Cosmic Present (5001)

~~Early Type Galaxies~~ ETGs

C: - 125 — 162

1) Intro & Table of Properties (5003)

2) Shape of Isophotes (5005)

3) Surface Brightness profiles (5005)

4) ETGs: Shape & Substructures (5007)

5) Line-of-Sight (los) Velocity ~~Dispersion~~ Distribution (LOSVD) (500

6) Fast & Slow Rotators (5011)

10) Proof of Virial Theorem (5021)

11) Hot Gas & X-ray Emission (5021)

12) Mass Determination (5031)

13) Mass Distribution (5037)

14) Fundamental Plane (5041)

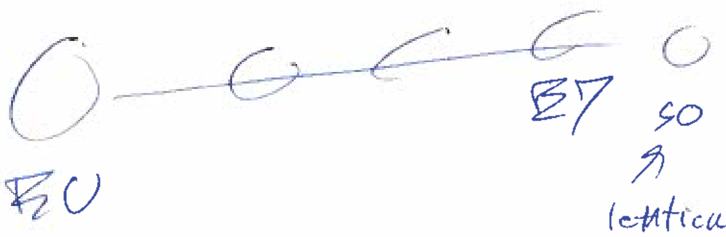
5002

1) Intro to ETGs & Table of Properties

15003

These include

$E = 10\varepsilon_e$
$\varepsilon = 1 - \frac{b}{a}$
(see p 50)



- dEs dwarf elliptical (which are somehow not dSph)
- Es just Es
- BCGs → brightest cluster galaxies (also called cD or supergiant elliptical or central dominant ellipticals (Wik))
  - often (at / near) the center of mass of clusters.
  - probably result of many mergers

(Wik ~47% of noticeable SF.)

They are mostly quenched
low starFR $\lesssim 0.1\, M_\odot/yr$
to nearly none

Ci-94 Where from

Quenching to main channels with lots of variations and quantitative debate

$M \gtrsim 10^{12} M_\odot$ = Golden mass quencher

Ram pressure stripping in clusters → smaller galaxies whose self-gravity can't hold on to cool and cooler gas

5004)

ETGs due have gas
→ It is just radiates mostly in X-ray and cools slowly
— when I was young we ~~used th~~ ~~thought~~ ETGs had little gas but X-ray astronomy showed it was there

(Brightest Cluster galaxies giant of super giant ellipt.)

Table

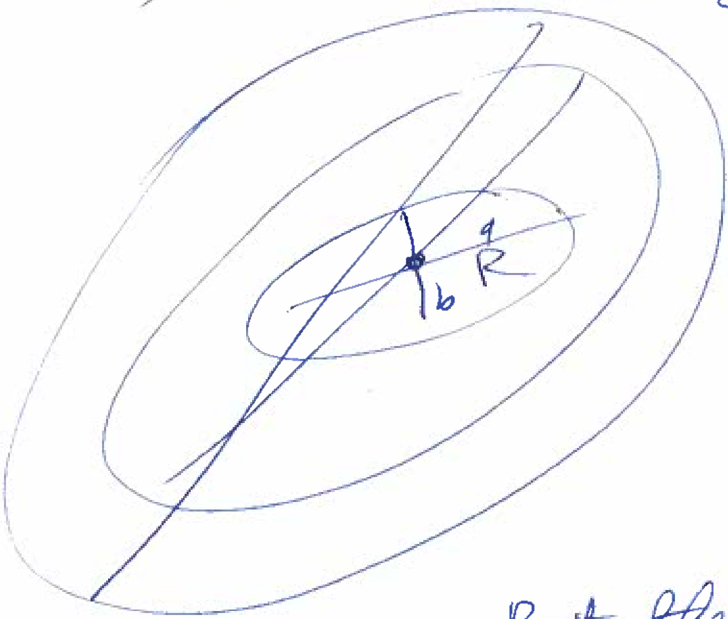
	dEs	Es	BCGs
L (B band $L_\odot$)	10^7-10^9	10^9-10^{11}	$10^{11}-10^{12}$
M (B band)	$-13 \to -17$	$-17 \to -22$	$-22 \to -24$
M_* ($M_\odot$)	10^7-10^9	10^9-10^{12}	$10^{11}-10^{12}$
Effective Radius (kpc) or half-life radius (ci - 31)	0.1-3	1-10	3-30
σ (km/s) ≈ 6e (usually) (Not much overall rotation)	20-100	100-300	250-400
Hot gas ($M_\odot$) (cold gas is much less)	—	10^8-10^{10}	$>10^{10}$
SMBH ($M_\odot$)	—	10^7-10^9	10^9-10^{10}
Virial Mass (fiducial total mass and we'll cover it's rather tricky nature)	10^8-10^{10}	$10^{10}-10^{13}$	$>10^{13}$

the SMBHs are very important in AGN activity and in Golden Mass quenching, but they are only ~ $\frac{1}{100}$ to $\frac{1}{10^3}$ of the virial mass.

(5005)

2) Shape of Isophotes

~~of surface brightness profile~~



Shape often varies with $R = (ab)^{\frac{1}{2}}$ the circularised radius. (can't get away from this)

$\varepsilon(R) = \left[1 - b/a\right]_R$ (Ci-12)

But the characteristic value is for the effective radius (half light radius)

$\varepsilon_e \in [0.1, 0.7]$ (Ci-125)

→ galaxy ellipticity ~~ε_e~~ $= \varepsilon_e = \varepsilon(R = R_e)$

3) Surface brightness profiles (can't get away from them)

$I(R)$

Sersic profile still works well

$$I(R) = I_e \, e^{-b(n)\left[(R/R_e)^{1/n} - 1\right]}$$

$$= I_0 \, e^{-b(n)(R/R_e)^{\frac{1}{n}}}$$

(Ci-128, Ci-31)

But not only rule: $n_d = 2.5$ dividing line, $n < n_d$ discs, $n > n_d$ ETG (Ci-32)

5006

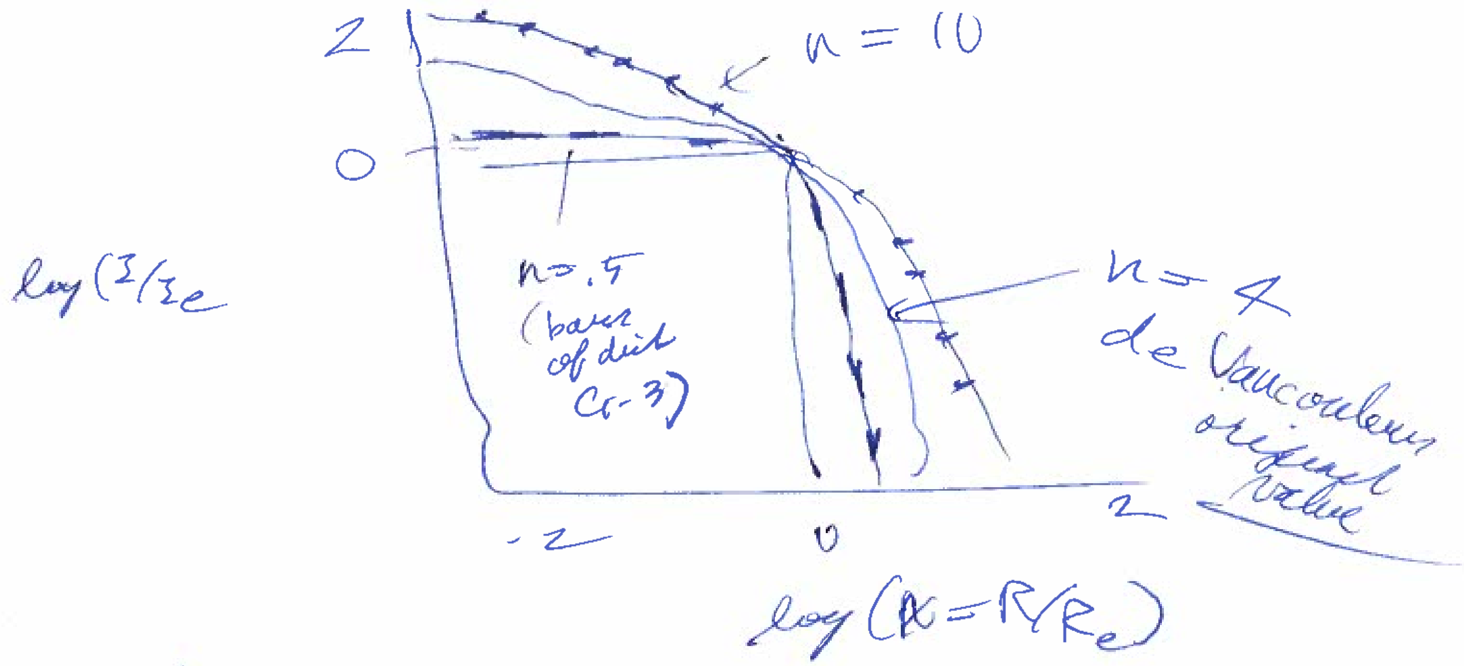
$n \simeq 2$ for low ~~[illegible]~~ surface brightest ETGs

to $n = 10$ for brightest

$n \uparrow$ ~~steeper~~ $R < R_e$
~~shallower~~ $R > R_e$

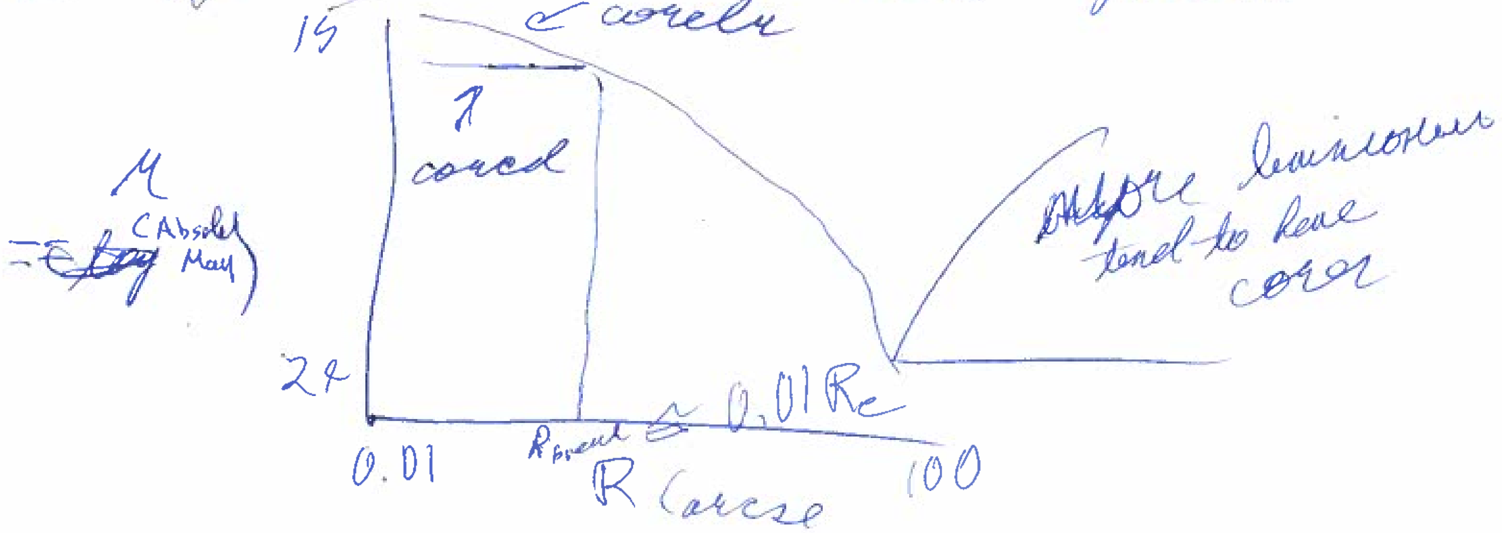
in linear plot
& log plot [illegible]

Ci - 31 Fig. 3.3



But ETGs can be coreless or cored in surface brightness

Ci-129



9.) ETGs — Shape + Substructure [5007]
(Ci-130)

~~are~~ often close to spherical
symmetry
but often not

Hubble sequence of observed
ellipticity
→ but what is ~~the~~
ε_e definition

Wiki: Galaxy morphology

$$E = 10 \times (1 - b/a) \stackrel{?}{=} 10\,\varepsilon_e$$

but for what isophote?

