UCL PHAS3136 2010

Extragalactic Astronomy Handout

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Course textbooks

- Jones & Lambourne, An Introduction to Galaxies and Cosmology (hereafter JL)
  - 22 copies in UCL science library
  - On amazon.co.uk 30 pounds
- Liddle, An introduction to modern cosmology
  - In UCL science library

Also, for further information:

- Peterson, Active galactic nuclei
- Binney & Merrifield, Galactic Astronomy

Normal galaxies: interface with JL

All of JL chapters 1 and 2 are examinable, except:

- 1.2.1 - 1.2.3 is (hopefully) a revision of earlier courses
- 1.4.1 paragraphs on open clusters and OB associations
- 1.4.2 paragraph on interstellar dust
- 1.5 is more detail on our galaxy, not in our course
  - (generally, features of our galaxy not readily observable in other galaxies are not in this course)
- 2.5.4 on galaxy mergers - non examinable

The following are examinable but not in JL:

- details of chemical evolution, including G-dwarf problem
- the luminosity function
- galaxy light profiles: exponential and de Vaucouleurs
- rotation curves for non spherically symmetric mass distributions
- more details on fundamental plane, Tully-Fisher, Faber-Jackson relations
- calculation of expected luminosity evolution of galaxies

1.1 Our Galaxy: basics

List of topics:

- Disk, bulge, halo
- Stellar populations: Baade’s observations
- Stellar populations: Current thinking
- Metal enrichment
- Age-metallicity relation
- Galactic fountain

See JL 1.2.1 to 1.2.4

Our Galaxy

- Why in this lecture course?
  - An example of a well studied galaxy

- Contents:
  - stars ($\sim 10^{11}$)
  - gas ($\sim 10^{10}$ M_o)
  - dust ($\sim 10^{8}$ M_o)
  - dark matter ($\sim 10^{12}$ M_o)

Location of galaxy contents

- Most of the stars are in a with spiral arms
- Significant concentration of stars in the center
  - The
- Also: stellar (~10^9 stars) and some
- Mass is believed to be mainly in a halo, dominated by
  - Extends out to >100 kpc diameter
- clusters, clusters
  - clusters of stars distributed throughout halo

Stellar populations: Baade's observations

- Population I ('pop one')
  -
  - Galactic , open clusters
- Population II ('pop two')
  -
  - Galactic globular clusters
  - galaxies
  - Bulges of galaxies

Read JL p14-15

Stellar populations: Current thinking

- Pop I
  - Z= 0.01 – 0.04
  - orbits within plane of Galaxy
  - Myr to 10 Gyr
- Pop II
  - stellar halo: Z<0.002 (minimum observed: Z=2e-6)
  - bulge Z ~< 0.02
  - orbits (high-velocity stars)
  - 12 to 15 Gyr, so only low mass are visible
- Pop III
  - Theoretical idea = the

Read JL p16-18

Metal enrichment

- After big bang nucleosynthesis
  – low metallicity gas
- Massive stars inject metals into the ISM
  – Stellar winds
  – Planetary nebula shells
  –
- Metallicity of ISM gas depends on
  – Masses of stars in that region
  – Efficiency of enrichment as fn of star type

Read JL p 19

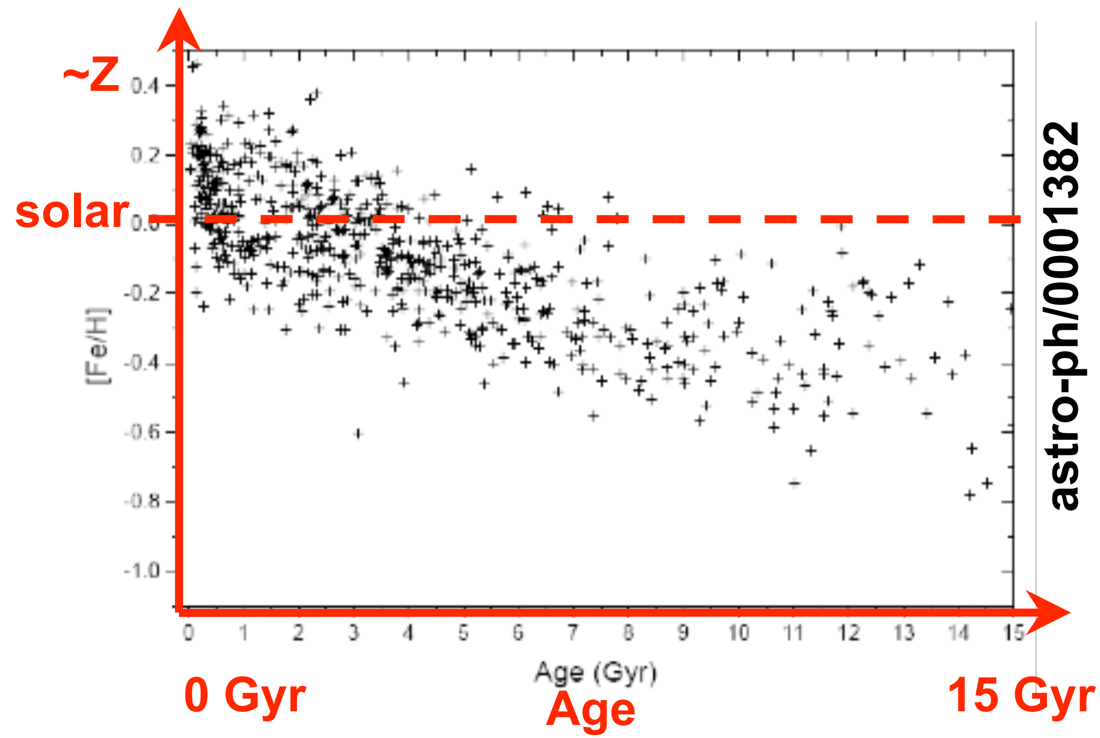
Age-metallicity relation

- Z of a main sequence star

= Z of the star formed

We observe a strong age-metallicity correlation

- – explained by



Read JL p 19

Galactic Fountain

- make a superbubble
  - of hot ionized gas
- Gas cannot expand far sideways into disc
- Can burst out of disc into
- If it falls back to the disc this is like a fountain
  - Why would it fall back to the disc?
- Could be the cause of the diffuse gas in the halo

Read JL p 54

1.2 The Galactic Disk

List of topics:

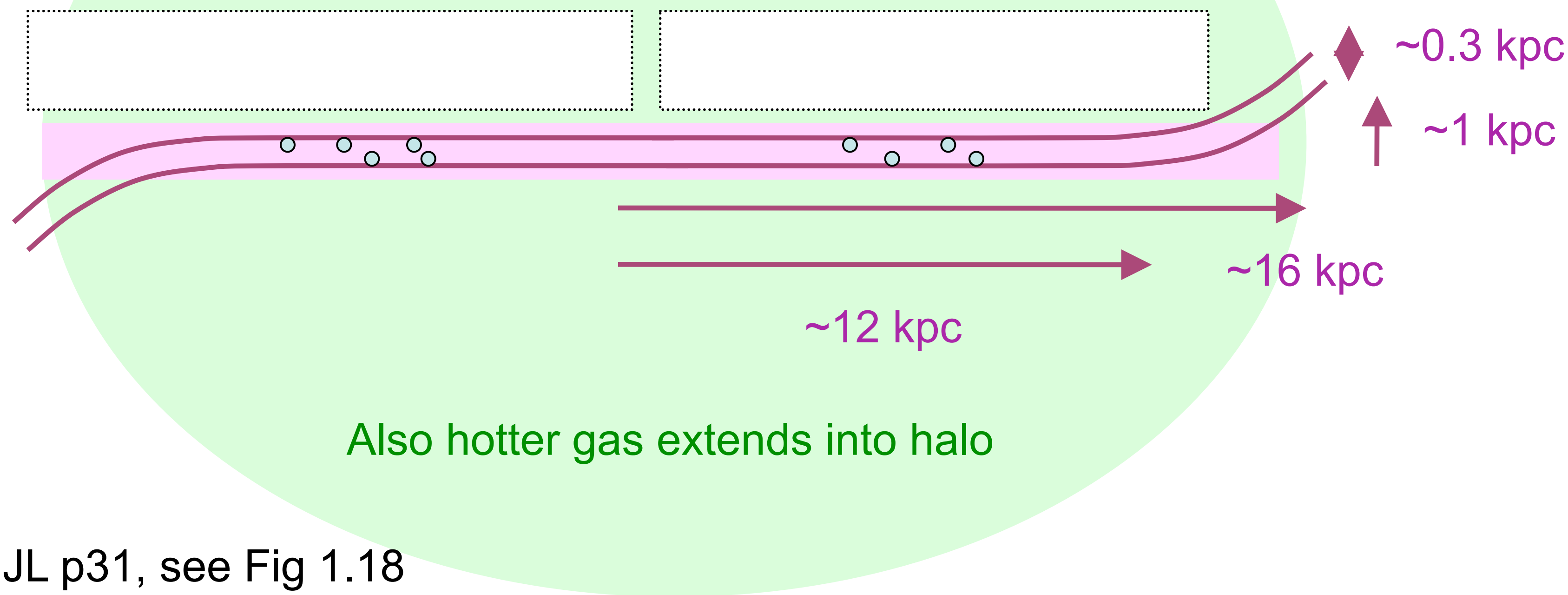
- Gas in the disk
- Different wavelengths probe different components
- Populations as a function of position
  - The scale height
- Spiral arms

All covered in JL p26-40

Gas in the disk

- Gas mass = ~ % of the stellar mass
- Observed using 21cm emission by
- ~1/4 of galaxies have warped disks

Thin gas disk:



Read JL p31, see Fig 1.18

What determines form of H?

