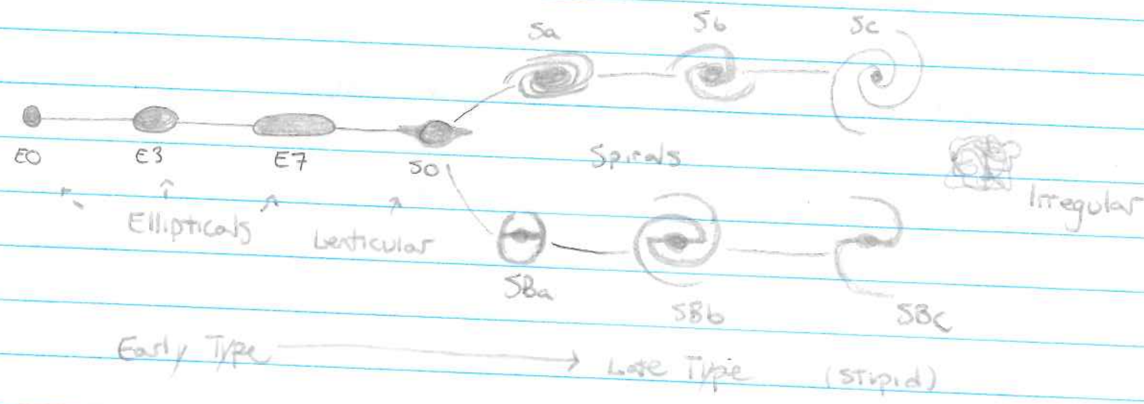
EG 1

- Shows shape, luminosity profile, velocity dispersion, amount of gas, color(?)
- Sa's have less gas, smoother arms, less structure, larger bulges, fewer resolvable SF knots
- Ellipticals have no gas, high velocity dispersion, no real structure

- Hubble sequence



$\varepsilon = 1 - b/a$

- Hubble sequence mostly captures shape; dynamics/mergers & luminosity profile
- Ellipticals have larger velocity dispersion,
- S0s are sort of like spirals; ordered rotation but no gas; can have bulges and disk, etc.
- Sc's have more knots/resolvable star clusters and regions of H II compared to Sa's; also have smaller bulges, and more gas. Sa's have smoother arms and show less structure in their bulges, which is more dominant.

- List masses
- invoke virial theorem to relate M & v.
- get v from 21 cm line width (Doppler broadened), Tully-Fisher (max rot. v ∝ L profile of spiral)

EG 2

- Mass determination of MW Galaxy

Galaxy	Mass w/ DM	Mass w/out DM
MW	$\sim 10^{12} M_\odot$	$\sim 10^{10} M_\odot$
M31	$\sim 10^{12} M_\odot$ > MW	$\sim 10^{11} M_\odot$
LMC	$\sim 10^{10} M_\odot$	$\sim 10^{9} M_\odot$

- Assume galaxy is virialized (dynamically relaxed, in equilibrium) and determine rotation curve

$U = -2K$

$-\frac{GMm}{r} = -mv^2$

$v = \sqrt{\frac{GM}{r}} \rightarrow M = \frac{v^2 r}{G}$

- Measure velocities (or velocity dispersion) of galaxy components as function of radius
- Measure width of Doppler broadened 21 cm line from HI to get velocity dispersion
- could use Tully-Fisher relation to get max. rotational velocity based on luminosity profile of spiral, and Faber-Jackson relation to get velocity dispersion based on luminosity of ellipticals.

R – Max rotational velocity v. L
S – spirals
T – Tully-Fisher

D – velocity dispersion v. L
E – ellipticals
F – Faber-Jackson

- The mass of a galaxy is often expressed in terms of its M/L ratio.

- distances to objects
- Radar, parallax, ~~spec.~~ spec. parallax, WB effect, cepheids, TF / FJ relation, Type Ia SNe

EG 3

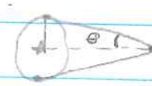
· Distance Ladder

LMC – 50 Kpc
SMC – 60 Kpc

M31 – 700 KpC (<1 Mpc)
Virgo cluster – ~10 Mpc

- Radar
  - not very far; solar system
  - send a signal and wait for it to bounce back at c

- Parallax
  - 20 pc
  - measure angle but need to resolve source



Spectroscopic Parallax
- ~7 Mpc but rly ~100 kpc
- ~~read~~ use spectrum to get T or sp.T., use HR diagram to get M, ~~then~~ then dist. mod.

