

**ASTR 1040: Stars & Galaxies**



HST Abell 2218

Prof. Juri Toomre TAs: Piyush Agrawal, Connor Bice  
Lecture 25 Tues 18 Apr 2017  
zeus.colorado.edu/astr1040-toomre

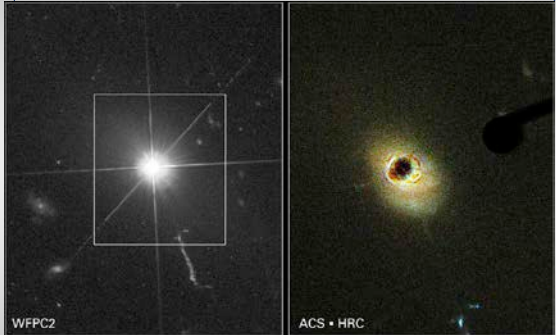
**Our Schedule**

- **Observatory Night #8 + #9** (proj A + spectro), both Wed and Thurs nights, by signup -- starting at 8:30pm
- Review session tomorrow, here 5:00-7:00pm
- **Third Mid-Term Exam** in class on Thursday
- Finish reading **Chap 22 Birth of Universe**
- Start overview read **Chap 23: Dark Matter, Dark Energy, Fate of Universe**
- Focus on **23.2 Evidence for Dark Matter**

**Dark Matter in the Universe**

- Briefly revisit **collisions between galaxies: "interacting galaxies" with bridges and tails**
- Also revisit **"radio galaxies" and quasars**
- Evidence for **dark matter** in galaxies
- **Gravitational lensing:** mainly by dark matter
- Measuring **really big distances** in universe, and concept of **"lookback time"**

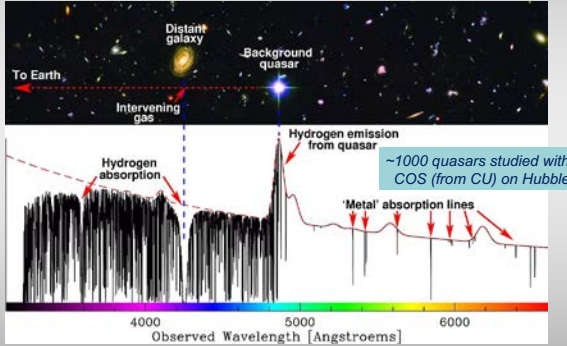
**Revisit Quasar 3C273**



WFPC2 ACS-HRC

With advanced HST instruments, can see extended surrounding galaxy

**Viewing distant quasar: "Lyman alpha forest" of absorption from intervening gas**



To Earth

Distant galaxy Background quasar

Intervening gas

Hydrogen absorption

Hydrogen emission from quasar

Metal absorption lines

~1000 quasars studied with COS (from CU) on Hubble


Observed Wavelength [Angstroms]

**REVISIT**

**Rich galaxy cluster**

Galaxies have many neighbors "interactions" most likely!

interesting "arcs of light"



Abell 1689 - HST

*Stefan's Quintet in HST detail*



*Present Day – distant Andromeda*



*Future: 2 billion years -- predicted*



*Future: 3.75 billion years*



*Future: 3.85 billion years (getting close)*



*Future: 3.9 billion years (very close)*





Future: 4 billion years (heading out)



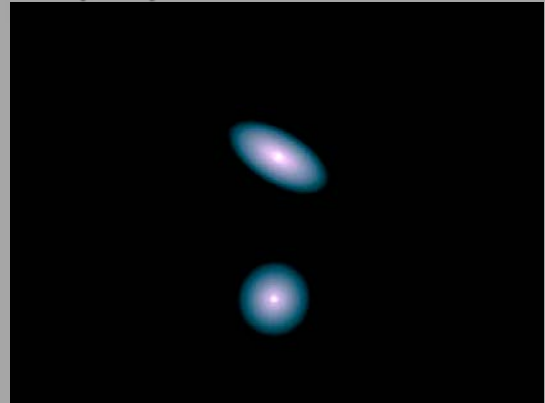
Future: 5.1 billion years (coming back in)



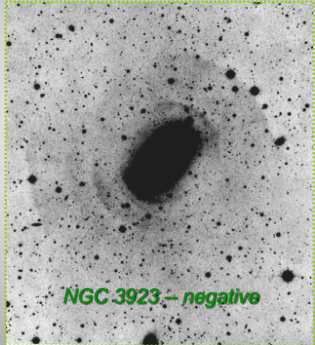
Future: 7 billion years



Milky Way collision with Andromeda ?