~~Well~~ → I infer yes ε_e since
Ci-127 give $\varepsilon_e \in [0.1, 0.7]$

Not fully virialized
but maybe close

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

$$\frac{1}{2} m v^2 = \frac{1}{2}\frac{GMm}{r}$$

$$KE = -\frac{1}{2} PE$$

but also all kinds of complex shells
and ripples reflecting (Ci-130)
accretion of satellites and
major mergers

5008

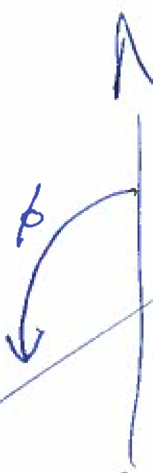
4) Line of Sight Velocity Distribution

LOSVD (Ci-131)

LOS = line of sight

$f(v_{los}, R, \phi)$

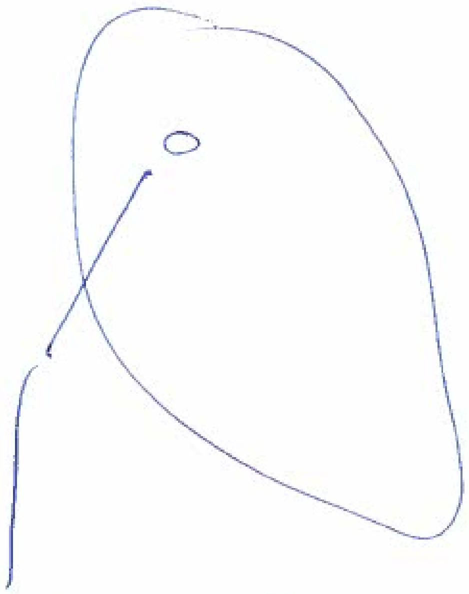
in general position angle Ci-93, 126



e.g. Hα line

but we won't bother with that definition

Doppler shift gives v_{los}



Integral field spectroscopy to measure for a 2-D sky map v_{los} and its moments

Seems more like differential than integral to me

0th is ~~measure~~ normalizatn

1st is mean $= \bar{v}_{los}$

2nd is variance $= \sigma_{los}^2$ standard deviation

But LOSVD deviate from Gaussianity (Ci-133)

Parameterizable is

5009

$$F(\bar{v}_{105}, R, \phi) = \underbrace{\frac{1}{\sqrt{2\pi}\,\sigma_{105}} e^{-\frac{w^2}{2}}}_{\text{Gaussian}} \left[1 + h_3 H_3(w) + h_4 H_4(w)\right]$$

(Bev-53)

(Ci-133)

$$w = \frac{M_{105} - \bar{v}_{105}}{\sigma_{105}}$$

$$H_3(w) = \frac{2w^3 - 3w}{\sqrt{3}}$$

$$H_4(w) = \frac{(2w^4 - 6w^2 + 3/2)}{\sqrt{6}}$$

are Hermite Polynomials (Ci-133 + Arf-712-7...)

Hermite polynomials are factors in the eigenfunctions of the quantum mechanical harmonic oscillator, one of the most important exact solutions in QM (Arf-715)

h_3 is skewness measure ordered motion along line of sight

i.e., overall rotation

$h_3 < 0$ shift to +ve velocity

$h_3 > 0$ shift to -ve velocity (Ci-134)

h_4 is kurtosis measure — symmetric deviation from Gaussianity

$h_4 < 0$ flatter top

$h_4 > 0$ peakier

~~But~~

5010) But frankly you often want something simpler (c0-133)

central velocity dispersion

surface brightness weighted dispersion — close to mass weighted dispersion

$$\sigma_0^2 \equiv \frac{\int_{S_{ap}} \sigma_{los}^2(R)\, I(R)\, d^2R}{\int_{S_{ap}} I(R)\, d^2R}$$

So the variance over some ~~Sap~~ an aperture → circular of course

but it's not likely to have the ellipticity ε which is ε(R,ϕ) in any case and can have position angle twist in ϕ (position angle)

So varying ellipticities and twists are lost track of ~~Conflated~~

If ε=0, then everything is simple and

$R_{ap} \in [0.1, 1] * R_e$

for low z observation (where R_e can be well determined)

but clearly the observer has to specify exactly what they are measuring

$\sigma_e \equiv \sigma_0(R = R_e)$

but this is a vague without specification

$R \equiv \sqrt{ab}$

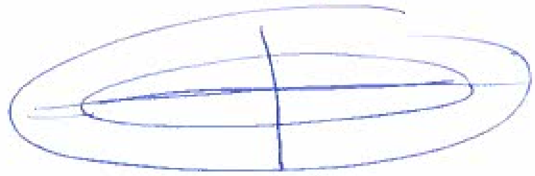
$= a\sqrt{1-\varepsilon}$

~~$2\pi R\, dR$~~

~~$\pi\, dR^2$~~

~~$= \pi\, 2R\, dR$~~

~~$= 2\pi\sqrt{ab}\, d\sqrt{ab}$~~



$A = \pi a b$ (c1-31)

$\varepsilon = 1 - \frac{b}{a}$

$\frac{b}{a} = 1 - \varepsilon$

$b = a(1-\varepsilon)$

$dA = \pi(2a)(1-\varepsilon)\, da$

$d^2R = 2\pi R\, dR$

~~$= 2\pi(ab)^{1/2} d$~~

$= 2\pi a\sqrt{1-\varepsilon}\, da\sqrt{1-\varepsilon}$

$= 2\pi a(1-\varepsilon)\, da$

Equal QED.

L5 011

6) Slow & Fast Rotators (cosmic present,

The vague measure of rotation is

$$\frac{V}{\sigma_0}$$

V ← ordered rotation

σ_0 ← dispersion (i.e., standard deviation)

(Doesn't necessarily apply to high-z)

But exactly.

Often

$$\frac{V}{\sigma} \equiv \frac{v_{los\,max}}{\sigma_0} = \frac{v_{los\,max}}{\sigma_e}$$

often → ; central velocity dispersion.

But exactly what aperture is used has to specified. (Ci-134)

More exact measures exist

$$\lambda_{Re} = \frac{\sum_i F_i R_i |\bar{v}_{los\,i}|}{\sum_i F_i R_i \sqrt{\bar{v}_{los\,i}^2 + \sigma_{los\,i}^2}}$$

$\bar{v}_{los\,i}$: mean for patch

$2\pi R dv$; 2π cancels

From binned 2D map of integral field spectroscopy

F_i: Flux of patch on sky i

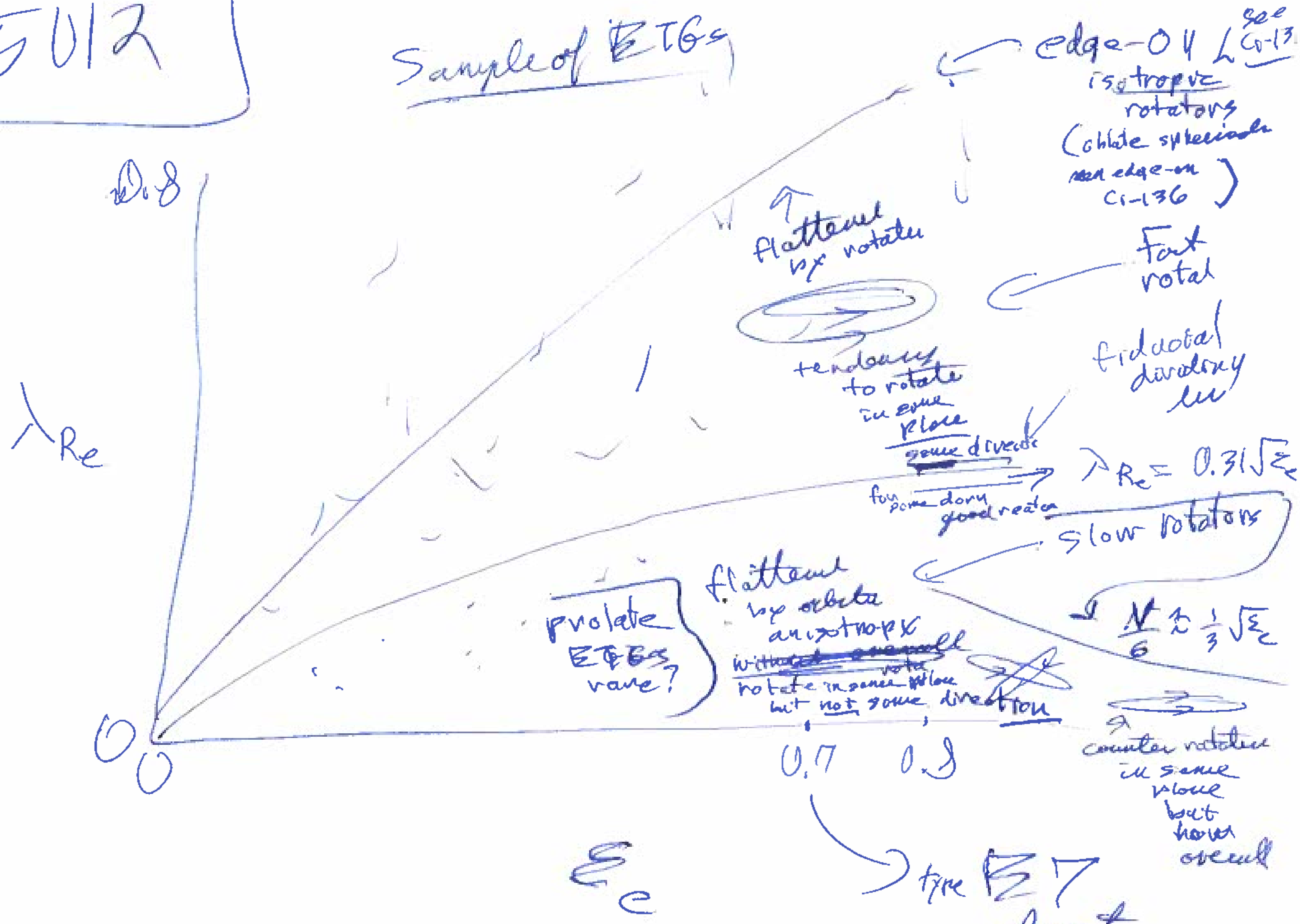
R_i: circular or ellipse

$\sigma_{los\,i}$: dispersion for patch

$\approx \frac{v_{los\,max}}{\sigma_e}$ of some order (Ci-135 Fig 9, ...)

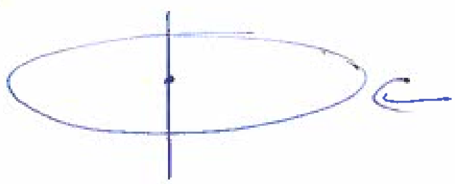
5012

Sample of ETGs



edge-on isotropic rotator

observation



defined $\delta = 0$ { a parameter explicated on Ci-136) — we'd have to get into dispersion tensor which is another day. (if ever)

isotropic rotators not edge-on — to left of curve

anisotropic rotators seen edge-on lie to the right

But not edge-on could be anywhere.