Wilson Bappu Effect
- width of narrow em. line w/in Ca absorption line is strongly correlated w/ M_V for late type stars

- Cepheids / Variable stars
  - 30 Mpc
  - relation b/w star's pulsation period and peak luminosity, use this plus apparent mag. & distance modulus to get distance $M \sim \log_{10} P$
  $m - M = -5\log_{10}(d/10pc)$

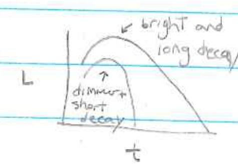
- Tully-Fisher Relation
  - > 100 Mpc
  - relation b/w max. rotational v and luminosity for spiral galaxies

$\underline{RST}$ — spirals; rotational v; Tully-Fisher

- Faber-Jackson Relation
  - > 100 Mpc
  - relation b/w velocity dispersion and luminosity for elliptical galaxies

$\underline{DEF}$ — ellipticals; v. dispersion; Faber-Jackson

- Type Ia Supernovae
  - > 1000 Mpc
  - relation b/w decay time of light curve and peak luminosity
  over 1st 2 mag : $M \sim \log_{10} \dot{m}$



★ Radar → Parallax → Spectroscopic Parallax → Wilson Bappu effect → Cepheids →
20pc — 100 Kpc — 30 Mpc

Tully-Fisher → Faber Jackson → Type Ia SNe
100 Mpc — 100 Mpc — 1000 Mpc

- evidence: Kinematics / orbits, high M/L ratio in tiny region, high speed & high energy jets imply high V_{esc} from tiny region
- accreting material is heated, radiates & heats IGM, preventing accretion & SF. Stars are flung out of galaxy.

EG 4

BHs at Centers of Galaxies

Evidence

- Kinematics / orbits of central stars in MW
  - ↳ appear to orbit some very massive non-luminous object of $\sim 4 \times 10^6 M_\odot$. Some SMBHs can be $\sim 10^{6-9} M_\odot$
- M/L ratio in central region
  - ↳ $M/L > \sim 10\text{-}100\ M_\odot/L_\odot$? in Andromeda center, in region smaller than Solar system, implying something very massive
- velocity dispersion in center
  - ↳ if individual stellar orbits can't be resolved, can measure high v. dispersion
- X-ray / radio emission
  - ↳ can observe jets and x-ray sources coming from very tiny region, requires very dense object (observe AGNs) w/ high V_{esc} to explain $v \sim c$ of jets

Interaction w/ Galaxy

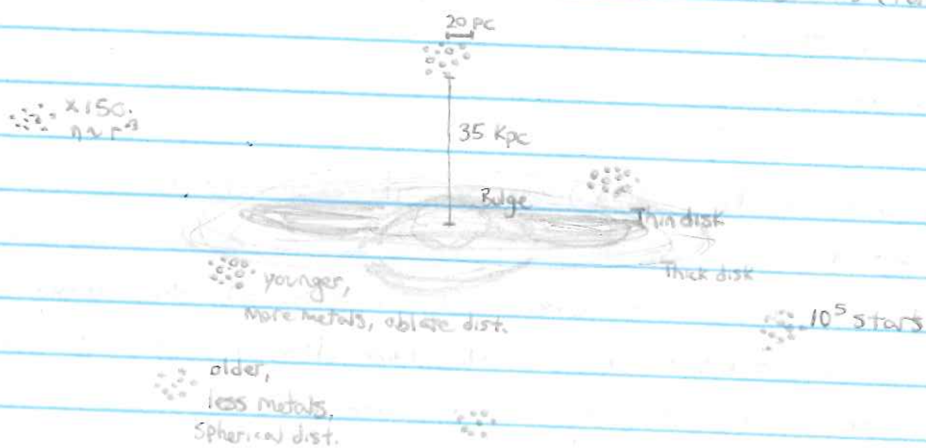
- Material falling into accretion disk is heated, producing radiation that heats up IGM, preventing further accretion onto galaxy, suppressing star formation
- Maybe also strong outflow during rapid accretion expells ISM, suppressing SF
- Stars are flung out of galaxy during BH orbit, so we can observe hypervelocity stars

EG 5

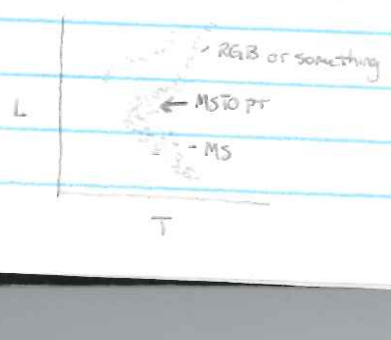
- Draw diagram & label properties
- GCs are collections of grav. bound stars w/ low metallicity b/c old ~ 10 Gyr
- Age determined by MS turn off point on HR diagram.

