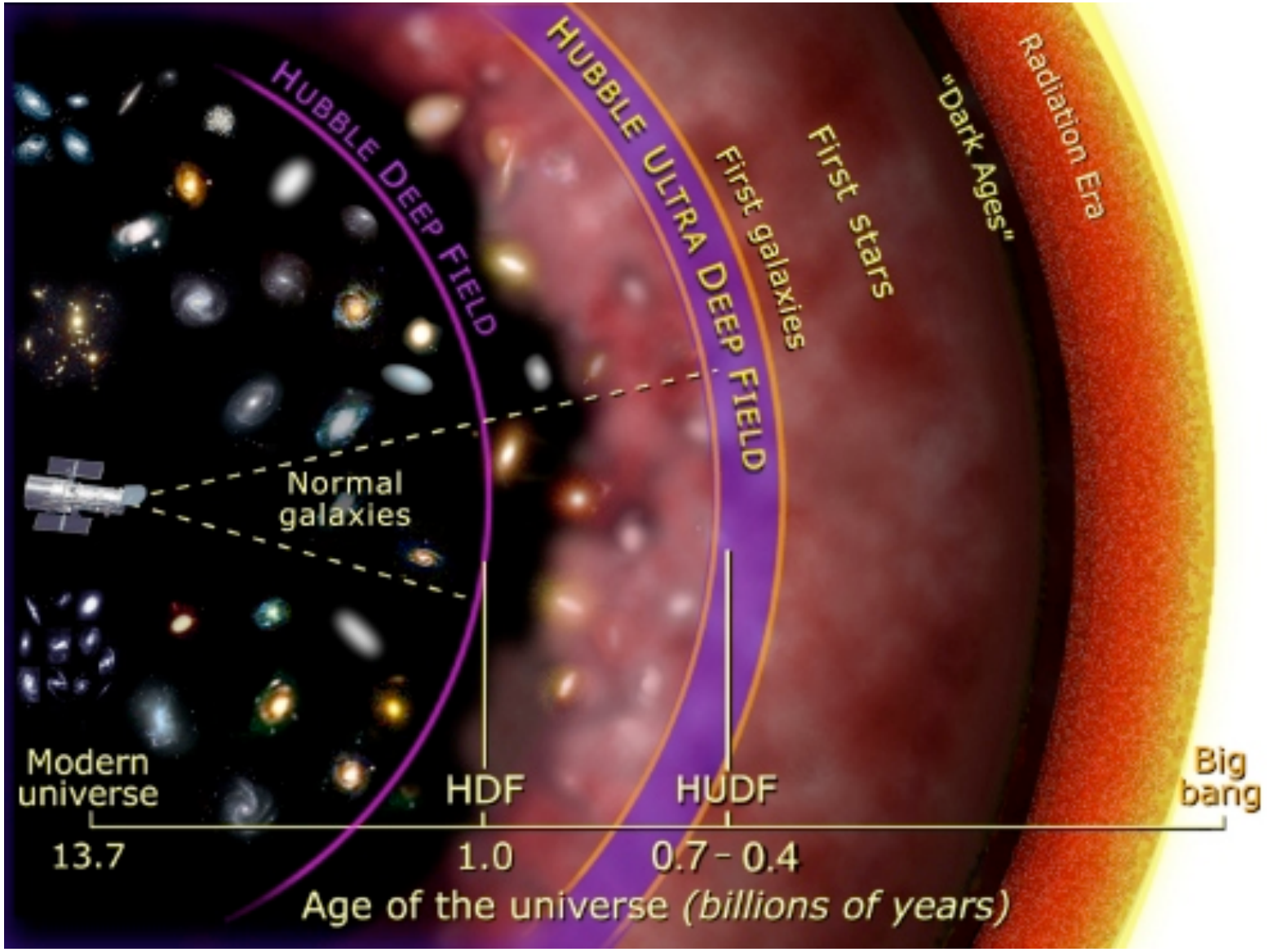
Palomar telescope, Southern California



Halton Arp, Caltech
(1927–present)

# Telescopes are time machines

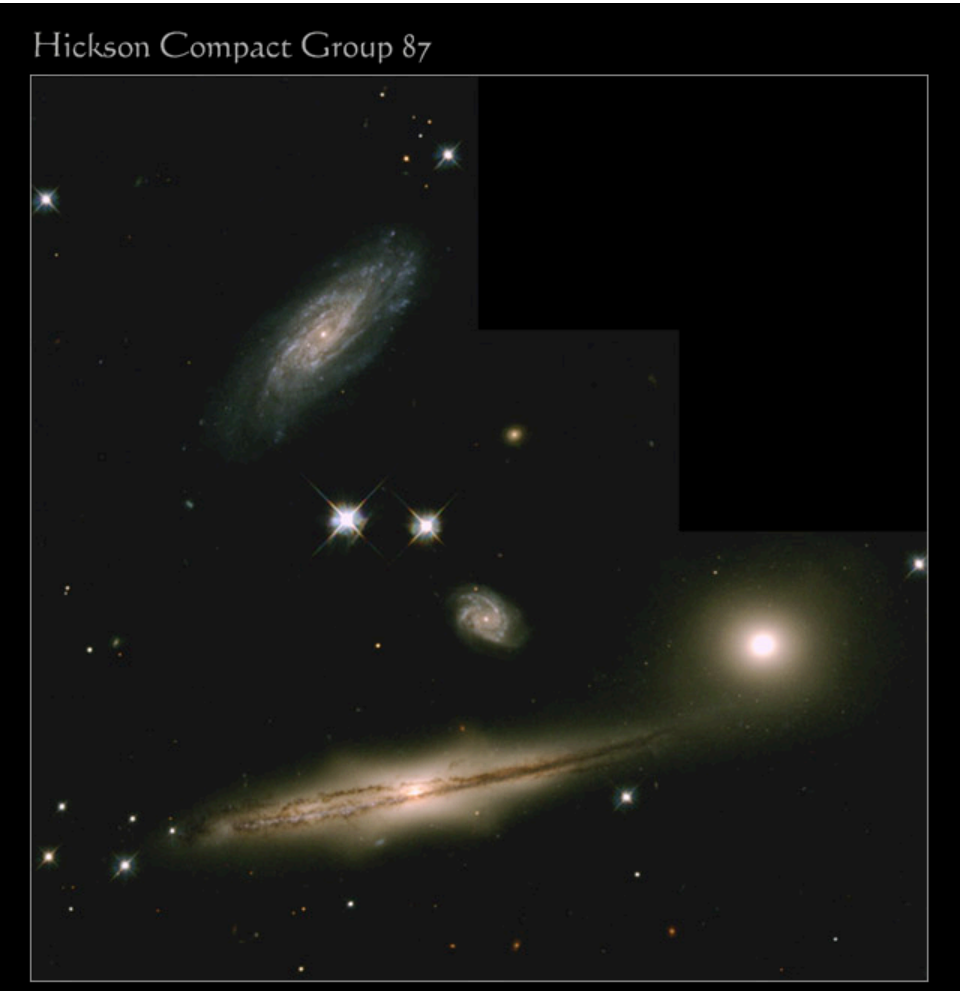
Irregulars more common in earlier Universe

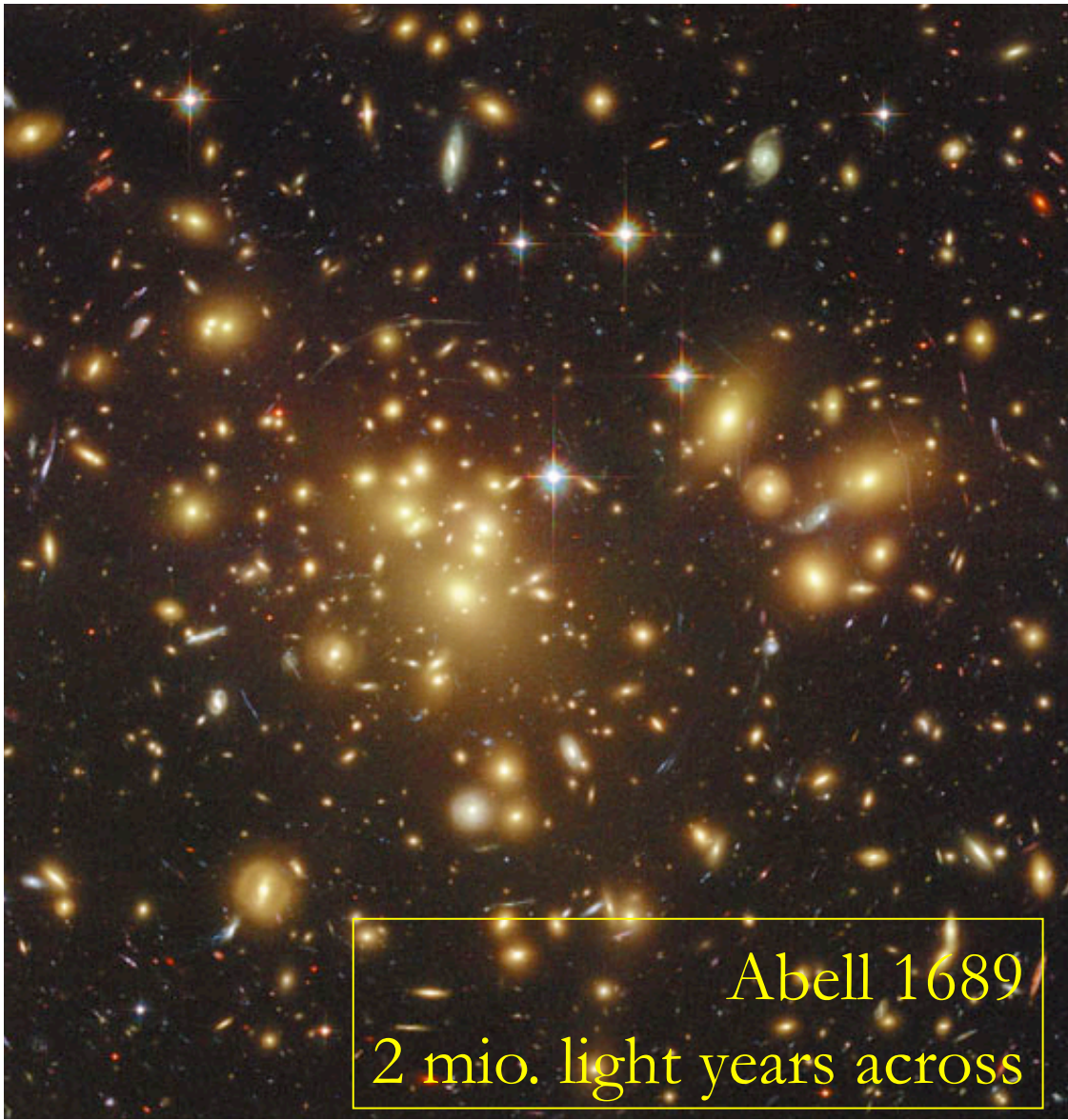


# Galaxies live in groups and clusters

Ellipticals more common in clusters

Giant ellipticals in center



# Galaxy interactions

If sun = grapefruit:

next star = grapefruit

New York

If Milkyway = grapefruit:

Andromeda = grapefruit

In the first row!

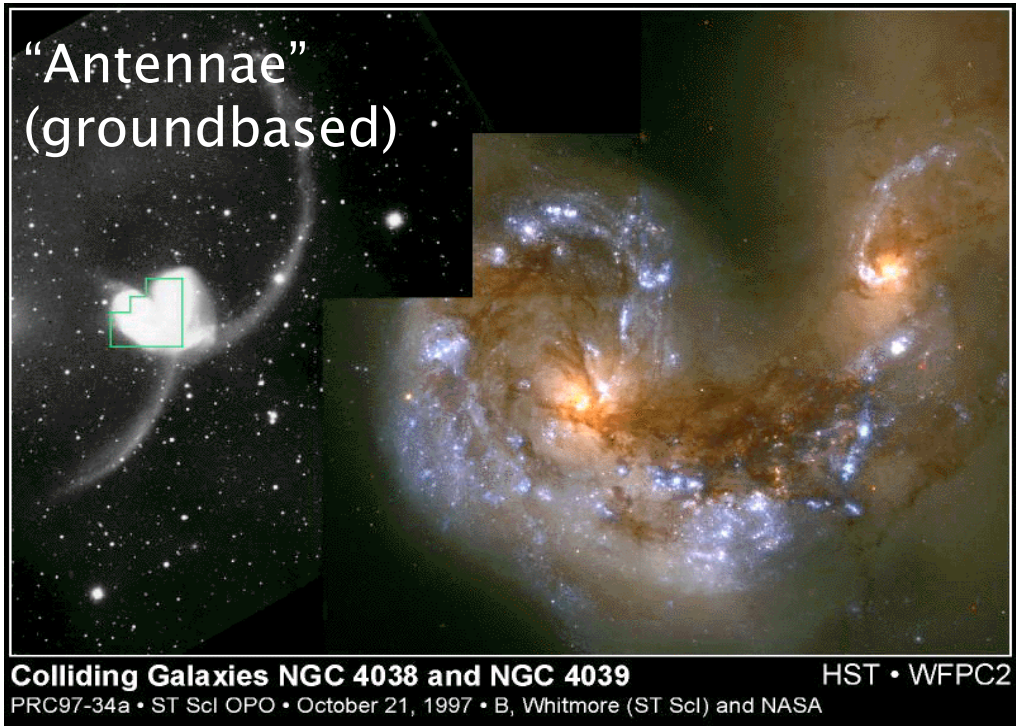
# Galaxy interactions

Galaxies interact, merge

More frequent in earlier Universe –
galaxies closer together (more irregulars)

