Lecture 6: Cosmic Present | 6001

Galaxy Environments:

Interactions, Groups, Clusters, Superclusters, Large-Scale Structure

1) Interacting Galaxies (6003)
2) Table: ~~for~~ Groups + Clusters (6008)
3) Local Group (6011)
4) Star Formation History (SFH) in Local Group (6015)
5) Chemical/Metallicity Patterns in Local Group (6017)
6) Galaxy Clusters (6021)
7) Galaxies in Galaxy Clusters (6023)
8) The Intracluster Medium (ICM) (6031)
9) Sunyaev-Zeldovich Effect (SZE) (6034)
10) Density + Temperature Distribution of Clusters in the Simple β-model (6046)
11) Cool-Core + Non-Cool Core Clusters (6060)

6002

12) Cluster Virial Mass, Mass Density Profile (mainly of Dark Matter), + Scaling Relations (6063)

13) Large Scale Structure (LSS) + the Cosmic Web (6066)

14) Influence of Environment on Galaxies (6069)

15) Large-Scale Structure (LSS) + Galaxy Clustering (6071)

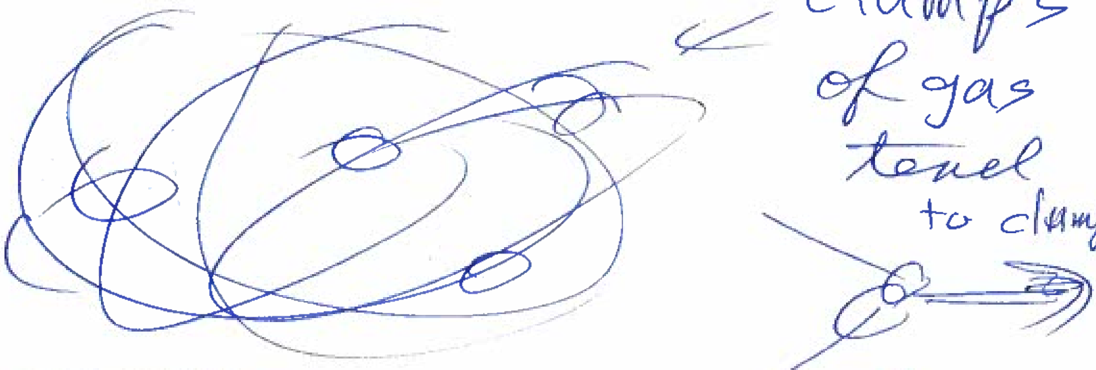
L 6003

1) Interacting Galaxies

a) Extreme limits are Mergers, and fly bys.

- "normal" galaxies are somewhat isolated but can be groups (just very poor clusters), clusters, etc.
- if not they are field galaxies; those in void are void galaxies
- peculiar galaxies are often interacting (can be extremely isolated)
  - ↳ connected by obvious luminous bridges of stars & gas
- disturbed morphology
  - ↳ warped disks since isolated disk galaxies have very disks

6004) b) Disks are due to formation process



clumps of gas tend to clump

when collide and go off in a common direction

this keeps happening until it can't anymore

→ i.e., when gas is all moving in one plane in circular orbits in one orbital direction → by definition prograde

– Relaxation ~~to~~ a disk.

> Part of the explanation of all disks in astrophysics

→ but magnetic fields and ~~asym~~ axisymmetric gravity around oblate ~~compact~~ ~~pressure supported~~ compact objects (stars, planets, ~~super~~ black holes, SMBHs) play a role too.

c) — mergers ~0.5 ~~to few~~ gigayears Gi–16 (cosmic prosecution... [illegible] | 600 5

— wet or dissipative mergers
one of gas rich galaxies /
→ but ~~this~~ does not include [illegible]
~~with~~ ellipticals ~~since~~
though ~~they are~~ hot gas rich.

(why don't ellipticals
have disks — some do
have a bit of disks — but
~~I suspect the~~ AGN
driven convection of hot
gas breaks up relaxation
to a disk mostly)

followed by a starburst ~~[illegible]~~
(if gas not all too hot)

Following a starburst of a major merger the merged galaxy ~~may~~ often quenches → maybe

— dry mergers been gas-poor
(~~or it that~~ or cold-gas poor
anyway)
→ so not much star formation
before or after.

goes over goldenmass ≙ $10^{12} M_\odot$ where conspiracy of dark halo and ~~AGN~~ AGN activity keeps gas mostly too hot.

6006

– all kinds of interesting shapes can occur

↪ rings and shells, tidal tails in interactions/mergers

d) Rates

merger rate $\Gamma_{merg} = \frac{n_{merg}}{\tau_{merg}}$ ← number of ongoing mergers per unit volume $\left(\frac{number}{time}\right)$

Cr-164

↗ time scale of a merger

Ci-165

$\tau_{merg} \simeq 0.5$ Gyr just a fiducial number for cosmic present

$\mathcal{R}_{merg} = \frac{n_{merg}/n_{gal}}{\tau_{merg}}$

fractional merger rate $= \frac{f_{merg}}{\tau_{merg}}$

– number of mergers per galaxy per time

cosmic present

$f_{merg} \simeq 0.01$

$\tau_{merg} \simeq 0.5$ Gyr

$\therefore \mathcal{R}_{merg} = \frac{0.01}{0.5 \text{ Gyr}} = 0.02 \text{ Gyr}^{-1}$

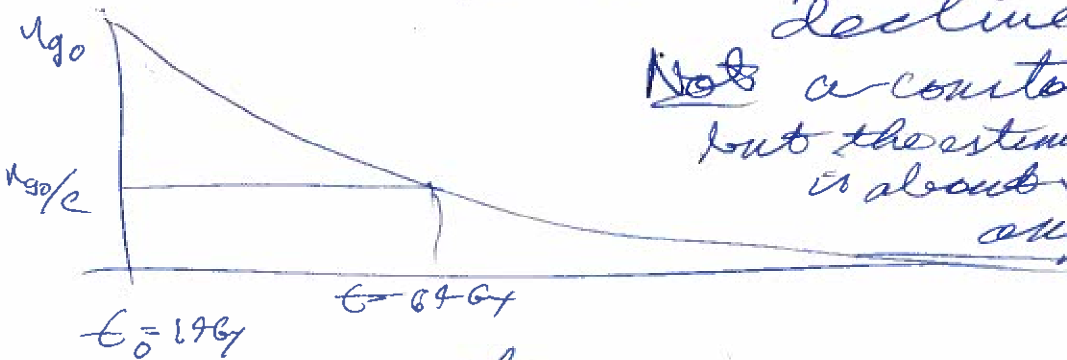
$\tau_e = \frac{1}{\tau_{merg}} = 50$ Gyr

every merger destroys 1 galaxy

$dn_g = -\mathcal{R} n_g dt$

$n_g = n_{g_0} e^{-\mathcal{R}t} = n_g e^{-t/\tau_e}$ ← e-folding time

So if you take R is a constant, then ~~there~~ must be an exponential decline



Not a constant but the estimate is about right anyway

However, in the future if the Λ-CDM model continues for 100 Gyr ~~Gyears~~, the large scale structure will freeze in comoving coordinate and universe will consist of mainly isolated receded quenched giant ellipticals

→ all out of each others event horizons (Nagamine & Loeb 2003)

much later (~100 Gyr)

p.12 of Nagamine & Loeb

→ the beings of ~~those~~ days won't have ~~a clue~~ many clues about the origin of the universe relative to us

But maybe we don't now!!

Maybe being 10 Gyr ago solved all of cosmic history to date.

6008 | 2) Table: Groups & Clusters

Ci-165

	Local Group (a poor double group Milky Way & M31)	Groups (very poor clusters)	Clusters
N number of galaxies $M_v < -16$ (M31 has $M_v = -21.8$ (wik) → so + middle low inner)	7 (more than 80 dwarf)	4-50	50-1000
M_* ($M_\odot$)	$1 \to 1.5 \times 10^{11}$	$\lesssim 10^{12}$	$10^{12} - 10^{13}$
σ (km/s) ~~σ~~ of galaxies relative to average galaxy (so not star in galaxies)	—	100-500	500-2000
X-ray L erg/s	—	$10^{41} - 10^{43}$	$10^{43} - 10^{45}$
M_{gas} ($M_\odot$)	—	$\lesssim 10^{13}$	$10^{13} - 10^{14}$
M_{virial} ($M_\odot$)	$2 \to 5 \times 10^{12}$	$\lesssim 10^{14}$	$10^{14} - 10^{15}$
T_g (10^7 K)	—	.5-2	2-10
r_{vir} (Mpc)	~1	0.4-1	1-3
Baryon fraction	—	.5 → .8	0.7-1
Baryon fraction, cosmic → 0.16 (Ci-27); Baryon fraction set by Big Bang Nucleosynthesis	—	.08-.128	.112-0.16

No sharp distinction but fiducial line $M_{vir} = 10^{14} M_\odot$

$C_i - 166$ ↙ Local Group is spiral group [600 ?]

a) group dominated by spiral — spiral group

b) dominated by Es or S0s — evolved groups
ETGs

↳ because mergers to $M_{gal} \approx 10^{13} M_\odot$ or ram-pressure stripping — largely quenched galaxies

c) ~~not~~ no dominate massive galaxies — dwarf association

$C_i - 54$ for BFGs (-55)
say $M_* \lesssim 10^9 M_\odot$
or a dIrr

$C_i - 426$ ~~says range~~
same for ETG

$M_{vir} < 10^{11} M_\odot$ dIrr $C_i - 54$

$M_{vir} < 10^{10} M_\odot$ Es $C_i - 129$

Intragroup medium not Intergalactic Medium (IGM)
(IGRM just made up not at $C_i - 498$) C_i 498 acronyms
but a lot like
Intracluster medium = ICM (C_i 498)