Globular Clusters

- A globular cluster is a collection of $\sim 10^5$ stars that are gravitationally bound and orbit in a common gravitational field. They usually span a spherical radius of ~ 20 pc. They exist in galactic halos, and the MW contains ~ 150 such clusters. The oldest clusters have low metallicity ($[Fe/H] < -0.8$) and are roughly spherically distributed around the galaxy. A second pop'n of higher metallicity (and thus younger stars) have a more oblate distribution around the galaxy and might be part of the thick disk, since they have roughly the same scale height. Most GCs are $\lesssim 35$ kpc from galactic center. The density distribution is a power law, $n \propto r^{-\gamma}$, with $\gamma \approx 3-3.5$ (for the 1st pop'n).



- The # of GCs is higher in early types and more luminous galaxies
- Typical age of $\sim 10^{10}$ yr. This is determined by comparing the HR diagram for the GC with that expected based on stellar evolution models to determine where the MS Turn-off Point occurs. The absolute Mag. of the MSTO pt. can be directly related to the age of the cluster. Since core H-burning lifetimes go inversely with stellar mass, continued evolution of the GC means the MSTO pt (where stars are currently leaving the MS) becomes redder and dimmer with age.



- velocity dispersion - assume virial equilibrium, $-U = 2K$
- hot x-ray gas - assume hydrostatic equilibrium, relate pressure/T to mass, get T from spectra of x-ray emission by collisional ionization w/ free-free radiation
- grav lensing - mass produces shear field, distorts images at $\sim \theta_E$, can relate to cluster mass

EG 6

- Galaxy Cluster Mass determination
  - gravitational lensing, hot x-ray gas, velocity dispersion

- Velocity Dispersion
  - assume in virial equilibrium (dynamically relaxed), so dynamical time scale < age of universe (approx. age of cluster)

    $T_{cross} \approx 2R/\sigma$, $R \sim 2$ Mpc, $\sigma \sim 1000$ km/s
  - use virial theorem

$2K + U = 0 \rightarrow U = -2K$

$K = \frac{1}{2}mv^2$, $U = \frac{-GMm}{r}$

$\langle v^2 \rangle = \sigma = \frac{1}{M} \sum_i m_i v_i^2$

$r_G = 2M^2 \left(\sum \frac{m_i m_j}{r_{ij}} \right)^{-1}$

$2K = -U$

$2\left(\frac{M}{2}\langle v^2 \rangle\right) = \frac{GM^2}{r_G}$

$\boxed{M = \frac{r_G \langle v^2 \rangle}{G}}$ $\sim 10^{15} M_\odot$

- X-ray Gas
  - Hot diffuse intracluster gas is collisionally ionized, emits free-free radiation due to accel. of e^- in Coulomb field of protons/atomic nuclei
  - use spectra of gas to determine gas temperature ($\sim 10^7$ K, 5 keV). The hotter the gas, the more ionized it is, and the weaker the emission line
  - assume gas in hydrostatic equil, so sound speed crossing time < age of universe/clst

    Meaning timescale on which deviations from P equil. are evened out is short.

    $T_{sc} \sim 2R/c_s$, $R \sim 2$ Mpc, $c_s \sim 1000$ km/s , $t \sim 10^8$ yr
  - if in hydrostatic equil,

$$\underset{nk_BT}{\nabla P} = -\rho_g \underset{-GM/r}{\nabla \Phi}$$

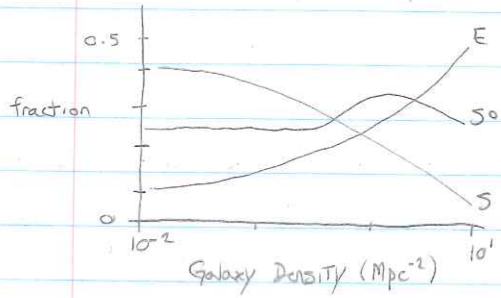
plug stuff in and get relation b/w T and M.