Collisions take hundreds of millions of years – snapshot only

Computer simulations



# Galaxy interactions

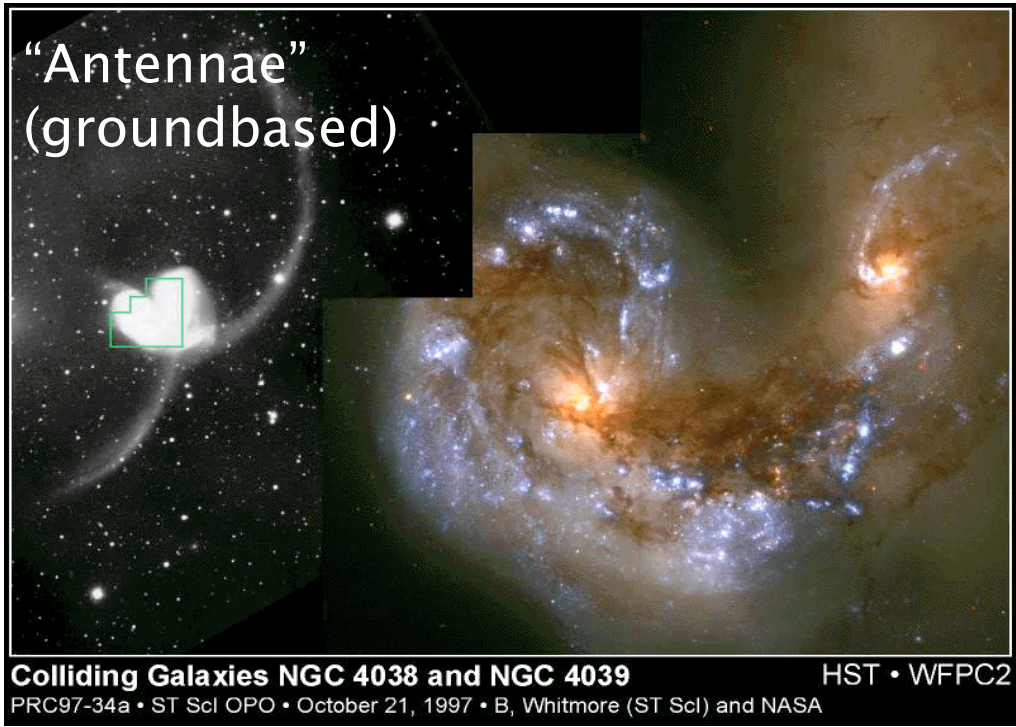
# Galaxy interactions

Ellipticals formed by mergers of spirals

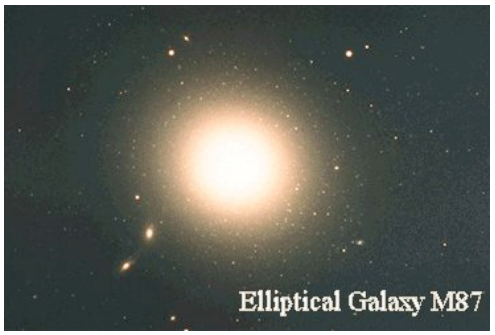
Tidal forces tear apart disks, randomize orbits

Gas forms new stars until used up/blown out

In center of dense clusters: giant ellipticals, galaxy cannibalism



# A simple equation

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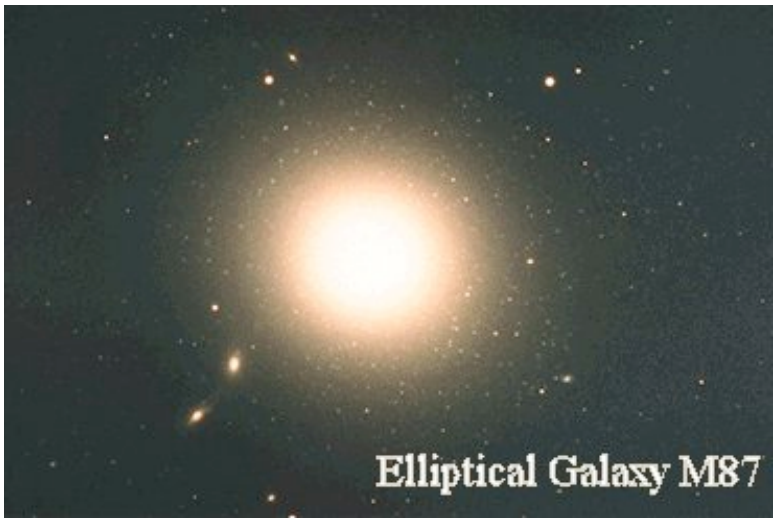
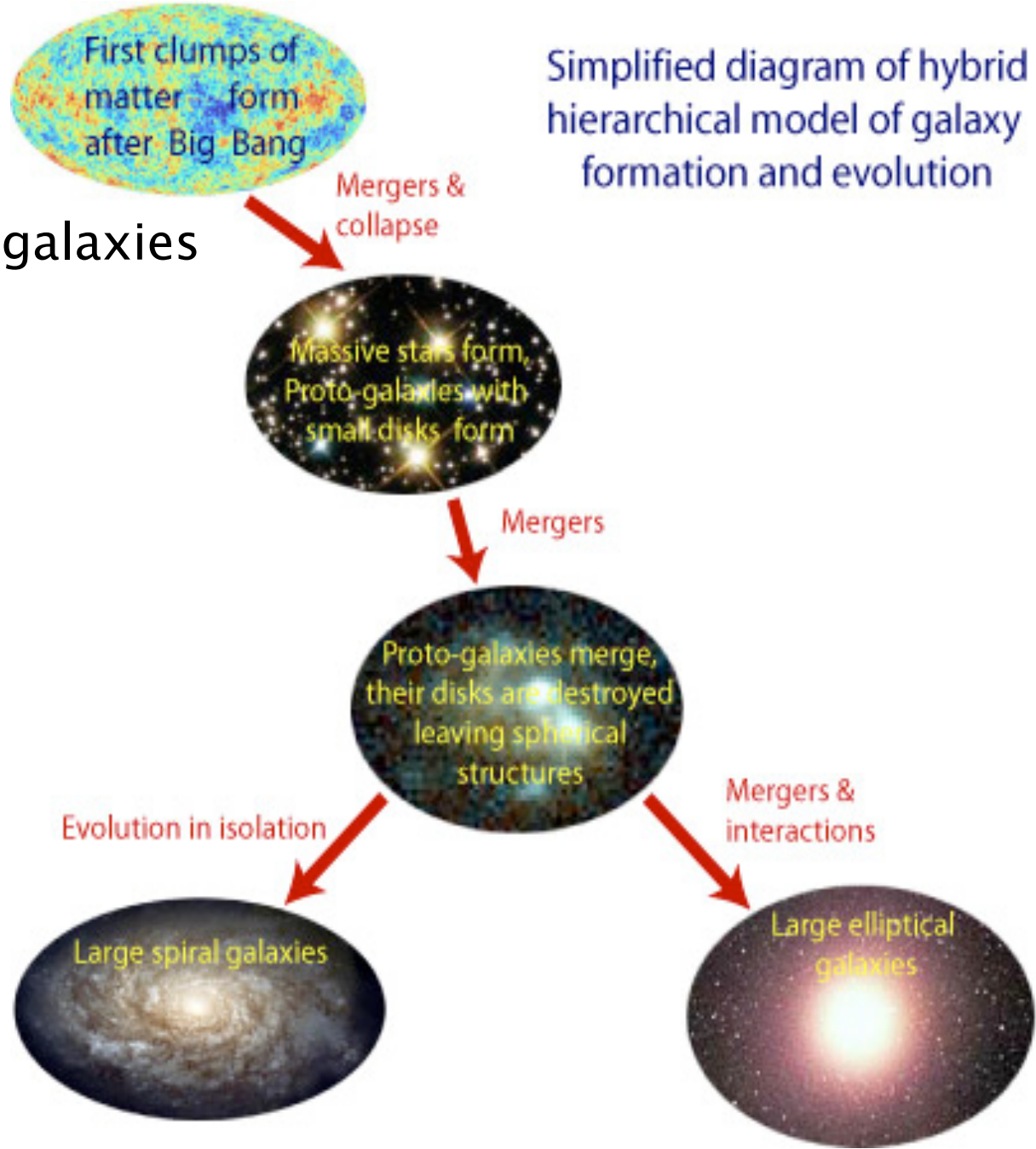


# Galaxy formation and evolution

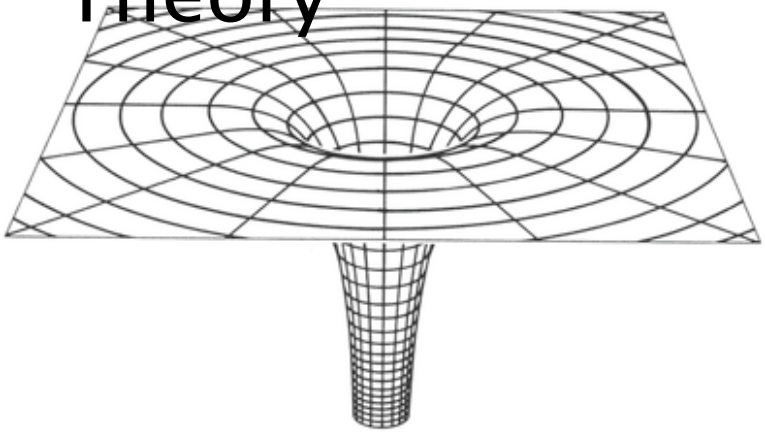
Hierarchical cosmology:
big galaxy today
= hundreds of smaller proto-galaxies




Simplified diagram of hybrid hierarchical model of galaxy formation and evolution

# The co-evolution of black holes and their host galaxies

## Intro II: Black Holes - Theory



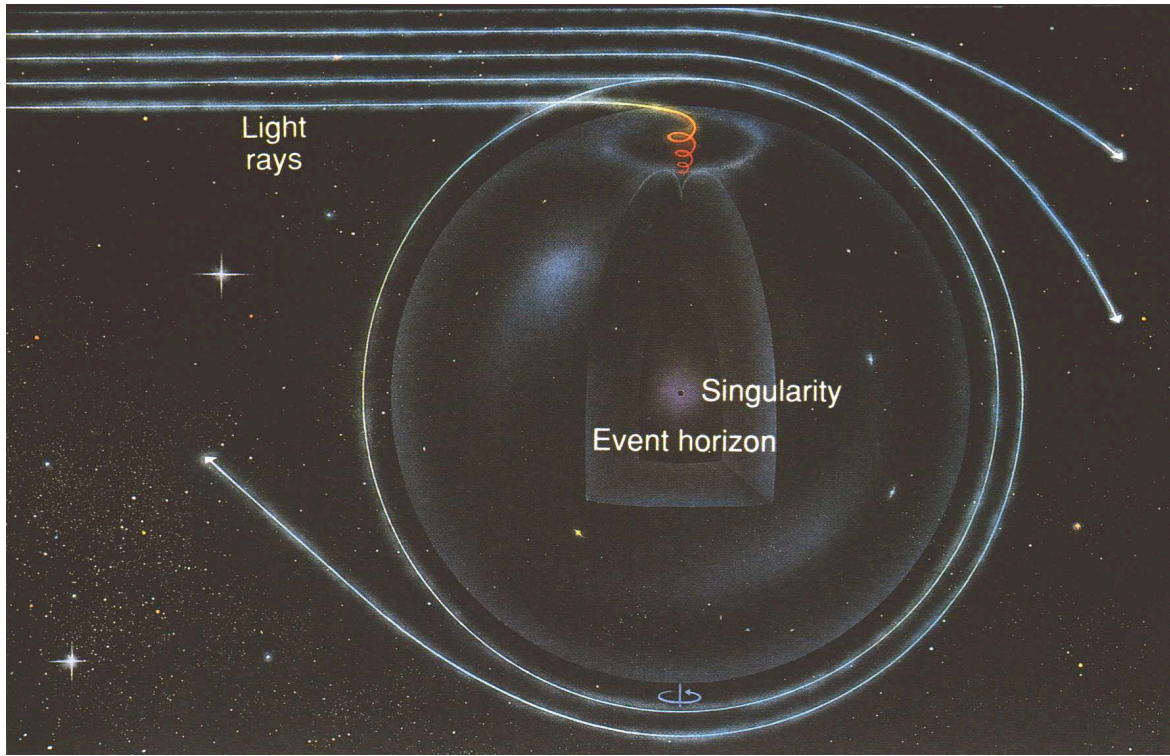
Predicted by Einstein's Relativity Theory

So massive that not even light can escape

But: BHs don't suck!

End state of very massive star

Large range of masses



# Black holes – observations

Stars orbit Galactic Center

Keplerian motion
(like planets in solar system)

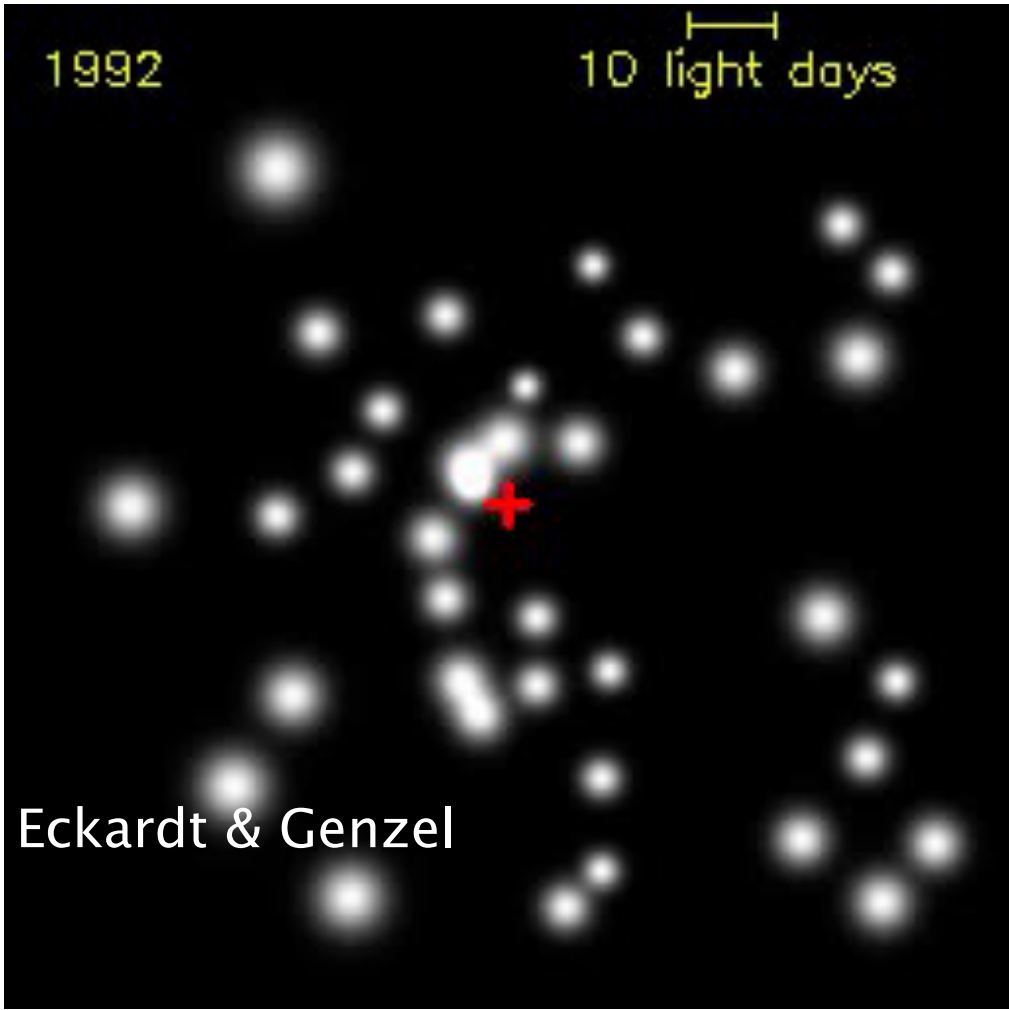
Calculate central mass: $M=v^2r/G$
~4 million solar masses