- Gas clouds cooler than about 100 K generally do not emit the 21 cm line; why not?

- Why are hot HII regions often found in association with cool, dense clouds?

Read JL p32

The Galactic Disk: Basics

- Majority of visible matter is in the disk
  - visible matter =
- Disk is dominated by visible matter
  - dark:visible matter is ~
- Observations:
  - X-ray:
  - Optical:
  - near ir:
  - far ir:
  - radio:

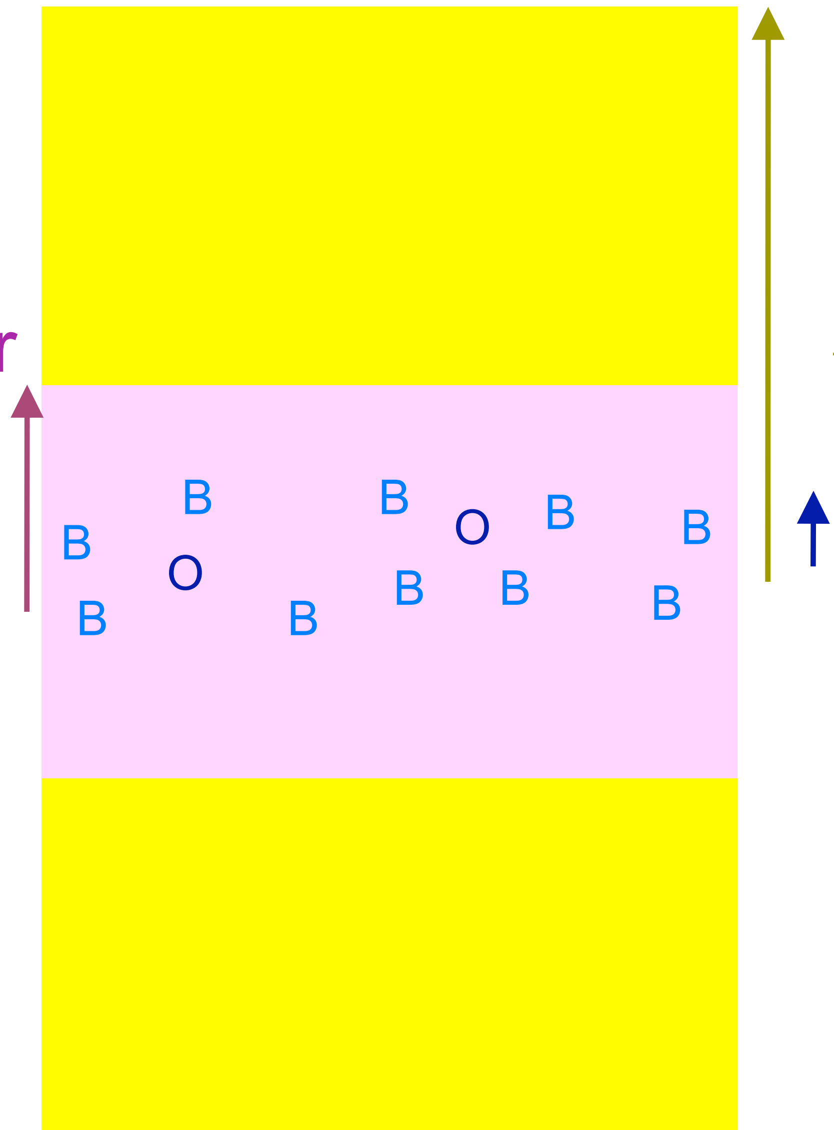
Read JL p26, 27

Scale height h

- $\rho(z)$ = density as function of height from mid-plane z
- To a good approximation:
  - $\rho(z) = \rho_0\, e^{-|z|/h}$
- h= distance on which ρ drops by factor 1/e
- Sketch $\rho(z)$

Read JL p 34 - 35

The thin disk



Interstellar gas, dust
h ~ 120pc

Main sequence stars
G, K, M
h ~ 350 pc
$\Sigma \sim 13\ M_o\ pc^{-2}$

Young stars
B, O
h ~ 50 pc
$\Sigma \sim 10^{-3}\ M_o\ pc^{-2}$

Why???

Explaining the relative h values

- O and B stars are formed from interstellar gas
  - why do they not have the same scale height as the interstellar gas?

- Ditto main sequence stars

Read JL p 36

1.3 The Galactic Rotation Curve

List of topics

- Keplerian rotation curve
- The rotation curve of our galaxy
- M(r) from v(r) assuming a spherical model M(r) from v(r) assuming a disk-like mass distribution
- The winding problem and density wave theory
- Metallicities of spiral arm stars
- Galactic archaeology

Some, but not all, of this material is in JL 1.3

The rotation curve of our galaxy

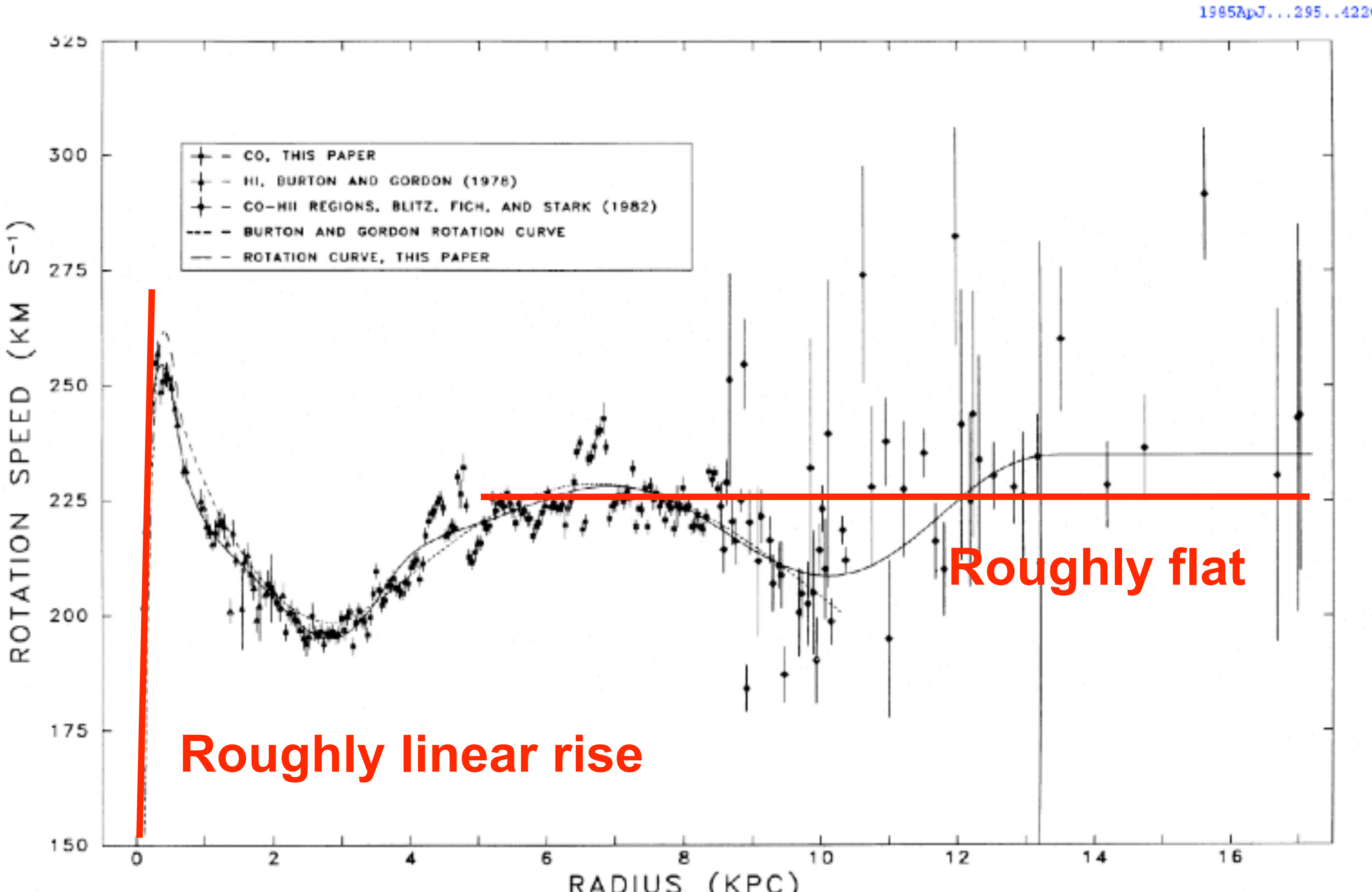


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)(R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