L 5013

Slow Rotation

$L_V \gtrsim 3 \times 10^{10} L_{\odot V}$

and ~ 20% of ETGs above dEs

Fast rotators

$L_V \lesssim 3 \times 10^{10} L_{\odot V}$

~ 80% of ETGs

Lv Less $< 3 \times 10^{10} L_\odot$ < more

dEs are more various

In other respects Slow + Fast rotators form distinct groups (ci-137)
^ somewhat → Table of Comparative Tendencies

Fast	Slow
Flattened by rotation	Flatten by anisotrop prolate
Oblate	Triaxial
Isotropic $\delta = 0$ <Ci 136	anisotropy $\delta \neq 0$
more flatten $\overline{\varepsilon_e} \sim .4$	less $\overline{\varepsilon_e} \lesssim .2$ < average
discy isophotes	boxy isophote
sersic index $n \lesssim 4$ ($n \in (2,8)$)	sersic ind $n \gtrsim 2$ → 10
cored? younger stars	cored older stars

5014

No α-element enhancement

~~abundance~~

α-particle
He-4

α-elements of nuclei made of He-4

Mg-12 Z = 12
A ≅ 24
is ~~the~~ fiducial ~~α~~ element

relative ~~to~~ ~~[Iron-5~~ Fe-56
[α/Fe]
(Ci-140)

Fe-56 Z = 26
A = 56 | fiducial
Not an α-element
so not α-element

younger

Weak Radio emission

(core-collapse SNe from stars ≥ 8 $M_\odot$ and lifetime < 30 Myr
⇒ so coincident with star formation

α-element enhancement

older
larger
$\log(M_*/M_\odot) > 10.5$
formed 80-90% of stars in z ≥ 2
(t ≥ 10 Gyr)

Somewhat counter intuitive results
But short early phase of star formation
t_{form} < 4
SNe core-collapse favor α-elements.
⇒ SNe I produce fewer and these occur on Gyr time scales but this is after star formation over and so they don't put α-elements into new stars
But longer star formation of Fast Rotators more SNe Ia Fe-56 in later stars

older → so their high z ~~analogs~~ progenitors seen by JWST

strong radio emission
⇒ radio lobes from jets from central engine

Weak diffuse X-ray (often dominated by X-ray binaries Ci-143)
less gas
No kinematically distinct cores

excludes faint some X-ray
... rich ... of Rotators X-ray

Strong diffuse X-ray ← Hot gas density Ci-143
more gas
~~Any~~ kinematically distinct core

Cored ETGs

more SF? ⟷ less SF?

Yes. See Ci-140

less massive
less red

more massive
more red

including rare counter rotators
See Ci-137

7) Stellar Populations

ETGs are ~~Old~~ Pop I & Pop II mainly

but slow ~~rotators~~ are more Pop II

But age etc. must be inferred mainly from integrated color & spectra

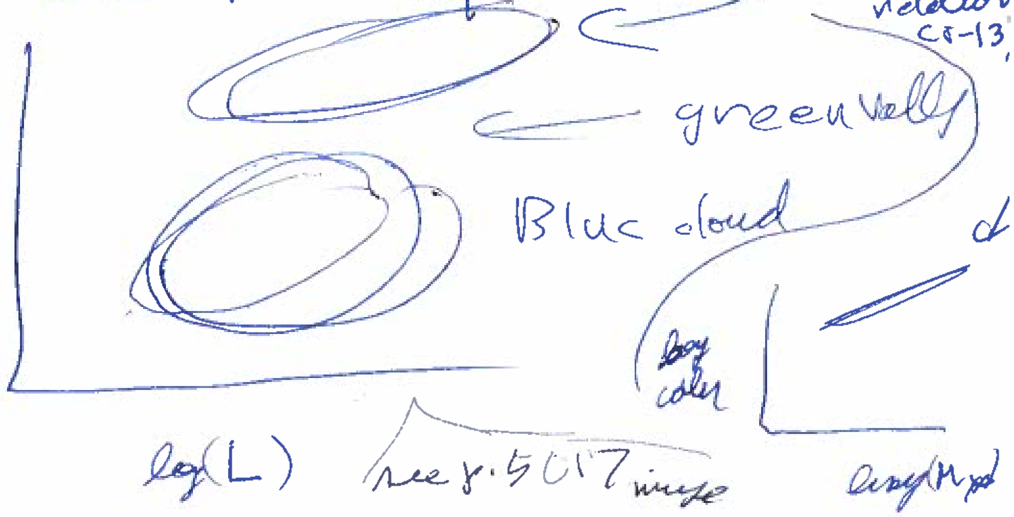
since except for a few close ones at ~ few Mpc ~~their~~ stars can't be individually resolved.

In fact only good case is local group dE M32 see Ci-32 + Ci-126

ETGs are redder in ~~color than SFGs~~ generally

generally quenched or ~~SFR~~ SFR < 0.1 of SFGs (Ci-94)

the Red sequence (ETG color mag relation Ci-13)



Originally just in clusters but Non-cluster ETGs follow too with more scatter

5016

Redder intrinsically
Not dust of which
they have little usually.

$A_V < 0.3$ mag typically
(V = visual band)

Ci-78

$F_\lambda = F_{\lambda 0} e^{-\tau_\lambda}$ < optical depth in dust

< F_λ for $\tau_\lambda > 0$

$$\log \frac{F_\lambda}{F_{\lambda 0}} = \log e^{-\tau_\lambda}$$

$$\log \frac{F_\lambda}{F_{\lambda 0}} = -\tau_\lambda \log e$$

$$A_\lambda = -2.5 \log\left(\frac{F}{F_{\lambda 0}}\right) = \tau_\lambda \left[2.5 \log e\right]$$

$$= (1.086\ldots)\tau_\lambda$$

$$\therefore F_V \cong F_{V0} e^{-\tau_V} \cong F_{V0}(1-\tau_V)$$

for $\tau_V << 1$

So at most 30% dust extinction and most far less.

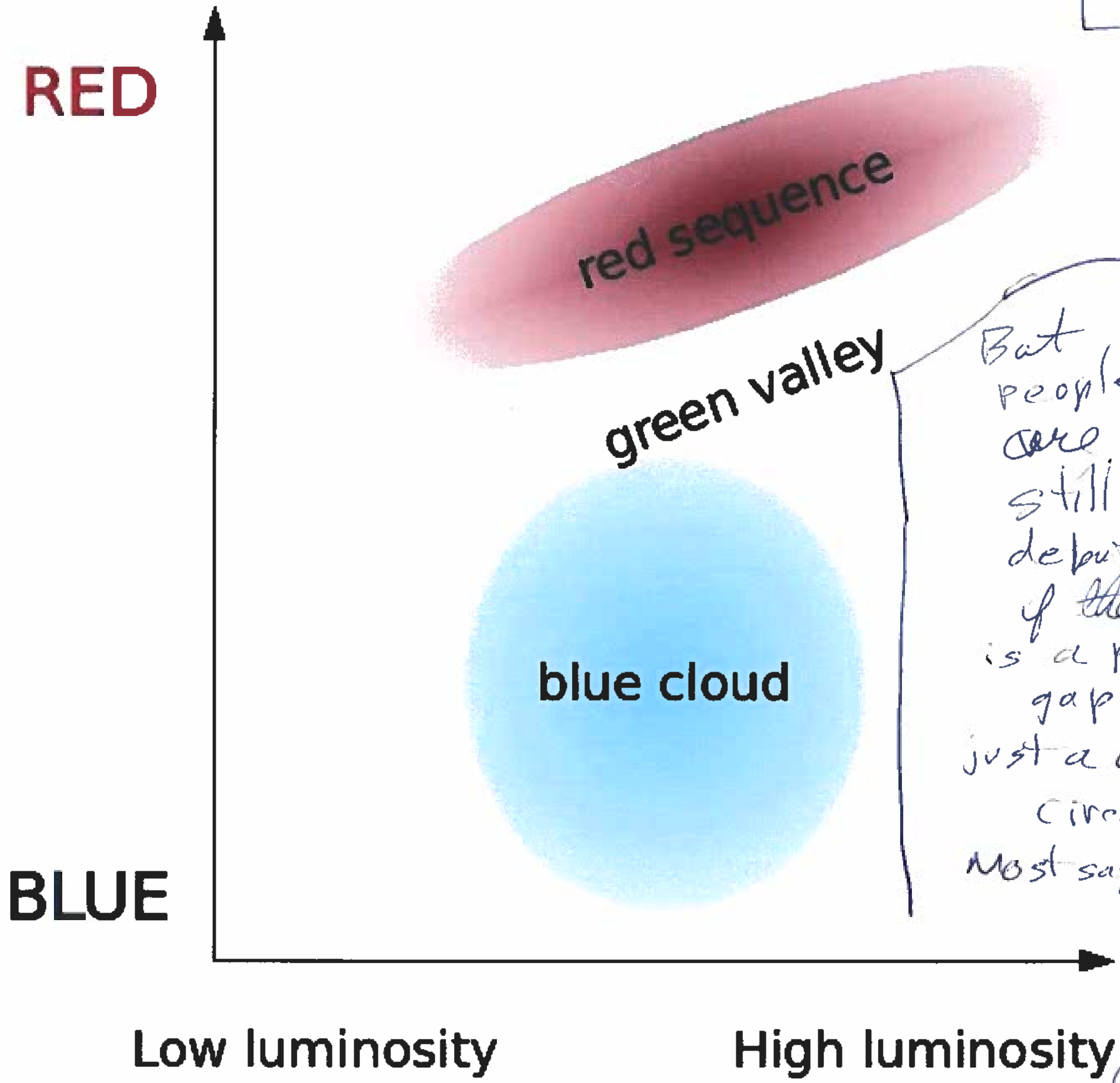
Older → Redder
higher metallicity → redder
} Which → in fact both are true (overdetermined result) (Ci-138)

the Age-metallicity degeneracy

Even enough redder ... [illegible] ... evident ... [illegible] F [illegible]

(redder)

5017



But people are still debating if there is a population gap or just a continuum circa 2024
Most say gap

Two ways to break degeneracy (more precise)
overall (1) galaxy modeling (harder to do accurate)
or (2) just analysis based on line equivalent width (easier to do but less precise I'd [illegible])