Signs of having collided:  
elliptical galaxy with shells



NGC 3923 - negative



"Polar ring" galaxy

Seyfert Sextet - HST



### Starburst Galaxies




M82 - visible                      Chandra - X-ray

- Milky Way forms about 1 new star per year
- Starburst galaxies form 100's of stars per year

### M82 "Cigar" composite HST+Chandra+Spitz



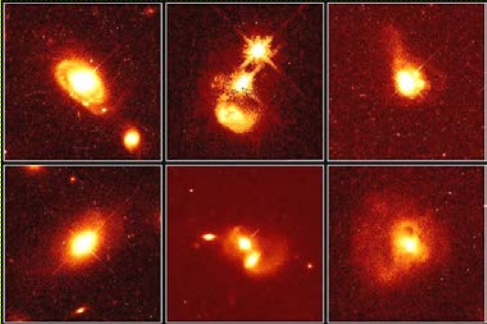
### Starburst galaxy in fine detail

NGC 3310 - HST

Big open two-sided spiral structure  
--> tidal interaction



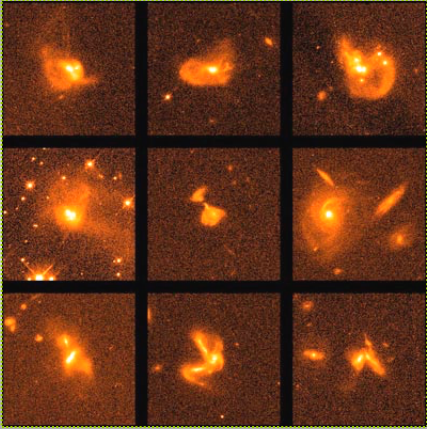
### Distant galaxies with "active nuclei" - HST



- Galaxies with odd stuff going on in their cores
- Nuclei as bright as rest of galaxy

### Many interacting galaxy systems

Very distant (big lookback time) with HST



### Messages from galaxy interactions

1. In dense clusters, galaxy collisions (grazing or even head-on) must have been common
2. With successive passages, spiral galaxies can tumble together to form a big elliptical
3. Vastly increased star birth from shocking the gas and dust (star burst galaxies)
4. Start rapid feeding of supermassive black hole lurking at center of most galaxies (quasars)



**Reading clicker – the boss galaxy**

- Which of the following is **NOT** a feature of a **central dominant (cD) galaxy** in clusters?

**A.**

- **A.** They are often spiral galaxies
- **B.** They are found in clusters of galaxies
- **C.** They often have multiple galactic nuclei near their centers
- **D.** They are thought to form by the merger of several smaller galaxies

**REVISIT**

**Prototypical "radio galaxy"**

Giant elliptical galaxy NGC 5128 with dust lane (from spiral galaxy?) + Centaurus A (Cen A) radio source (color lobes)

**REVISIT**

**Radio galaxies**

Central elliptical galaxy, huge lobes of emission, compact central source

**Synchrotron radiation**

**RADIO GALAXIES** OPEN ELLIPTICAL OR GIANT ELLIPTICAL GALAXIES

- FIRST DISCOVERED IN 1940s
- RADIO SPINDLE HAPPO OUT IN 1950'S
- VERY DETAILED IMAGES NOW WITH VLA

CENTRAL GALAXY

RADIO EMISSION (THE LOBES)

RADIO SOURCES OFTEN:

- HUGE DOUBLE LOBED
- VERY NARROW JETS
- VERY COMPACT CENTRAL SOURCE

RADIO EMISSION BROADBAND, EITHER:

- SYNCHROTRON RADIATION (STRONG MAGNETIC FIELD & VERY ENERGIC ELECTRONS)
- INVERSE COMPTON SCATTERING (STRONG RADIATION & FAST ELECTRONS)

SOME COMPACT SOURCES VARY IN A FEW DAYS ⇒ REMARKABLY DIM-FREE

LUMINOSITY IN RADIO : 0.001 → 1  
LUM IN OPTICAL

**REVISIT**

**Model for "active galaxies"**

Accretion disk, supermassive BH, beams on axis

**MODEL OF RADIO GALAXIES, QUASARS, SEYFERTS**

STRONG MAGNETIC FIELD

PARTICLE BEAM EMERGING FROM "CENTRAL ENGINE"