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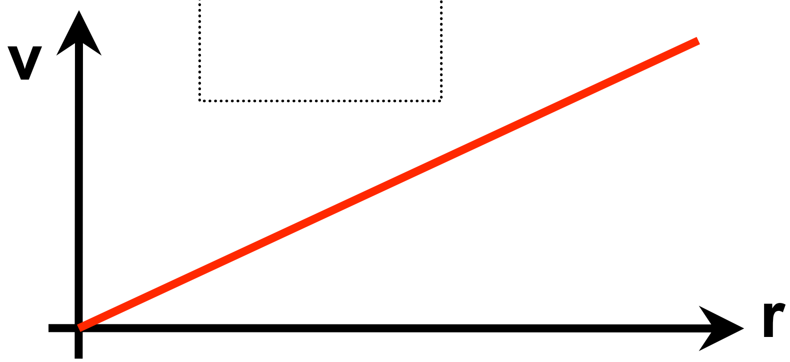
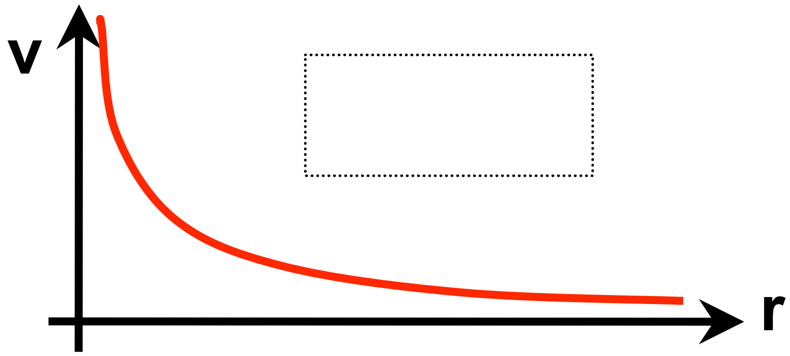
Rotation curves

- A



- B

- C



Problem class questions

- Estimate the mass of the galaxy within r_o
  - You may assume the galaxy is spherically symmetric
  - r_o = radius of the Sun = 8.5 kpc
- Estimate M(r)
  - M(r) = the total mass enclosed in a spherical radius r.
  - You may assume $M(r) \propto r^{\alpha}$.
  - You may assume spherical symmetry.
- What does this imply for the density ?
  - If spherical $M(r) \propto r^{\alpha}$ implies $\rho \propto r^{\beta}$ where β = ?
- How could you modify gravity to remove the requirement for dark matter at large radii?
  - If $F=GMm/r^{\gamma}$ what would γ need to be?

The winding problem

- Estimate the time for one orbit of the Galactic disk at (i) 5 kpc and (ii) 10 kpc from the galactic center

- Which is greater?

A. Time for 1 orbit at 5 kpc radius

B. Time for 1 orbit at 10 kpc radius

- Sketch the spiral arms after ~10^9 years

Read JL p 37 - 40

Density wave theory

- Solves the winding dilemma
- Spiral arms reflect overdensities in (not mass)
- Galaxy rotates at speed to these waves
  - cf sound waves in air do not travel at wind speed
- Roughly rotation of spiral pattern
- of gas causes star formation

Read JL p 37 - 40

1.4 Galaxy Light Distributions

List of topics

- Hubble classification scheme
  - see Binney & Merrifield text
- Galaxy surface brightness profiles (JL 2.3.1, plus additional material)
- Galaxy luminosity function (not in JL)
- The Tully Fisher relation (additional material cf JL)
- The Faber-Jackson relation (additional material cf JL)
- Metallicity and populations in typical spirals
- Metallicity and populations in typical ellipticals

See JL 2.2 for some background material only

Surface Brightness Profiles

- What is the total luminosity of a galaxy?
  - At what to stop adding up?
  - and instrument limit radius
- Surface brightness profile = apparent surface brightness as fn of
  - Apparent surface brightness = from source, per unit area of , per
  - Usually for a given
- Usually assume
  - de Vaucouleurs profile: I(R)
  - de Vaucouleurs bulge + exponential disk

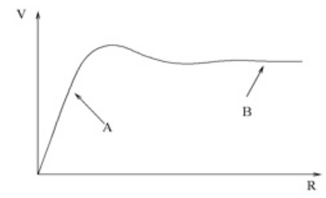
  exponential disk: I(R)

The Galaxy Luminosity Function

- Number of galaxies of given
- Schechter function fits well
  - $\phi(L) = (n_* / L_*)$
  - Where $\alpha \sim -1.1$, $L_* \sim 10^{10} L_{solar}$, $n_* \sim 0.01\ \mathrm{Mpc}^{-3}$ (depending on selection criteria of galaxies)
- L_* is a galaxy luminosity
- n_* is a typical galaxy
  - what is a typical intergalactic distance?
- $N = \int_{L(min)}^{\infty} \phi(L)\, dL$ as L(min) -> 0
  - not but emphasises large number of

The Tully-Fisher relation

- Relates to for
  - Tully & Fisher 1977
- v(r) shape for our galaxy is typical of spirals
  - Observe other galaxies using
  - call v_{rot} the



- We observe $L \propto v_{rot}^{\ \beta}$
  - $\beta \sim$ in B-band
  - $\beta \sim$ in the infrared
- What would you expect for β ?
  - Assume $M \propto L$ (constant mass to light ratio)
  - Assume $L = L_o \pi r^2$ (with L_o same for all gals)

The Faber Jackson relation

- Relates and central velocity of
- Stars in ellipticals seem to be
  - all move in random directions, velocities v
  - velocity dispersion = σ_v =
  - virial theorem: so σ_v^2
- Faber-Jackson relation: L
- The Fundamental Plane:
  - plot galaxies in 3d: L, σ_v, R
  - find R

Mass-to-light in ellipticals

- Virial theorem: $M \propto \sigma_v^2 R$
- The fundamental plane: $R \propto \sigma_v^{-2} L^{1.25}$
- Suppose $(M/L) \propto L^{\gamma}$
  - Find γ

- The bigger the luminosity, the $\boxed{}$ the mass, the more $\boxed{}$ matter

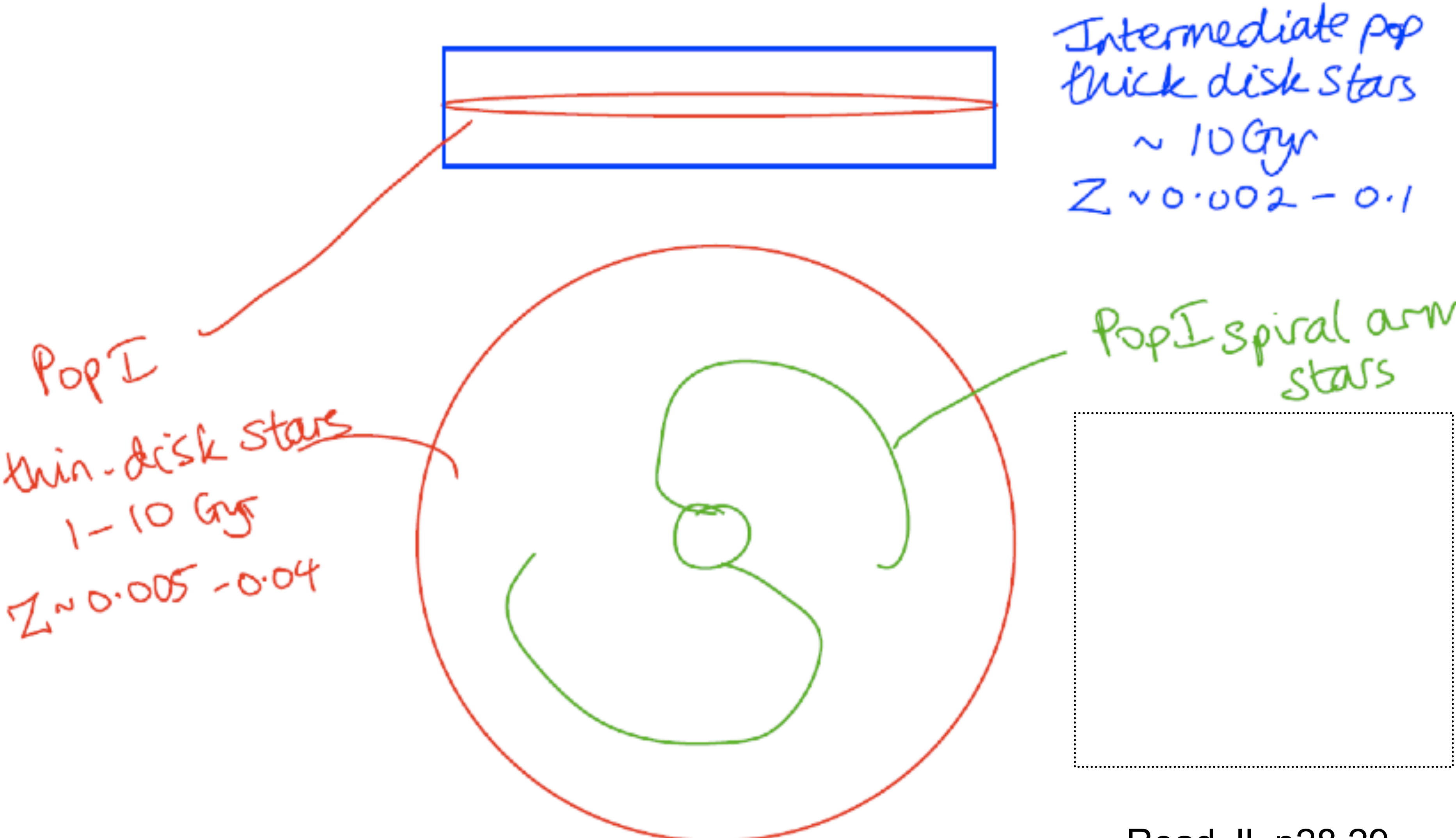
Spiral galaxies

- See notes on our galaxy
- spiral arms, , Z
- disk population, Z
- mass Pop II stars in bulge and spheroid
- in Z with increasing r
  - e.g. bulge metallicity is than solar

Elliptical galaxies

- of gas or recent star formation
- Stellar populations are and (Pop)
  - (B-V ~ 1)
  - most light from
- Small E/S0 gals have metal content
  - Large E/S0 galaxies are relatively metal