$T \approx (0.5 - 2) \times 10^7$ K

↳ so X-ray emission
ff + emission and highly ionized metal recombination lines

He^+
$E \propto \frac{1}{Z^2}$
$\lambda_{He^+} = 180$ Å

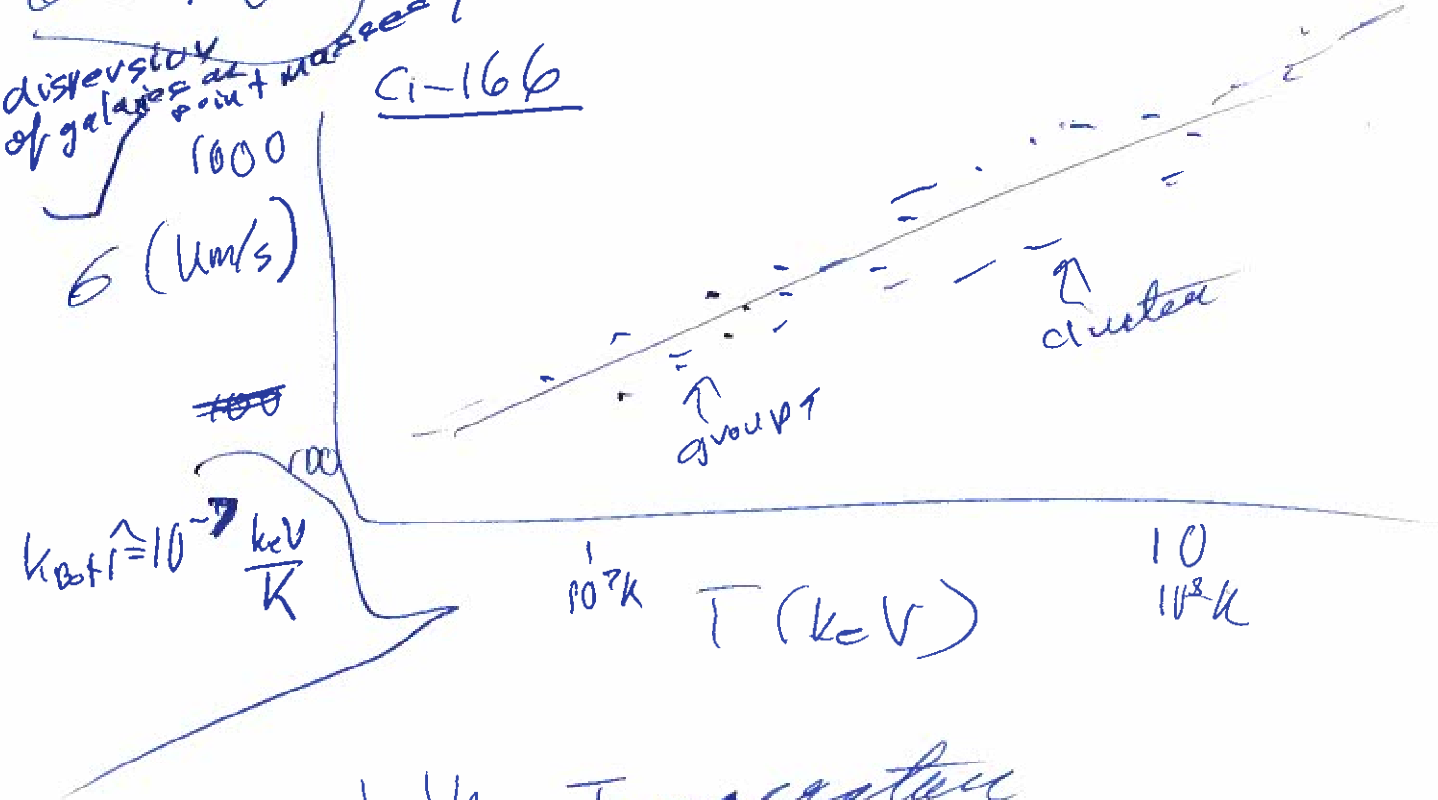
Lyman limit
$\lambda = 91.13$ nm $= 911.3$ Å
$= 0.09113$ μm

Recall H has no x-ray lines

$C_i - 179$ plot

$\lambda_{x-ray} \approx 1$ Å or $0.1 - 100$ Å

6010



both Temperature
+ Galaxies (as point masses in group)
are virialized for groups + clusters mostly (if some cosmic processes)
i.e., in equilibrium

σ used to determine
M_{vir} Ci-146 mutatis mutandis

$$M_{vir} = \frac{k_{vir} R_{group} \sigma^2_{galaxies}}{G}$$

from galaxies to groups/clusters

Stars have $\frac{M}{L} \sim 1$ as for sun - stars contribute little mass as Table on p.6008 show

galaxies M/L ~10 Ci-168 except UFDs

Or weak lensing → statistical.

Group Mass-to-light ratio $\frac{M_{vir}}{L} \sim 100 - 400$ dark matter dominated

in $M_\odot/L_\odot$ units = 5133 kg/W (WOK)

As table (p.6008) show clusters are a bit less dark matter dominated.

6 U 11

Special group case

Hickson Compact groups

4 – 5 bright galaxies

one scale ~10s of kpc

not ~1 Mpc

rare and

will probably are merge to

a ~~on~~ giant elliptical

in 1 → 30 Gyr

(Mazzarini & Loeb 2002)

Fossil Group

↳ on bright Elliptical

with no large companion

just small satellite galaxies

~~and~~ an extended

(group size ~1 Mpc)

X-ray halo

remnant of

IGRM.

3) Local Group

a) – rather poor group only

3 large Galaxies (fiducial limit is 5?)

Milky Way, Andromeda = M31

$M_{vir} \sim 1.5 \times 10^{12} M_\odot$ Wiki

$1.19 \times 10^{12} M_\odot$ Wiki

though revisit 2024 maybe 1/5 smaller

Triangulum = M33

Not all that large

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

Ci-163

6012

Partial solution to missing satellites problem - Ci-172
Not solved

Actually Local Group is sort of two sub groups

Milky Way and M31

& its satellites & neighbours — and its satellites & neighbours

All dwarfs not UFDs are classical dwarfs Ci-172

UFDs discovered by SDSS Ci-172

ultra faint dwarf

b) Table

	MW	M31 (And)	M33 (Tri)	M32	dIrr	dSph	UFD
M_V	-20.9	-21.4	-18.8	-16.4	-12 → -10	-16.5 → -9	-8 → -1.5
L_V ($10^6 L_\odot$)			2800	300	1-500	0.3-300	.0003-0.1
R_e (kpc)			2.0	0.11	0.4-2	0.2-1	0.02-0.5
M_* ($10^6 M_\odot$)	4×10^4		2900	320	1-500	0.3-300	.0003-0.?
HI Mass ($10^6 M_\odot$) atomic not ionized	4000		1900	— ionized; Not gas poor Co-16.8	0.4-500 gas rich SFGs	— gas poor, not SF	≲ 0.3 Not SF
M_{dyn} ($10^6 M_\odot$)	10^6	1.5×10^6	5×10^4	1082	20-3000	10-800	0.5-10 tiny
M_{dyn}/L_V ($M_\odot/L_{V\odot}$)			17	3	~10	2-100	5000 really DM dominate
SFR ($M_\odot$/yr)	1-3	.7 Ci-K7	~.5	—	0.001-.1	—	$<2\times10^{-5}$
Z in [Fe/H]			-.6	-.25	-1 → -2	-0.5 → -2	-1 - -2.5

rather low metallicity

[Fe/H] = log $\frac{Fe/H}{(Fe/H)_\odot}$

role of L_V ~ 1

M_{dyn}: i-H6 stars & HI except

$\left(\frac{R_{max} V_{rot}^2}{G}\right)^{1/2}$ for M33 and dIrr

where R_{max} = outer most HI-21 line of rotation curve

Most DM dominated at universe Pop III

$t_{cool} \approx 1$ Gyr wik → before reionization though may be later on

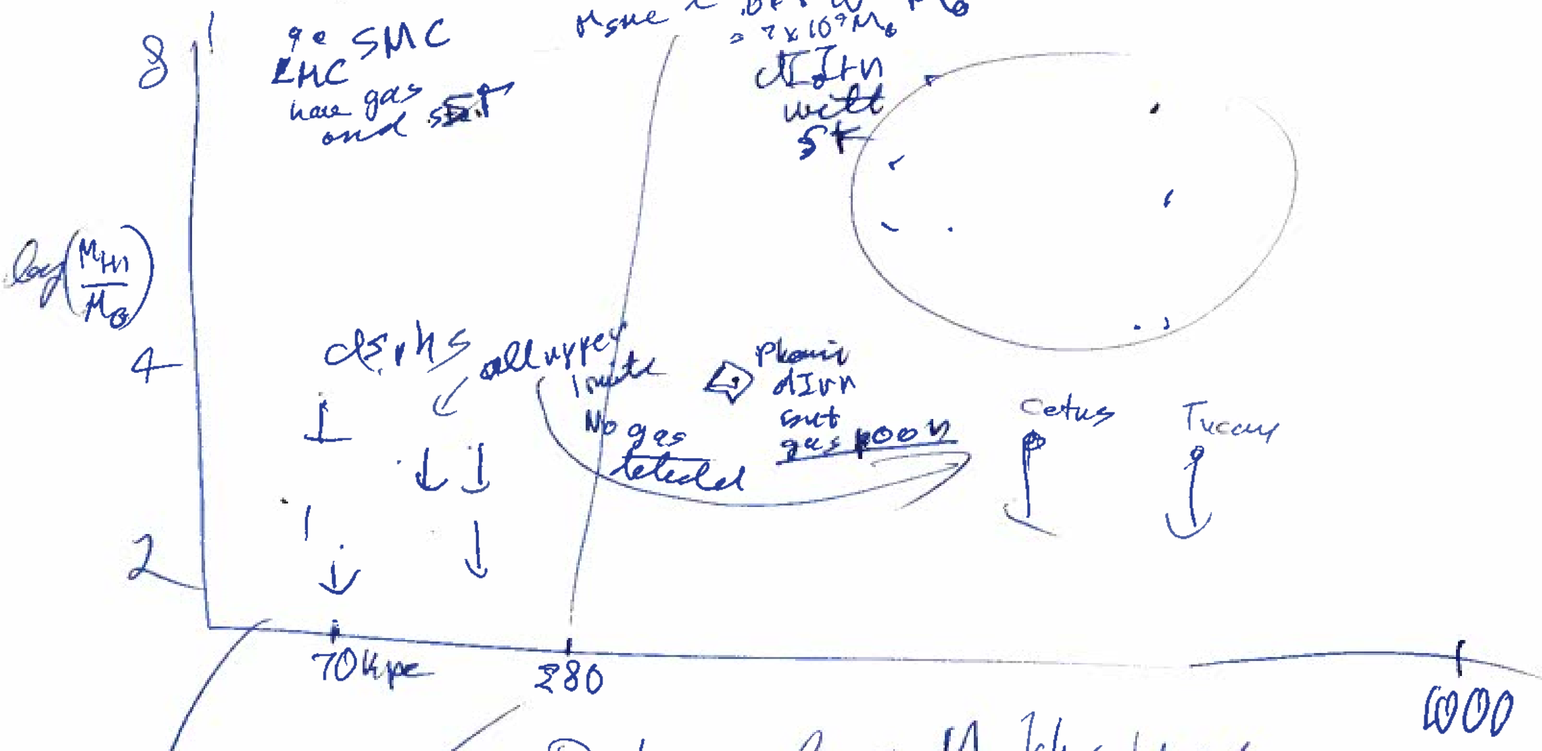
dIrr are SF (gas-rich)
dSph are not SF (gas-poor ↳ to zero)
} but there are a few transition dIrr/dSph

c) Plot

Probably not gas-stripped because more self-gravity

Not gas-poor
$M_{LMC} \sim 1.4 \times 10^{11} M_\odot$
$M_{SMC} \sim .07 \times 10^{11} M_\odot = 7 \times 10^9 M_\odot$

$M_{dIrr} \lesssim 3 \times 10^9 M_\odot$
$M_{dSph} \lesssim 10^8 M_\odot$



$R_{vir\,MW} \lesssim 280\,kpc$
for $M_{vir} \sim 1.3 \times 10^{12} M_\odot$

But 2024 downward revision ~ 1/5 ?