Gravitational Lensing
- Model cluster as singular isothermal sphere, which will magnify and distort images close to its Einstein radius (and not really anywhere else)
- the mass of the cluster can then be determined, since $M(\theta_E) \sim (D\theta_E)^2$ where D is the distance to the cluster and θ_E can be determined based on the separation b/w the cluster & the distorted galaxies

EG7

- density-morphology describes abundance of galaxy types w/ density of galaxies. Ellipticals = $\downarrow R$, v.v.
- spirals transform to S0s to ellipticals via interaction and mergers
- Ram pressure stripping removes gas via ICM wind but also creates local SF w/ compression by head wind.

Density-Morphology Relation and SFR



- Clusters dominated by early types, esp. near center, while field ~70% spirals
- Fraction of spirals in cluster decreases w/ increasing ρ, opposite for ellipticals and S0's (but less so)

- In outer regions of clusters, spirals lose gas due to motion through ICM, transforming into S0's
- Closer in, S0s are transformed to ellipticals via gas-free (dry, LOL) mergers

Follow up: • Looking at $\uparrow z$, we see higher fraction of blue galaxies in clusters, meaning spirals were more prevalent at early times. At $z \gtrsim 1.3$, blue fraction in clusters $\approx$ field.

- Ram Pressure Stripping – motion of galaxy causes galaxy to experience ICM 'wind' which, if $F_{pressure} > F_{grav}$, blows atomic gas out of galaxy. Molecular gas is most concentrated near disk, so more strongly bound. Thus HI in ISM is stripped, limiting further/later SF. However, RPS heats up gas + triggers local SF by compressing gas. The new stars won't be grav. bound to galaxy.

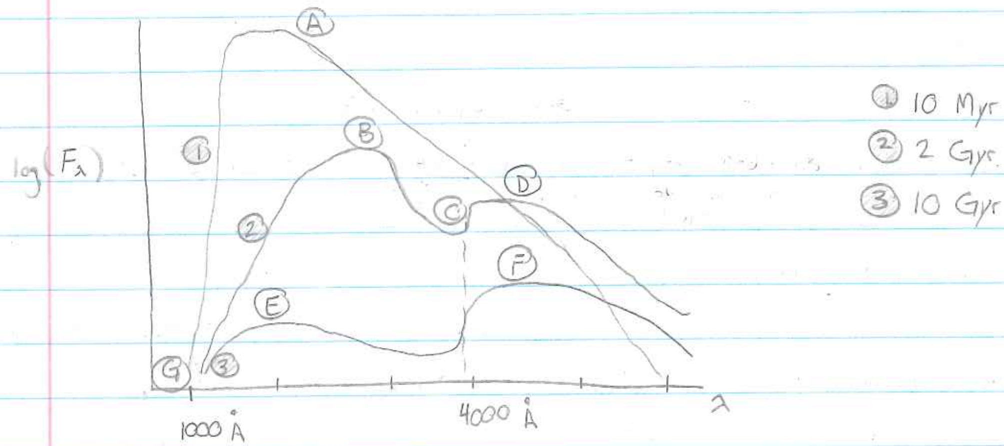
- Harassment – high speed collision/fly by of galaxy affects internal properties by changing grav. potential. The gas & stars are heated, causing the matter to expand and become more easily affected by tidal interactions. Thus the galaxy can become more spherical. (Not sure how this affects SFR)

- Strangulation – As a galaxy's orbit approaches inner cluster, where ICM gas and galaxy # density are large, all galactic gas can be removed. Or, if it doesn't get quite as close, it'll retain some core gas which can form stars for a little while until that gas is depleted.

- initially dominated by O/B stars, moves down
- Develop IR bump from red giants and 4000 Å break from metal absorption in cooler stellar atms
- Develop UV bump from WDs, Ly-α break due to neutral H

EG 8

SED of Galaxy w/ Single Burst of SF



Features

A. SED dominated by O/B stars w/ lifetime of $\sim 10^7$ yr
B. SED dominated by cooler A/F-ish stars
C. 4000 Å break due to accumulation of absorption lines of ionized Metals in stellar atms (Ca, Balmer H)
D. O/B stars have transitioned to red giants, increase in IR & drop in UV
E. Cooling WDs contribute to UV bump
F. SED dominated by cool G-K stars
G. Lyman break around 912 - 1216 Å due to absorption by neutral H

• Makes use of spectral breaks in SED
• use multiple bands to get color, determine location (λ) of break by comparing to redshifted template (need to know type)
• can also perform search for galaxies of specific z.