Stellar populations in the disk



Read JL p28,29

Galactic Archaeology

- Observe positions and velocities of all stars in our galaxy

- Compare with simulations to

- Future experiments:
  - RAVE: just started, Australia
  - GAIA: satellite
  - WFMOS: proposed, UCL is involved

1.5 Galactic Chemical Evolution (GCE)

List of topics:

- Aims and issues with GCE
- The initial mass function
- derivation of f(Z,t) for closed box model
- the 'G-dwarf problem'
- possible solutions of the G-dwarf problem

Not in JL

Aims and issues with GCE

- Aims:
  - predict history and future of
  - explain as fn of Z and M
  - unravel facts about how
- Issues
  - we can't calculate massive star well
  - we don't know how well these metals
  - we don't know well how many stars form (or how this depends on metallicity, radiation levels...)
  - we don't know how many stars form at different
- Simple models attempt to provide some insight

The initial mass function

- of stars per unit that form, as function of stellar mass, $\psi(M)$
  - $\psi(M)\,dM =$
- Simple fit to observations:
  - Salpeter IMF $\psi(M)$
  - $\alpha \sim$
  - Fits well in our
- Theorists speculate about a "top heavy IMF"
  - lots of stars
  - may occur in regions with levels

Qualitative problems

- Sketch $Z_{ISM}(t)$
- Sketch $M_S(Z)$, the total mass of stars with a given metallicity, as a fn of metallicity
  - (i) for an early time
  - (ii) for a later time
- Sketch the fraction of stellar mass in stars of metallicity Z or less, f(Z,t)
  - (i) for an early time
  - (ii) for a later time

Popular GCE assumptions

- 'Closed box' model
  - M_{TOT} =
- Instantaneous recycling approximation:
  - In a short time Δ t, a mass Δ M_S' of stars are formed.
    - "Short lived" stars to ISM
    - "Long lived" stars
    - A mass Δ M_S of stars are formed
  - The mass of metals returned to the ISM is by defn of p (called the yield).
  - So there are no remnants, so M_{TOT}=

Galactic Chemical Evolution calculations (page 1 of 2)

1. Derive the metallicity of the interstellar medium Z_{ISM}, as a function of the mass in stars M_S
   - assume a closed box model
   - assume instantaneous recycling approximation
2. Derive the fraction of stellar mass in stars of metallicty Z or less, as a function of time t, f(Z,t)
   - assume a closed box model
   - assume instantaneous recycling approximation
3. Derive the fraction of stellar mass in stars of metallicty Z or less, as a function of time t, f(Z,t)
   - estimate p using today: $Z_{local} \sim Z_{solar}$, $M_S \sim 0.9 M_{TOT}$
   - assume an initial metallicity of zero

Galactic Chemical Evolution calculations (page 2 of 2)

4. Suppose that the initial metallicity were not zero, could that solve the problem?
   - What initial metallicity is required to match the observations in this model?
5. Suppose instead that the closed box assumption were wrong, and that gas is falling into the region.
   1. Re-calculate Z(t) for the case of constant ISM mass
   2. Re-calculate the fraction of objects with Z< 0.25 Z_{solar}

Summary of the G-dwarf problem

- Simple model predicts % of stellar mass in local neighborhood has $Z<0.25\ Z_{solar}$
- Observations find ~
  - Called the G-dwarf problem
- Lifting the closed box assumption is expected to
  - Instead assuming ISM to keep ISM mass gives
  - How likely is it that the ISM mass is topped up like this?
    - Not clear: likely ISM flows into our solar neighborhood from larger radii, but also likely ISM flows out of our solar neighborhood towards the bulge.
- Dropping assumption that ISM initially has is expected to match observations.
  - To exactly match the observations need $Z_{ISMi}=$ Z_{solar}
  - Is this level of likely?
    - Not clear: Some theories suggest an early burst of massive star formation, that left only metals (and no long-lived low mass stars).

1.6 The Hubble Constant

List of topics

- Measurement methods and results
- Age of Universe

JL Section 2.4 (p 83 – 100)

Hubble constant calculations

1. How far away does a galaxy have to be to alone yield a good H_0 estimate?

(Assume a typical galaxy has a peculiar velocity of 500 km s^{-1} and that H_0~70 km s^{-1}.)

4. Estimate the age of the Universe using the HSTKP value for the Hubble constant.

(Make simple assumptions).

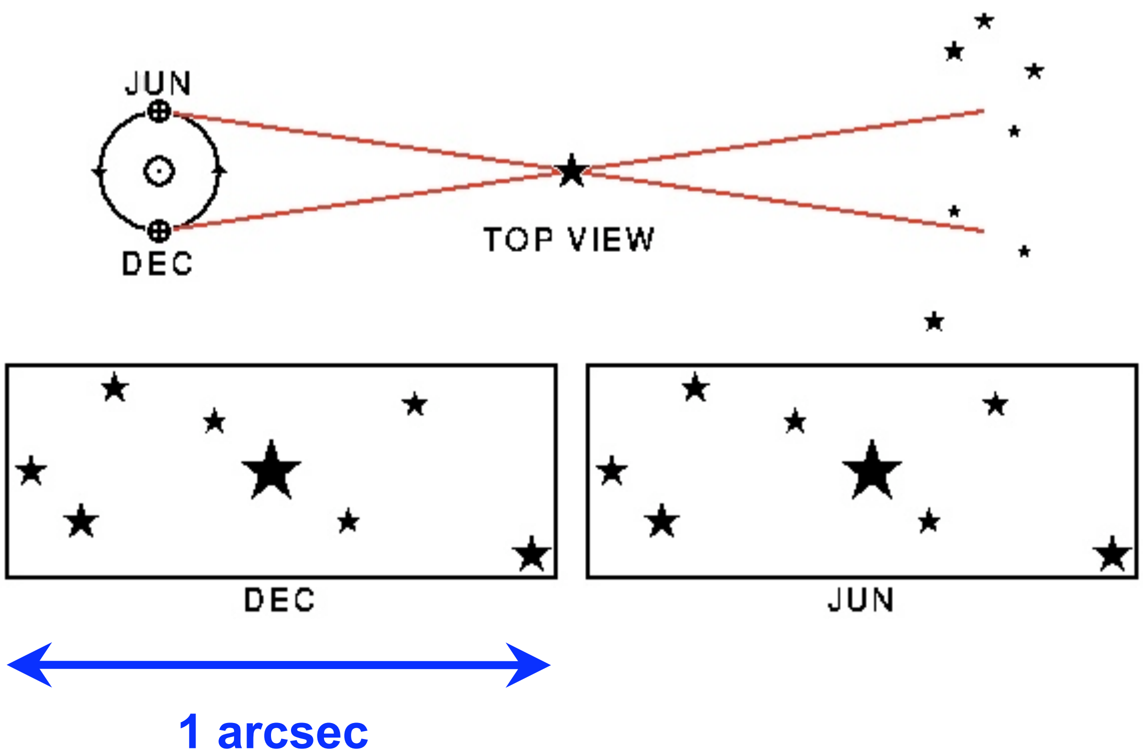
Hubble estimated $H_0 = 530$ km s^{-1} Mpc^{-1}.

What age did he get?

Hubble constant calculations

2. Estimate the distance of this star

http://www.astro.ucla.edu/~wright/distance.htm



(a) ~0.07 pc
(b) ~1 pc
(c) ~5 pc
(d) ~15 pc

1 parsec == 1 A.U. / 1 arcsec

Hubble constant calculations

3. Galaxies A and B have the same apparent magnitude in the infrared but galaxy A has twice the rotation velocity of galaxy B.

What is the ratio d_A / d_B ?

(a) ~1/4

(b) ~1/2

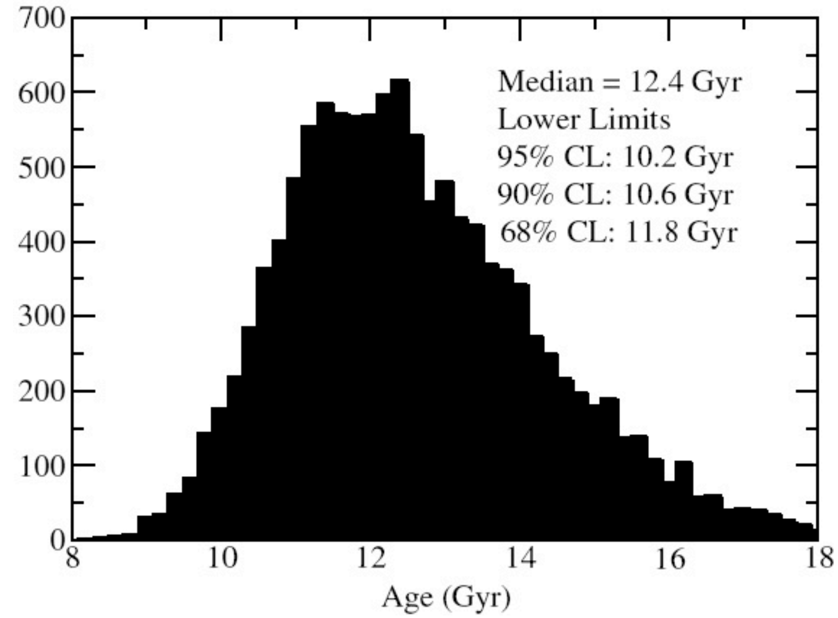
(c) ~2

(d) ~4

http://www.astro.ucla.edu/~wright/distance.htm

Measurements of the age of the Universe

- Age of the Earth ~ 5 Gyr
  - Lower limit: t_0 >
- isotopes in our galaxy
- Cooling of
- Star [globular]
  - Stars' age ~ 12.4 Gyr
  - Estimate ~ Gyrs for formation
  - t_0 ~ Gyr
- → t_0~13.7 Gyr
  - See later lectures