Region: hardly larger than solar system

Dark

Best evidence of very massive Black Hole

Black Hole:
best explanation of massive object
that still remains unseen



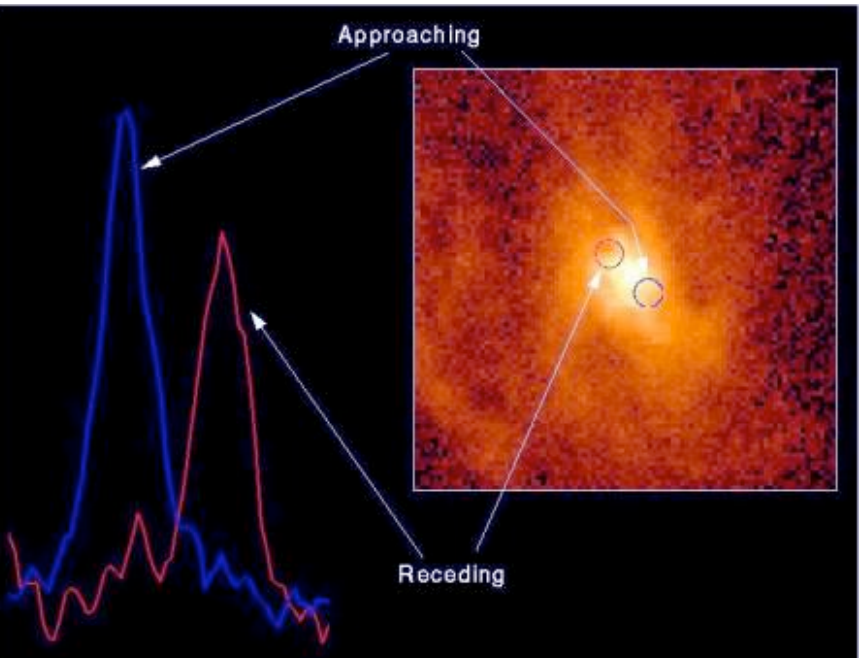
# Black holes – observations

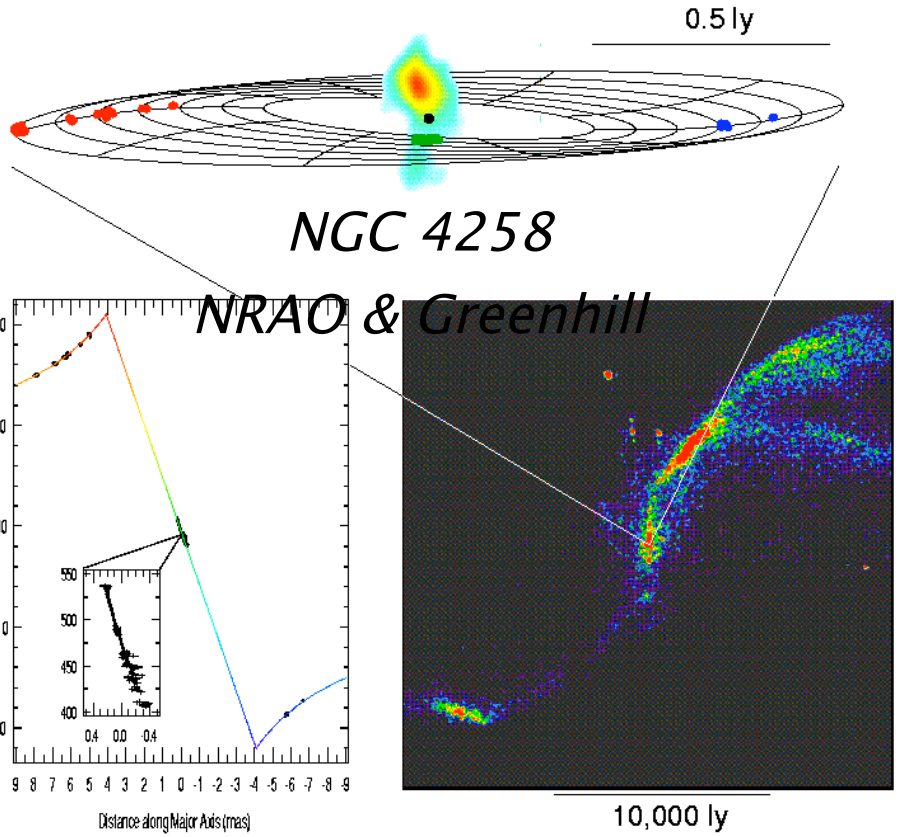
Weighing black holes:

motion of stars and gas („Doppler shift“)


Black holes in all galaxies (with bulge)?

*M87 (HST)*



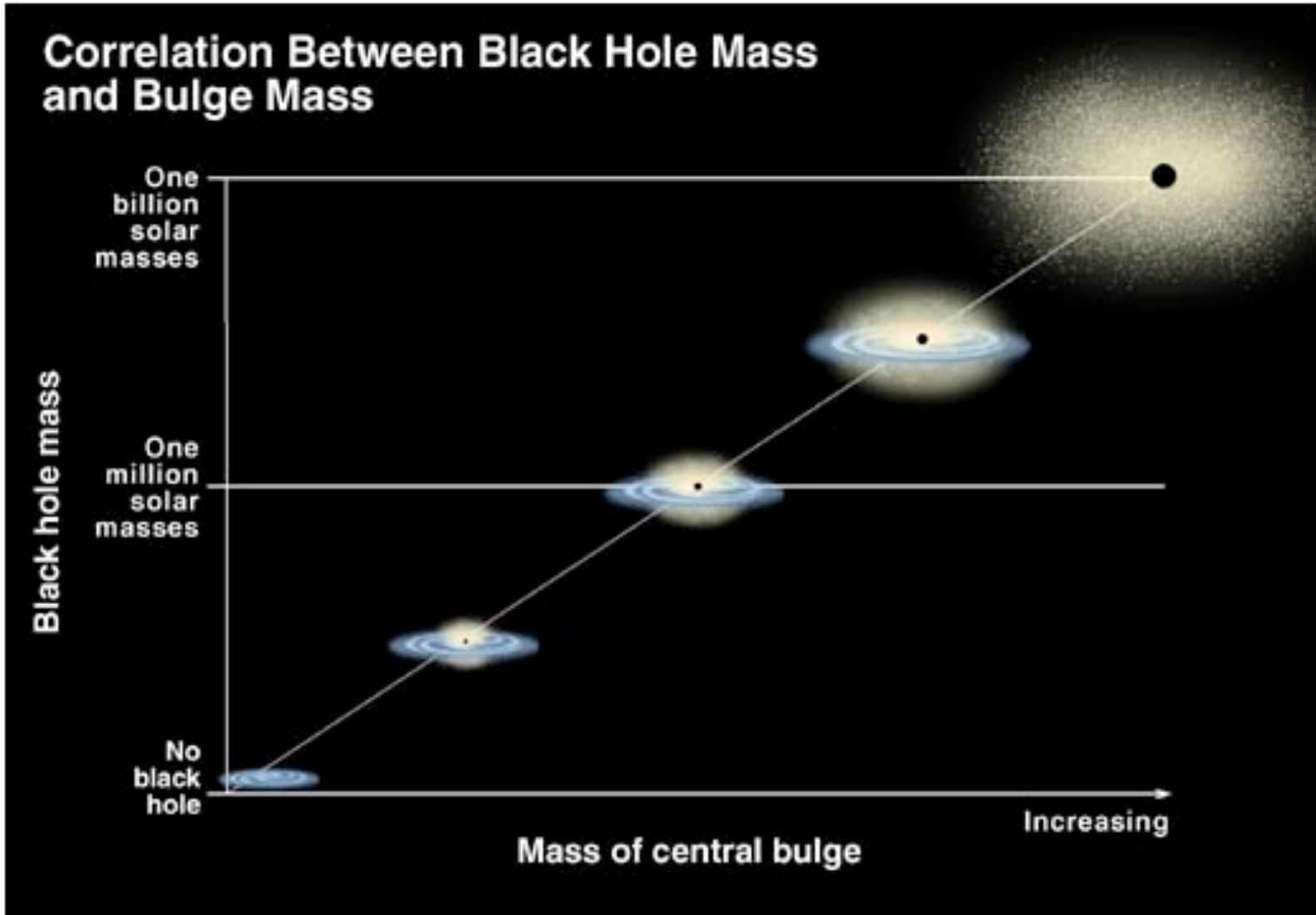

*NGC 4258*

*NRAO & Greenhill*

# The co-evolution of black holes and their host galaxies

In local Universe:

Mass of BH ~ 0.2 % of mass of stars in bulge!



# The co-evolution of black holes and their host galaxies

Why are masses of black holes and their host galaxy bulge related?

Very different scales involved:

Size of bulge ~ 1000 times gravitational sphere of influence of BH

Suggests that formation and evolution of BHs & hosts are linked!

Chicken-and-egg-problem:

What was first, the BH or the galaxy?

# The co-evolution of black holes and their host galaxies

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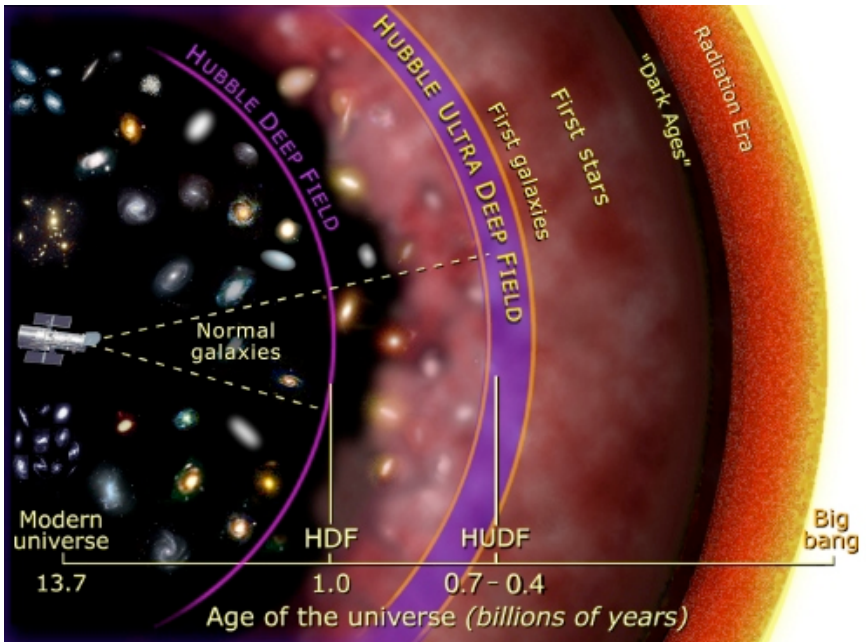
Chicken-and-egg-problem:

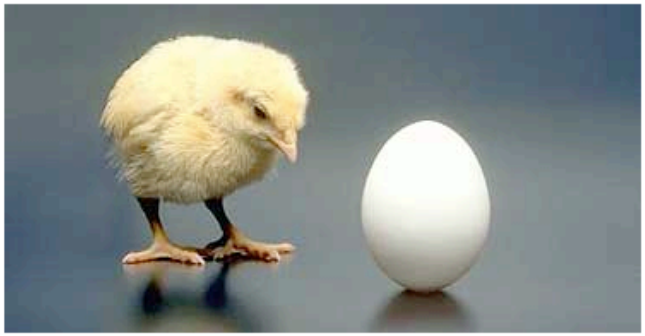
What was first, the BH or the galaxy?

Idea:

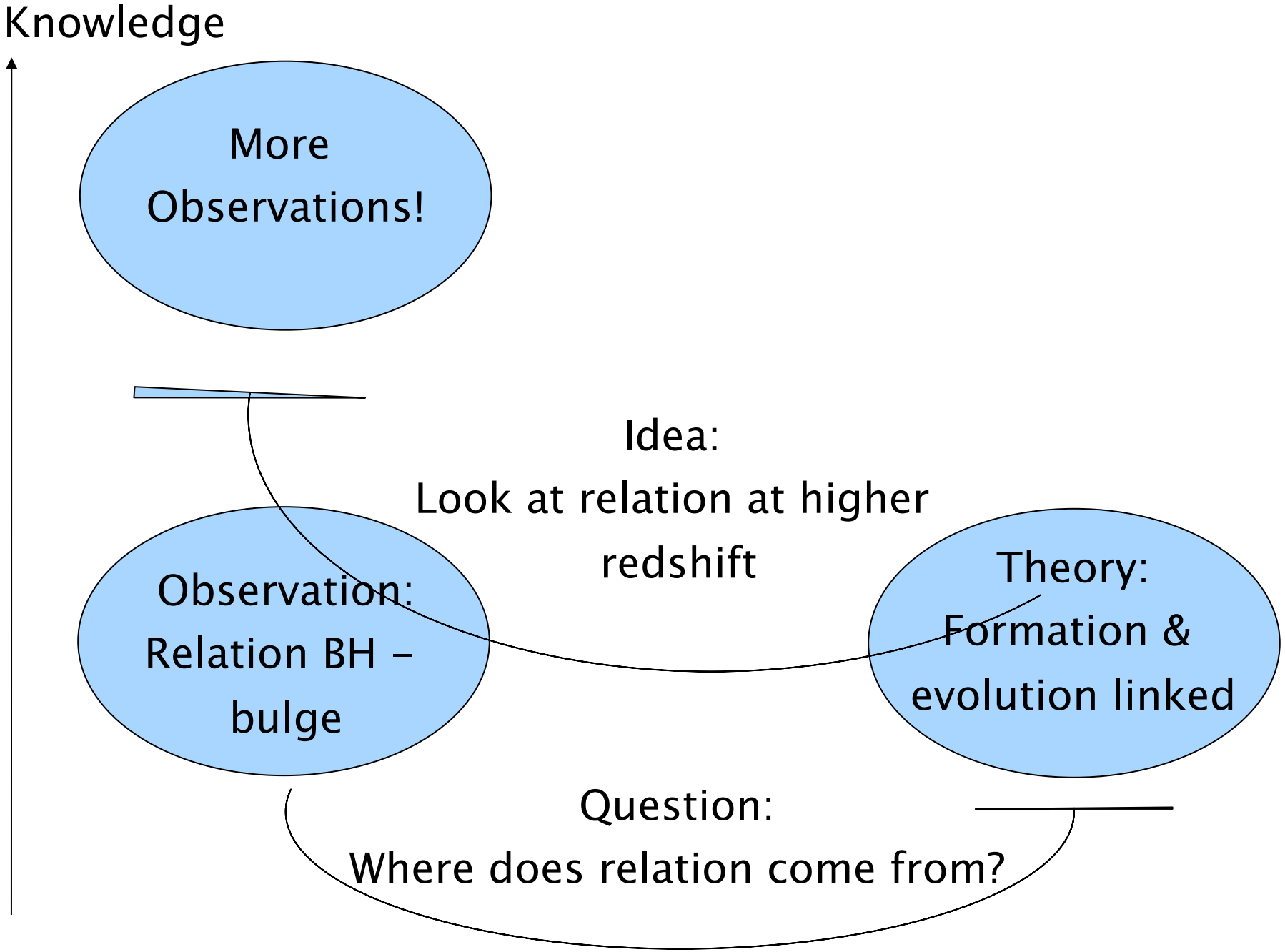
Look at evolution with time



# What was first?



# The natural cycle of science spiral



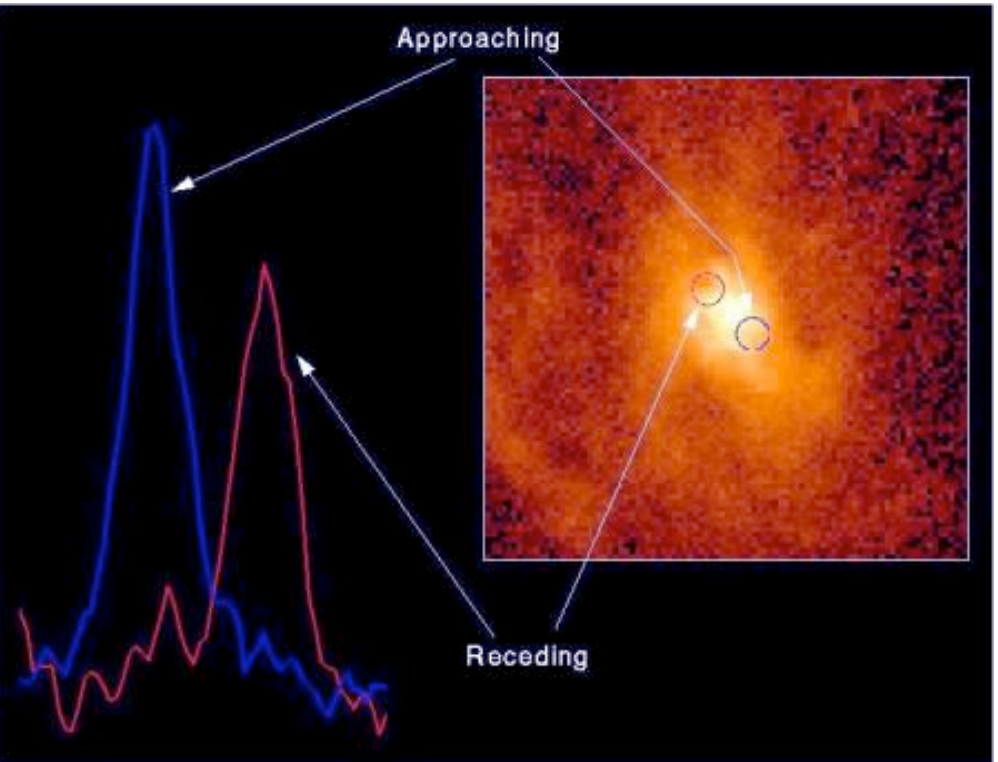
# The co-evolution of black holes and their host galaxies

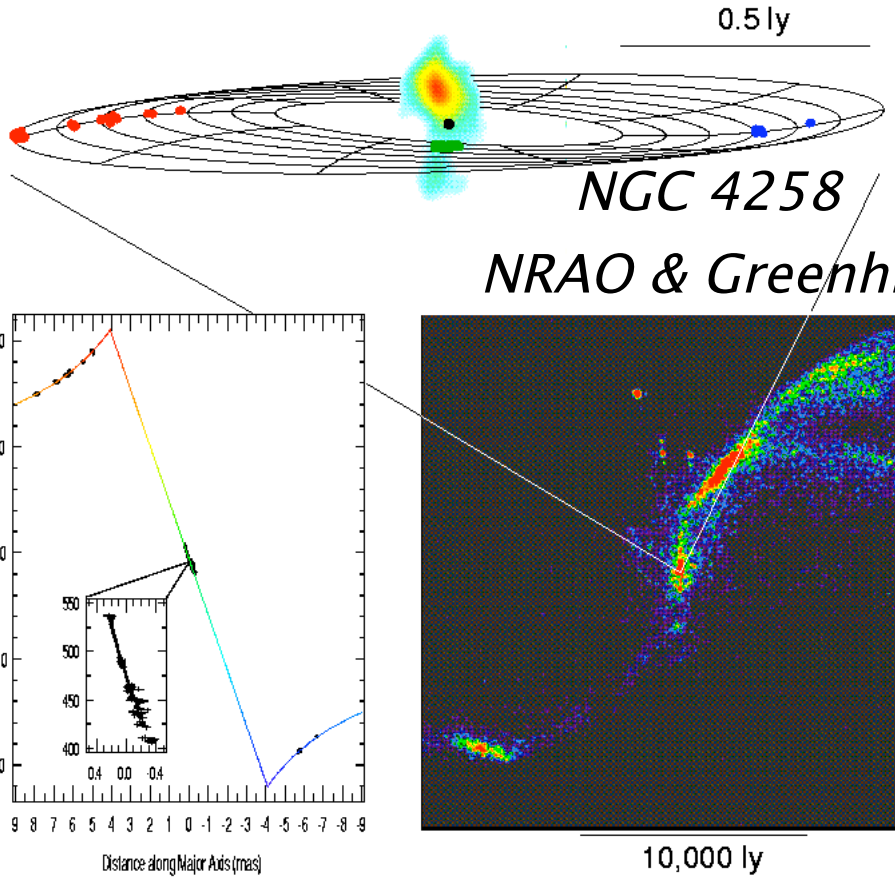
Problem:

How to weigh BHs?

Resolve gravitational BH sphere of influence

Limited to local Universe



# Intermission: Active galaxies

Luminosity:

Center as bright as whole galaxy

Detected out to large distances (more common)

Size:

Not resolved on images

Rapid variability (weeks) – light week across

(Sun – closest star: ~4 light years)

How is large luminosity produced on small scales?

# Intermission: Active galaxies

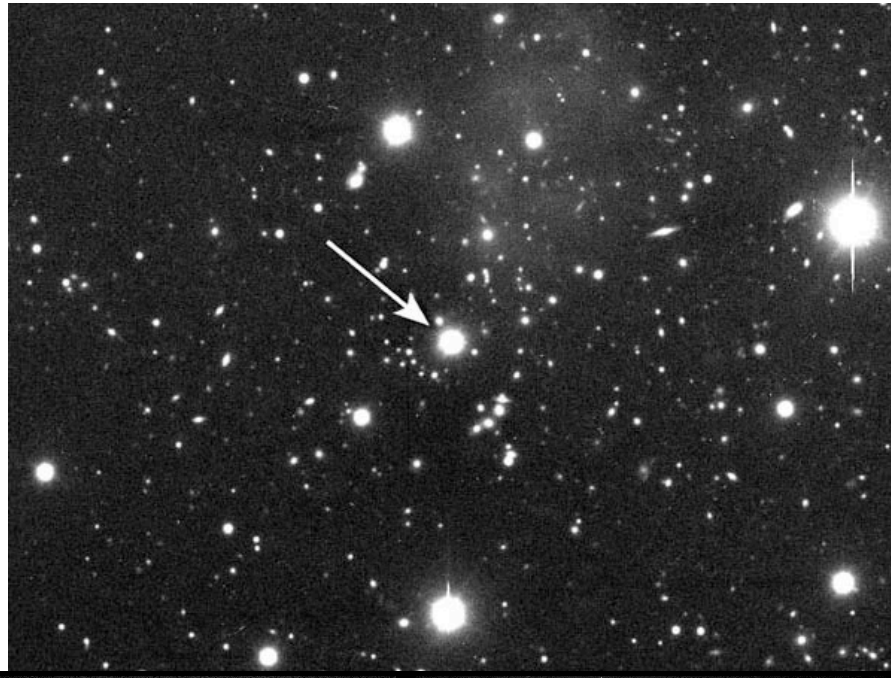
QSOs: Quasi-stellar objects

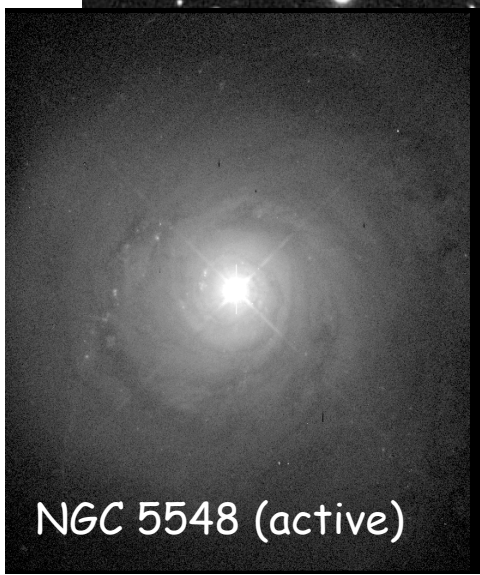
look like stars

„Twinkle, twinkle quasi-star
Biggest puzzle from afar
How unlike the other ones
Brighter than a billion suns
Twinkle, twinkle, quasi-star
How I wonder what you are”
(George Gamov 1964)

Particularly bright AGNs

Can be found to very great distances





NGC 5548 (active)

NGC 3277 (not active)

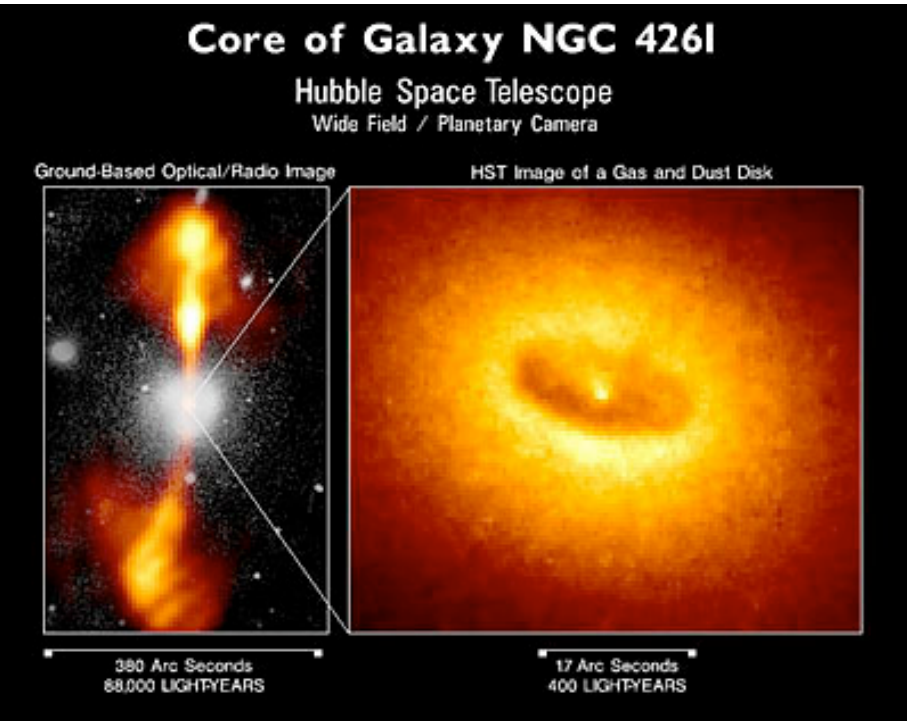
# Intermission: Active galaxies

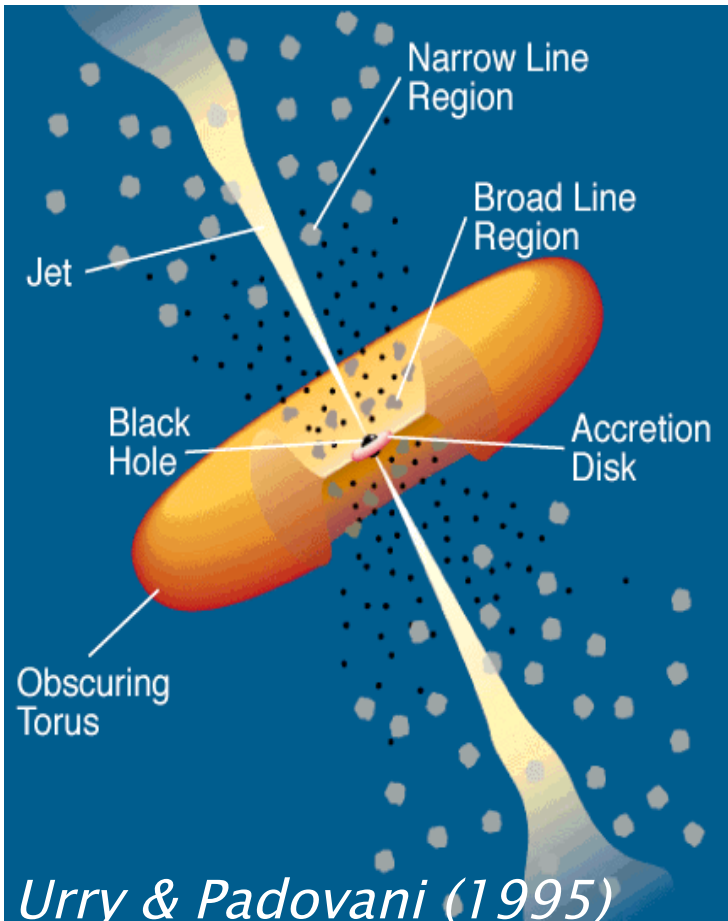
Accreting black holes!