EG 9

• Photometric Redshift Techniques

– Makes use of spectral breaks in galaxy SEDs to determine redshift

↳ Lyman-α break

• Drop in UV blueward of 1216 Å

• After few Gyr, single burst of SF galaxy will have fewer O/B stars left so mid-MS stars dominate SED. These produce quite a few high energy γs but also aren't hot enough to lose all HI in their atms (also in ISM??), so the HI absorbs all the <1216 Å light, resulting in break

↳ 4000 Å Break

• Drop in visible (blue) light

• Stellar pop'ns older than ~ 10 Myr have increase in atm opacity due to Ca transition and Balmer transition of H. The older the galaxy, the more noticeable the break.

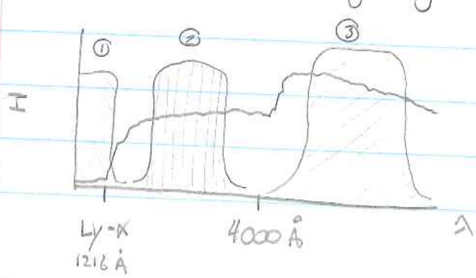
– By using multiple photometric bands you can determine the color and the flux in each. If your bands are strategically placed on either side of the break you can determine the λ of the break and thus the z.

– you can either search for galaxies w/ a specific z by searching for specific colors, or use a galaxy template to figure out the z of a specific galaxy.

↳ create template galaxy from pop'n synthesis models or from real standard spectra. Redshift the spectra in λ. Apply the filters you're using and determine colors as a function of z for that galaxy type (ie integrate the SED × the transmission functions of filters over λ). Compare your observed colors to the template set to get z.

– Photometry is a lot faster than spectroscopy and can be applied to fainter mag

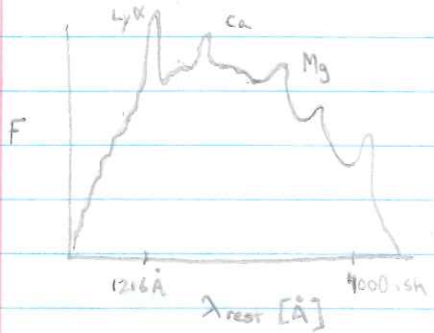
– requires at least 4 bands, otherwise risk mistaking Ly-α break for 4000 Å break (or v.v.) and getting z really wrong.

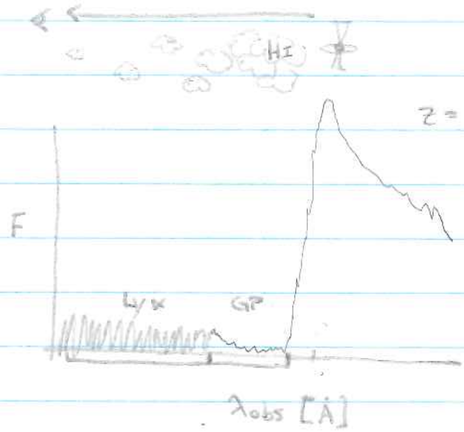


- rest λ spectrum has Ly-α, narrow + broad emission lines
- obs λ spectrum has GP trough, Ly-α forest due to absorption by neutral H in IGM at various z along our LOS.

EG 10

- Quasar Spectra





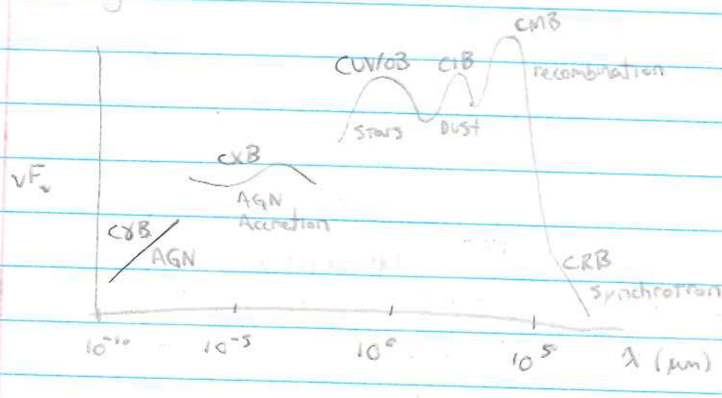
- The main emission line is that of Ly-α, due to intense UV radiation from quasar
- Quasar emission lines can either be broad or narrow. Broad lines come from material nearer to the accretion disk, which have higher velocities and are thus Doppler broadened. Narrow emission lines are from regions of lower velocity.