Krauss & Chaboyer astro-ph/0111597

Measuring the Hubble Constant

- Difficulties:
  - Need distances and velocities
    - Redshifts give
    - Get distances
  - Nearby galaxies are moving relative to Hubble flow
    - Can see SN1a far enough away
  - We don't know the of SN1a

- Distance ladder:
  - Use parallax to determine absolute magnitude
  - Use Cepheids to determine SN1a
  - Can use SN1a to measure H_0

Standard Candles

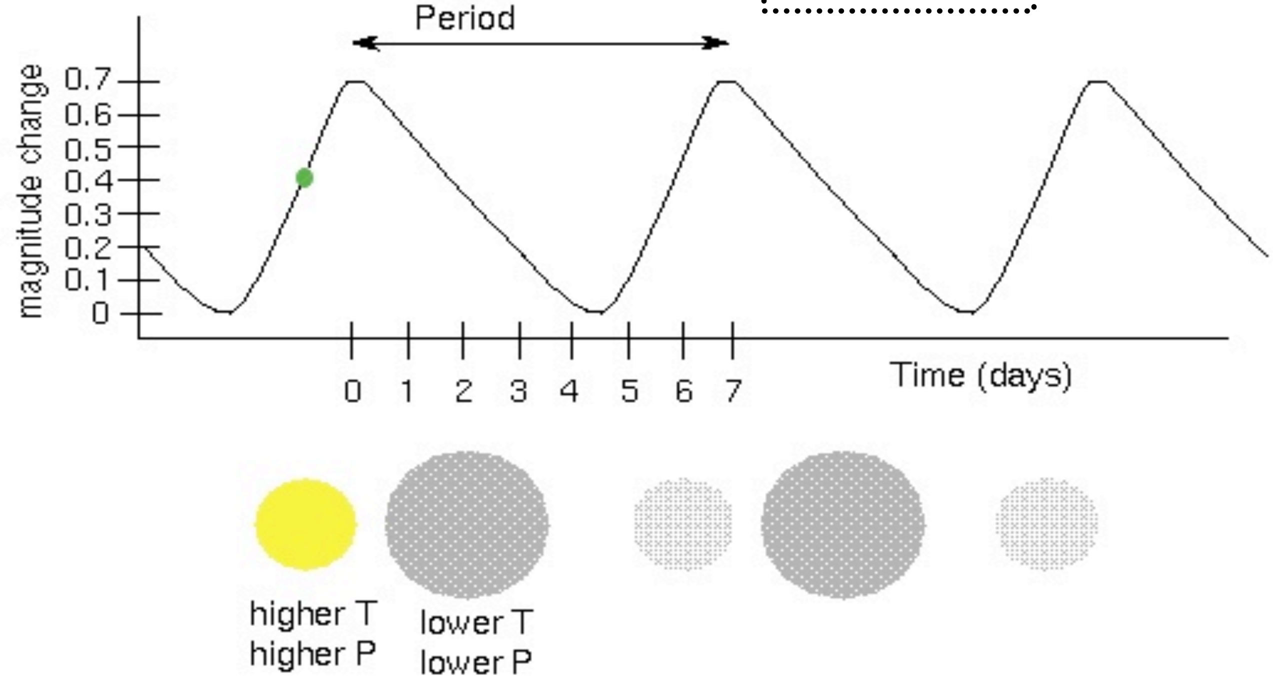
- Definition:
  - Anything that is the same brightness wherever it is placed
- e.g.
  - Could estimate distance to nearby farmhouse by looking at apparent brightness of
- Historical example
  - e.g. Hubble used for discovering expansion

Galaxies as standard candles

- Hubble: assume all galaxies are same
- Measure of spirals
  - Use to find intrinsic luminosity
  - Compare with luminosity -> distance
- Measure velocity dispersion and size of
  - Use Fundamental plane to find
  - Compare with observed luminosity ->
- Typical uncertainties of on distance

Cepheid variables

- Pulsate with a that depends on luminosity
- Measure period -> luminosity
- Compare with apparent luminosity ->
- Uncertainty of about



Cepheid variables: outward pressure (P) and inward gravity compression are out of sync, so star changes size and temperature: it **pulsates**. *RR-Lyrae* variables are smaller and have pulsation periods of less than 24 hours. Also, their light curve looks different from the Cepheid light curve.

http://www.astronomynotes.com/ismnotes/s5.htm

SNIa as Standard Candles

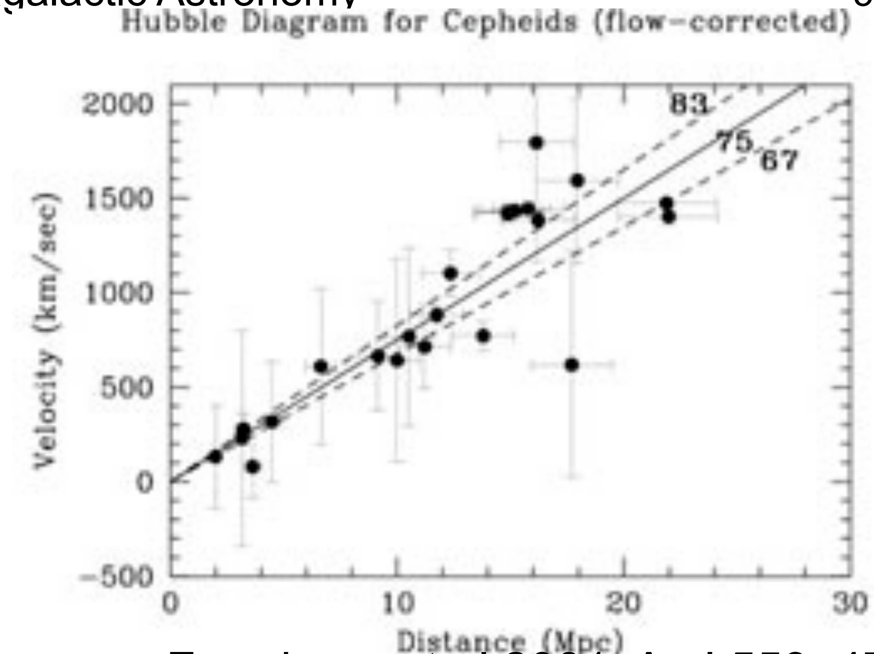
- Theoretically plausible (1.4M_solar limit)
- Observations support it
- Simulations are to dispute
- Open questions:
  - Is there a dependence on
  - Are SN different at

- We don't know the absolute magnitude of supernovae
  - $5 \log_{10} (D_L / 1\mathrm{pc}) = m - M + 5$
  - Results in unknown scaling of D_L

- Uncertainty of about 5% on distance

HST Key Project

- HST = Hubble Space Telescope
- Attempt to end the great debate
- + 5 other distance indicators
- Conclusion: H_0 = 72 +/- 2 +/- 8 km s^{-1} Mpc^{-1}
- Main uncertainty (+/- 8) is



Freedman et al 2001, ApJ 553, 47

Uncertainties in H_0 for Secondary Methods

Method	H_0	Error (random, systematic) (%)	References
36 Type Ia SN, $4000 < cz < 30{,}000$ km s^{-1}	71	$\pm 2 \pm 6$	1, 2, 3, 4
21 TF clusters, $1000 < cz < 9000$ km s^{-1}	71	$\pm 3 \pm 7$	5, 6, 7
11 FP clusters, $1000 < cz < 11{,}000$ km s^{-1}	82	$\pm 6 \pm 9$	8, 9
SBF for 6 clusters, $3800 < cz < 5800$ km s^{-1}	70	$\pm 5 \pm 6$	10, 11
4 Type II SN, $1900 < cz < 14{,}200$ km s^{-1}	72	$\pm 9 \pm 7$	12

Note—Combined values of H_0: $H_0 = 72 \pm 2$ (random) km s^{-1} Mpc^{-1} (Bayesian), $H_0 = 72 \pm 3$ (random) km s^{-1} Mpc^{-1} (frequentist); $H_0 = 72 \pm 3$ (random) km s^{-1} Mpc^{-1} (Monte Carlo)

1.7 Clusters of galaxies

List of topics:

- Our local environment
- What is in a (galaxy) cluster?
- Mass estimates from
  - (a) Velocity dispersions
  - (b) X-ray observations
  - (c) Strong gravitational lensing
  - (d) Weak gravitational lensing

Read JL section 4.3

Our local environment

- We do not live in a cluster of galaxies, but a "group"
  - The "Local group"
  - members within
  - sparse and non-symmetrical
- Nearest cluster is Mpc away
  - Virgo has of galaxies in
  - Irregular, dominated by 3 cD galaxies
- is larger than Virgo, spherical
  Mpc away

Clusters: summary

- Many elliptical galaxies
- Usually one giant elliptical, or “cD” galaxy
  - giant ellipticals ~ Mpc across, ~ local group size
- Composition: (not just galaxies!)

  of mass is in galaxies

  of mass is hot gas

  the rest is dark matter
- The largest gravitationally bound systems
  - Typical mass is up to
- “Field galaxies”: galaxies not in clusters
  - galaxies are not in clusters

The Abell catalogue

- The first comprehensive cluster catalogue
- Abell (1958) inspected red sensitive photographic plates of Northern sky
  - identified 2712 clusters
  - Used: cluster = overdensity of galaxies in radius 1.7'/z
- Many clusters studied today are in this
  - e.g. A2218 (A stands for Abell)
- Since updated to southern sky
  - contains 4073 clusters

galaxies per cluster

Cluster masses from velocity dispersions

- First applied by Zwicky in 1930s
  - Discovered that Coma had much invisible matter
- Virial theorem