Accretion: accumulation of gas & dust (~1 solar mass/year)

Matter falls into BH through accretion disk

Gravitational potential energy transformed into light



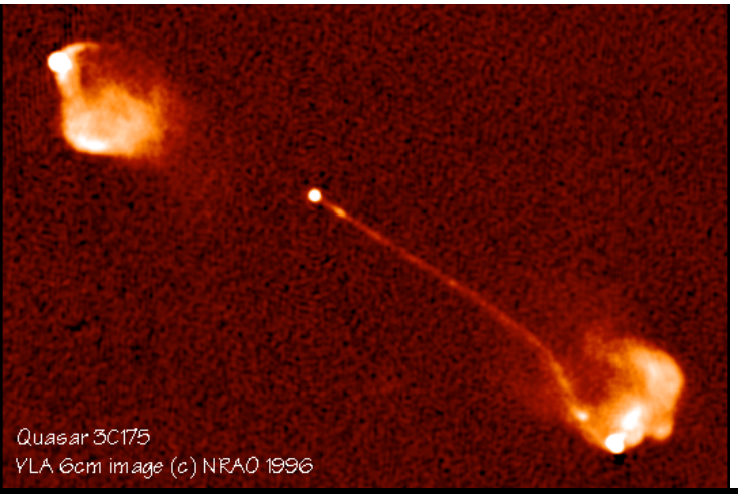

*Urry & Padovani (1995)*

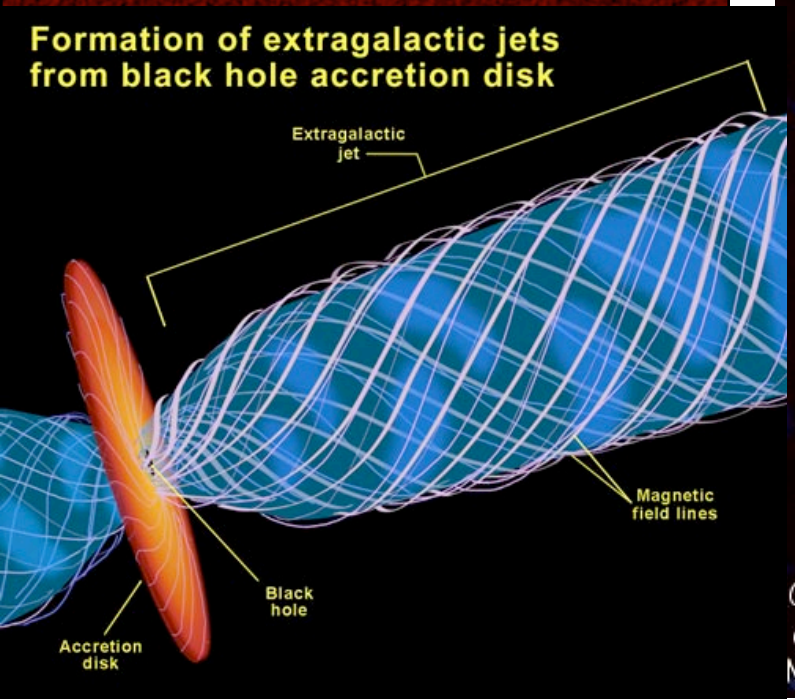
# Intermission: Active galaxies – jets

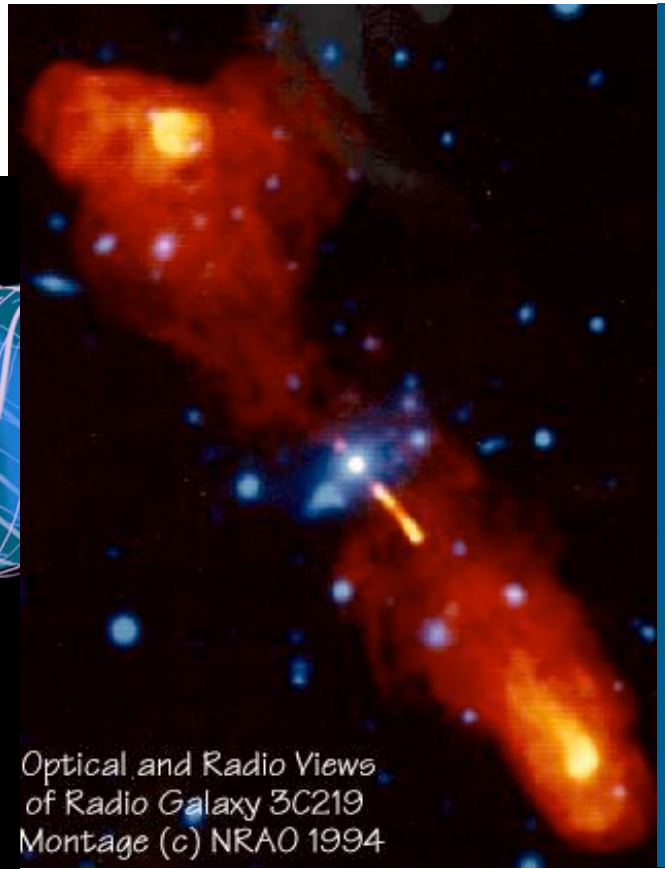
„Feedback”

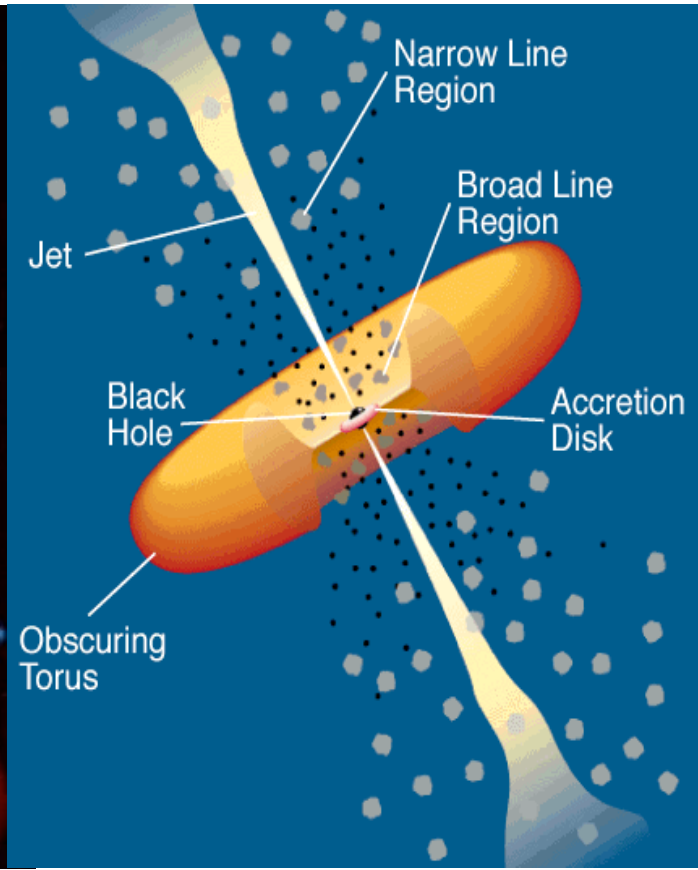
BH regulates its own growth?

Regulates bulge growth by quenching starformation?



# Why are some galaxies active and others are not?

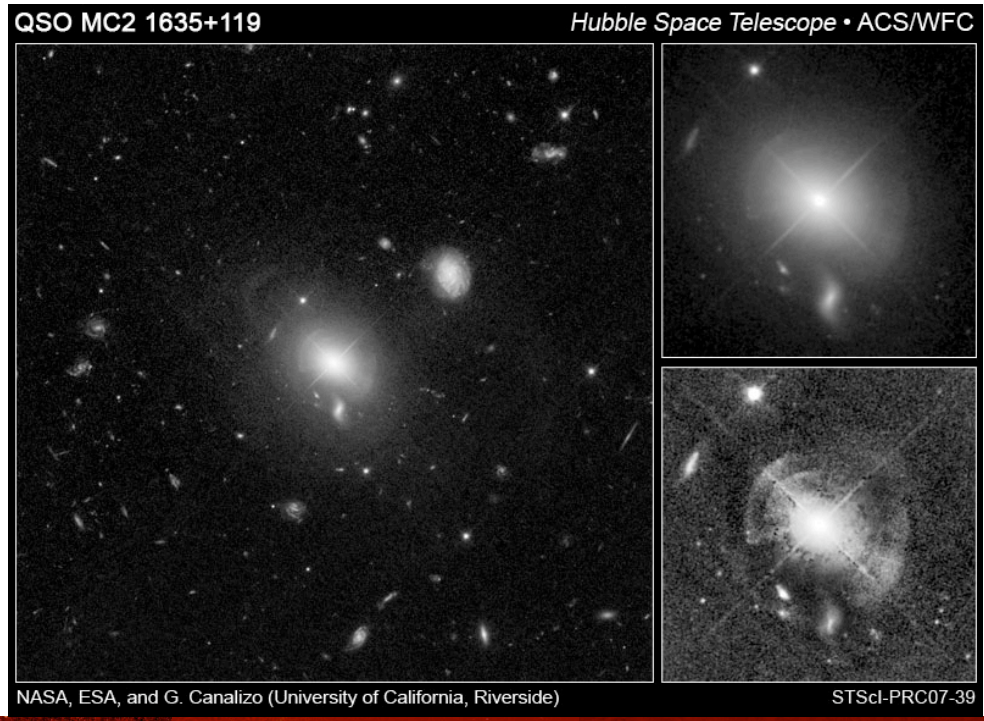
Presence of BH not enough (Milkyway is “dormant”)

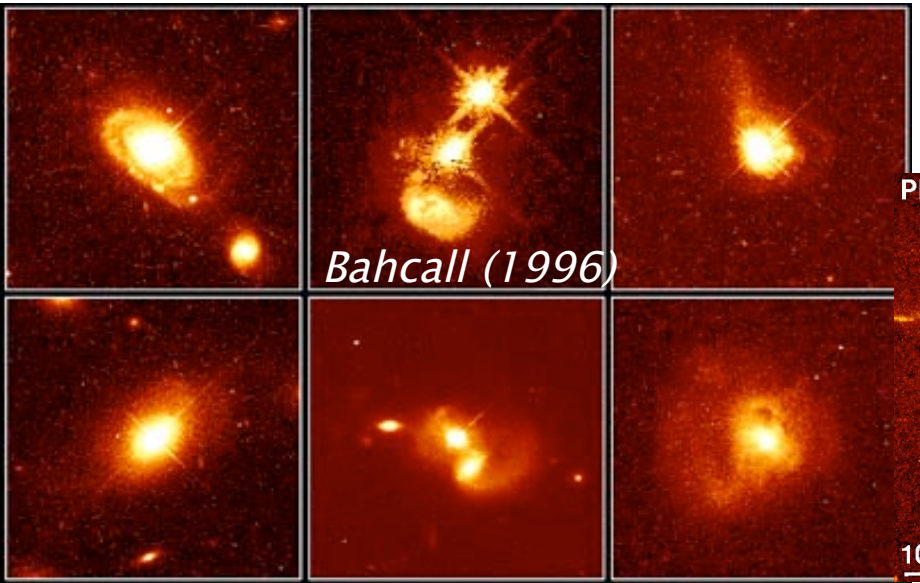
Galaxy interactions & mergers?

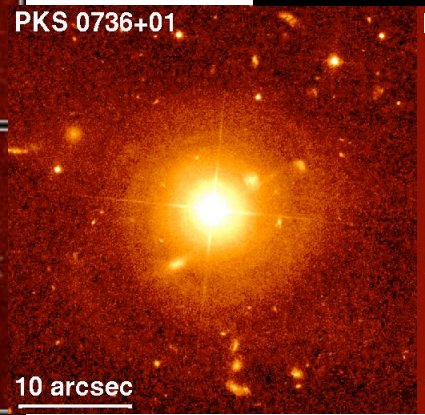
Phase in the evolution of galaxies?

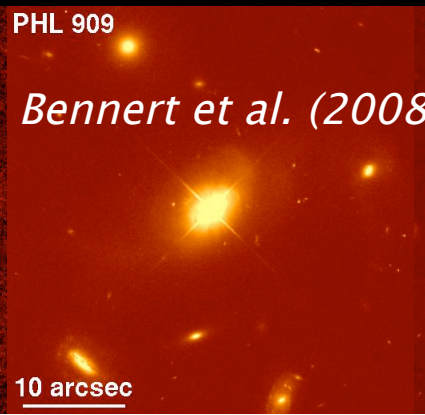
Evolutionary sequence:

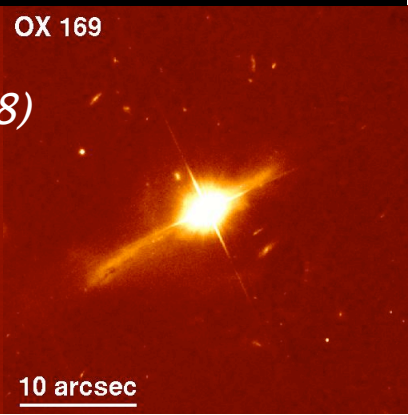
Merger → starburst → QSO → Elliptical



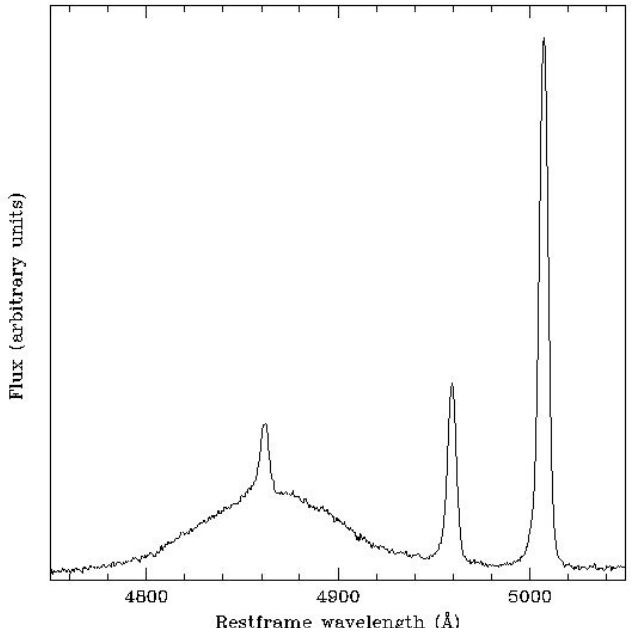



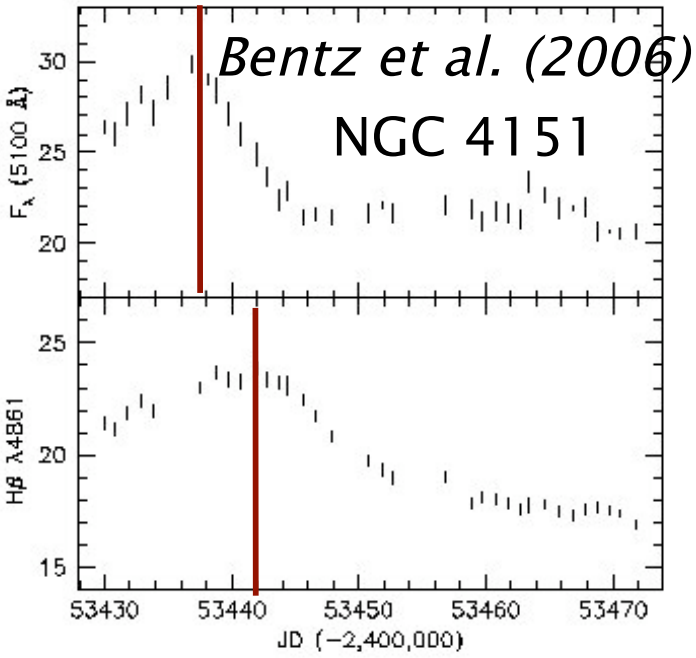



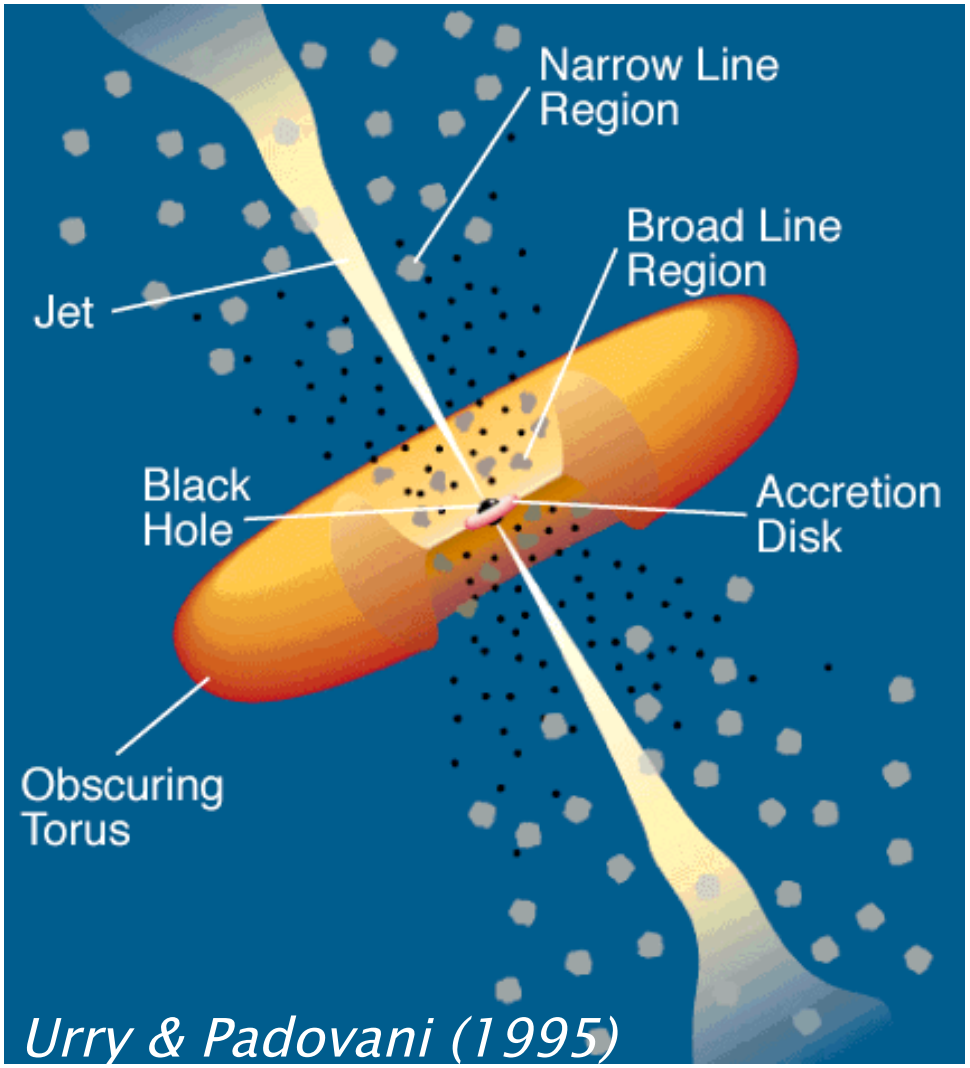



# Black holes on a „scale“: reverberation mapping




$$M_{\rm BH} \propto \frac{R_{\rm BLR} \cdot v_{\rm BLR}^2}{G}$$

# Black holes on a „scale“: reverberation mapping

Resolve BH sphere of influence in time!