M31 and its neighbour dwarfs show similar pattern Cr 171
Real LG is kind of double group: MW part, M31 part

by Milky Way ↳ halo gas for ram pressure stripping

→ Cr-171 ram-pressure stripping → gas pushed out
+ Tidal stripping → gas stretched out
→ so once probably dIrr

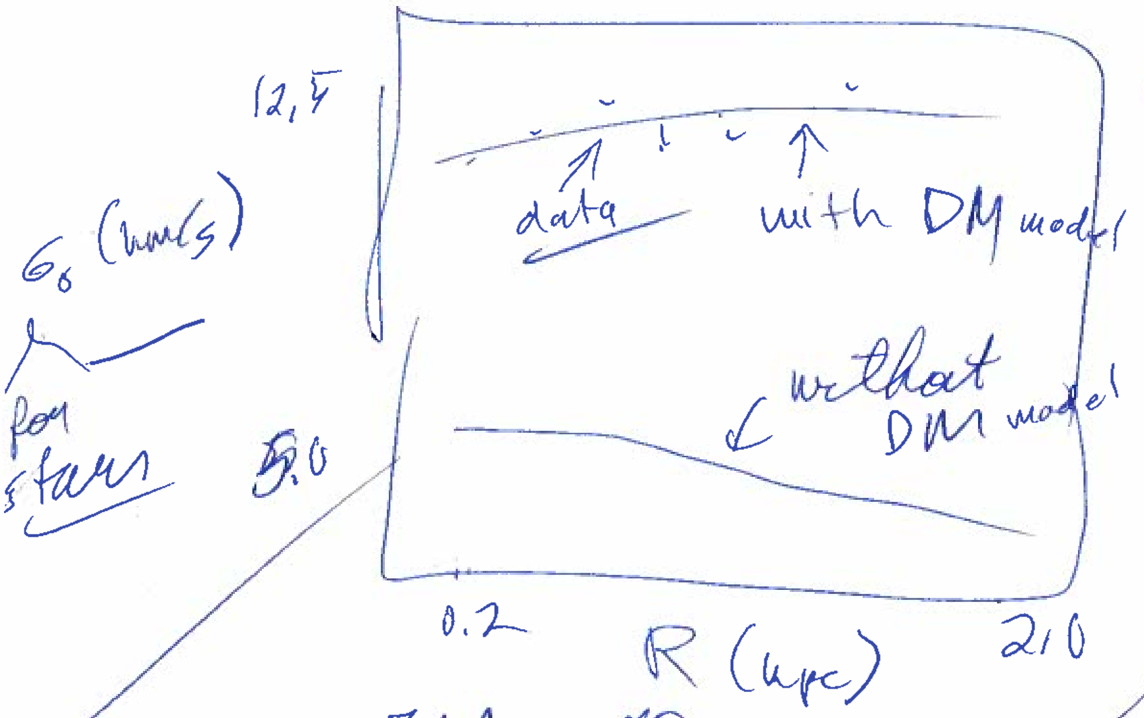
(6014)

We can study Local Group galaxies in vastly more detail than other groups & clusters

— because we can measure individual stars among other things.

- ~~Doppler shift~~
- spectra → and there metallicity and Doppler shift velocity

Example of detail from stars in dSph



Fornax dwarf at 140 kpc from Milky Way and so stripped with R in Milky Way ≈ 280 kpc

$M_* = 2.8 \times 10^7 M_\odot$

R_e?

M_{vir} ~~A~~ ~~B~~ M_*? (see Ci-168, but guess estimate)

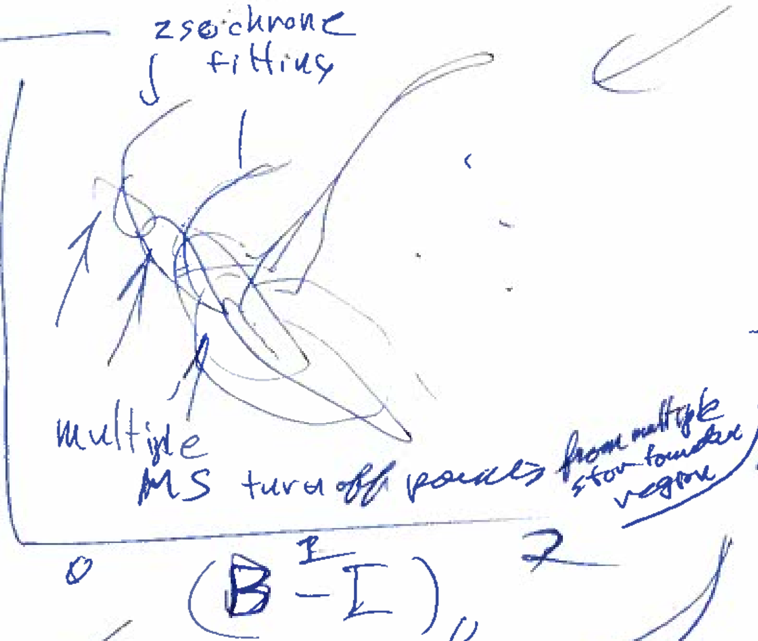
4) Star Formation History (SFH) in Local Group | 6015

Because the local groups stars can be resolved, the star formation histories (SFHs) can be worked out.. Something not currently possible to the same level of precision beyond the LG

(But for stars at different distances is distinct from HR)

~~SFHs turn out to~~

CMD (color magnitude diagram) [Cf - 510 HR diagram for absolute mag; CMD for apparent at same distance — the CI uses CMD as a synonym for HR diagram]



Location of a common age from stellar evolution modeling

I band
Near infrared
$\lambda = 806$ nm
$\Delta\lambda = 149$ nm

Bloby without the sharp (clean) Main sequence — stars not all formed at same time so multiple MS turn-off points for star groups (star clusters formed at different time)

- also the range of distance might be a factor even in one galaxy.

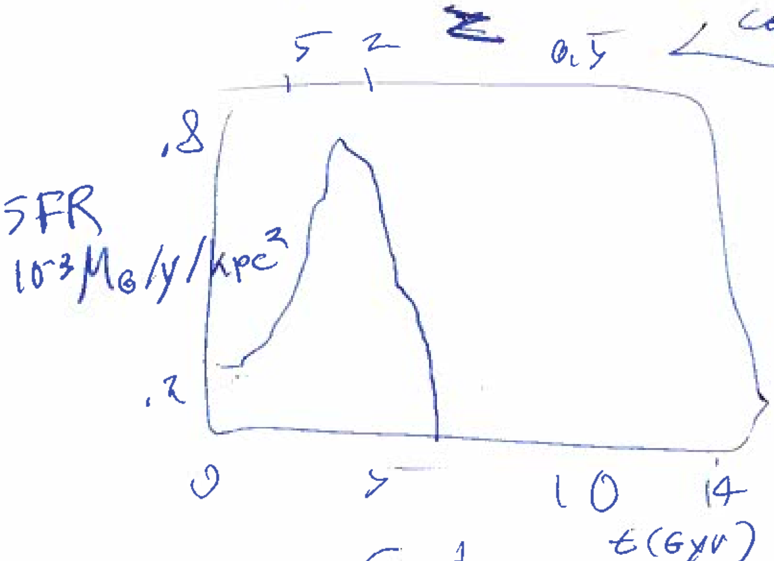
wrong way scale for B and so brighter in B gives lower value relative to I.

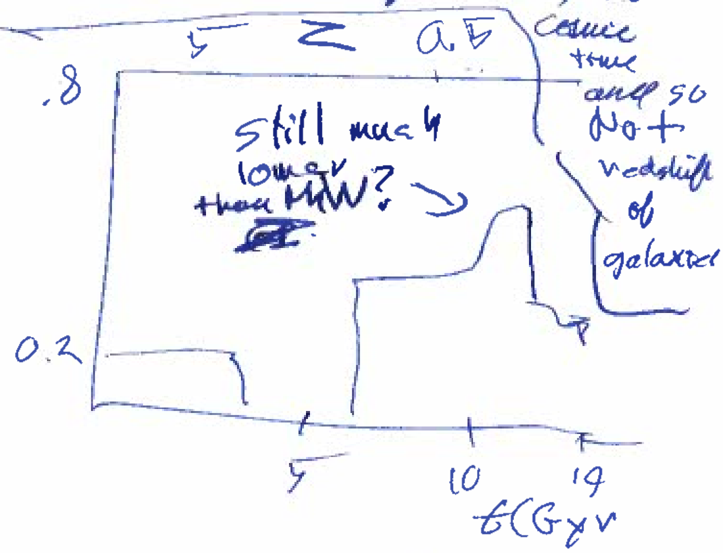
6D(6)

One salient result all galaxies in LG have old stars (Pop II mainly) with ages ≳ 10 Gyr.

Also many ~~Some~~ galaxies quenched early but some had rejuvenations

cosmic redshift corresponding to cosmic time and so Not redshift of galaxies





Cetus

typical dSph

↪ quenched early

Cosmic Noon ~4 Gyr

Leo A

dIrr

quenched rejuvenated and most stars formed in last 10 Gyr and ongoing

Ci-170 Cetus at distance ~750 kpc near neither Milky Way nor M31 (Ci-169)

Ci-170 Leo A at ~800 kpc near neither Milky Way nor M31 (Ci-169

6017

Cetus — must have been stripped early or never had much gas or gas replenishment

Leo A — may have been stripped early and then replenished w/ gas somehow.

→ Maybe two dwarfs merged — old one and younger formed one?

→ but a younger had no early SF then which is unlikely.

5) Chemical/metallicity Pattern of Local Group

(but also probably not dissimilar to other groups/clusters to some degree)

Local group can be studied for chemistry/metallicity pattern
- individual stars can be resolved and so their spectra obtained.

6018

spectral modeling gives metallicity

Determining metallicity from ISM and IGrM ICM IGM harder Z ques. Do not have the same robust modeling I guess.

→ Vast catalogue of high quality LTE & NLTE models of all spectral types exist,

and so determining metallicity and other features is easy.

Note relative abundances are always easier than absolute abundance.