  K.E. ~ | P.E.|
-
  - This time σ_v is that for the
  - Measure from range of
- How reliable is the virial theorem for clusters?
  - Many clusters are believed to be
- Virgo has a velocity dispersion of 550 km s^{-1}
  - Estimate its mass

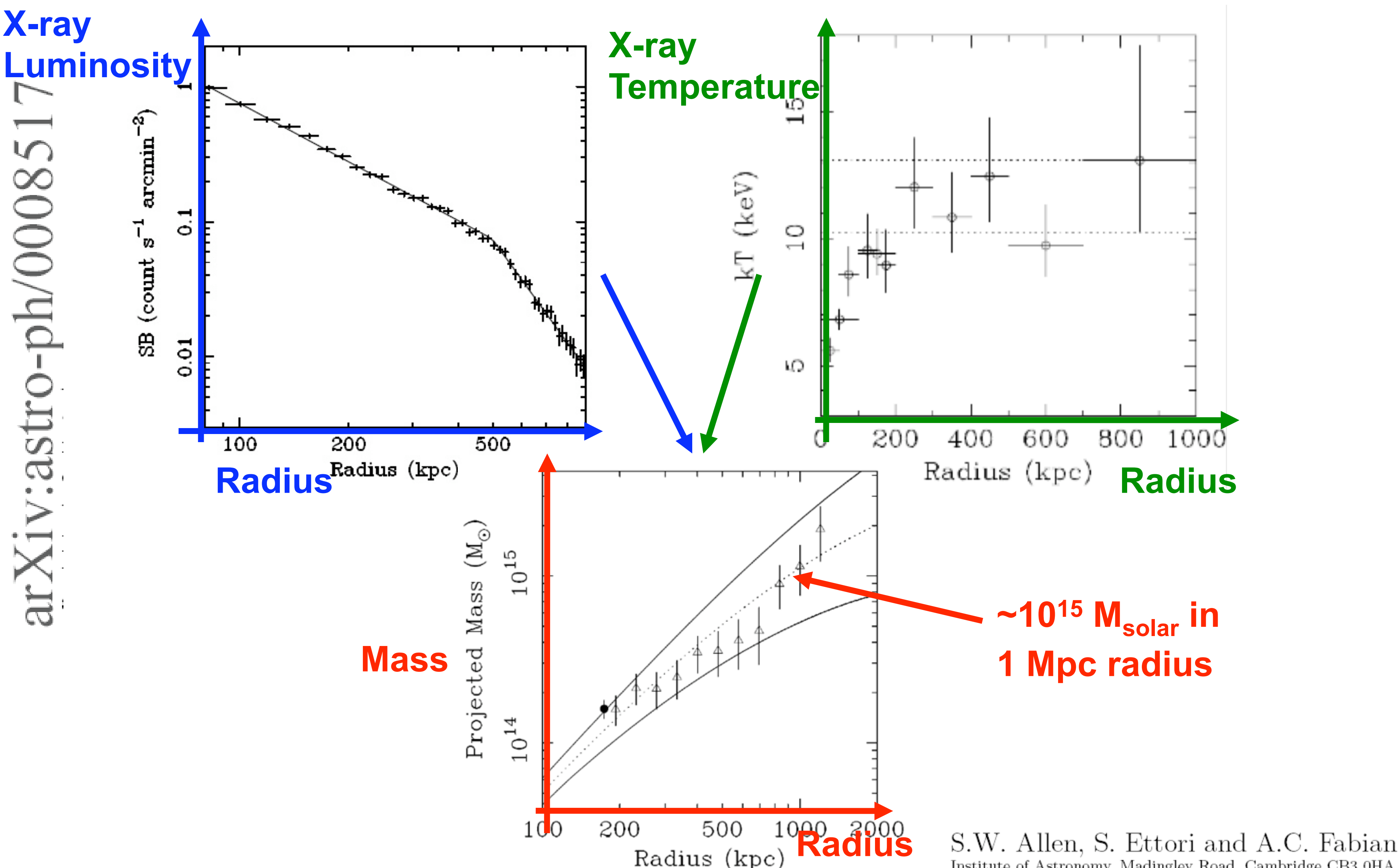
Cluster masses from X-rays

- Hot gas in clusters emits lots of X-rays
  - thermal bremsstrahlung
- X-ray observations are good for finding clusters
  - can observe luminosity and T as fn of position
- If spherically symmetric and stationary:
  - can apply hydrostatic eqm to find mass

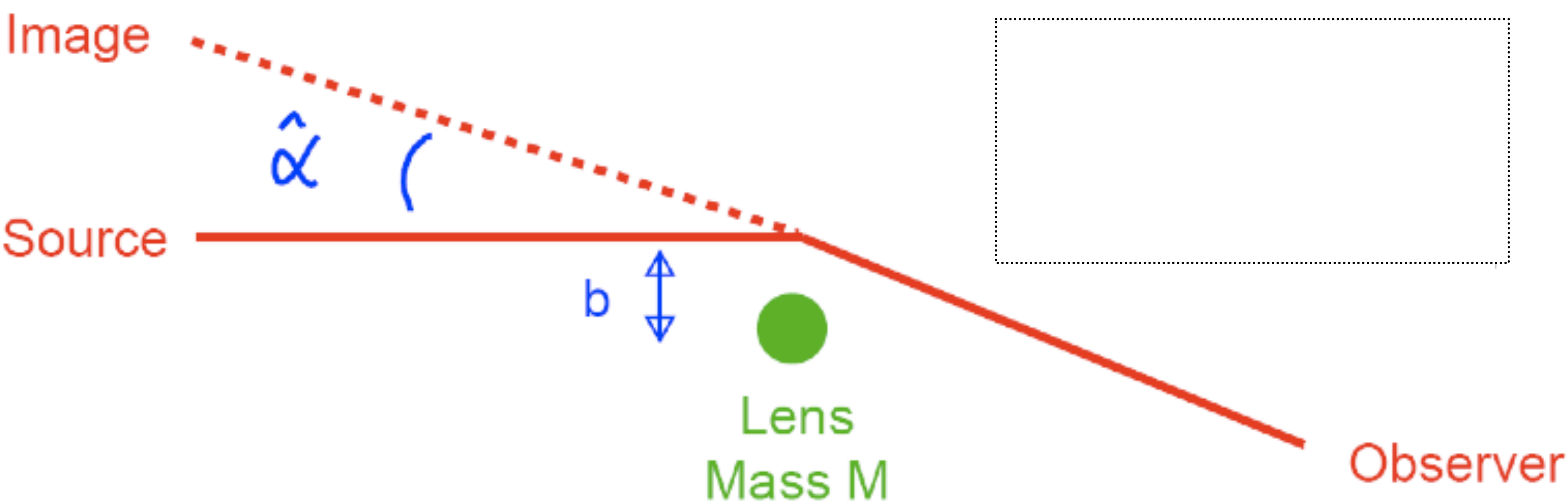
Hydrostatic equilibrium equations

- Observe $T(r)$ and $\rho_g(r)$ from X-rays
  - T from spectra; ρ_g from X-ray luminosity