Time consuming

~36 objects until 2008

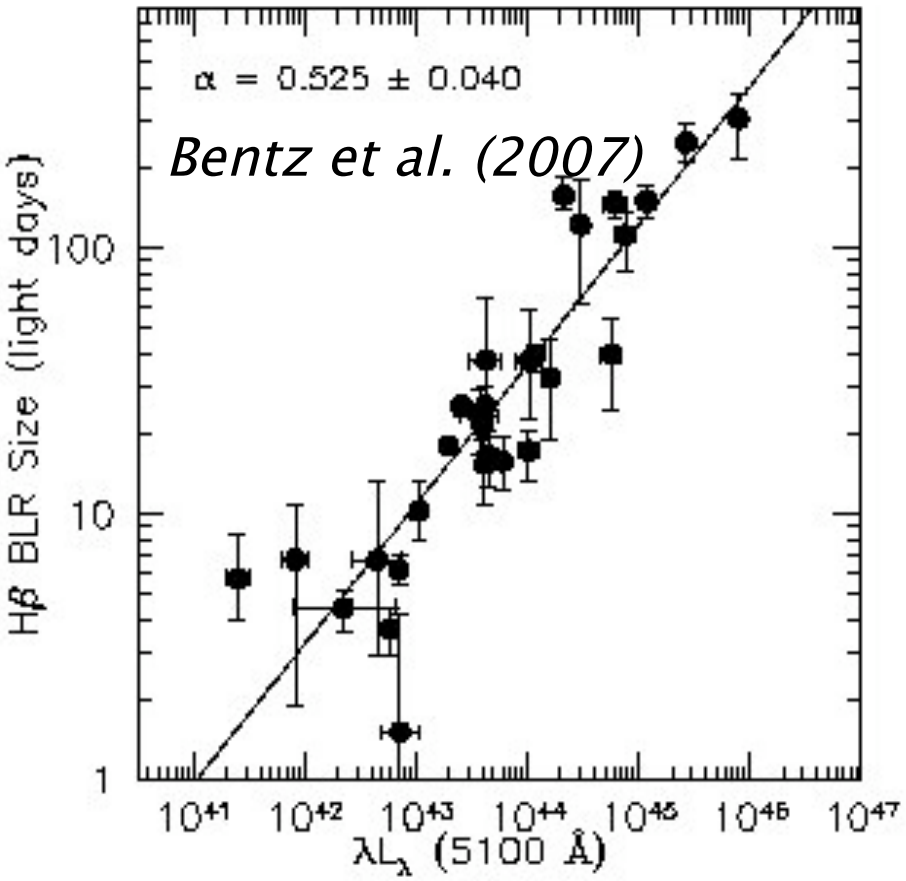
+9 Lick AGN monitoring program 2008

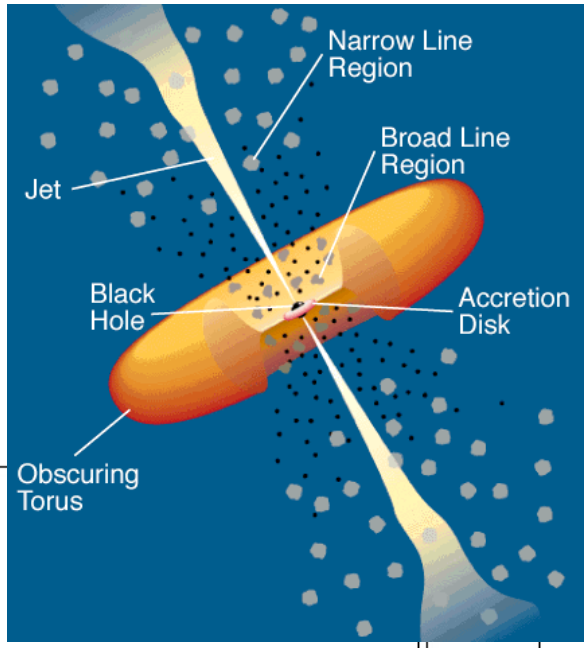
+~10 Lick AGN monitoring porgam 2011

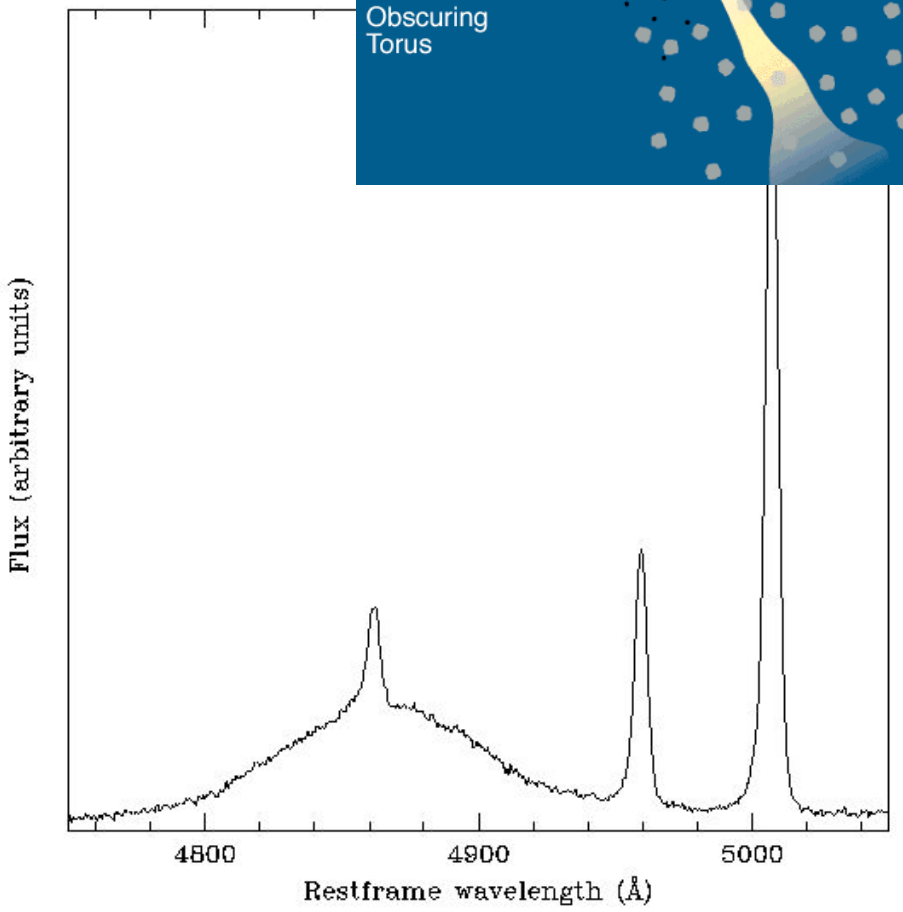
# Black holes on a „scale“: reverberation mapping

BLR size-luminosity relation

$$M_{\rm BH} \propto \frac{L_{5100}^{0.5} \cdot v_{\rm BLR}^2}{G}$$



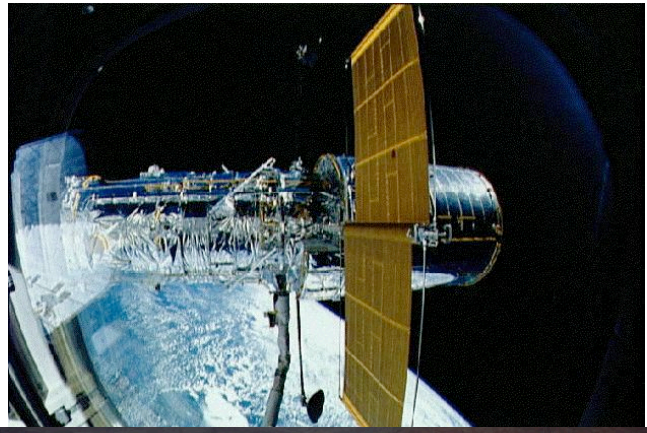



# The co-evolution of black holes and their host galaxies
## My current research

Use active galaxies!

Selected from Sloan Digital Sky Survey
(2.5m telescope in NM, 8 years: deep, multi-color images of ¼ of sky)
Broad Hβ



40 objects, lookback time ~ 4-6 bio. years

HST images:
Spheroid luminosity

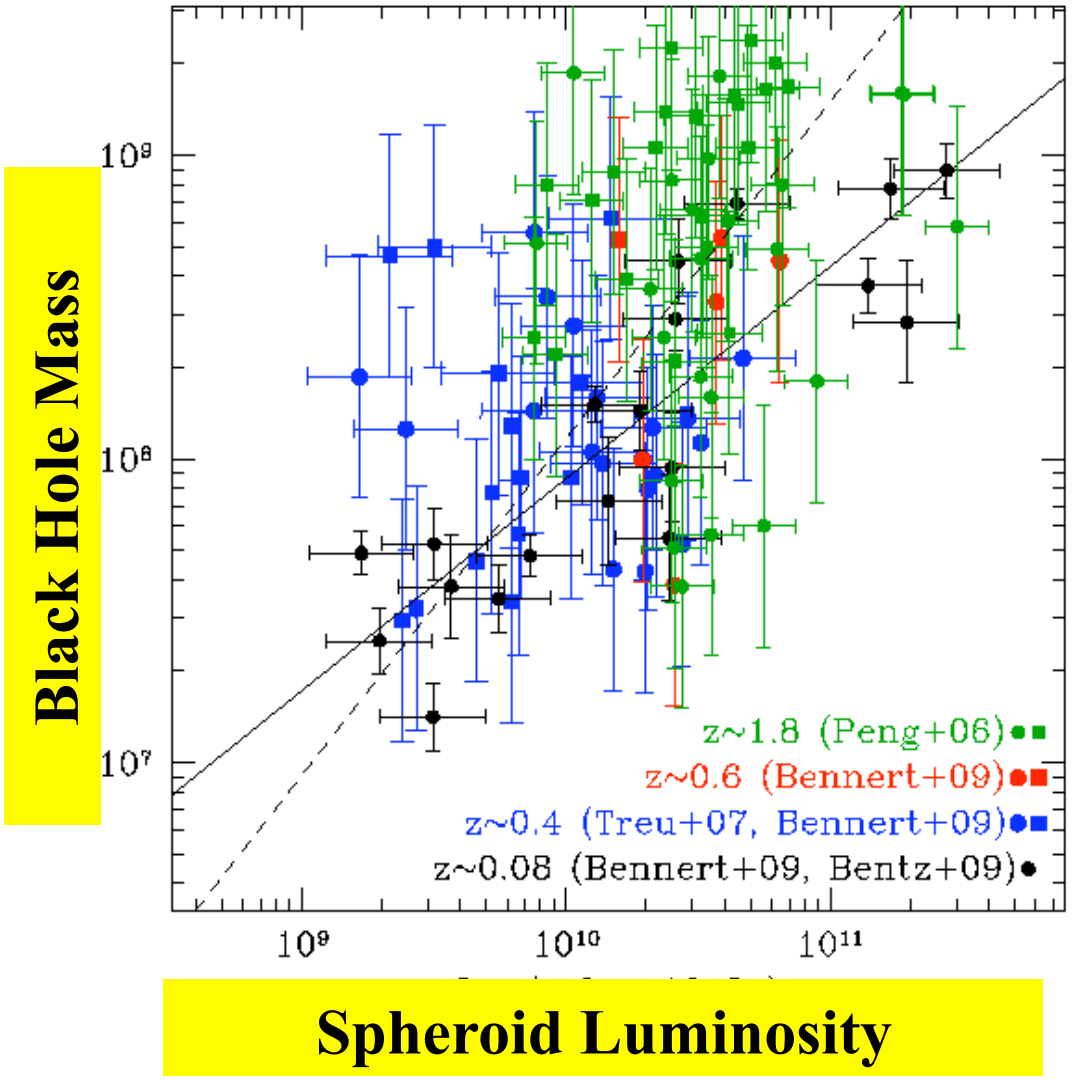
Keck spectroscopy:
M(BH)

# Where is the relation?!

Scatter larger

Relation does not exist at earlier times yet? Only end-product?