For relative to solar values (primordial solar nebular value from sun & primitive meteorite) Asplund et al (2009)

$Z_\odot = 0.0134$ Wik

High precision but there is still some debate as to accuracy

In older literature and still as a fiducial value, $Z_\odot = 0.02$

Wik $X+Y=0.979$ $\therefore Z_{cosm} = 0.0201$ (1996) or $Z_{cosmic} = 0.02$

All dwarf galaxies somewhat metal poor compared to Milky Way, M31, M33? but ~~comparable~~ overlap with MW halo stars

includes dIrr SF ← though they are star forming still they have not been efficient at producing metals over cosmic time

+ dSph quenched (and gas poor)

How poor? Pop II ish it seems

Fig 6.7 Ci-174 suggests $[Fe/H] \simeq$ [illegible]

$$[Fe/H] = \log\left(\frac{Fe/H}{[Fe/H]_\odot}\right)$$

so $Z \sim 0.1\, Z_\odot \cong 0.0013$

Reference data

$\frac{1}{3}$ factor, 2 factor

Pop I $[Fe/H] \underset{\sim}{\in} [-.5, .3]$

Pop II $[F/H] \in [-3.0, -1.0]$ Halo

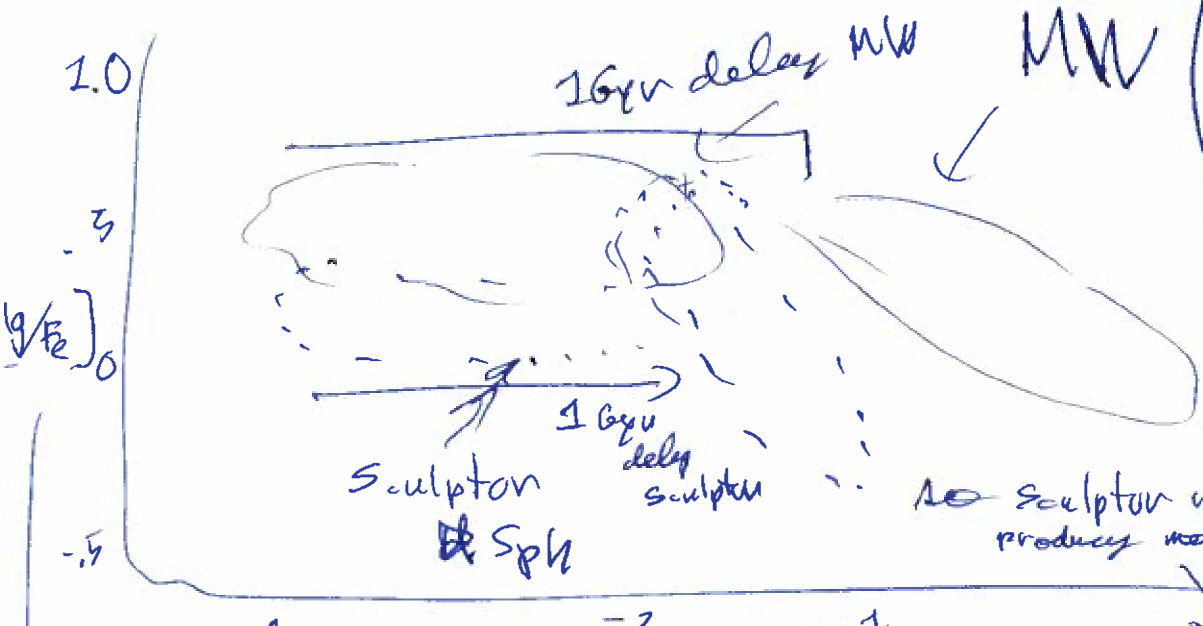
Pop II or old Pop I but metallicity saturated early. } $[-0.5, 0.5]$ Bulge

But why are these are Pop I value.

5020

dSph < mostly quenched and gas poor now

have distinct chemical pattern from Milky Way



so Sculptor was just producing metals by generation of star formation. But there star formation was still going when SNe Ia started pollution

Recall ETGs that are slow rotators are α-element enhanced because SF turned off mostly after 1 Gyr. So the SNe I ejecta did NOT go into new stars Ci-140

Mg is the fiducial α-element produced in core collapse SNe mainly ($t_{delay} \simeq 30$ Myr for CCSNe) occur at SF nearly cosmically

$J_p = 14 = N_{Al}$
He-4

While SNe Ia dilute α-elements by high Fe-56 production

delay of 1 Gyr Ci-174

6) Galaxy Clusters (Ci-174)

Recapitulate some number

$N_{gal} = 50 - \text{few } 10^3$ { groups just very poor clusters — no sharp line

$\sigma \approx 10^3$ km/s (galaxy dispersion not stars)

Regular clusters — mostly circular on sky
— spherical in 3-d space

are virialized

$M_{vir} \gtrsim 10^{14} M_\odot$

$r_{vir} \gtrsim 1$ Mpc

irregular clusters NOT
not virialized so much;

Originally cluster identified optically

But 84 — 90% DM

84% for largest clusters
which 16% baryonic

$f_{cosmic\ bary} = 0.16$ (Ci-27)

This number set by Big Bang Nucleosynthesis

6022

using CMB temperature & photon density and current cosmic abundance of H, D, He, Li

leads $\Omega_0 f_{cosm\ baryon} = 0.16$
cannot be change without some drastic revisions of BBN which are not expected – astonishing if they were needed.

(Li is not fitted so well – the cosmic lithium problem)

Missing baryon problem & outwater and inflow & outflow

Most baryonic matter is hot ICM$_{gas}$ = intracluster medium (gas)

$T \approx (2-10) \times 10^7 K$ (ci – 16E)
(radiates in X-ray band)
exponential cut off (ci – 14.2 of ff omic p. 524)

Only 1 – 5% in stars

In fact $\frac{f_{bary}}{f_{bary\ cl}} = 0.7 \rightarrow 1$
↑ smaller ↑ larger

Pakel 2014 Fig. 2 golden mass range Cons ... 20.0...

Φ_v $f_{bary} \simeq 0.10 \longrightarrow 0.16$

and in galaxies $f_{baryon} \lesssim 0.03$

and in cosmic present mostly in ~ 10% in gas.

G023

at cosmic noon
z ≈ 2, t ≈ 4 Gyr
maybe ~0.50 of mass in galaxies was gas
(ref.?)

7) Galaxies in Galaxy Clusters (G-175)

a) — optical emission mainly from stars — how identified → foreground & background galaxies excluded by redshift.

— galaxy richness

Abell rich cluster survey 1958–1989 4073 rich clusters at z ≤ .2

i) Abell richness = number of galaxies brighter than 2 mag than 3rd brightest galaxy

the brightest ~~cluster~~ galaxy BCGs are outliers in high brightness and so are not representative — maybe 2nd brightest are outliers too

G-176
~~for E~~
~~E~~

	E_s	BCGs
L_B ($L_\odot$)	10^9–10^{11}	10^{11}–10^{12}
M_B	−17 → −22	−22 – −25

So BCGs up to 10 times the brightness of ordinary brightest Es.

within Abell radius of center (often at BCG or at z cluster).
→ usually 2 Mpc (G-175)

6024)

ii) Luminosity function of cluster also well fit by Schechter function

Ci-43 $$\Phi(L)dL = \Phi^*\left(\frac{L}{L^*}\right)^{\alpha} e^{-L/L^*}\, d\left(\frac{L}{L^*}\right)$$

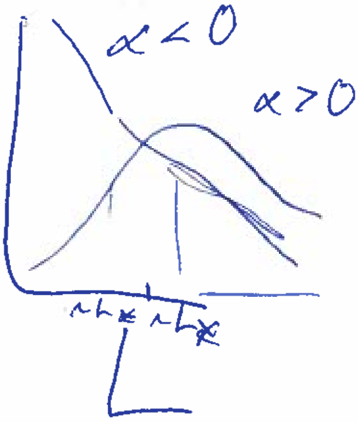
↳ L^* knee luminosity

where

Ci-44 {
$\alpha \sim -1.12$ ~~for~~ all type

$\Phi^* = 4.00 \left(\frac{10^{-3}}{\text{mag Mpc}^3}\right) \Phi$

$M^* = -21.71$
}



Richness = number of galaxies with $> 2 - L^*$

Regular	Irregular
- mostly spheroidal structure – and no substructure	— not so spherical with substructure
e.g. Coma Cluster	— not so virialized
virialized	e.g., Virgo cluster

ETG are more common in clusters than spirals

Mergers ~~than~~ ~~than leave~~ more common in spirals ~~than~~ in field or(?) groups

$F_{ETG} > F_{spiral}$

$F_{spirals\ irr} > F_{spiral\ reg}$

In field and groups ~75 spirals 20% E 5 Irr

spirals more common away from center

Not counting dwarfs

b025

and mergers of big galaxies often/usually lead to E's ~~at least~~ ~~of~~

quenching → go over golden mass ≅ 10^{12}

Dekel et al 2019 observation

and Schaye et al. 2024 simulation → p. 20 AGN quenching

(but don't use expression golden mass no one does except me — not even Dekel it seems

also ram pressure stripping ~~can remove~~ ~~and keep out hot~~ cold replaces cold gas with hot gas and quenches smaller galaxies with low self-gravity → dwarfs and smaller spirals → anemic spirals — gas poor & quenched or quenching

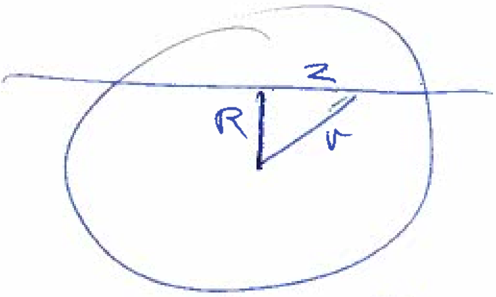
b) Surface density of galaxies (not stars)

R annulus

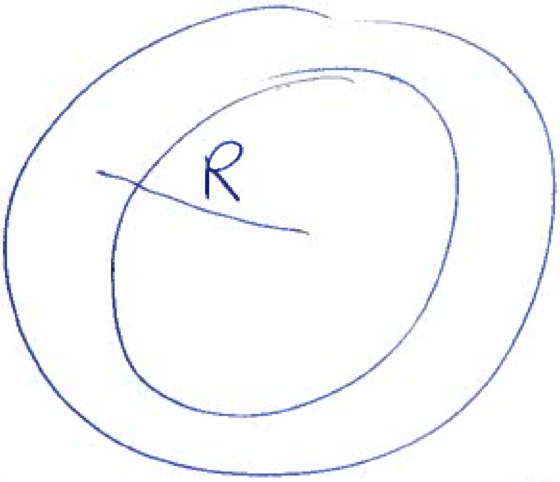
$$\Sigma_{gal}(R) = 2\int_{z=0}^{z=z_{edge}} n(z)\,dz$$

at R from center for regular galaxies

6026



side view



Face-on view

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

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

$$\Sigma_{gal}(R) = 2\int_R^{r = r_{outer} \overset{?}{=} \infty} \frac{n(r)\, r\, dr}{\sqrt{r^2 - R^2}}$$

King Profile often used

$$n_{gal} = \frac{n_{g0}}{\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{3/2}} = \begin{cases} n_{g0} & \text{for } r/r_c \ll 1 \\ \dfrac{n_{g0}}{2^{3/2}} & \text{for } \dfrac{r}{r_c} = 1 \\ \dfrac{n_{g0}}{(r/r_c)^3} & \text{for } \dfrac{r}{r_c} \gg 1 \end{cases}$$

But $n_{gal} \propto r^{-\alpha_{inner}}$ $\quad \alpha_{inner} \in [1, \frac{3}{2}]$

$\propto r^{-\alpha_{outer}}$ $\quad \alpha_{outer} \in [3, 4]$

may be a better in modern work.