ACCRETION DISK

SUPERMASSIVE BLACK HOLE OF ABOUT  $10^8 M_{\odot}$

RADIO LOBES

QSO IS PROBABLY A VERY ACTIVE GALAXY CONTAINING A "CENTRAL GRAVITELY MAJOR OBJECT" I.E. SUPERMASSIVE BLACK HOLE WHICH IS BELIEVED ABOUT  $1 \rightarrow 10 M_{\odot}$  PER YEAR FROM INFALLING MATERIAL DRAGGED ONTO ACCRETION DISK

**Cygnus A radio jets**

400,000 ly

hot spot

lobe

jet

core

hot spot

Jet as fine thread, big lobes at end, central hot spot

VLA

**Cygnus A in more detail**

lobe

active galactic nucleus

jet

hot spot

jet

hot spot

visible galaxy

100,000 light-years

VLA imaging

**Radio tails: many shapes**

NGC 1265 – 100K ly

3C 31 – 2 M light years

**M87 – elliptical with jet**

800 km/s  
60 ly away

- Active galactic nucleus beams out **very narrow jet**
- Accretion disk shows gas orbiting a **2.7 billion solar mass black hole – first real proof!**

**Another example of “central beaming engine”**

radio

active nucleus - HST

- 400 light year wide disk of material in core of elliptical galaxy with radio jets – looks like supermassive BH at work!

**Disk around ‘black hole’ in NGC 7052**

GROUND

HST

**Jet in Chandra view of very distant quasar**  
(10 Bly, 1 Mly jet)

**Typical properties of “active galaxies”**

**synchrotron emission!**

**source very small in size**

**Most quasars present when universe was young**

**PROPERTIES OF “ACTIVE GALAXIES”**  
RADIO GALAXIES, SEYFERT GALAXIES, BL LACERTINE OBJECTS, QUASARS \*SOME HAVE MORE THAN OTHERS!

- HIGH LUMINOSITY**  
= MUCH MORE LUMINOUS THAN NORMAL GALAXIES
- NON-THERMAL EMISSION**  
= EXCESS RADIATION IN UV, IR, RADIO, X-RAY  
= IMPLYING SYNCHROTRON EMISSION FROM RELATIVISTIC ELECTRONS SPINNING IN MAGNETIC FIELD
- SMALL, COMPACT SIZE OF INTENSE EMISSION**  
= INCLUDE VERY BRIGHT COMPONENTS WITHIN CORE OF GALAXY
- RAPIDLY VARYING EMISSION**  
= SOURCE MAY BE A FEW LIGHT HOURS OR DAYS IN SIZE
- EXPLOSIVE FEATURES**  
= JETLINE EXTENSIONS, FRAGMENTS
- GRAVITATIONAL DISTURBANCES**  
= VERY HIGH INTERNAL VELOCITIES DERIVED FROM BROAD SPECTRAL EMISSION LINES  
= PECULIAR OPTICAL APPEARANCE
- LARGE REDSHIFTS**  
= IMPLYING HIGH RECESIONAL VELOCITIES, VERY LARGE DISTANCES

**Clicker: galaxy collisions**

- Why are collisions between galaxies more likely than between stars within a galaxy?

**C.**

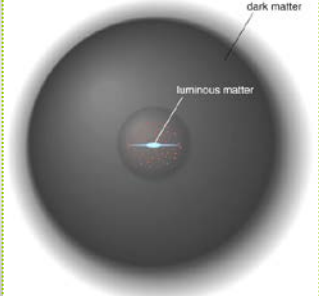
- **A.** Galaxies are much larger than stars
- **B.** Galaxies travel through space much faster than stars
- **C.** Relative to their sizes, galaxies are closer together than stars
- **D.** Galaxies have higher redshifts than stars