$W = \dfrac{\int (I_c - I_\lambda) d\lambda}{\int I_c d\lambda}$

$= A_{nl}$

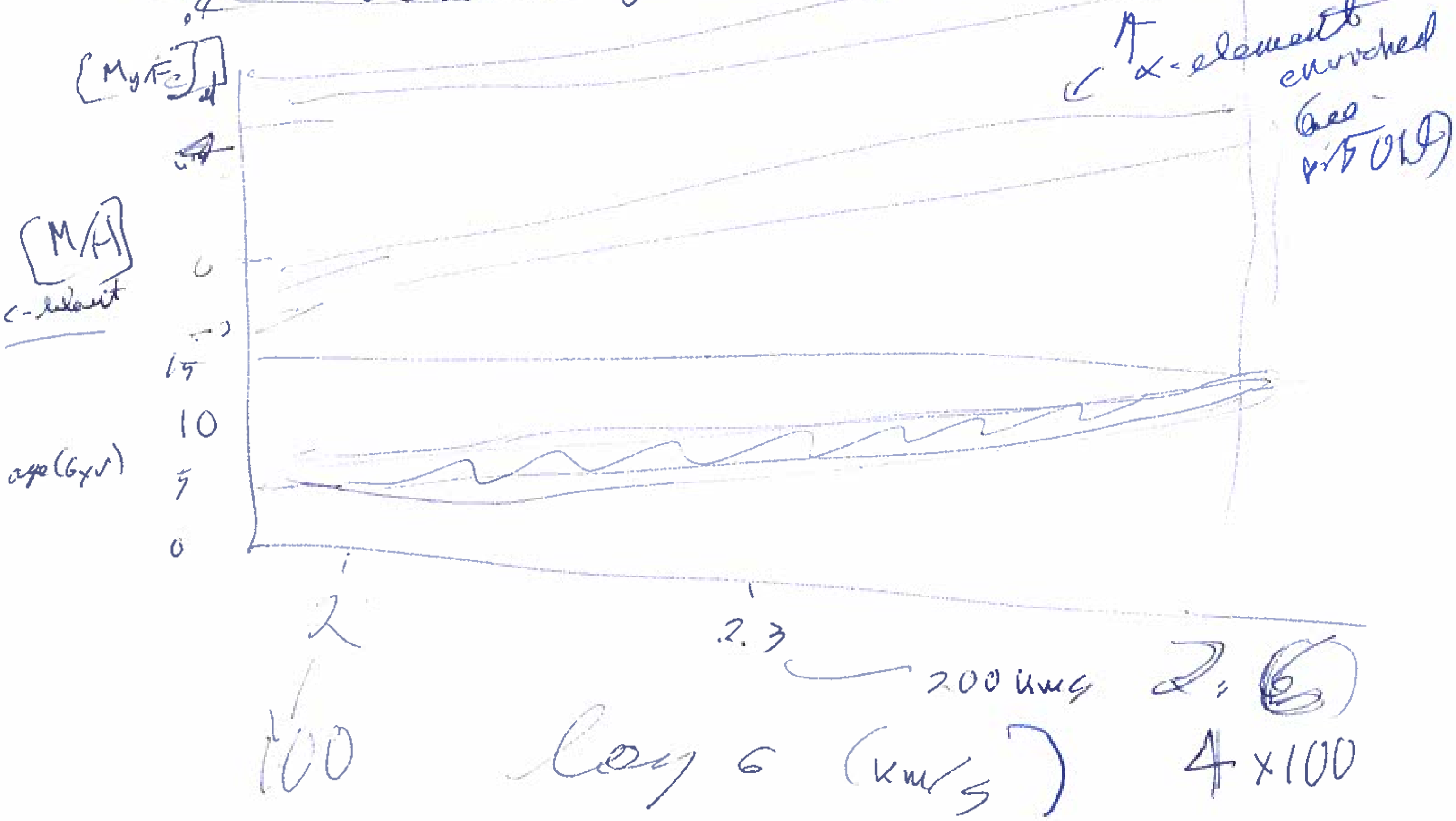
$A = \int_{line} (J_c - J_\lambda) d\lambda \cong \int_{line\ block} (J_c - 0) d\lambda = J_c \Delta\lambda$

$\therefore$ Equiv $W = A / J_c$

5018

Both give same result
redder, larger, slower,
cored BGTs
tend to be older & more metal rich

Correlation Fig 6.9 (61-139)



~~Most~~ Do not depend much on
environment
cluster or field galaxy,
and are mostly determined
by mass

50/19

8) Young Stars in ETGs (ci-190)

$SFR_{ETG} < 0.1$ of ETGs (ci-54)

often much less

but some at $z \triangleq 0$

also show recent SF: now turned off $= < 1$ Gyr ~~0.5-1Gy~~ old

(From cluster Isochron modelling on spectral type A-stars)

- Lower mass ETGs and only 1-3%

so called E+A (A-star) SF episode 0.5-1 Gyr ago

only about 3% of all ETGs ~~and~~ with $\log(M_* / M_\odot) > 10.2$ at $z=0$

$(M/M_\odot) \triangleq 3 \times 10^{11} M_\odot$

rejuvenated ETGs

→ mostly in dense environments

⇒ so mergers, accretion ~~or~~ interaction generally probably cause. ~~may because~~

5620

9) Small points

a) UV upturn in spectra of BTG without young stars

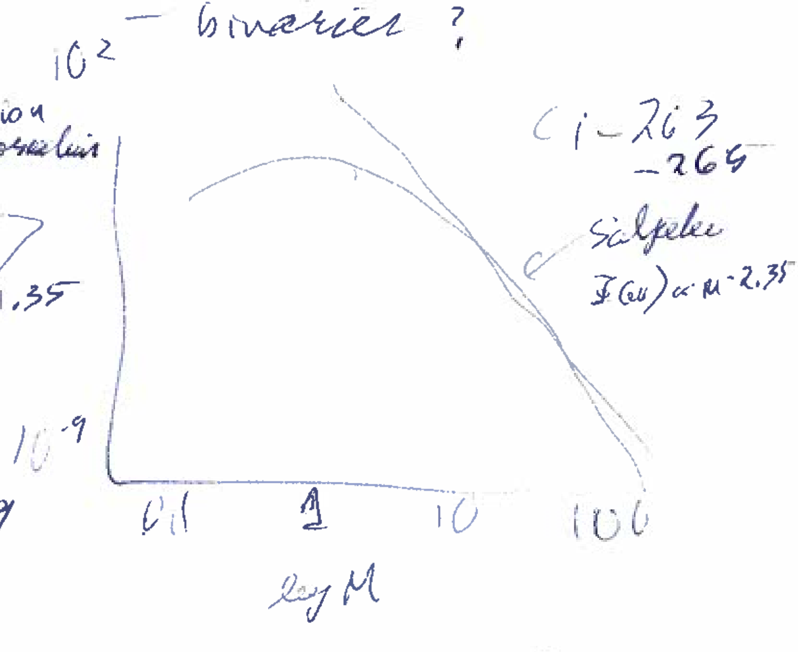
but smooth and so Not AGN which is nonthermal

Possibilities — low metallicity old stars
↳ low opacity
— extreme horizontal branch stars
burn He in core
— a sort of main-sequence analog
— extreme He enrichment?
— binaries?

b) IMF = initial mass function of stars at formation

Still important ingredient in population synthesis

Often plotted
$m \times \Phi(m) \propto M^{-1.35}$
to reduce range of horizontal axis even on log plots



$dN = \Phi\, dm$
$= J_0 m^{-\alpha} dm$

one power law version
Original $\alpha = 2.35 \simeq \frac{7}{3}$ Salpeter

5021

— only well known for Milky Way

— other galaxies may be different and some these days suggest top heavy IMFs

But JWST is rewriting the textbooks

So soon we might know

10) Proof of Virial Theo
— online or Internet

10) Hot Gas & X-ray Emission

— circa 1950s we thought ETGs were gas & dust poor.

— they still are mostly dust poor, but now we know they have lots of gas — see p. 5004 Table (Ci-126)

It's just hot ionized gas and radiates mainly in the X-ray and was hard to observe until recently.

→ Also neutral + molecular Ci-141

(still gas poor compared to SFGs Ci-141)

5022

But hot ionized gas — H, He, Z — is dominant — at least most massive Ellipticals (Ci-14)

$T = 10^6 - 10^7$ K < similar to sun corona temperature; $T_{sun\ center} = 16 \times 10^6$ K, but no nuclear reactions, $\rho_{sun} = 150$ g/cm³

a) Virial temperature (Ci-234)

internal energy $E_k = \frac{3}{2} \sum_k n_k kT$ — ideal gas law of bare particles per unit volume

$$n_k = \sum \frac{X_k \rho}{A_k m_p} = \frac{\rho}{\mu m_p}$$

m_p proton or AMU dalton as you prefer, but whatever terrestrials may think the universe is made of protons, not daltonium

$\rho_{gas} = \frac{10^{11} M_\odot}{\frac{4}{3}(10\ kpc)^3}$; pc = 3×10^{16} m, kpc = 3×10^{19} m = $10 \cdot 3 \times 10^{21}$ cm; $\frac{10^{44}\ g}{4(10)^3 \times 10^{21}\ cm}$, $\frac{10^{44}}{100 \cdot 10^{63}} = 10^{-24}$ g/cm³ ... $\rho_{ISM} = 1 \ldots = 10^{-24}$ g/cm³

∴ KE_{total}

mean molecular mass

$$\frac{1}{\mu} \equiv \sum_k \frac{X_k}{A_k}$$

primordial cosmic abundance:

$$\simeq \frac{.75}{1} + \frac{.25}{4} = \frac{3 + .25}{4} = \frac{3.25}{4} \simeq \frac{1}{4/3.25} \simeq \frac{1}{5/4}$$

$$\frac{1}{\mu} = \frac{.73}{1} + \frac{.25}{4} + \frac{0.02}{30} = \frac{1}{1.26}$$

rough order of average for metals

Not much difference

Can't use T for KE here since T is temperature

$$E_k = \int E_k\, dV = \frac{3}{2} \frac{kT}{\mu m_p} M_{gas}$$

where T is an average temperature

$$U = -\frac{G M_{gas}^2}{r_g}$$ (see Ci-146)

virial estimate of gravitational potential energy?

Well if you calculate U really from a model and M_{gas} from a model or somehow else

$$r_g \equiv -\frac{G M_{gas}^2}{U}$$ is a characteristic radius (gravitational radius Ci-146)

But maybe usually M_{gas} and r_g are estimates

$$\therefore \quad KE = \frac{1}{2}(-1)U$$ virial theorem for gravity

$$\frac{3}{2}\frac{kT}{\mu m_p} \cdot KE = \frac{1}{2}\frac{G M_{gas}^2}{r_g}$$

$$KE = \frac{1}{2}\sum_k k U_k$$

but here $k = -1$

$$mg_{earth} = -\frac{GMm}{r}$$

so $k = -1$

$$T \equiv \frac{G M_{gas} \mu m_p}{3 k r_g}$$

The virial temperature (estimate)

The exponential cut-off temperature Ci-142 p. 5028 (is an alternative way)

We will omit doing our own calculation.

50 24

Mainly emit by free-free emission (CC:-524, HH-137 -143 / HH-167 -169)

& free-bound recombination (CC:-523) to metals not H or He

b) I imagine the ionization state is high.

But H is virtually completely ionized and may not emit lines — But O, Ne, Mg, Si, S, Fe (CC-146)

See Vague notes for LTE calculation Saha formula for high ionization

Local Thermo equilibrium — Super sensitive to target. Can it be LTE? Maybe if ff dominates since that is always LTE. But I'd have to look more closely in HH and mind

will want high ionization states? maybe fully ionized

$n_e \simeq 1 \; cm^{-3}$ for high, $N_H \simeq 1 \; cm^{-3}$

$T \simeq 10^6 \; K$ ← very high T plasma

$k = 10^{-4} \; eV/K$ (Wik)

$\chi_{ion} = 13.6 \simeq 10 \; eV$

ionization ratio for Hydrogen $\frac{N_{ion}}{N_{neut}}$

$$\Psi \simeq \frac{1}{C_\Phi} T^{3/2} e^{-\chi/kT}$$

C_Φ: 2×10^{-16} cgs

$$X_0 = \frac{\Psi}{N_H} = \frac{\frac{1}{10^{-16}} 10^9 e^{-\frac{10}{10^2}}}{1} \simeq 10^{25}$$

For low T this exponential makes X_0 small

at $T = 10^3 K$: $e^{-100} = 10^{-.43 \cdot 100} = 10^{-43}$ low ionization

No! H lines not in X-ray. Some He lines, He II lines maybe.

but H, He, Z are the same problem for recombination — low electron density. So some atomic physics reason — recombination efficiencies must be stronger for some metals than H, He.

$$\frac{n_e}{N_H} \simeq 1 - \frac{1}{X_0} \quad \text{for } X_0 \gg 1$$

$= 1 - \frac{1}{10^{25}} \simeq 1$ if I've done this correctly.