Mass of Abell 2390 from X-rays

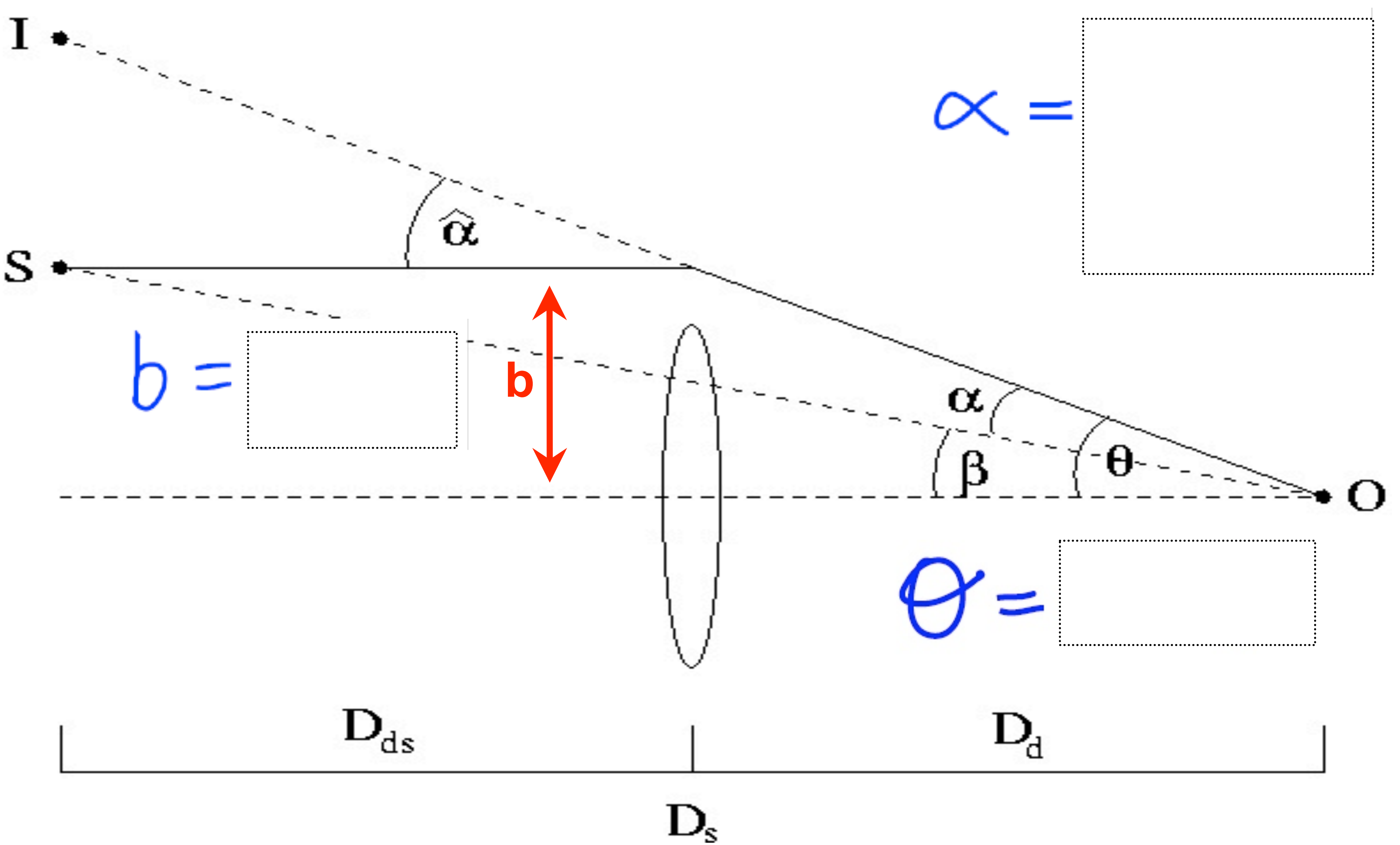


Just one equation from GR

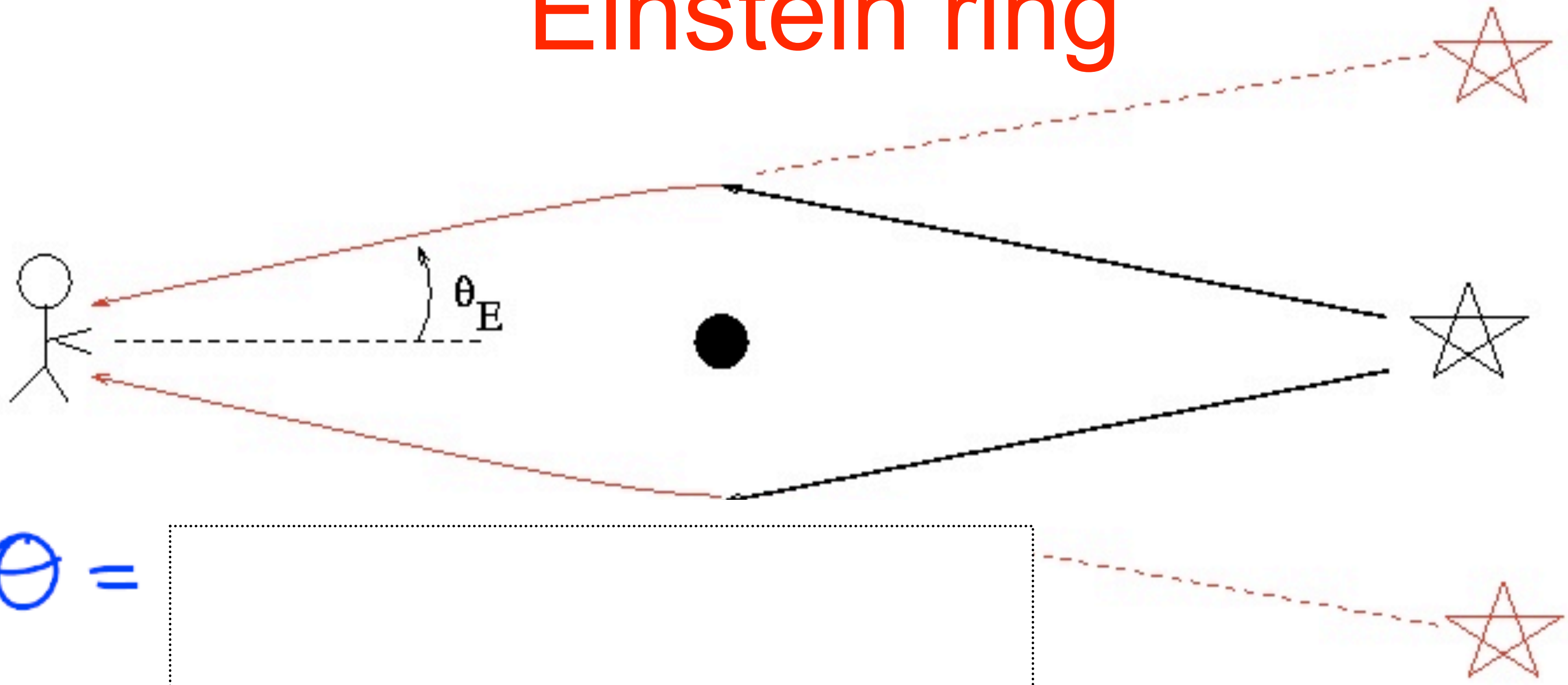


- NB. Independent of light wavelength

Apparent deflection angle, α



Einstein ring



$\theta =$

Einstein ring $\beta =$ $\theta =$

$\theta_E =$

Estimate the mass of A2218

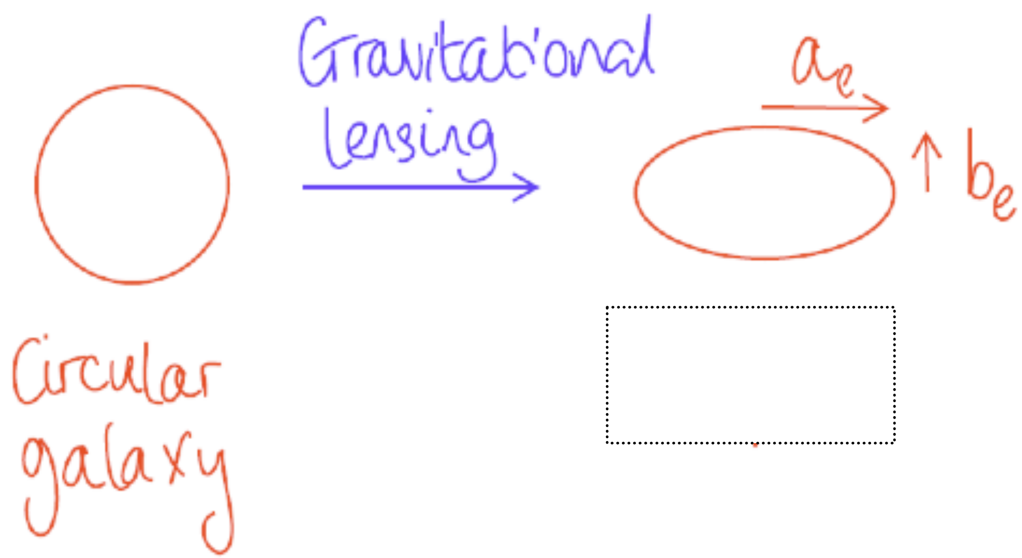
- $\theta_E \sim 0.01$ degrees
  - Assume is a point mass
  - Assume background galaxy is very far
  - Assume distance ~700 Mpc
- If another cluster has arcs of size 0.02 degrees, how massive is it relative to A2218?

Read JL p185

Weak versus strong lensing

- Strong lensing:
  - images
  - shaped arcs
  - parts of massive clusters/ galaxies
- Weak lensing
  - ellipse is changed
  - , clusters, parts of massive clusters
  - have to average over galaxies to measure mass

Weak lensing shear



"shear" ≡ $\boxed{}$

For point mass lens (e.g. cluster):

$$\frac{a_e - b_e}{a_e + b_e} = \frac{4GM}{c^2} \frac{D_d D_{ds}}{D_s} \frac{1}{b^2}$$

Impact parameter

(Proof beyond this course)

Stretch is always $\boxed{}$ mass

Weak lensing method

- Divide image up into boxes containing ~ galaxies in each
- Average galaxy images together
  -
- Guess mass map
  - predict shear map
  - compare to observed shear map
  -

1.8 The distribution of galaxies

List of topics

- Galaxy surveys
- Features of the galaxy distribution
- The galaxy power spectrum
- Qualitative meaning of a power spectrum

See JL p 189 to 198 and p 205 to p209 for a qualitative introduction

Some galaxy surveys

- Hubble catalogue (1934) : 44,000 galaxies
- Lick catalogue (1967): 1,000,000+ galaxies
- APM (1990): 2,000,000 galaxies
- 2dF (2003): 250,000 galaxies *with redshifts* (z~0.2)
- SDSS: 675,000 galaxy redshifts so far (z~0.2)
- 2SLAQ LRGs: 1,000,000 approximate (photometric) redshifts (z~0.6)
- WFMOS: 20,000 redshifts per night, at z~1

Features of the galaxy distribution

- Filaments
- Pancakes
- Voids
- Superclusters
- Fingers of God
  - Surveys are measuring not distances.
  - High in clusters lead to a wide range of redshifts at a given position on the sky. Therefore a on a plot of z versus angle.