**Now to Case for Dark Matter**

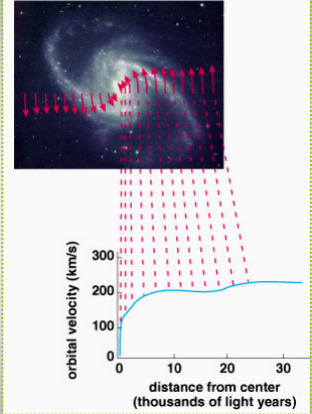
- ~ 80+% of mass of universe is dark matter (invisible, missing matter)
- Detectable ONLY via its gravitational forces on "light" matter (gas and stars)
- Note -- this dark matter is NOT the same as black holes, brown/black dwarfs, or dust

**Individual galaxies show it**

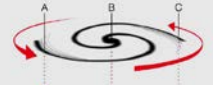
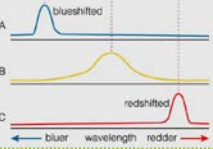
- **Rotation curves:** motions of stars in the galaxy
- Reveal that dark matter extends beyond visible part of the galaxy, mass is 10x stars and gas



- **Flat rotation curve of galaxy**
- **High speeds far from luminous center:** means there is dark matter in the outer regions

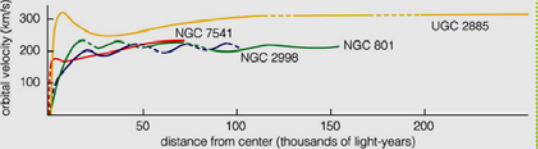


**Spiral galaxy ROTATION CURVES**



• Discovered by Vera Rubin in the 1970's

• Highly controversial until many rotation curves confirmed



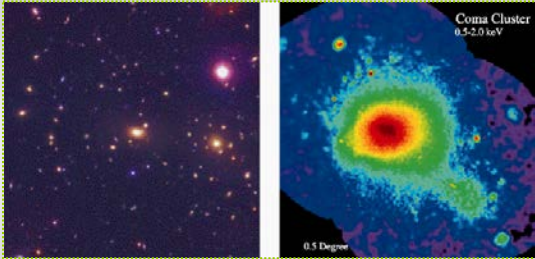
**Galaxy Clusters: reveal dark matter in three ways**

- **# 1: Galaxy velocities too large to be explained by gravity of visible galaxies**
- Expected ~100 km/sec for a typical cluster, found 1000 km/sec!
- Discovered in 1930's by Fritz Zwicky (they didn't believe him, either)



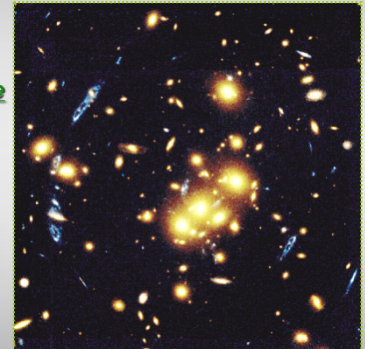
#2: Hot x-ray emitting gas in cluster



- Gas between galaxies is also moving because of gravity of dark matter: **gets very hot**
- 1000 km/sec → 100 million K: emits x-rays!

#3: Gravitational Lenses

- Dark (& visible) matter warps space  
→ acts like a lens and distorts and magnifies the view of more distant galaxies
- Can form circular arc segments



REMINDER

Effects of strong gravity on light (Einstein GRT)

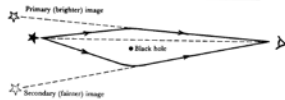
can act like lens

can redshift light

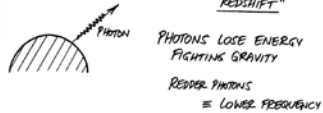
EFFECTS OF GRAVITY ON LIGHT

... COURTESY OF EINSTEIN

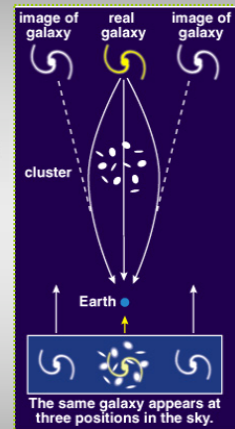
1. STRONG GRAVITY CAN BEND LIGHT: USUALLY SLIGHT DEFLECTION, BUT IF VERY STRONG GRAVITY ⇒ GRAVITATIONAL LENSES!



2. LIGHT ESCAPING STRONG GRAVITY FIELD IS REDSHIFTED: "GRAVITATIONAL REDSHIFT"



Gravitational lensing: how it works



The same galaxy appears at three positions in the sky.