- Blueward of 1216 Å (Ly-α), we see the Gunn-Peterson trough and the Ly-α forest. Neutral H in the IGM along our line of sight absorbs Ly-α γs, and since this HI is sporadically distributed, the absorption happens at different redshifts (but actually blueshifts since the HI is closer to us than the original source, ie the quasar). At high redshifts, the universe was more neutral, as reionization wasn't totally done, so we see so much absorption that the Ly-α flux is totally decimated here - GP trough. As we move to lower redshifts, the fraction of ionized H increases, and there is less Ly-α absorption. The absorption lines get shallower and narrower as the universe becomes more ionized. The GP trough is super sensitive to any HI, so it's a good probe for the end of the epoch of reionization.

- γ, X, UV/O, I, M, R
- Blazar inverse Compton, AGN accretion disks, stars and thermal Brem. in IGM, dust, recombination, synchrotron from quasar jets

EG 11

Extragalactic Radiation Sources



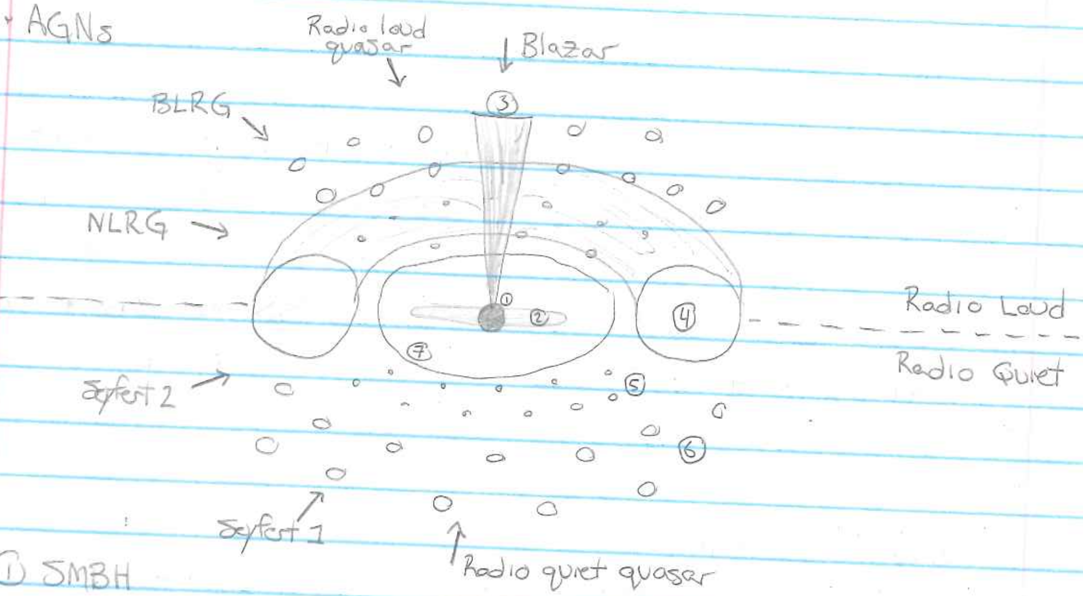
inverse compton in jet?

- CGB – blazars, interaction btw cosmic rays & ISM in star-forming galaxies
- CXB – AGN accretion disks; Flatness in SED due to self-absorption
- CUV/OB – reflected stellar light off ISM, thermal Bremsstrahlung from hot IGM, thermal emission from stars
- CIB – dust in SF regions re-radiates star light in IR, mostly low-z galaxies
- CMB – last scattering event at $z \sim 1100$, near perfect blackbody
- CRB – quasar synchrotron radiation, radio SNe, star-forming regions

- Draw AGN structure
- Label viewing angles
- Explain observed emission for each class