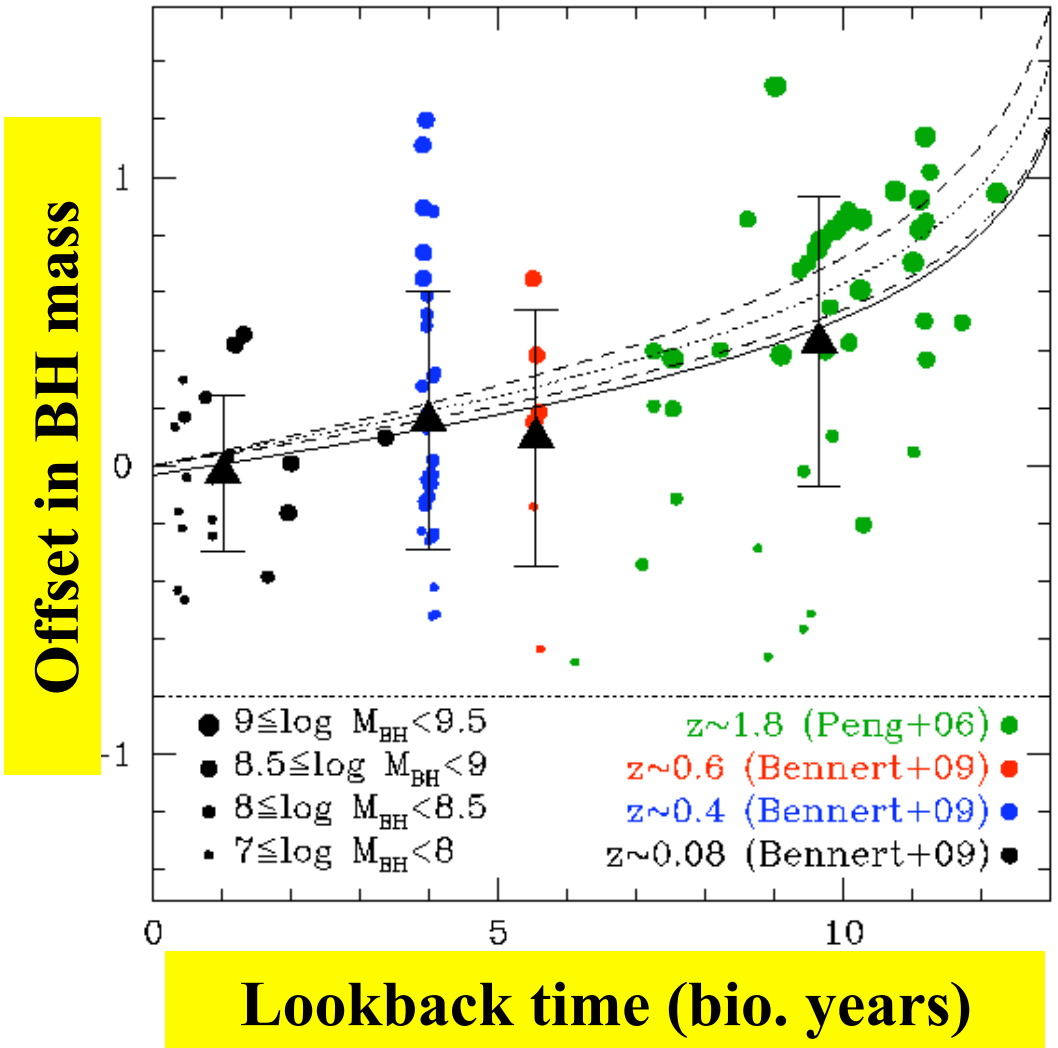
BH growth precedes bulge assembly



# Where is the relation?!

BH growth precedes bulge assembly

Evolution mass dependent?

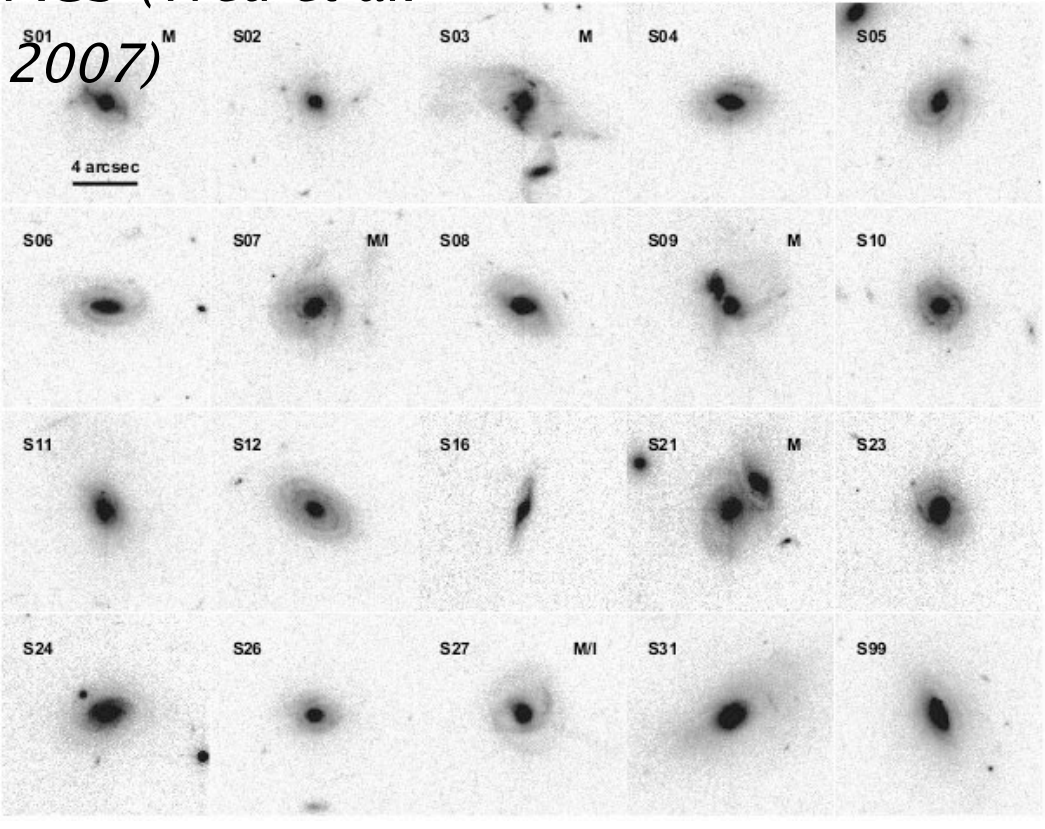


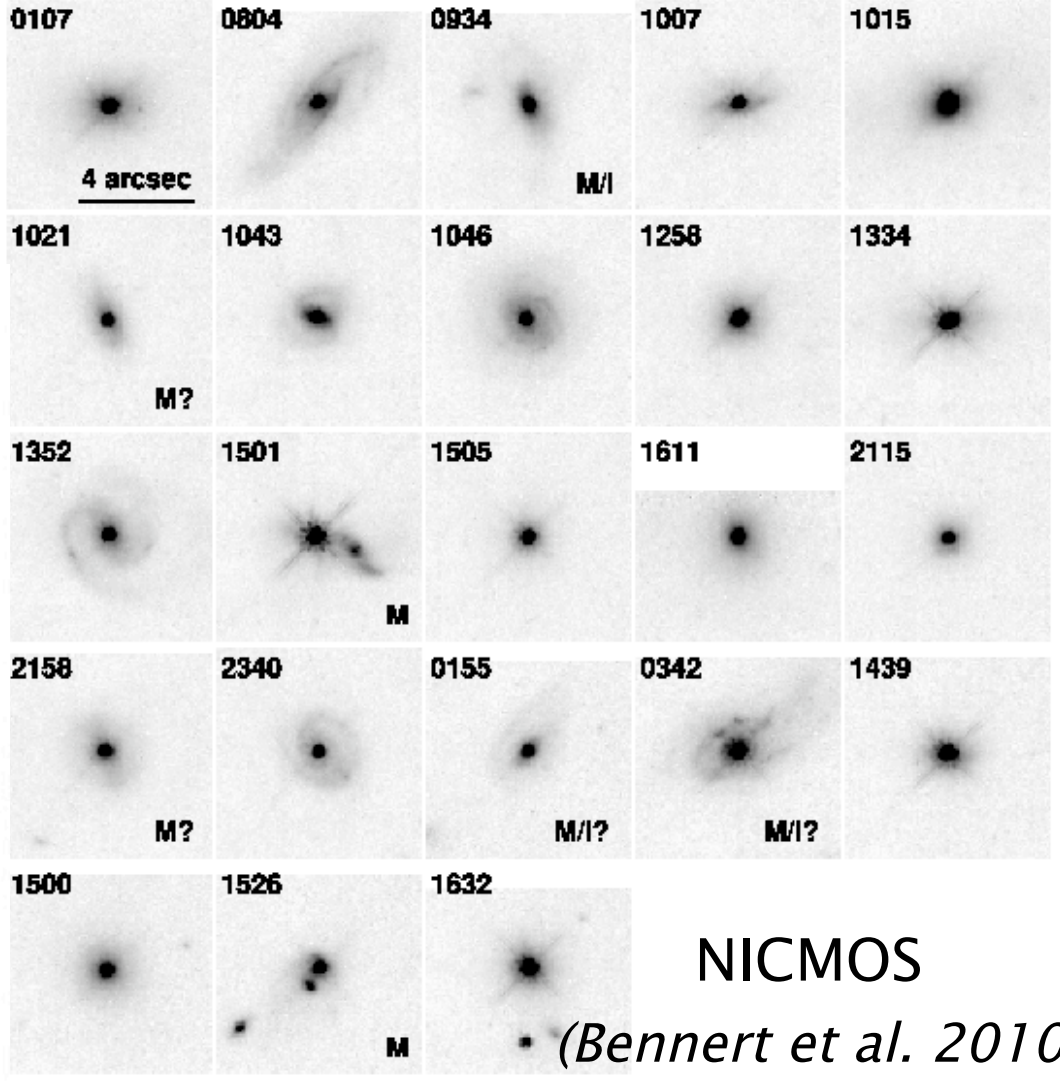
# BH is first – bulge needs to catch up!

How?

Mergers?

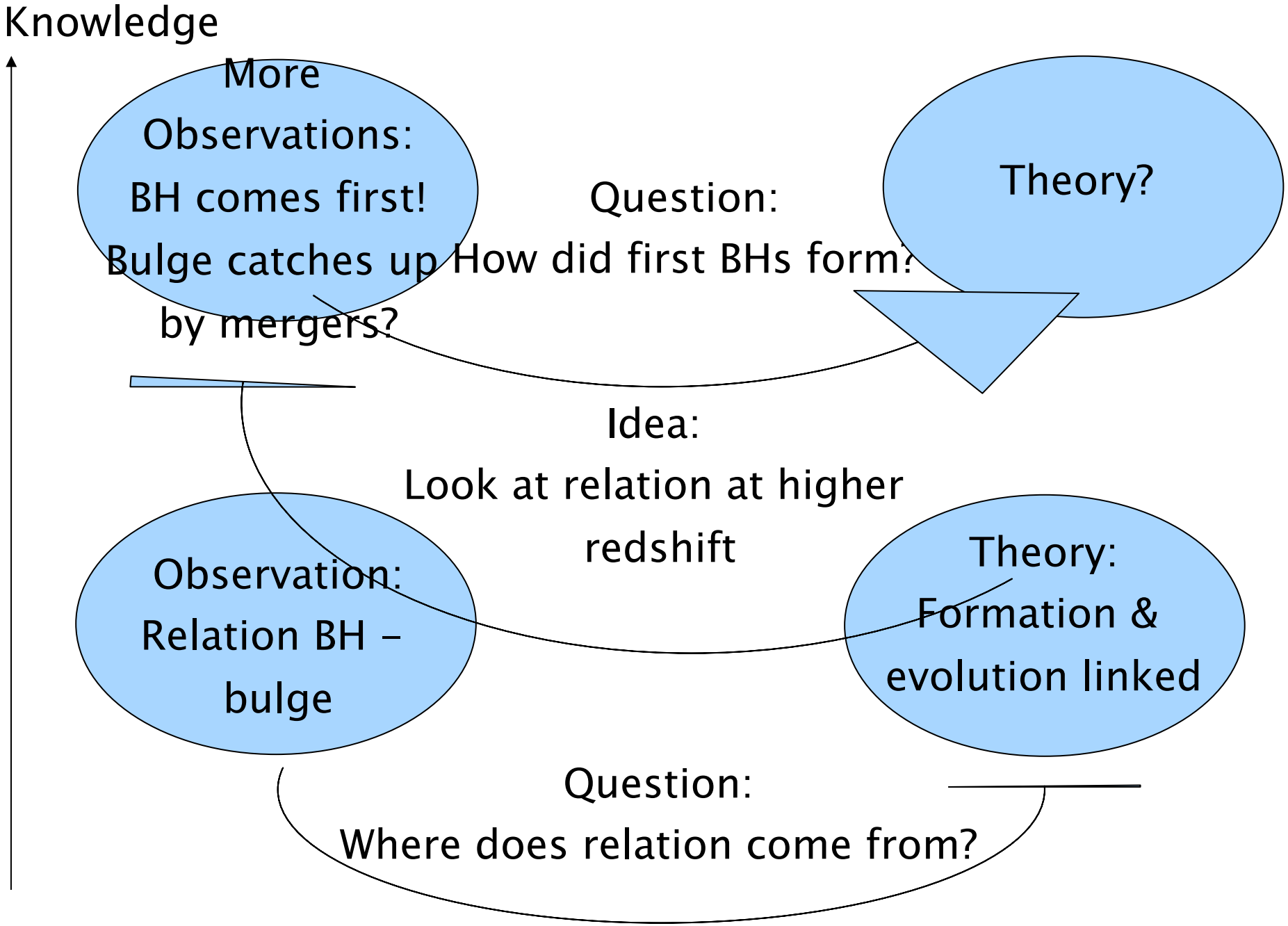
ACS *(Treu et al. 2007)*




NICMOS *(Bennert et al. 2010)*

# The natural cycle of science spiral



# To do (theory): formation of black holes

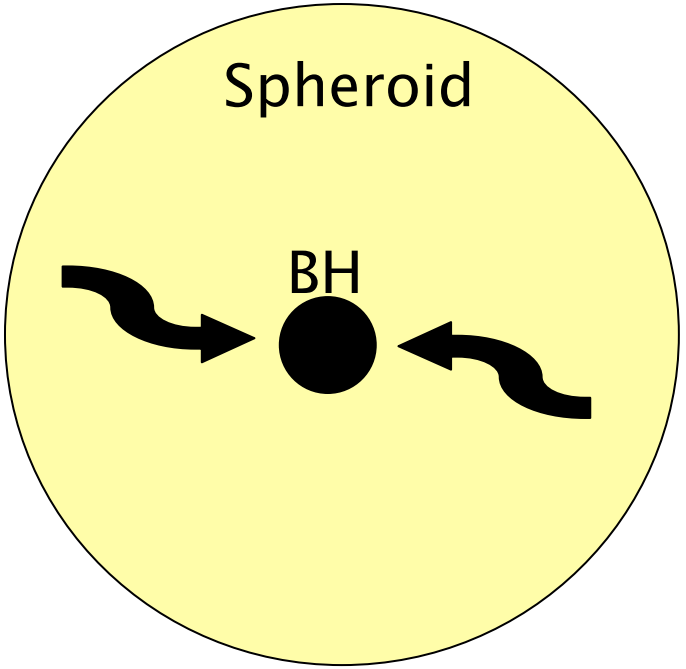
First QSOs: Universe was ~1 bio. years old

BH grows by accretion

But: what are “seed” BHs?

- remnants of the first generation of stars?
- formed out of gas at center of proto-galactic cloud?