5025

~~emission coefficient~~
emissivity ~~from both~~ ~~$\frac{1}{4\pi}$~~ n

c) ~~Emission & luminosity~~

$$j_{\nu_k} = n_e \sum_{jk} n_{jk} \frac{\Lambda_{jk}(\nu, T)}{4\pi\,?}$$

electron density

element k

~~element~~ ionization

Ci-192 with notation changed to conform to Mi-112

In Mi-25 jargon emission coefficient = j emissivity but ~~[illegible]~~ Ci-521 define $j = 4\pi n$ Yikes

But on Ci-504 they admit the other convention is used ~~they~~ ~~[illegible]~~ by the same

Lumping altogether

term emissivity seems to be falling out of favor

emission coefficient in Ci-592 jargon

$$j_x(\nu) = n_e n_{ion} \frac{\Lambda(\nu, T)}{4\pi\,?}$$

x-ray band (Ci-504 say generic band)

complex dependence on composition H, He, metallicity Z

$$j_X(x) = \int_x j_\nu \, d\nu = n_e n_{ion} \frac{\Lambda(T)}{4\pi}$$

x-ray ~~band~~ or generically any band.

Same with surface brightness of specific intensity Ci-504 use $I_{SB} = 4\pi I$

I think Ci-504 -521 take wrong convention

A beam points in one direction so why multiply by 4π!

X-ray energy emissivity

x-ray energy per unit time per unit volume

x-ray specific intensity or surface brightness for optically thin case

$$I_X(R, \phi) = I_X(R) = \int_{z_1}^{z_2} j_X \, dz$$

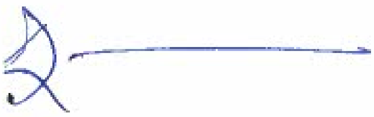
project

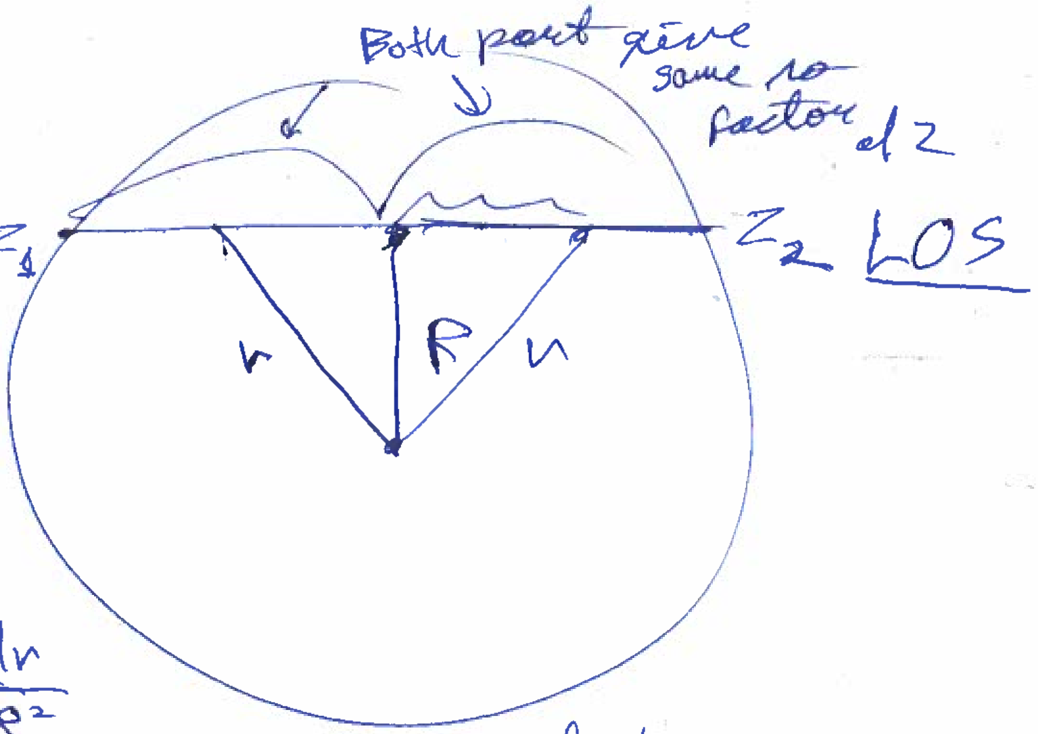
same for all position angles of spherically symmetric which is assumed,

No extinction

Extinction would require an $e^{-\tau(z)}$ in integrand

5026





$$z = \sqrt{r^2 - R^2}$$

$$dz = \frac{1}{2} \frac{2r\,dr}{\sqrt{r^2 - R^2}}$$

r_{max} = may be infinity

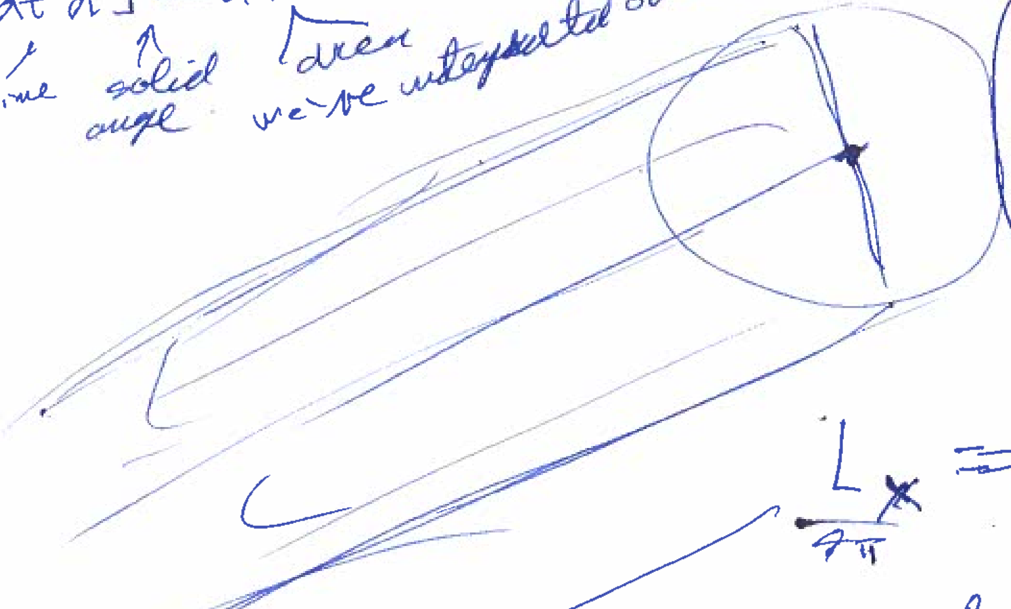
$$I_x = 2 \int_R^{r_{max}} \frac{j_x(r)\, r\, dr}{\sqrt{r^2 - R^2}} \quad (Ci-142)$$

I_x: $\frac{dE}{dt\, d\Omega\, dA}$ (time, solid angle, area)

2: both directions from R contribute equally

we've integrated over X-ray band and so no $d\nu$

Finally discussed on p.50 + that they define $I_{sum} = 4\pi I_{spec}$ (specific intensity)



R_{max} = maybe ∞

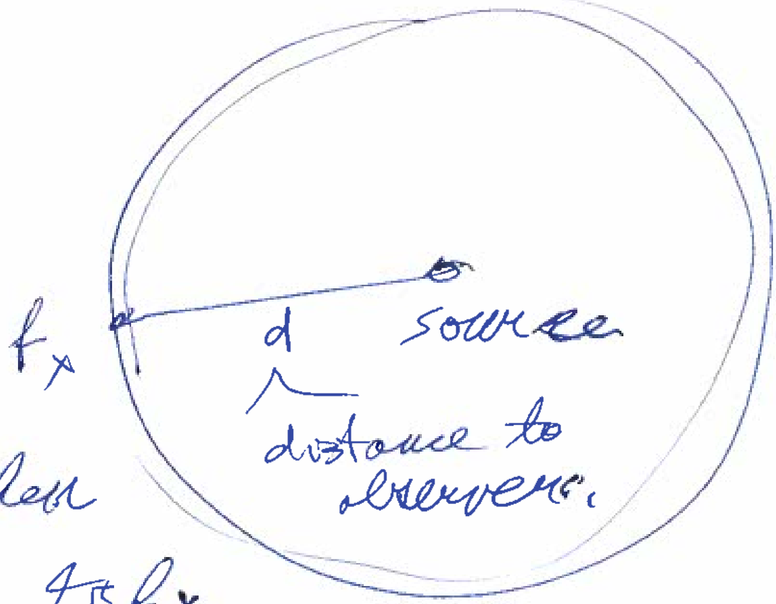
$$\frac{L_x}{4\pi} = f_x = \int_{R=0} I_x \, 2\pi R\, dR$$

$$f_x = \int_{vol} j_x \, d^3x$$

whole volume assuming optical thinness

f_x: $\frac{dE}{dt\, d\Omega}$

$\therefore L_x = 4\pi f$ luminosity in X-band



But then

$L_x = 4\pi f_x$

integrated over an isotropic emitter.

5028

gives continuum emission

$\mathcal{L}/4\pi$

$$j_{ff} \sim n_e n_i T^{-1/2} e^{-\frac{h\nu}{kT}}$$

Ci-524

∴ for $\frac{h\nu}{kT}$ there is exponential cut-off (Ci-142) not a sharp one.

But it is distinct enough to be able to esimate T especially in integral fixed spectroscopy of X-ray resolution enough.

Better than virodl temperature estimate

Easier and can be found as a function of R and position angle Φ

Also contribution from Not completely ionized metals gives line feature O, Ne, Mg, Si, S, Fe are often dominant and usually important

recombination line

But not in Pop III "galaxies" if seen by JWST

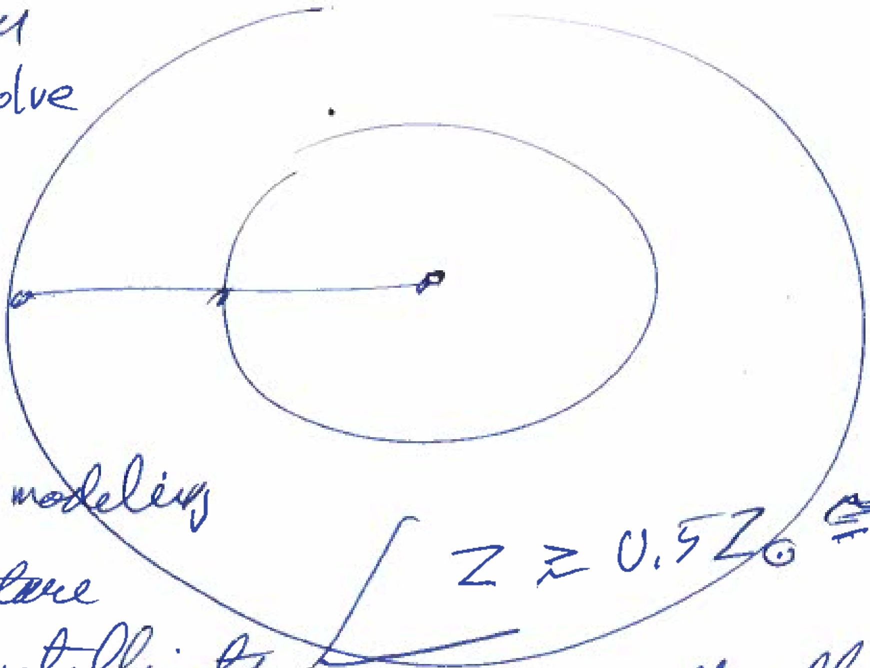
Metals and H, He have some on electron density for recombination lines. So the recombination coefficients must favor these metals over H & He recombination lines

H Not in X-ray

lines. Some He lines may be

5029

d) If you can resolve patches then you can trace density by modeling



— Temperature and metallicity gradients are typically small often which is useful

$Z \gtrsim 0.5 Z_\odot \approx 0.01$ mass fraction

— out to R_e gas fraction of baryonic mass is small.

but brightest Elliptical show $M_{gas} \gtrsim 10\, M_*$ from outer regions

But outer regions are faint

C_i-126 Table does not convey this information

Complication

X-ray emission from hot gas has to be distinguished from X-ray binaries and other point sources

more important in smaller lower luminosity Elliptical

5036

slow rotators
→ biggest, brightest
→ highest gas mass.
→ stellar wind ~~emission~~ ejection does escape from ~~the~~ larger gravity

→ X-ray cooling is slow at low density
$\mathcal{J}_{ff} \sim n_e n_e$
and grows as density increases

→ So a cooling catastrophe Ci-144 in central region expected naively leading to star formation

what keeps it hot? shock inflow on more ~~prop~~ AGN activity — phase of hot gas bubbles from AGN region

→ But this doesn't show up. mostly in larger ETGs → quenched golden mass $\gtrsim 10^{12} M_\odot$

AGN activity is ~~the~~ probable (even certain? cause)

12) Mass ~~Distribution~~ Determination

a) It's harder to determi ~~the total mass~~ $M(r)$ for ETGs than SFGs

ETGs — ellipticals mainly — kinematic tracers are harder to find.