6027

c) Redshift of Cluster

σ of annuli

Related but different effects. They have different formulae → Doppler shift ↓ cosmological redshift ↓

Redshifts are cumulative $\left(\frac{\lambda_4}{\lambda_1}\right)_{tot} = \left(\frac{\lambda_4}{\lambda_3}\right)_{local}\left(\frac{\lambda_3}{\lambda_2}\right)_{clus}$ (

$$(1+z)_{total} = (1+z)_{local}\,(1+z)_{cos \,\&\, cluster}\,(1+z)_{pe}$$

(C5-517

assume we corrected for

$$(1+z) = (1+z)_{cluster}(1+z)_{galaxy\ in\ clust}$$

so $$z_g = \frac{(1+z)}{(1+z)_{clus}} - 1$$

$$= \frac{1+z-1-z_{clus}}{1+z_{clus}}$$

$$z_g = \frac{z - z_{clust}}{1+z_{clust}}$$

Omit $z_{clus} = \langle z_g \rangle = \langle 1 + z_{clus} z_g + z_{clus} + z_g - 1 \rangle$

$= z_{clus}$ since $\langle z_g \rangle = 0$

you-are-you proof and $\langle z_{clus} z_g \rangle =$

Using the 1st order Doppler formula $v_{los} = c z_g \left(\frac{z - z_{clus}}{1+z_{clus}}\right)$ for local universe

$\frac{\Delta\lambda}{\lambda} = v/c$ valid for all cluster Doppler shifts

6628

Notice

$\frac{v}{c} \lesssim \frac{10^3 \text{ km/s}}{3\times 10^5 \text{ km/s}}$

$\lesssim \frac{1}{3} \times 10^{-2}$

$\left(\frac{v}{c}\right)^2 << \frac{v}{c}$

Actually cosmological redshift 1st order formula the same for in general Doppler shift and cosmological redshift formulae are different. Not the same effect though related.

The cluster dispersion (over the whole galaxy)

$$\sigma_{los} = c \sqrt{\frac{1}{(N-1)} \sum_{i=1}^{N} \frac{(z_i - z_{cl})^2}{(1+z_{cl})^2}}$$

standard correction estimate for going from variance of a sample to variance of population. (Bov-19)

~~$\sigma^2 \propto T$ of ICM~~

~~for virialized cluster~~

~~$M_{vir} \propto T^{3/2} \Rightarrow$ empirical scaling law~~ (Ci-185)

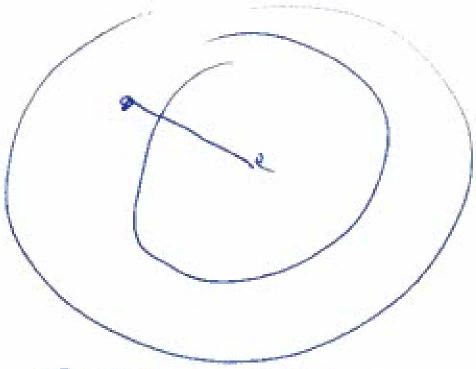
~~Estimate T from X-ray gas~~

~~then test the estimate gas mass M_g~~ (Ci-184)

~~and use to get M_{vir}?~~

But you can also do annular averages of σ_ℓ

$$\sigma_\ell(R) = \sqrt{\langle v_{\ell os}(R) - \langle v_{\ell os}(R)\rangle^2 \rangle}$$



How is center defined?

a) galaxy with v_{los} (overall)

b) BCG

c) obvious center for regular clusters

d) all of the above

d) ~~BBC~~ BCGs

BCG $\gtrsim 10^{13} M_\odot$

M_{vir} $L \approx 10^{12} L_\odot$

not fitted by the ~~Schechter~~ Schechter funct

2 two ~~nuclei~~ or more ~~often~~ surface brightness peak

→ merger probably of many galaxies

→ galactic cannibalism

→ following from dynamical friction (topic for another day)

(30)

Some BCGs
have extended
low surface brightness
~~envelope~~ halo

BCGs import Gaunt.?
Called then cD galaxies
but ~~the~~ name cD
seems ~~to~~ be becoming
~~old~~ obsolete

if not clearly with BCG
it is considered intracluster light
from stars not in galaxies

→ ≲ 10% of light from galaxies in cluster

~~in Abell~~

in regular cluster BCGs are
almost always radio galaxies
but also in irregular(?)
— other radio galaxies in
cluster.

8) The Intracluster Medium (ICM)

603

a) $T_{gas} \approx (2 \rightarrow 10) \times 10^7 K$ (CG-16

$L_X \in [10^{43}, 10^{45}]$ erg/s CG-178

10-16 % baryons

and only 1-5 % stars CG-179-180

- So most baryons are ICM

↳ primordial?

- at least somewhat metal enriched

since recombination lines in X-ray from metals. Δ → [illegible]

b) Optical selection of cluster can err due to chance alignment of galaxies

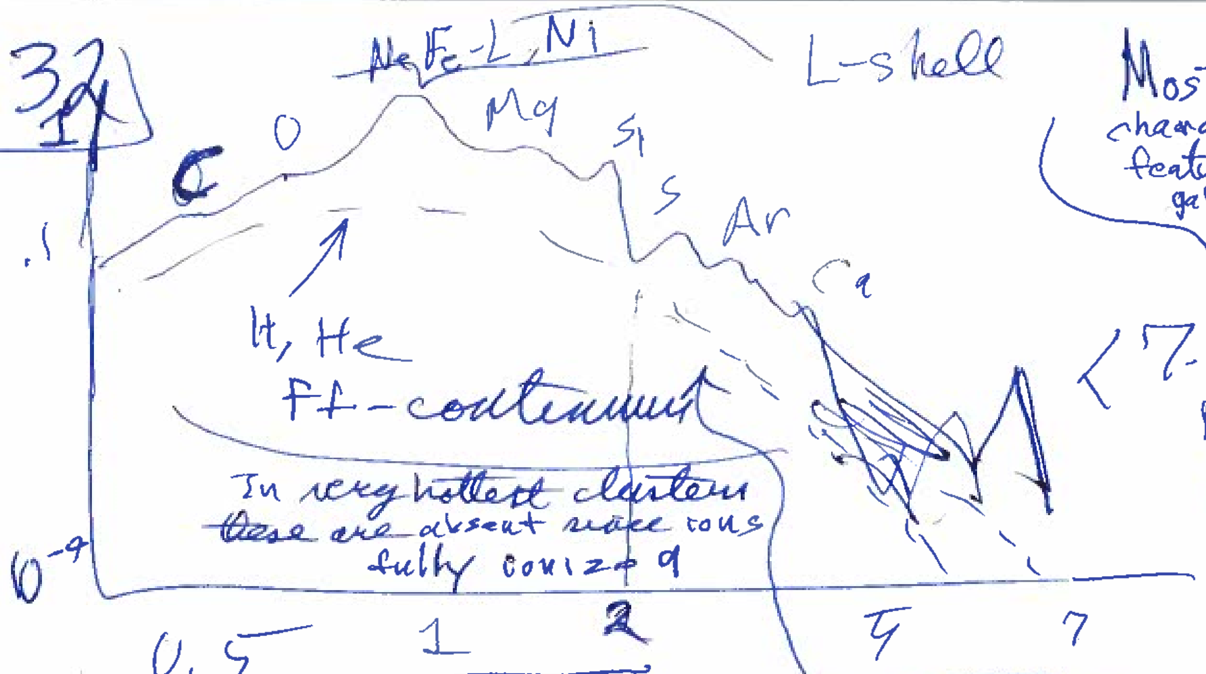
Not a cluster just alignment in optical

X-ray selection doesn't have that weakness

↳ there is a gravitational well containing hot gas.

6032 1

b) Plot Ci-179



Most characteristic feature of galaxy cluster x-ray spectra.

< 7 keV Fe line complex

soft x-ray (in thin continuum)

log E (keV)

$T = 2 \times 10^7 K$

exponential cutoff

overall exponentials are only straight on semi-log plots $e^{-E/kT}$

mixture of Fe XXV ion He-like L-shell

Fe XXVI Hyd-like K-shell

$^{56}_{26}Fe$ - 5

$H \; Ly\alpha \quad \lambda = 121.567 \text{ nm}$

$E_{Ly\alpha} = h(2.47 \times 10^{15} \text{ Hz})$

$= (4.135 \times 10^{-18} \text{ keV Hz}^{-1})(\ldots)$

$\approx 10 \times 10^{-3} \text{ keV}$

$= 10^{-2} \text{ keV}$

$He^+ \; Ly\alpha = Z^2 E = 4 \times 10^{-2} \text{ keV}$

O to N He$^+$ lines in reduced x-ray band

$X\text{-ray band } \text{tidusted} = (\ldots)(3 \times 10^{16} - 3 \times 10^{19} \text{ Hz})$

$= 15 \times 10^{-2} - 15 \times 10 \text{ keV}$

~~15×10^{-1}~~ $- 150$ keV

$= .15$

From the lines and Equivalent width abundances can be estimated

for C, N, O Ne, Mg, Si, S, Ni as well as Fe for ICM $[Fe/H] \simeq -.5$

i.e., factor of $\frac{1}{3}$ ~~below~~ of solar value (primordial solar nebula value)

$10^{.5} = 3$

$10^{-.5} = \frac{1}{3}$

The continuum emission is ff-emission, $\sim n_i n_e \left(\frac{T}{10^{7}K}\right)^{-\frac{1}{2}} e^{-\frac{h\nu}{kT}}$

(Bremstrahlung) (Ci - 524)

exponential cutoff for $\frac{h\nu_c}{kT} \gtrsim 1$

$T = \frac{h\nu_{cutoff}}{k}$ ν gives T.

So crude estimate of ~~temperature~~ as for galaxy X-ray halo is easy → estimate Not a detailed mode

$T = (2-10) \times 10^{7} K$ (Ci - 178)

$T \simeq$ [illegible] keV / 10^{-7} keV/K

~~For~~ For graph ~~about the right~~

$T \simeq 10^{7} \frac{K}{keV} \times E_{keV}$

Fig $E_{keV} \simeq 2$

$T = 2 \times 10^{7} K$

So E_{keV} cutoff gives T

and non-cool core clusters (see GI-183 plot) $T \approx 10^8$ K are very roughly isothermal.