# Putting it all together

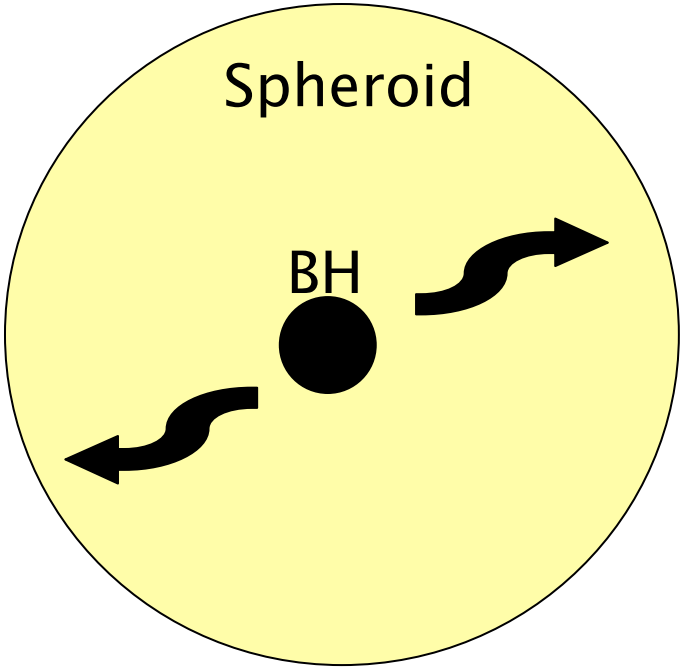



Ageing of stellar pop. (L decreases)

Accretion onto BH: active phase

M(BH) can only increase

# Putting it all together

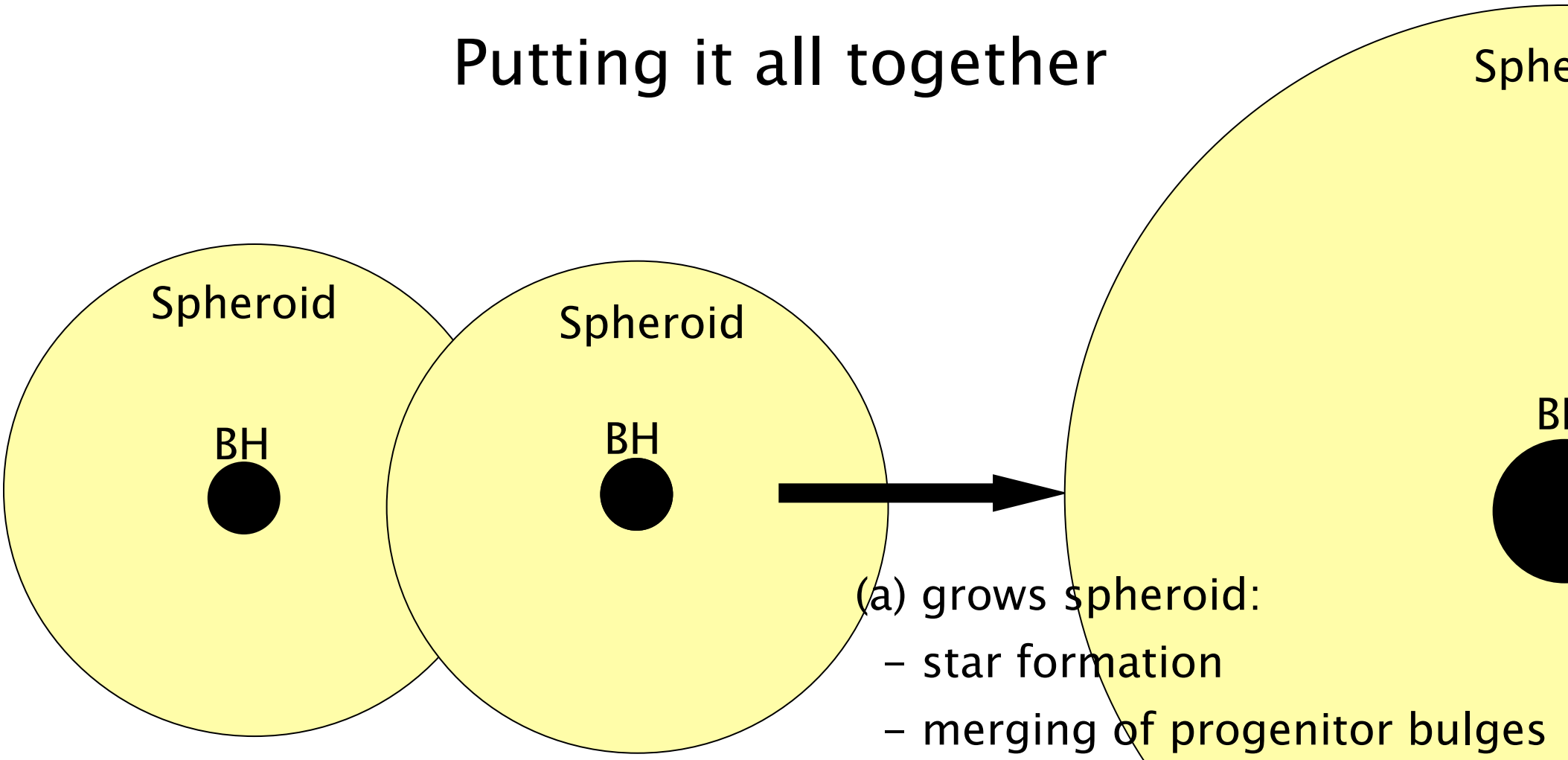



Ageing of stellar pop. (L decreases)

Accretion onto BH: active phase
M(BH) can only increase

Feedback from BH (e.g. jets):
quenches star formation in bulge
(L decreases)

# Putting it all together




Merger

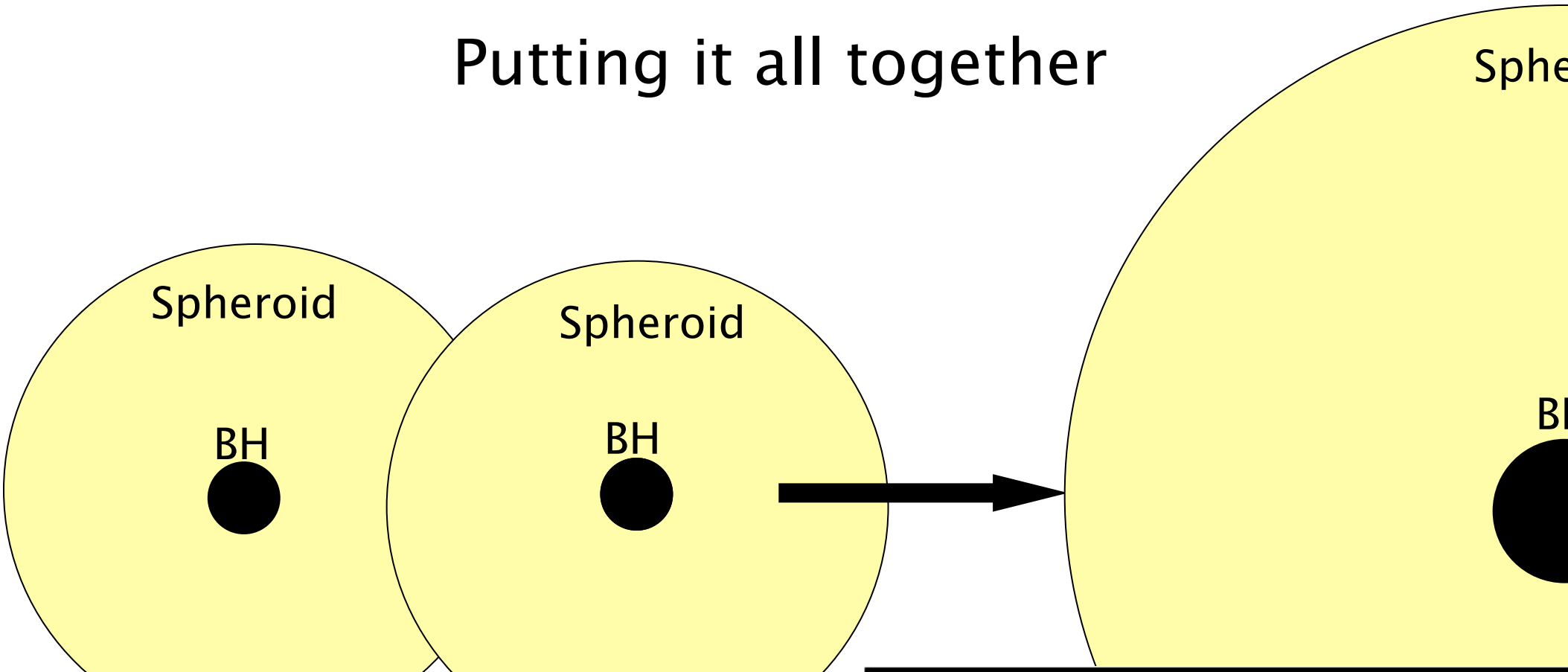
(a) changes L

(b) Increases M(BH)

(a) grows spheroid:
- star formation
- merging of progenitor bulges
- transforming disk into bulge

(b) grows BH:
- accretion
- merging of progenitor BHs

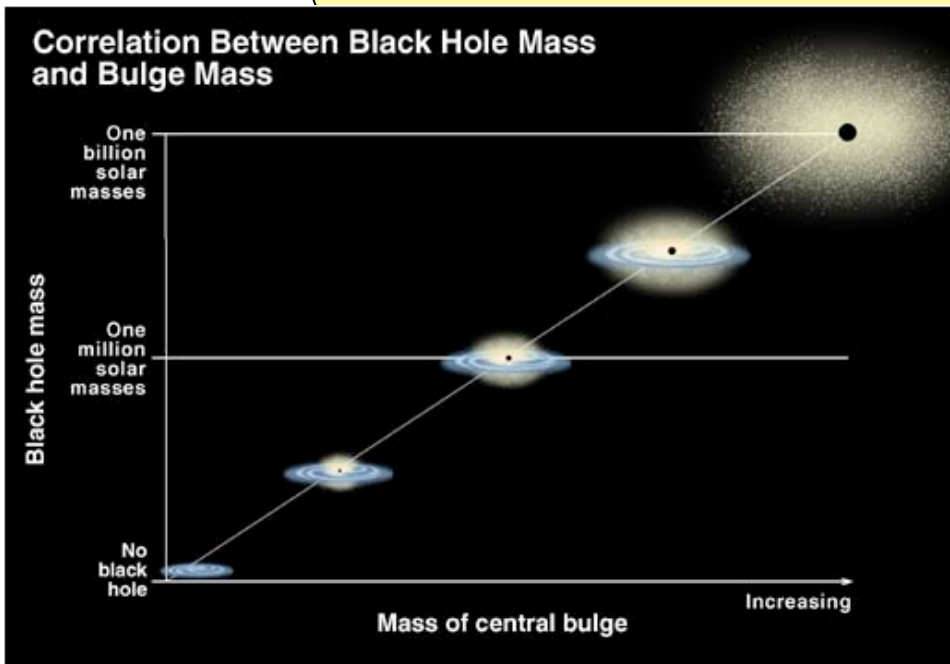
# Putting it all together




Evolution of BH – bulge relation depends on:

- relative timing of processes
- type of merger

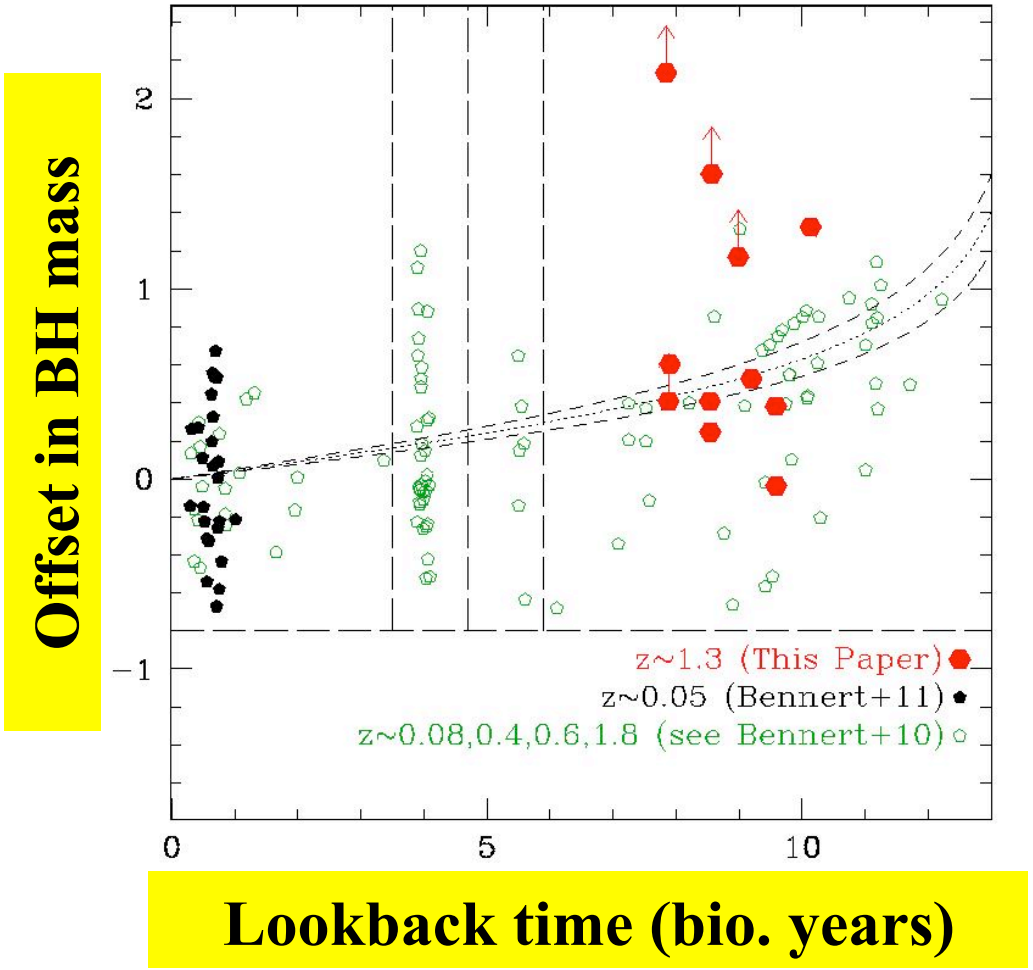
Explains observed large scatter?



# Work in progress

Test result “BH comes first” for larger and more distant sample

*(Bennert et al. 2011, submitted)*



# Work in progress

Test result “BH comes first” for larger and more distant sample

*(Bennert et al. 2011, submitted)*

Understand local relations better:

Creating a local baseline of the BH mass scaling relations

100 AGNs in local Universe

Keck spectra and SDSS images

*(Bennert et al. 2011; Harris et al. 2011, in prep.)*

Rebecca Rosen (CalPoly): measure BH masses!

# Future

HST proposals (images: archival for high z - accepted
snapshot for local sample - to be submitted Feb 2012)

VLT/Keck proposals (spectra for high z - accepted)

Use SDSS to study larger local sample

CFHT proposal (groundbased NIR images, submitted)