SFGs — star forming galaxies — spirals & dIrr

Recall

$$\frac{v_{circ}^2}{r} = \frac{GM(r)}{r^2}$$

~~$v_{circ} = \sqrt{\;}$~~

and so

$$M(r) = \frac{1}{G} r v_{circ}^2$$

spirals but maybe dIrr hard — if you measure r and know you have circular orbits or for stars in a thin disk (or other kinematic tracer)

then $M(r) = \int_0^r \rho(4\pi r^2 dr)$

and $\frac{dM(r)}{dr} = \rho(4\pi r^2)$

$$\rho = \frac{1}{4\pi r^2}\frac{dM(r)}{dr}$$

(are relatively easy

Both baryonic and dark matter:
Have to independently determined — Modelling → use of NFW profile to model DM.

5032) But in ETGs the orbits of stars may be rather chaotic and hard to identify.

Hamilton & Fouvry 2024 ARAA give a review

Stellar system formalism ~~of~~ can be used to model ETG.

Ci-517 tells me in point-mass systems (which is Not the Wiki definition ~~whi~~ → they are that or ~~four~~ a synonym for multiple star systems, binaries, triples etc.

So Point masses I'd call N-body systems ~~least st.~~ → since many stars or Dark matter particles

— my drift velocity discussion was very naive theoretical foray into this

But ETGs both large Es and dEs are qualitatively similar and similar to SFGs in that — baryonic star M_* dominated in center and DM dominated further out

Ci-145

G 033

dSph are distinct
→ they are much more dark matter dominated Co-167, 120

b) Vivial Theorem understanding

$R_e \sim 1$ kpc and $\sigma_0 \simeq \sigma_e \simeq 100$ km/s

(central dispersion of v_{los} (line of sight) over some aperture)

$$\sigma_0^2 = \frac{\int_{A_p} \sigma_{los}^2 I(R)\, d^2R}{\int_{A_p} I(R)\, d^2R}$$

surface brightness average Ci-133

i) Crossing time

$$t \sim \frac{R_e}{\sigma_e} = \frac{1\ \text{kpc}}{100\ \text{km/s}} = ~~3 \times 10^{16} \ast 10^3 \cdot 10~~$$

$$= \frac{1\ \text{kpc} \ast \left(\frac{3\times10^{13}\ \text{km}}{\text{pc}}\right) \ast \left(\frac{10^3\ \text{pc}}{1\ \text{kpc}}\right)}{100\ \text{km/s}}$$

$$= \frac{3\times10^{16}\ \text{km}}{100\ \text{km/s}} = 3\times10^{14}\ \text{s}$$

$$= 3\times10^{14}\ \text{s} \ast \left(\frac{1\ \text{yr}}{\pi\times10^7\ \text{s}}\right)$$

$$= 10^7\ \text{y} = ~~10\ \text{Myr} = 10\ \text{Gy}~~$$

$$= 10^{-2}\ \text{Gy} \ll 10\ \text{Gyr}$$

(lifetime of sun)

i- stars have had many crossing and dark matter too if ~~moving~~ at similar speeds (~~we may not be the case~~) which is probably the case (but not necessarily?)

503~~7~~

but anyway we can assume virialization

i.e., the distribution is not changing in a time averaged sense very quickly

and ~~there~~ quasi-equilibrium

∴ Virial theorem holds (The system is virialized

$$\langle K \rangle = \frac{1}{2}\sum_{\ell} \ell \langle U_\ell \rangle$$

use K not T since we need that for temperature

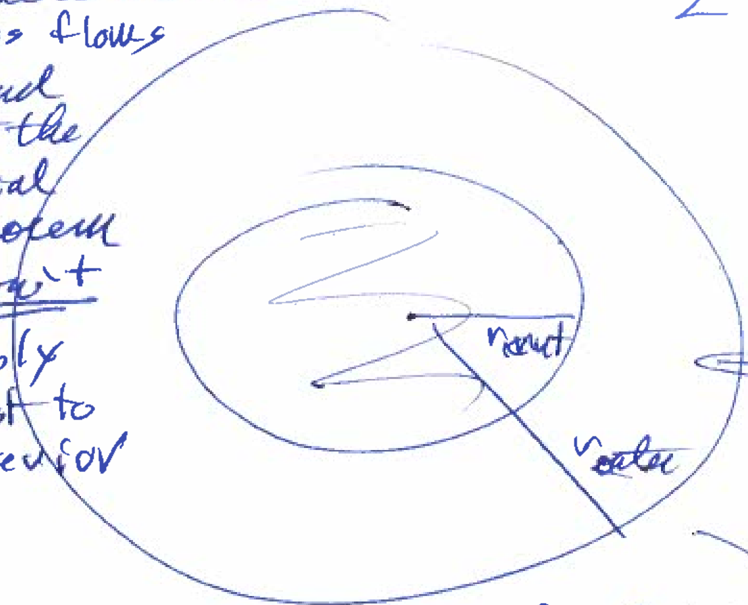
$$= \frac{1}{2}\left[-\langle U_{grav}\rangle + 2\langle U_\Lambda \rangle\right]$$

cosmological constant potential

$$\simeq -\frac{1}{2}\langle U_{grav}\rangle$$

small deep inside halo

If there were mass flows in and out the virial theorem won't apply just to interior



Recall shell theory if the distribution is spherically symmetric — even if time varying it has no effect on the interior region. and ~~No mass~~ flows in or out

So we need only consider out cut off wherever we ~~put~~ put it.

503B

$$M_{vir} = \left(\frac{1}{ab}\right) \frac{R_e \sigma_0^2}{G}$$

$$M_{vir} = \frac{k_{vir} R_e \sigma_0^2}{G}$$

M vir is the mass within the cut-off radius we defined. Not Re and not the area for determining σ_0 in general.

$k_{vir} = \frac{1}{ab}$ is the virial coefficient

$k_{vir} \approx 5$. Not just of order 1. So really galaxy modeling is built into this factor — cut to cutoff where density is so low inflow & outflow small to negligible and the outside spherical symmetric so shell theorem guarantees no gravity effect from outside.

It can be determined for assumed density profiles and parameterizing "observational" quantities ~~to or calculate~~ or from N-body simulation.

In a nova... Mo...

Obviously will vary from system to system but the fiducial value is 5.

So interior is virialized by itself.

and $\sigma_0 \neq \sigma_e$ but σ_0 for aperture area with $R \approx \frac{R_e}{8}$ Ci-14

$$M_{vir} = \left(\frac{k_{vir}}{5}\right) M_{dyn} = \left(\frac{k_{vir}}{5}\right) \frac{5 R_e \sigma_0^2}{G}$$

$$= \left(\frac{k_{vir}}{5}\right)(4.65 \times 10^{10})\left(\frac{R_e}{\text{kpc}}\right)\left(\frac{\sigma_0}{200\,\text{km/s}}\right)^2 M_\odot$$

$$\approx 5 \times 10^{10} M_\odot$$

for the fiducial numbers.

5035

i.e. $K = \frac{1}{2} M_{vir} \sigma_{vir}^2$

If you actually know all the masses and system M (which is M_{vir} itself out to $r_{cut-off}$) you could calculate

virial velocity dispersion $\sigma_{vir} \equiv \sqrt{\frac{2K}{M_{vir}}}$

definitely, but we don't for real galaxies but we do for N-body calculations

Also

$U = -\frac{GM_{vir}^2}{r_g}$ ← gravitational radius ci-146 [illegible]

Again if we knew all as for an N-body calculation we'd know U and M_{vir}

and $r_g \equiv -\frac{GM_{vir}^2}{U}$ ← characteristic radius not radius of anything exactly

i.e. $\sigma_0^2 = a\,\sigma_{vir}^2$ $R_e = b\,r_g$

central dispersion ci-133

a is a fudge factor of order unity?

b is a fudge factor of order unity?

$$\sigma_0^2 = \frac{\int_{Ap} \sigma_{los}^2(R)\, I(R)\, d^2R}{\int_A I(R)\, d^2R}$$

perfect intensity weighted σ_{los}^2 over an aperture r — maybe usually $\sigma_e^2 = \sigma_0^2$ ci-133

$K = -\frac{1}{2} U$

~~and going beyond~~

$$\frac{1}{2} M_{vir} \frac{1}{a} \sigma_0^2 = \frac{1}{2} \frac{GM_{vir}^2}{R_e/b}$$

The discussion shows a and b can probably vary from 1 by a factor ~10

M_{dyn} is the best one can do if there is no spatially resolved kinematic information.

One does have resolved surface brightness information to obtain R_e and σ_0.

12) Mass Distribution

Ci-155-156

Not a complete story. (See Ardeni ... Cj-199-20...)

Virial Mass M_{vir} are determined by some combination of observation and modeling (see p. 5031-5037)

But what is the cut-off radius. M_{vir}

$$\phi = -\frac{GM}{r^2} + \frac{\Lambda}{3} r$$

$$\dot{\phi} = 0$$

$$\frac{GM}{\Lambda/3} = r^3$$

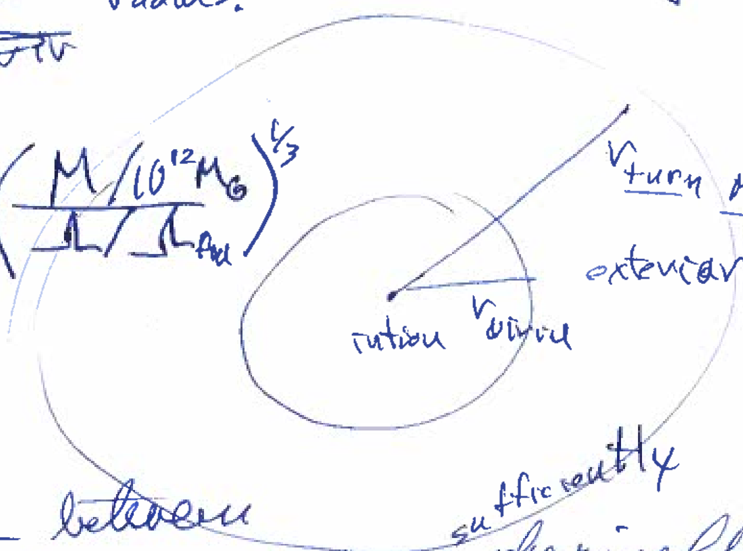
$$r_{turn} = \left(\frac{GM}{\Lambda/3}\right)...$$

M is total mass within r_{turn} if sufficiently sphere...

a) Modern r_{turn}?

$$r = (1.1082\,\mathrm{Mpc})\left(\frac{M/10^{12}M_\odot}{\Lambda/\Lambda_{fid}}\right)^{1/3}$$

but this is really too big.