— but cool cores can vary in T from $T \sim 3$ keV $= 3 \times 10^7$ K in core to $T \sim 7$ keV outside $= 7 \times 10^7$ K so still roughly isothermal

Soft X-ray = .5 - 2 keV for massive clusters the emissivity is close to temperature independent and electron density n_e and density n can be determined

So rough profiles in T and n_e, n are sometimes easy to obtain

9) Sunyaev-Zeldovich Effect SZE (1970) (therma) ~~1907~~

Rashid Sunyaev (1943—) → Saw give a talk in circa 1990 at Max Planck when I was postdoc-ing in Munich

$\tau_{CMB} = 0.058(6)$ (2023)

electron scattering — mostly cold electrons — so pure Thomson scattering the non-relativistic limit of Compton scattering?

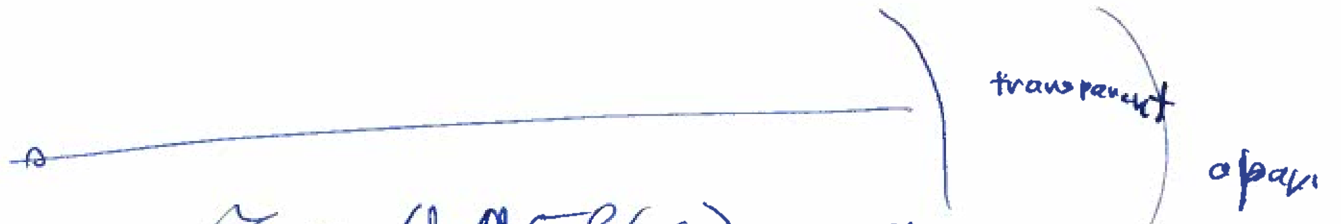
No IGM hot too.

t = 15 → 1 Gyr
z = 6 → 20
reionization t =

recombination t = 377.7 k
z = 1089.90
Planck

L6035

~~B~~Between the 2 eras the universe was very transparent since the reionization era



reion
$t = 1.5 \to 1\,Gy$
$z = 6 \to 20$

~~recombina~~ recombination
$t = 377.7\,Gy$
$z = 1089.?$

$$\tau_{cmb} = 0.058(6)$$

(Nasa based Planck)

almost ~~totally~~ all Thomson/Compton scattering off free electrons

IGM $T = 10^5 - 10^6\,K$
Ci-193 no ~~hot~~ hot much colder than clusters $T = (2-10)\times 10^7\,K$

$$I = I_o e^{-\tau} \approx I_o(1-\tau)$$

So only about 6% of photon have been scattered.

— Not negligible, but small enough ~~that~~ the original density fluctuations of early universe $t \lesssim 377.7\,kyr$ still imprinted on CMB

which an important ingredient in cosmology and large scale structure simulations.

the scattering world randomize the CMB and wash out the hot & cold spots — actually before COBE(1992) people were beginning to fear this might have happened

6036)

But there is also higher scattering in galaxy clusters, where denser concentrations of ionized gas, and it's hotter → so more scattered than IGM.

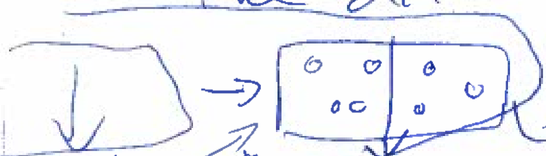
ICM ^ in $T = (2-10) \times 10^{7}$ (ci-165) ↑

(But in fact ~~[illegible]~~ only modestly (see p. 6040))

IGM

$T = 10^{5} - 10^{6}$ K (ci-193)

~~The [illegible]~~



optically thick → compact mass into clumps - now optically thin

So ~ 1%

$\tau_{clusters} = 10^{-2}$

$\tau_{CMB} = 0.058(6)$

is this included in that? Obvious question:

~~I think the answer~~ – the clusters are patchy and so on average they may contribute $\Delta\tau_{CMB} << 10^{-2}$ but Cimatti doesn't say

I infer that they don't contribute to τ_{CMB} very much

6038) is low enough there are still based on coherent scattering and the NR phase function in the electron rest frame

~~But~~ if the photon shifted into ~~the~~ electron frame has a high frequency enough then the scattering becomes relativistic and the there is a frequency shift in the electron frame and an asymmetric phase function dictated by ~~the~~ Klein-Nishina formula

See p. 6039 figure.

$$E_{photon} = h\nu = \frac{hc}{\lambda} = \frac{12398.4198\ldots\ eV}{\lambda_Å}$$

1.24... eV $\lambda_Å = 10^4$ Å NIR

12.4... keV $\lambda_Å = 1$ Å x-rays

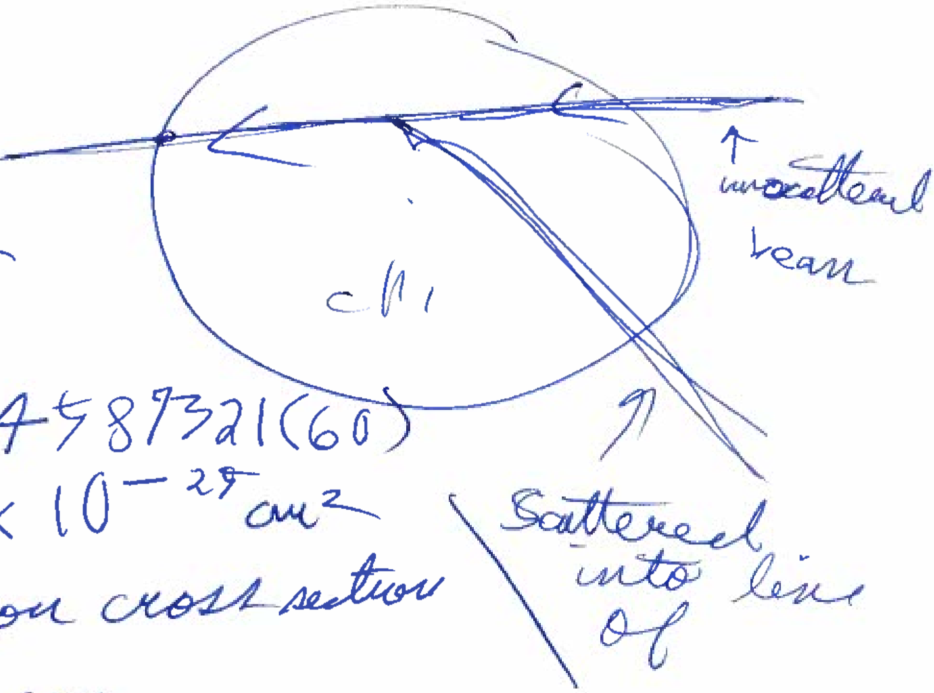
12.4... MeV $\lambda_Å = 10^{-3}$ Å γ-rays

6037

$$y = \sigma_T \int n_e(l)\, dl_{los}$$

$y \simeq 10^{-2}$

dimensionless



$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2$$

$$= 6.652458732(60) \times 10^{-25}\ \mathrm{cm}^2$$

Thomson cross section

The NR limit is electron rest frame is coherent scattering

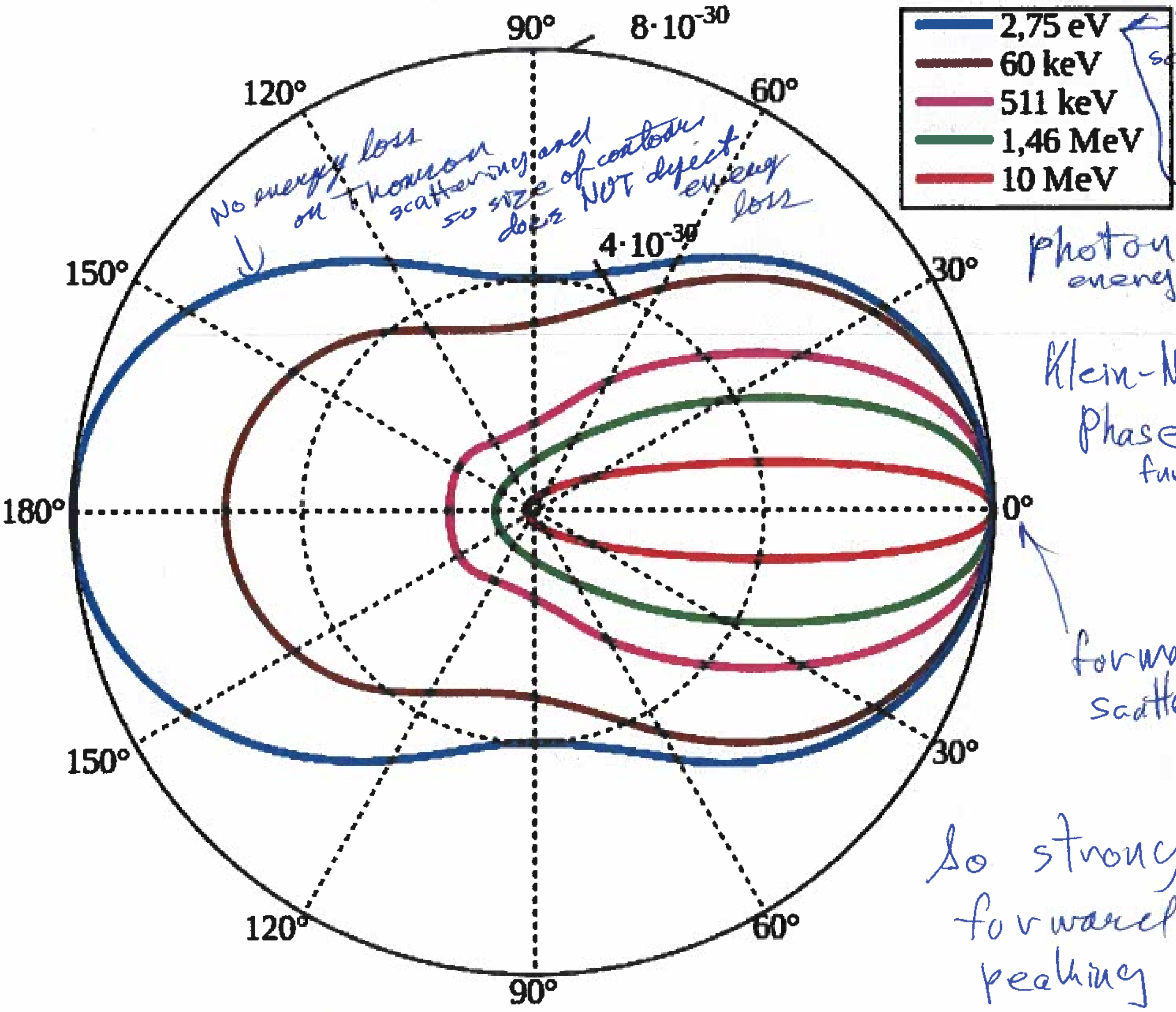
$v_{in} = v_{out}$

and the angular redistribution is a phase function $g(\Phi)_{NR} = \frac{3}{4}(1 + \cos^2\phi)$ (MB — 80)

(— and in fact cluster gas electrons are only somewhat relativistic — see p.6040)

~~In the elec~~ However ~~in NR lim~~ electrons do have thermal motion and so there is a frequency redistribution and a more elaborate angular distribution (MB — 420)

→ Doppler shifting → but if the electron temperature / velocity



But the electrons in clusters are ~~only marginally~~ only somewhat ~~not~~ relativistic in my view

$$E_e \hat{=} kT_e$$

$$f_{Rel} = \frac{kT_e}{m_e c^2} = \frac{10^{-7}\,\frac{keV}{K}\,T_e}{511\,keV}$$

$$= \frac{(T_e/10^7 K)}{511} \lesssim \frac{10}{511} = 0.02$$

What of the photon Doppler shifts?