EG 12

- AGNs



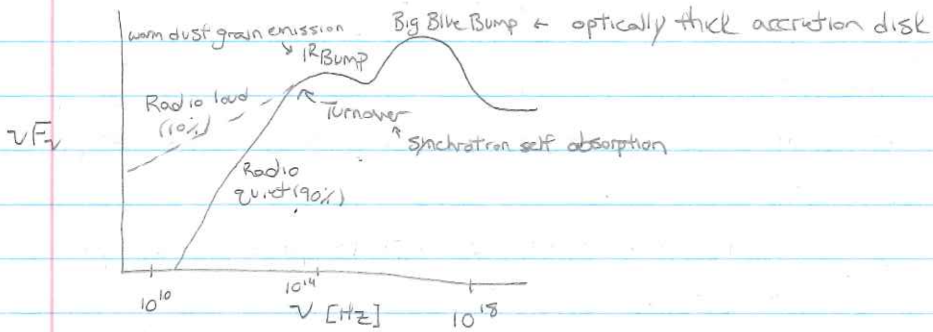
① SMBH
② Accretion Disk – UV/X-ray
③ Relativistic jet – Radio (synchrotron) & γ-ray (inverse compton)
④ Optically thick Taurus – IR
⑤ Broad line emission region – optical, photoionization by continuum radiation
⑥ Narrow line emission region – optical "
⑦ electron plasma

- <u>Blazar</u> – almost no emission <u>lines</u>, strong radio emission and polarization. 90% of all blazars found in ellipticals. Rapid variability
- <u>Radio-loud quasar</u> – broad + narrow emission lines, strong radio emission, some polarization, variable
- <u>Radio-quiet quasar</u> – broad + narrow emission lines, weak radio emission and polarization, variable
- <u>BLRG</u> – Broad Line Radio Galaxy. Broad (and narrow) emission lines, strong radio emission, weak polarization, variable. Found in ellipticals.
- <u>NLRG</u> – Narrow Line Radio Galaxy. Narrow emission lines only, strong radio emission, <u>no</u> polarization, <u>not</u> variable. Found in ellipticals.
- <u>Seyfert 1</u> – Broad + narrow emission lines, weak radio emission, X-ray emission, variable. Found in spirals
- <u>Seyfert 2</u> – narrow emission lines only, weak radio emission, weak x-ray emission, <u>not</u> variable. Found in spirals.

• General description of AGN:

- active galactic nuclei: are found at the centers of some galaxies, and are the galaxy's central engine. A SMBH at the center is surrounded/orbited by an accretion disk. The AGN (rotating!) is powered by the conversion of grav. P.E. to synchrotron radiation. The structure of the disk depends on the ratio of $L_{accretion}$ to $L_{Eddington}$. The classification of an AGN depend on the perspective of the observer, BH mass, and mass accretion rate.

• General AGN continuum



EG 13

- clusters are grav. bound collections of galaxies, and are in virial equilibrium
- List properties
- Look for extended xray sources, SZ effect on inverse compton scattered CMB, lensing signals due to mass of clusters warping space

Galaxy Cluster Detection

- Galaxies aren't uniformly distributed in space, but instead are found in grav. bound clusters (which have a characteristic separation of ~150 Mpc due to growth of density perturbations in early universe). Clusters are dynamically relaxed (in virial equilibrium). They're classified as regular if they're spherical & centrally condensed

- Properties:

$N_{galaxies} \gtrsim 50$ to 1000 (groups have <50)

Diameter $\sim$ 2-10 Mpc

Mass $\sim 10^{14} M_\odot$

Velocity dispersion $\sim$ 1000 km/s

M/L ratio $\sim 10^2\ M_\odot/L_\odot$ (indicates a lot of DM)

- Detection Methods

– X-ray emission

↳ extended x-ray sources are more likely to be clusters (15%) than quasars (85%) of all x-ray sources, which have point-like x-ray emission. The extended source implies the radiation doesn't come from just a single galaxy, so we can search for these sources.

↳ the x-ray emission is due to hot optically thin gas where the e^-'s experience thermal Bremsstrahlung during collisions. e^-

– Sunyaev-Zeldovich Effect

↳ e^-'s in the hot ICM gas can inverse Compton scatter CMB photons, giving them an energy boost. This causes the CMB spectrum to deviate from a perfect blackbody, as low-ν γ's are shifted to higher ν's. We will therefore see an increase in the temperature fluctuation of the CMB in the direction of the cluster.