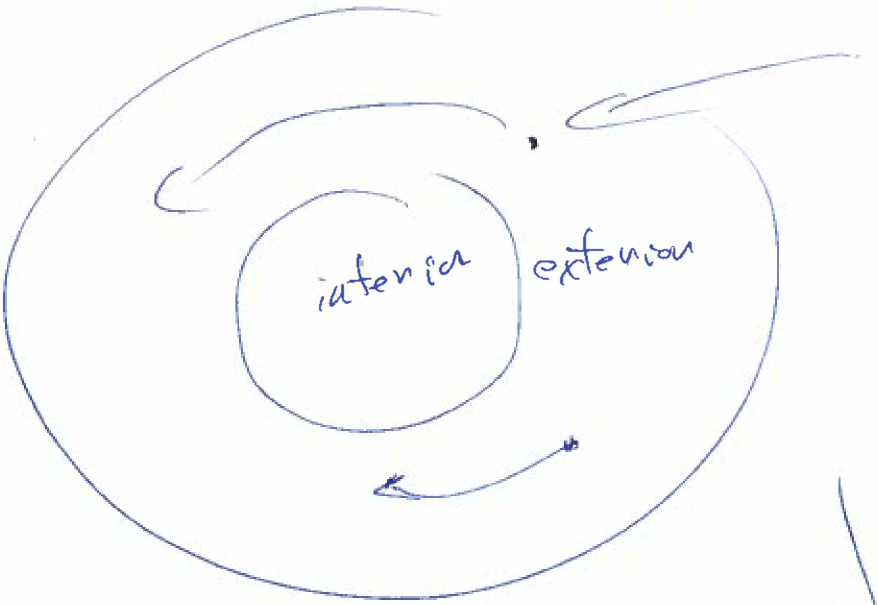


There is mass between r_{virial} and r_{turn} but if sufficiently spherically symmetric and no inflow/outflow from interior

5038) then ~~the~~ interior by the shell theorem is gravitationally decoupled from exterior

and ~~no~~ inflow/outflow means ~~that the~~ will usually be internally virialized ~~by itself~~

Exterior mass & distribution may be all indeterminate



if the interior is spherical symmetric it is like a point mass

If the exterior mass (DM or whatever) interact with each other negligibly, ~~then~~ individually virialized

any distribution determined by peculiar history

Study exterior important question but can be ideally ~~a bit~~ isolated from interior

→ Not can't be exactly true in reality

b) Model of collapse to dark matter halo over cosmic time

gives idealised formulae for interior [Ci-204-205, now Co-199-20…

$$r_{vir} = (259.0\ \mathrm{kpc})\left(\frac{M_{vir}}{10^{12}M_\odot}\right)^{\frac{1}{3}}\left(h_{70}\right)^{-2/3}$$

$$V_{vir} = (128.9\ \mathrm{km/s})\left(\frac{M_{vir}}{10^{12}M_\odot}\right)^{\frac{1}{3}} h_{70}^{1/3} \qquad h_{70} = \left(\frac{H_0}{70\ \mathrm{km/s/Mpc}}\right)$$

circular velocity at r_{vir}

h_{70} is 1 to within about 4% probably, however the Hubble tension is resolved

Recall $V_{cm}^2 = \frac{GM}{r}$

and then results are consistent.

$$r_{vir} V_{vir}^2 \propto \left(\frac{M_{vir}}{10^{12}M_\odot}\right)$$

So M_{vir} estimated as on p. 5031–5037

then gives $r_{vir} = r_{cutoff}$.

c) Then for ETGs

X-ray observations and modelling give M_{gas} and $\rho_{gas}(r)$

M_* and $\rho_*(r)$ } estimated from SED fitting plus and assuming an IMF which is a weak point. Only well known for Milky Way

5040

Recall
$\int \rho(x)\, 4\pi x^2 dx$
$= 4\pi r_s^3 \rho_s f(x)$
converges for $x \to 0$
diverges for $x \to \infty$
but we have a edge radius
$= \frac{GM_s}{r_s} \frac{x}{x}$
$\Rightarrow$ constant

$$M_{DM} = M_{vir} - M_{*} - M_{gas}$$

Inferred from resolved kinematic information
SED fitting (need IMF too)

Recall

$$\rho_{DM} = \rho? - \rho_*(r) - \rho_g(r)$$

$\rho_{tot} \propto r^{-2}$ to $R = 4R_e$
seem valid, Ci-156

I think has at least a partial physical justification? Think 5 quality

N-body simulations give for dark matter

$$\rho_{NFW}(r=r_s) = \frac{4\rho_s}{x + 2x^2 + x^3}$$

better 10% accurate mostly

$x \in [0.1, 10]$
from vast N-body simulation over 20 orders of Mass
Wang et al 2020

$$\rho_{Einasto} = \rho_s\, e^{-[\frac{2}{\alpha}(x^\alpha - 1)]}$$

few percent accurate mostly

But are systematic deviations which vary and so the ideal analytic profile fit not yet.

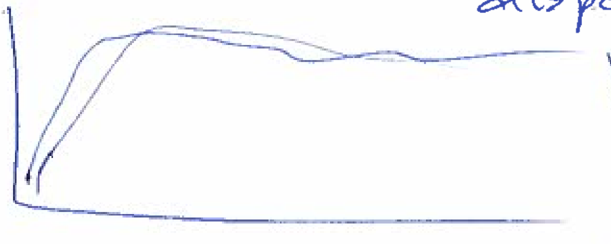
really just a fit function

$\alpha \approx 0.16$ — No special physical justification

Jie Wang 2020

Either used to help fit ~~rotation~~ dispersion curves

$\sigma(R)$ — projected radius



Rotation curves hard to determine for ETGs since hard to determine circular orbits which are natural in thin disks of Spirals

However the modeling (fitting ~~theory~~ observations) put

$$f_b(R_e) = \frac{M_* + M_{gas}}{M_{vir}}$$

is 60 – 90% for ETGs

(effective radius R_e half-light radius)

Ci-156

but $f(R = \infty) = 10^{-2}$
similar to spirals

14) Fundamental Plane

Ci-156-158

⇒ an important scaling relation

a) — which a jargon name in sense since not fundamental physics

It's a relation between 3 ETG variables

independent of absolute

R_e — depends on absolute — effective or half light radius

σ_0 — central velocity dispersion Ci-133

Aperture size need to be specific

$$\sigma_0 = \frac{\int_{Ap} \sigma_{los}^2(R)\, I(R)\, d^2R}{\int I(R)\, d^2R}$$

so surface brightness weight line of sight dispersion

L } and

$$\langle I_e \rangle = \frac{L}{2\pi R_e^2} = \frac{L/2}{\pi R_e^2}$$

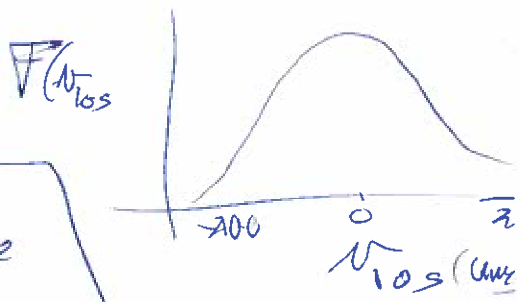
Depended on EMR band

Ci-504 clarify

$$I_{specific} = \frac{1}{4\pi} I_{surface\ brightness}$$

I think the $\frac{1}{4\pi}$ is nuisance since I_{sp} is direction dependent in general and so multiplying it by 4π creates a quantity without a direct meaning

$$I_{SB} = 4\pi I_{sp}$$

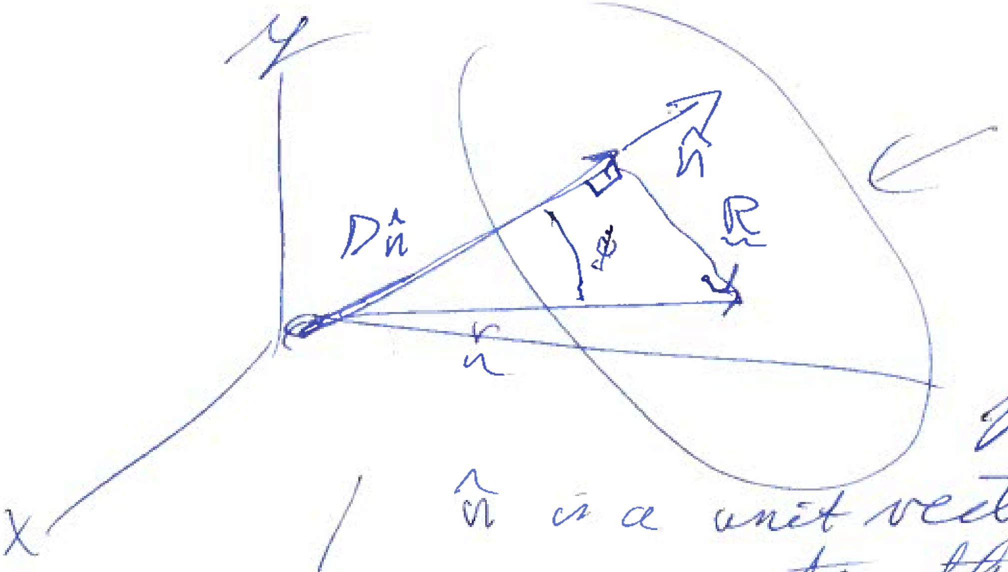


5042

~~Of course~~

So one has to actually specify band and aperture but the relation holds more or less it seems for various choices, but the coefficients vary.

b) A bit of geometry with vector formalism



a plane in 3-d space

[illegible]

$\underset{\sim}{R}_1 \cdot \underset{\sim}{R}_2 = (-D\hat{n} + \underset{\sim}{r}_1)\cdot(-D\hat{n} + \underset{\sim}{r}_2)$

[illegible] $= D^2 - D\hat{n}\cdot r_1 - D\hat{n}\cdot r_2 + r_1 \cdot r_2$

$\hat{n}\cdot\underset{\sim}{R} = \hat{n}(-\hat{n}D + \underset{\sim}{r}_1)$

$= -D\hat{n}\cdot\underset{\sim}{r}$

$= 0$

if $\underset{\sim}{r}$ ends on plane defined by $\hat{n}$ and D.

These define the plane:

$\hat{n}$ is a unit vector normal to the plane

D is the shortest distance to the plane.

$$\underset{\sim}{r}\cdot\hat{n} = D$$

$$r\cos\phi = D$$

$\underset{\sim}{r}$ is a vector ~~to the plane~~ to a point on the plane

r is the distance from origin to the plane the distance is shortest for $\phi = \emptyset$ and that is D

Now $D = \underset{\sim}{v} \cdot \hat{n}$

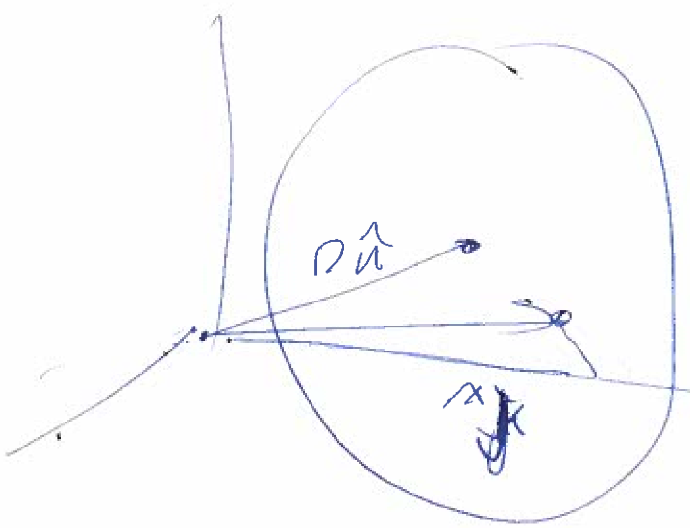
$$D = \sum_i x_i n_i$$

The components of the vector v

The components of the unit vector of course $\hat{n}$'s!

$$x_j = \frac{D - \sum_{i \neq j} x_i n_i}{n_j}$$

You isolated this component as a function of the others



As you vary the x_i's freely, the x_j varies in a determined manner.