— in the rest frame of the electron the photon increasing loses energy on scattering as it becomes relativistic $E \gtrsim$ keV X-ray like

040

Electron velocity $v_{Probable} = \sqrt{\frac{2kT}{m_e}} = c\sqrt{2}\sqrt{f_{rel}}$ (Wiki Maxwell-B. distribution)

$\simeq 3\times10^5\,km/s\,\sqrt{2}\cdot\sqrt{2\times10^{-2}}$ ~~$2\times10^5\,km/s\times10^{-2}$~~ ~~$10^4\,km/s$~~

$= 6\times10^4\,km/s$ ~~$\frac{v_{rn}}{c} \simeq \sqrt{2}\,f_{rel}$~~ ~~$\simeq .03$~~

speed parameter $\beta = \frac{6\times10^4}{3\times10^5} = 0.2$ somewhat relativistic

$\frac{\Delta\lambda}{\lambda} \simeq \frac{\Delta V}{V} \simeq \beta = 0.2$, $\beta^2 = 0.04$

first order Doppler effect only. ~~and~~ so CMB photons are still microwave band and are still scattered by Thomson scattering

It seems to me there is virtually no relativistic effect at all. ~~We~~ are in the Thomson limit for scattering

Inverse Compton effect on Compton cooling for electrons Ci-180 Ci-331

But photon shifts really small in this case — only marginally cooling I say. Not a significant process with $f_{rel} = 10^{-2}$

Some photons are scattered into line of sight with significant Doppler shift to red and blue and there is convolution of CMB Blackbody spectrum and

~~thermal~~ scattering.

The upshot is a distorted blackbody spectrum with a varying brightness temperature

$$I_{\nu\,\text{observ}} = B_\nu(T_b)$$

$$= \frac{2h\nu^3}{c^2}\frac{1}{e^x - 1}$$

where $x = \frac{h\nu}{kT_b}$

$$T_b = B_\nu^{-1}(I_{\nu\,\text{observ}})$$

$e^{x}-1 = \frac{2h\nu^3}{c^2}\frac{1}{I_\nu}$

$x = 1 + \ln\left[\frac{2h\nu^3}{c^2}\frac{1}{I_\nu}\right]$

General case

If in the Rayleigh-Jeans limit

$x << 1$ and $e^x - 1 \approx x$

Wien limit $x >> 1$

$e^x = \frac{2h\nu^3}{c^2}\frac{1}{I_\nu}$

$x = \ln\left(\frac{2h\nu^3}{c^2}\frac{1}{I_\nu}\right)$

$$B_{\nu\,R\text{-}J} = \frac{2h\nu^3}{c^2}\frac{1}{x}$$

$$= \frac{2\nu^2}{c^2}kT_b$$

low frequency limit

and $T_b = \frac{c^2}{2\nu^2 k} I_{\nu\,\text{observ}}$ (Co-505)

In the SZE case

$$I_{\nu\,\text{obser}} = \int B_\nu(T_{cmb})\, g(x)\, d$$

some sort of convolution ~~averaging over angle range and frequency~~ redistribution by electrons

with negligible relativistic effect.

averaging over angular and frequency distribution of thermal photons

6042

To Jump to the result

1st order correction formula since

$$\frac{\Delta T_b}{T_b} = \frac{\Delta I_\nu}{I_\nu}\frac{d\ln T_b}{d\ln I_\nu} = f(x)\,y$$

specific intensity $= \frac{1}{4\pi} I_\nu^{\text{surface area}}$ as Ci define it

$x = \frac{h\nu}{kT_{cmb}}$, T_b

$T_b = T_{cmb}$ (I think)

$\Delta I_\nu = B_\nu \left(\frac{d\ln B_\nu}{d\ln T}\right)_{T=CMB} f(x)\,y$

where $y = \int \frac{kT_e(\tau)}{m_e c^2}\,d\tau \propto n_e T_e$

the Compton y-factor — an overall measure of the distortion

and $f(x) = \frac{x}{\tanh(x/2)} - 4$ $= x\coth(x/2) - 4$

$\tanh(z) = \frac{e^z - e^{-z}}{e^z + e^{-z}}$ hyperbolic tangent.

If $\tau = 0$, $y = 0$ and $\Delta T_b = 0$

Solve for x_0 by iteration formula: $4 = \frac{x}{\tanh(x/2)}$

$x = 2\tanh^{-1}\left(\frac{x}{4}\right)$ not a good one

$4 = x\coth(x/2)$

$x = 2\coth^{-1}(4/x)$ not good either

$x_0 = 4\tanh(x/2)$

solution $x_0 = 3.8300160963\ldots$ to machine precision 10^{-18}

So this is a first order correction formula

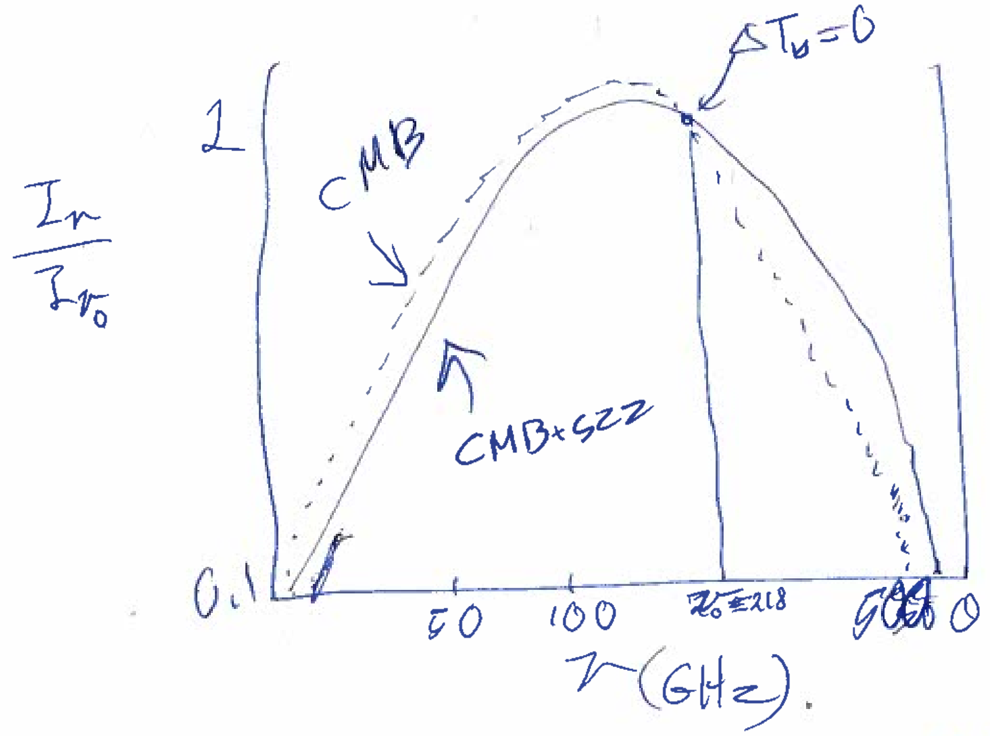
$0 = f(x) = \frac{x_0}{\tanh(x_0)} - 4$ gives $\Delta T_b = 0$ and no shift

$x_0 =$ ~~218... GHz~~ $3.830016\ldots$

$\nu_0 = 218\ldots\ldots$ Hz

Ci – #80 do not give a high precision value.

60/43



$B_\nu(T_{CMB} + \Delta T)$ CMB+SZE

same

$B_\nu(T_{CMB})$ CMB

$y = 0.05$ overall distortion

~~unrealistically large~~

$y \simeq 10^{-4}$ for largest hottest cluster

$T \approx 10 \times 10^7$ K

Ci-165

So the SZE effect requires very precise measurement to be detected and CMB very pure blackbody spectrum

— fortunately the CMB is maybe the most perfect Blackbody spectra in nature

6044

So what is SZE good for

It is possible to map over cluster ~~out~~ $\frac{\Delta T_b}{T_b}$, and so determine $n_e T_e$ (using y see p. 6043) rather precisely and so get pressure $P \propto n_e T_e$ rather precisely over the cluster.

You can also get total Mgas with some more trickery.

Gas in ICM not ISM that gives the ~~SZE~~ thermal SZE

The ICM ~~not~~ due to ~~galaxies clusters~~ (Ci-181)

Above is all thermal SZE

There is also a kinetic SZE just due to overall cluster center of mass ~~on~~ peculiar motion superimposed on the mean expansion of the universe.