– Weak Gravitational Lensing

↳ The high mass concentration produces a tangentially-oriented shear field, bending light around the cluster and distorting the appearance of more distant galaxies behind

the cluster into arcs and multiple images. By searching for such lensed signals you can infer the presence of a cluster.
↳ the advantage of this method is that it depends only on cluster mass, not its EM radiation

- Red Cluster Sequence
↳ Color-mag diagrams of cluster members show a horizontal sequence (RCS) of early type galaxies, meaning these galaxies have the same color, only weakly depending on L or metallicity. The RCS gets redder w/ redshift, so you can constrain the z based on the RCS color, and determine if the galaxies are spatially associated in 3D rather than just 2D (on the sky).

EG 14

- SFQ is a process through which feedback slows down or halts SF
- Methods: SNe, AGN, Strangulation. All remove gas
- Evidence: bimodal galaxy distribution in color-mag, galaxy evolution simulations

Star Formation Quenching

- SFQ is generally when some feedback process causes SF to decrease or halt entirely, or some event removes gas from a galaxy, limiting SF.

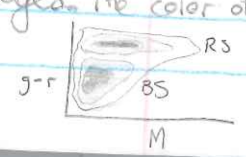
- SNe Feedback
  - high SFR leads to high rate of SNe explosions, which can do 2 things to the ISM:
    - ↳ heat the gas due to its release of KE into the ISM, resulting in gas expansion and decreased density, making cooling less efficient and further SFR harder
    - ↳ in low mass galaxies, the ISM can be blown out of the disk and into the halo, removing gas and limiting SF as the gas is no longer available

- AGN Feedback
  - as gas accretes onto the SMBH / its accretion disk, the grav. PE is converted to KE/Thermal E, so the AGN heats and expells the gas from the galaxy. The removal of gas limits SF.

- Strangulation
  - as a galaxy approaches the inner cluster, the high density of ICM gas and other galaxies can strip all the gas from the galaxy, limiting SF.

- Generally these processes serve to slow down the SFR rate such that galaxies can still be seen with SF after billions of years, not just when they're very young. The quenching has to happen quickly.

- We see evidence of this SFQ in the bimodal distribution of galaxies in color-mag diagrams. Red-sequence galaxies are more luminous, high mass, spheroidal and narrowly distributed in color, since the color of an old stellar pop'n depends little on its exact age. The galaxies have an old stellar pop'n w/ no/little recent SF. Blue-sequence galaxies are star-forming, low-mass galaxies that are disk dominated, and their spread in color reflects different levels of SFR, leading to different mean ages. The color of B.S. galaxies is more correlated w/ luminosity than is R.S. galaxies



- We can also find 'evidence' of SFQ if we look at galaxy evolution simulations. If we dont include feedback processes (like SNe), SF proceeds way too quickly to explain the galaxy types and ages we see today.

- Also consider the epoch of reionization. At first H_2 cooling allowed the first stars to form from condensed gas, but then the stars produced a bunch of UV photons capable of photo-dissociating H_2, preventing further cooling + SF.

EG 15

- SNe heat and expell ISM
- AGN heat and prevent IGM from infalling
- AGN remove gas from merging galaxies
- Pop'n III stars limit further SF w/ UV γs that destroy cooling H_2

• Feedback processes

• Supernovae - galactic scale

- high SFR leads to high rate of SNe explosions (this obviously depends on the assumed IMF)
- SNe release part of their E in form of KE to the ISM, locally heating it. This causes the gas to expand, lowering its density, and reducing its cooling efficiency. This limits further SF in those regions
  ↳ self-regulating process. Prevents all the gas in a galaxy from being made into stars on a short timescale, otherwise SF would proceed too quickly for us to see new stars today.
- if the E transferred to the ISM is high enough, a galactic wind can develop which drives part of the ISM out from the galaxy to its halo, further limiting SF.
  ↳ SNe feedback is more efficient at suppressing SF in low mass galaxies since its easier to drive gas out; the binding energy is lower.

• AGN - galactic scale

- As cool gas (gas cools +) falls into accretion disk of SMBH, its grav. PE is converted to KE in the form of radiojets and/or radiation from the accretion disk (ie it fuels the SMBH).
- The radiation heats the gas again, preventing efficient cooling (similar to SNe) and limiting further accretion (negative feedback)

• AGN - extragalactic scale

- Galaxy mergers can trigger AGN by channeling gas to central SMBH, producing active nuclei w/ accretion disk, etc.
- the AGN will heat and expell the infalling gas, stopping further SF and impacting the nature of the resulting merger remnant.

• Also consider formation of first stars via H_2 cooling, which the photodissociated the H_2 and paused H_2 cooling in those regions.