5044)

3-d space with perpendicular direction

c) We Return to our quantities

R_e , ~~σ_0~~ , $\langle I_e \rangle$

or rather their logarithms
they magically obey nearly the relation

$$\log R_e = \alpha \log \sigma_0 + \beta \log \langle I_e \rangle + \gamma$$

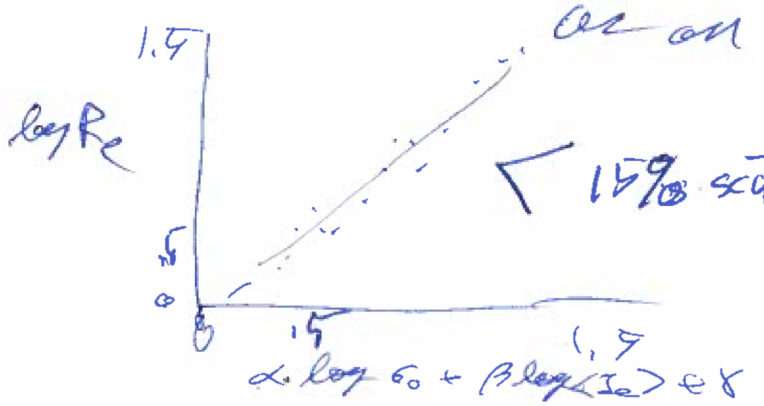
It seems $\log R_e$ is the favorite variable to isolate, but one could isolate the others as well.

$\alpha \in [1, 1.4]$ $\beta \in [-.9, -.75]$

Depend on ~~[illegible]~~ Electromagnetic band

γ ~~depends on~~ a normalization constant that depends on units

Ci-157 debuies plotting $\log R_e$ versus $\alpha \log \sigma_0 + \beta \log \langle I_e \rangle + \gamma$ or an edge on view



15% scatter

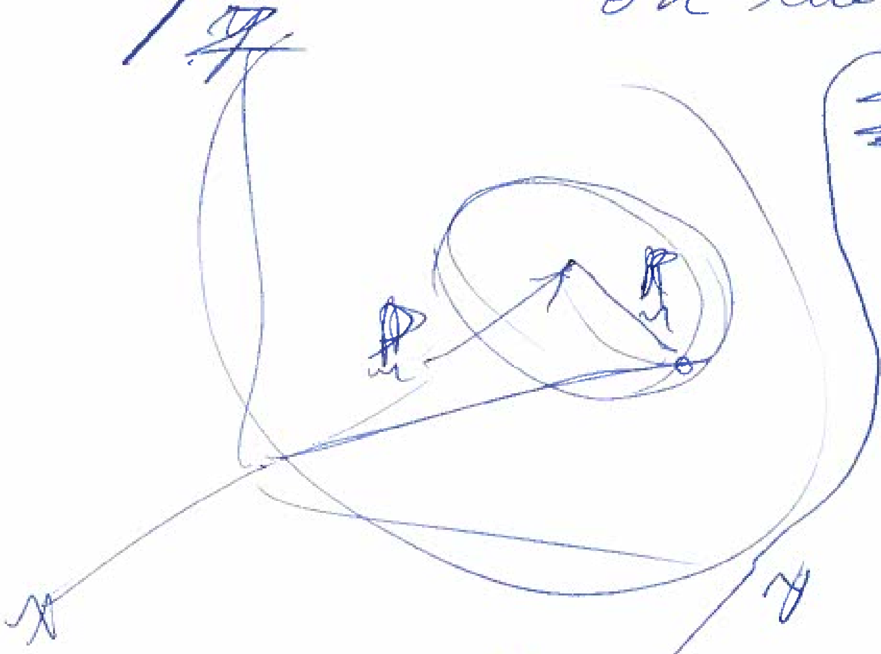
The scatter in R_e $\frac{\delta R_e}{R_e} \simeq 15\%$ which smallish.

Just what the rho

5045

I suspect edge-on view
is a bit of a jargon expression.
— At least I don't see
a direct geometric sense
— the log R_e is a projection
of the overall vector
on the log R_e axis

I suppose just because it looks like a line on a plot



~~If you~~ Omit Returning
to geometry
for a moment
~~the~~ trace behavior
on a circle in
the plane ~~the~~
Pythagorean Theorem
dictates

$$D^2 + R^2 = x^2 + y^2 + z^2$$

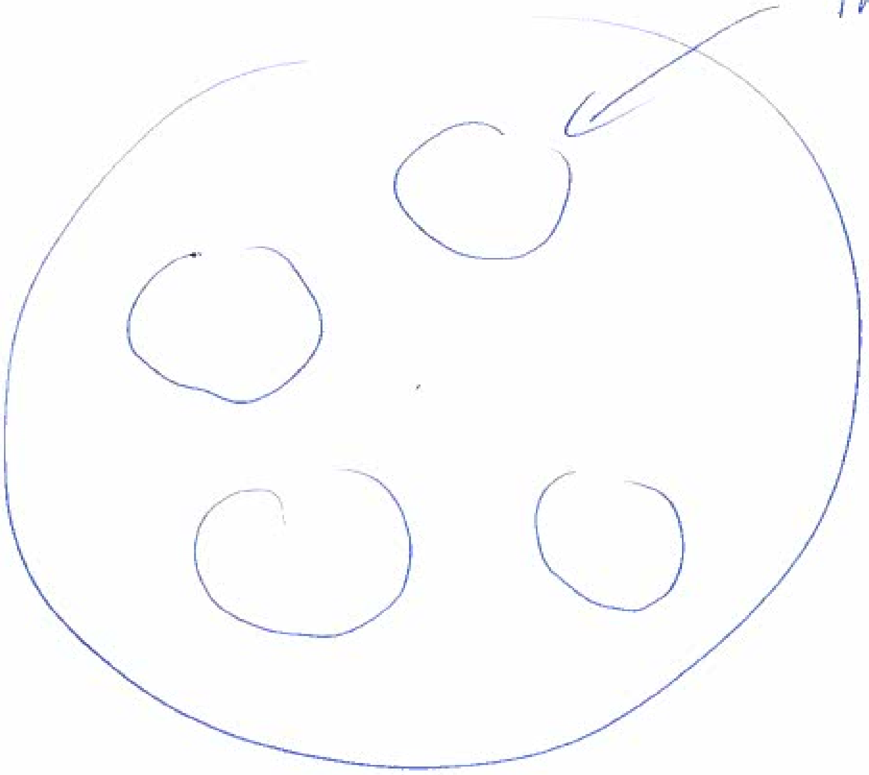
so $z = \pm\sqrt{D^2 + R^2 - y^2 - z^2}$

gives z as you move
around a circle on a
plane
This makes a bit more sense
tho as an edge-on view.

~~But~~ I guess
~~on~~ edge-on
is just what
the plot
looks like.

5076)

Face-on view makes a sense



there are avoided zones. So not all the fundamental plane is covered

d) Using the Fundamental Plane Relation to Determine distances

R_e and $F_e \left(\langle I_{e_{sp}} \rangle\right) = \int_0^{R_e} I_{sp}\, d^2R$

specific intensity

but $\langle I_{e_{sp}} \rangle \equiv \frac{F_e}{\pi R_e^2}$ Just the definit

I just can't think of surface brightness with the extra 4π factor

σ_0 check R_e σ_0 mean $\langle I_e \rangle$ from Fundamental Plane relation

$F_{tot} = \int_0^\infty I_{sp}\, d^2R$

$F_e = \frac{1}{2} F_{tot}$ by definit

$L = 4\pi F_{tot} = 4\pi (2F_e) = 4\pi (2\pi R_e^2)\langle I_{esp} \rangle$

$= 2\pi R_e^2 \langle I_e \rangle$

$F_{at\,earth} = \frac{L}{4\pi r^2}$, $r = \sqrt{\frac{L}{4\pi F_{tot}}} = \sqrt{\frac{2\pi R_e^2 \langle I_e \rangle}{4\pi F_e}}$

R_e and σ_0 are ~~distan~~
measurable without distance information
the fundamental plane then
gives $\langle I_e \rangle$

and so $r = \sqrt{\frac{2\pi R_e^2 \langle I_e \rangle}{4\pi \, ?}}$

is determined.

Sort of a round-about derivation

~~→ Inte~~ But only for
low redshift
since it seems likely
that the parameters of
the fundamental plane
vary to the cosmic past
and maybe the fundamental plane
doesn't hold then.
→ it emerges from cosmic
evolution not fundamental
physics ~~not~~ some ~~thi~~
fixed relaxation process always
applicable.

5048) e) Understanding the Fundamental Plane

Ci-146

$$M_{vir} = \frac{k_{vir} R_e \sigma_0^2}{G}$$

central velocity dispersion defined for some aperture — often σ_e

virial coefficient } k_{vir} is a fudge factor ~~that~~ some dynamical modeling must give

e.g. N-body simulation or more elaborate hydro

but $k_{vir} \sim 5$ is the fiducial value, but it clearly varies ~~a~~ lot.

$$\Upsilon = \frac{M}{L}$$

is the ~~stellar~~ total mass-to-light ratio ~~light ratio~~

Not just stars — all mass to light ratio.

$\Upsilon_\odot = 5133$ kg/W (wiki)

but the solar value is often used as natural unit Υ in $M_\odot / L_\odot$

$$L = \frac{M_{vir}}{\Upsilon_*}$$

$$L = \frac{k_{vir} R_e \sigma_0^2}{G \Upsilon}$$

but from r. 5046 $L = 2\pi R_e^2 \langle I_e \rangle$

$$R_e^2 = \frac{1}{2\pi} \frac{L}{\langle I_e \rangle} = \frac{1}{2\pi \langle I_e \rangle} \left(\frac{k_{vir} R_e \sigma_0^2}{G \Upsilon} \right)$$

15049

$$R_e = \frac{1}{2\pi \langle I_e \rangle} \frac{k_{vir} \sigma_0^2}{G \Upsilon}$$

$$\log R_e = 2 \log \sigma_0 - \log \langle I_e \rangle + \log \left\langle \frac{k_{vir}}{\Upsilon} \right\rangle + \text{Constant}$$

If all ~~galaxies~~ EGIs ~~were~~ structurally (current shapes) ~~homologous~~ and kinematically (current motions) ~~homologous~~ ~~homologous → identical~~ ~~them~~ ~~and~~

homologous (same except for overall scale) and had the same Υ,

then k_{vir}/Υ would be same ~~and~~ for all galaxies and $\alpha = 2$, $\beta = -1$ for all galaxies.

But $\alpha \underset{\sim}{\in} [1, 1.4]$ and $\beta \underset{\sim}{\in} [-.9, -.75]$

Depends on band But not 2 ~~and~~ -1 in any case

Ci-156

5050

But the fundamental plane is tilted.

S_0 k_{vir}/Υ depends on σ_0

on $\langle I_e \rangle$, ~~and σ_0~~

$\log k_{vir}/\Upsilon \simeq \alpha_1 \log \sigma_0$

C1-148 suggest Υ shows most variation. Higher L galaxies (bigger σ_0) have bigger Υ

$+ \beta_1 \log \langle I_e \rangle$

This tilt must result not from virialization since virialized ETGs could exist anywhere in $(R_e, \sigma, \langle I_e \rangle)$ space.

It must result from the galaxy formation process evolving thru cosmic time.

Reproducing ~~the~~ Fundamental plane is a fine test of large-scale structure simulations.