2. Active Galaxies

- 2.1 Taxonomy
- 2.2 The mass of the central engine
- 2.3 Models of AGNs
- 2.4 Quasars as cosmological probes

Read JL chapter 3

Active galaxies: interface with JL

All of JL chapter 3 is examinable, except:

- 3.1 and 3.2 are (hopefully) a revision of earlier courses
- 3.4.4 An accretion disk should be basic stuff

Additional examinable notes will be provided on:

- Eddington limit will be derived
- Quasar luminosity function and evolution (log(N)-log(S) and V/V_{max} tests)

Definition of an active galaxy

- What is an active galaxy?
  - Radiation is not directly attributable to
  - Usually very powerful:
- What is an AGN?
  -
  - Non-stellar radiation comes from
  - Is in the of galaxy, if galaxy is seen
  - AGN used interchangably with "active galaxy"
- Role in galaxy formation unknown
  - Special type of galaxy? or short phase of every galaxy?
- Four main classes:
  - Seyfert galaxies, Quasars, Radio galaxies, Blazars

2.1 Taxonomy

List of topics and summary of properties:

- Seyfert galaxies
  - Galaxies with very
- Quasars
  - extremely bright
- Radio galaxies
  - beyond galaxies (often in pairs)
- Blazars
  - Extremely

Read JL section 3.3 (pages 136 – 145)

Seyfert Galaxies

- Galaxies with very bright nuclei
  - Nuclei are in optical
  - Almost all are galaxies
  -
- Excess radiation in far IR and other bands
- Type 1 Seyferts: Two sets of emission lines
  - Widths ~400 km s^{-1}. Mostly
    - NB. this is wide cf typical HII region
  - Widths ~10 000 km s^{-1}. All permitted lines.
- Type 2 Seyferts: Only lines, no lines.
- Type 1.5 Seyferts: somewhere in between

Quasars

- Point-like, extremely bright
  - in both radio and optical
  - Quasi-stellar radio source/object -> quasar
  - Many are variable on times of
- Spectral excesses in ir and other λ s
- host galaxies ("quasar fuzz")
- broad lines, narrow lines
  - Strong Lyman-α
- Radio loud quasars: in radio
  - of quasars
  - many have

Radio galaxies

- The majority of known radio objects
- Pairs of bright
  - fed by narrow jets from faint core
- Two types:
  - Broad-line radio galaxy
  - Narrow-line radio galaxy
- Often in galaxies
  - these often have

Read JL pages 142 – 143

Blazars

- Like quasars, but variable on
- All radio loud
- Two subclasses
  - BL Lac: emission lines are
    - Not very bright
    - Originally thought to be a variable star
  - OVVs: Optically violent variables
    - Much brighter
    - Strong emission lines

Read JL page 145

2.2 The central engine

List of topics:

- The size of AGNs (JL 3.4.1)
- The mass of the supermassive black hole
  - based on Schwarzchild radius (JL 3.4.3)
  - based on Eddington Limit
  - based on reverberation mapping (JL p163)
- Accretion power (JL 3.4.5)

The size of AGNs

- Nuclei are in optical and radio
  - Radio resolution ~0.001 arcsec (VLBI)
  - Nearest AGN (NGC 4395) 4.3 Mpc away
  - Must be
    - Size = θ (in radians) x distance
- Nuclei are highly variable ~ hours ~10^4 s
  - Size ~ c x time
- Quasars are brighter than entire galaxies

  ~10^{11} L_{solar} in

  Believed to contain a

Mass from Schwarzchild radius

- Observed size > Schwarzschild radius
  - Puts an upper limit on the mass of a BH
- $R_s = 2\ GM / c^2 <$ Observed size

Peterson p 32-33

Mass from Eddington limit

- Gravitational attraction > radiation pressure
- Consider HI on spherical shell, lit by luminosity L
  - Radiation pressure = momentum flux
- Force on an electron = pressure x cross section
- Gravitational attraction > radiation pressure
- black hole
  - cf black hole produced on death of massive star

Mass from reverberation mapping

- Broad lines imply rotation at
  - Can't be thermal broadening since
- Broad line variation by ~10 days
  - Assume is due to to BL region
  - Radius of BL region is
- Apply virial theorem to get the mass
- Consensus of all three methods: M ~

JL p163

2.3 Models of AGNs

List of topics:

- The dusty torus (JL 3.5.1)
- The broad line regions (JL 3.5.2)
- Unified models (JL 3.5.3)

First task:

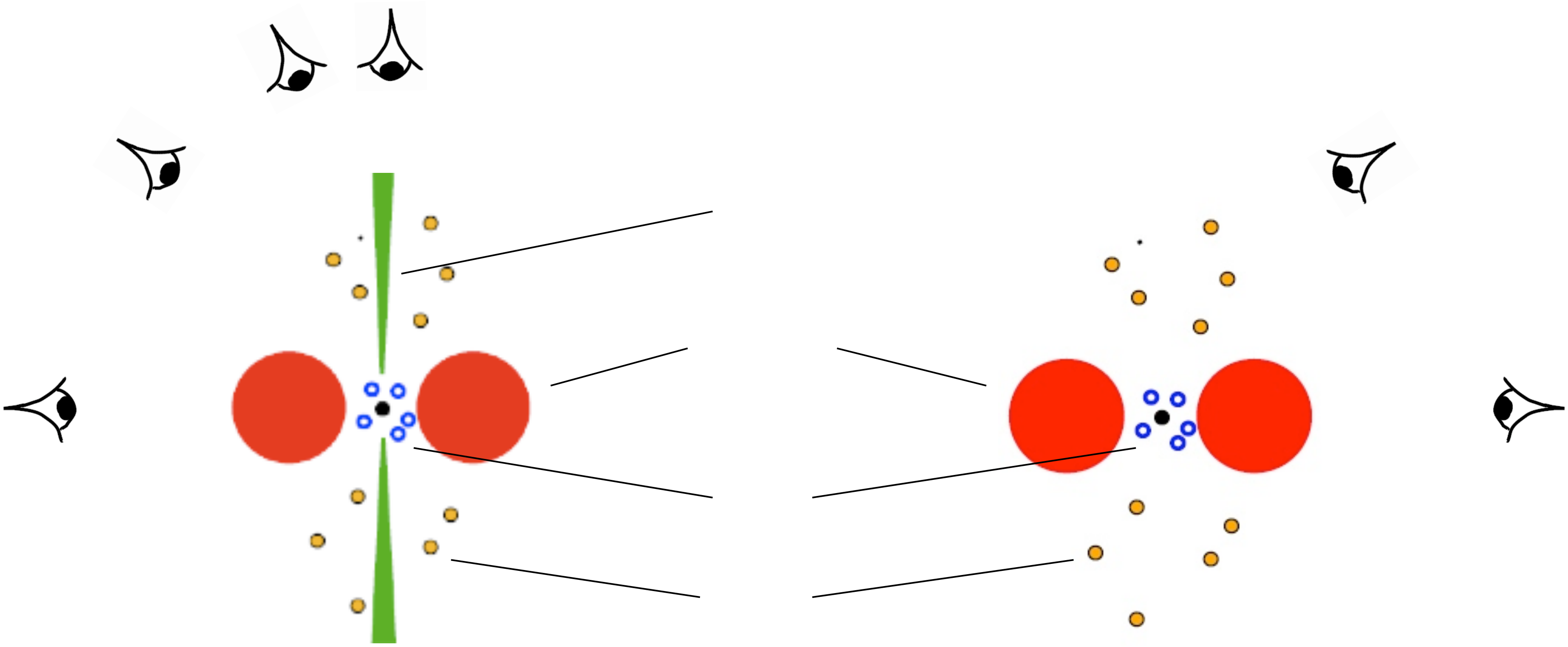
Dust evaporates at ~2000K
Estimate the minimum radius of the torus

The broad-line region

- Made up of
  - illuminated by central engine esp uv, X-ray
  - re-emit energy as
  - see similar gas content to
- No forbidden lines, so not very
- From reverberation mapping slide
  - radius ~0.01 pc
  - rotation speed ~ 7000 km s^{-1}
- Current estimates:
  - individual clouds
  - total mass of gas

Unified models

- Theory: there are only two types of AGN



Radio Loud AGN

Radio Quiet AGN

2.4 Quasars as cosmological probes

List of topics:

- Gunn-Peterson test
- log(N)-log(S) test
- V/V_{max} test

Not in JL. See Peterson

Gunn-Peterson Test

- Quasar light is absorbed by
  - Hydrogen clouds
  - Damped Ly-α systems (proto-galaxies?)
- If continuous neutral hydrogen exists over range of z
  - Expect Ly-α to be absorbed
  - Expect absorption of quasar Ly-α
  - Called Gunn-Peterson
- Only observed five years ago at

log(N) – log(S) test

- Aim: see if quasar numbers
- If quasar no. density is constant $n(r)=n_0$
  - and quasars all have the same luminosity L
- Observe with a limiting flux S
  - See all objects out to r_{max}
  - See a number $N(S) = \int_0^{r_{max}} n(r)\, r^2\, dr$
- Plot log(N) vs log(S).
  - Should see slope of if no evolution
- Problems with log(N) – log(S)
  - Assumes one L, or non-evolving lum. fn.
  - Gives false-positive if survey is incomplete

Peterson p 159 - 161

V/V_{max} test

- Does not give false positive if incomplete
- Consider each object, distance r
  - Find maximum distance at which could have seen object = r_{max}
  - Calculate $V/V_{max} = (r/r_{max})^3$
- If uniform number density

Peterson p179, 180

Prove that for a single object, expect $\langle V/V_{max} \rangle = 0.5$

- Object has some r_{max} so $V_{max} = 4 \pi r_{max}^3 / 3$
- Average over possible positions of object, r
  - If uniformly distributed $n(r) = n_0$
- $\langle V \rangle = [\int_{V_{max}} n(r)\, V\, dV] / [\int_{V_{max}} n(r)\, dV]$

We observe $\langle V/V_{max} \rangle =$ for quasars

So there were quasars in the past!