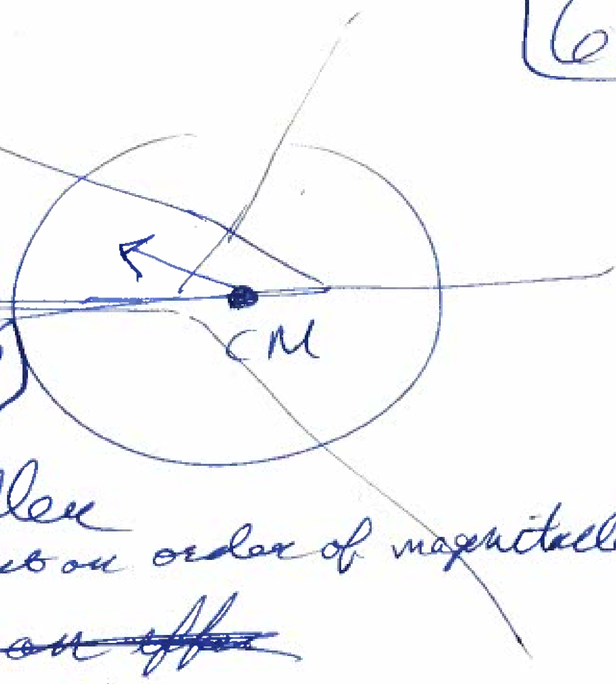
→ we usually ~~think of this as zero the~~ cluster CM defining a comoving frame but it this only approximate in general

Individual galaxy motion and macro-motions in the galaxies. Probably approximate Gaussian and so may add in quadrature to thermal Doppler. But maybe insignificant — Too small comp to IC

[6045

But ~~the~~ CM of a cluster is typically moving at $\lesssim 10^3$ km

$v_e \simeq 6 \times 10^4$ (see p. 6040)



observance so much smaller by at least one order of magnitude

and only has ~~an effect~~ noticeable effect near $\nu_0 = 218$ GHz where $\frac{\Delta T_b}{T_b} \to 0$ where the thermal SZE is small

The CM of the cluster has only one velocity, and so no averaging over range of velocities as for electrons

and so it seems still gives a shift at $\nu_0 = 218$ GHz

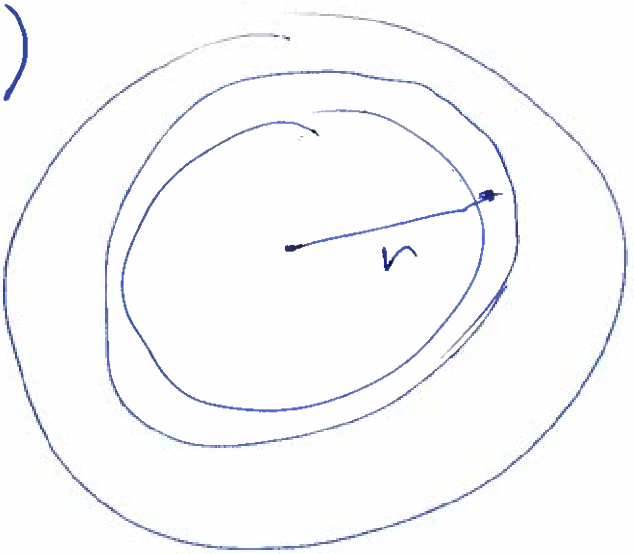
But we'd have to look up details to see both ~~how~~ thermal and overall CM motions are ~~combined~~ convolved to produce a shift in brightness temperature, Too far a digression for us.

6046

10) Density + Temperature Distribution of Clusters in the simple β-model

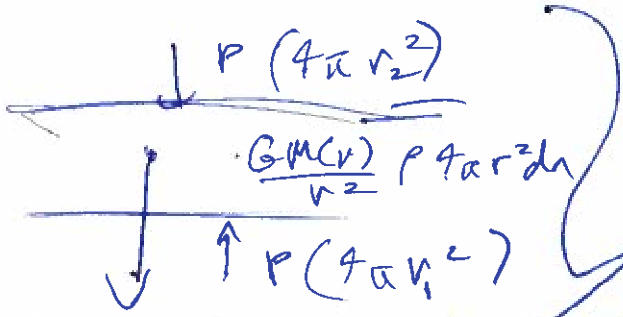
→ a reference model that does NOT capture full variety of behavior — a standard of comparison

a)



Consider a spherically symmetric distribution of ~~galaxies~~ gas or galaxies

And recall from hydrostatic the spherical pressure support equation



balance leads to

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho$$

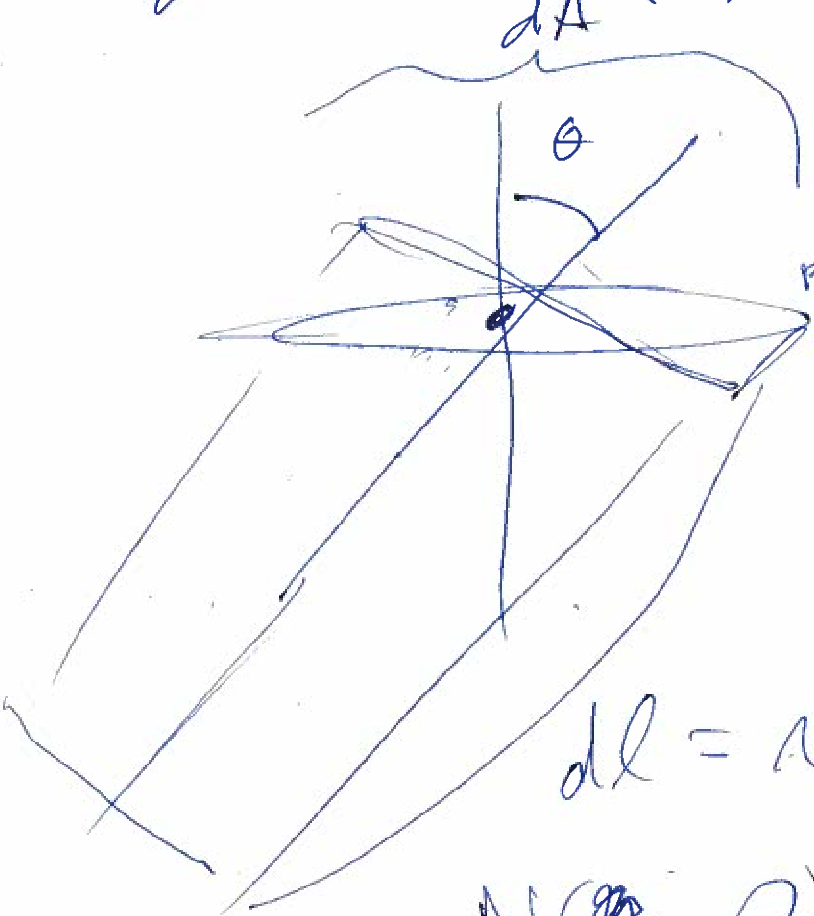
{ M(r) is interior mass — gas, galaxies, dark matter not in galaxies

But what is Pressure

For gas and galaxies

6047

b) a diquession at this point into the isotropic pressure formula, classical derivation (i.e., non-quantum mechanics)



momentum flow

$d\mathcal{R} = p\, v \cos\theta$
$\ast (dA \cos\theta)$
$\ast\, dt$
$\ast\, N(p, \Omega)$
$d\Omega \ast dp$

partial momentum

Particle momentum distribution to accommodate light

$dl = v\, dt$

$N(p, \Omega) \Rightarrow \frac{n(p)}{4\pi}$ ← density per unit volume distribution

flow in a particular direction

if isotropic $N(v, \Omega)$

Pressure is momentum flow per unit time per area

$\therefore\; dP = p\, v \cos^2\theta\, \frac{n(p)}{4\pi}\, dp\, d\Omega$

$\int \cos^2\theta\, d\Omega = 2\pi \int_{-1}^{1} u^2\, du$
$= 2\pi \left(\frac{2}{3}\right)$

6148

$n(\wp_p)\,d\wp_p = n(v)\,dv$ for NR case

$$p = \begin{cases} \frac{1}{3} \int_0^\infty \wp_p\, v\; n(\wp_p)\, d\wp_p \\ \frac{2}{3} E \\ \frac{1}{3} E \end{cases}$$

NR: $\frac{1}{2}\wp_p v = \frac{1}{2} m v^2 = KE$

Note the $n(v)$ is unspecified and could be anything. However, in thermodynamic equilibrium it is set by temperature.

$\frac{2}{3} E$ — kinetic energy density

NR limit — non-relativistic limit: $\wp_p \Rightarrow mv$, $\frac{1}{2}mv^2 \Rightarrow KE$

$\frac{1}{3} E$ — Extreme relativistic: $v \Rightarrow c$, $\wp_p = mc$, $mc^2 \Rightarrow KE$ mass energy; $\wp c = KE$ for photons $KE + E$

integrated energy density for photon

Photon gas where $P = \frac{1}{3} a T^4$, $E = a T^4$ (Wih Photon gas)

To conform to Ci-147, 182

$$P = \frac{1}{3} \int_0^\infty v^2\, m\, n(v)\, dv$$

$$P = \frac{1}{3} \rho \int v^2 f(v)\, dv$$

$P = \sum_i m_i n_i \sigma_i^2$

$= \rho\, \sigma_r^2$, $\sigma_r = \frac{1}{3}\sigma$ and so

Remarkably there is a quantum mechanics derivation which yields exactly the same result from exactly the opposite perspective.

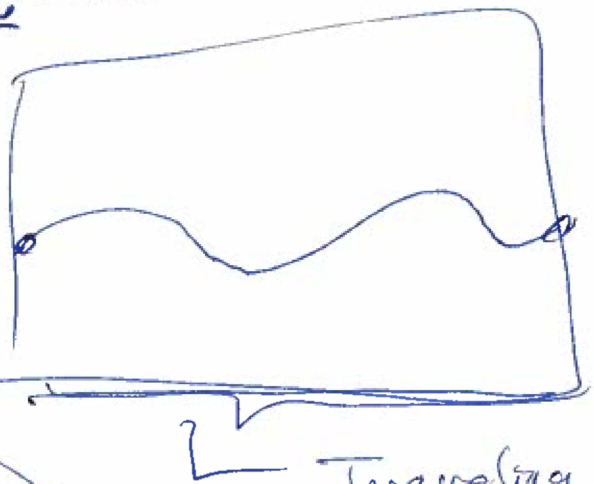
(variation of mixers)

the classical result assumes point particles or very compact wave packets

the QM derivation assumes completely de-localized wave functions

Omit unless time

Quick Derivation with lots of basic QM assume



Traveling wave $\varphi = e^{ikx}$

single particle wave functions

where $k = \frac{2\pi}{\lambda}$ wave number

for periodic BC $= \frac{2\pi n}{L}$

$n = 0, \pm 1, \pm 2, \ldots$

n vector for 3-D

$p = \hbar k = h/\lambda = \frac{2\pi\hbar}{\lambda}$

$N(n)$ contains all symmetrization and state degeneracy implicitly

$$E \propto \sum_{n} k^{\alpha} g N(n)$$

g is state degeneracy

$g = 2$ for most fermions, explicit.

$N(n)$ is the occupation of state n

in general $KE \propto k^{\alpha}$

$\kappa \propto k^{\alpha}$ { $\alpha = 2$ for NR; $\alpha = 1$ for ER (e.g. photons) }

6050) Go to the continuum limit

$$dk = \frac{2\pi}{L} dn$$

Note $k \propto \frac{1}{L} = \frac{1}{V^{1/3}}$

$dk \propto \frac{1}{L} = \frac{1}{V^{1/3}}$

$$dn = \frac{L}{2\pi} dk$$

$$d^3n = \left(\frac{L}{2\pi}\right)^3 d^3k = \frac{V}{(2\pi)^3} 4\pi k^2 dk$$

$$\therefore E \propto \int_0^\infty k^\alpha N(k) \frac{V}{(2\pi)^3} 4\pi k^2 dk$$

where $\alpha = \begin{cases} 2 & NR \\ 1 & ER \end{cases}$

$$\propto V^{-\frac{\alpha}{3}} V V^{-1} = V^{-\alpha/3}$$

Invoking thermodynamics

$$P = -\left(\frac{\partial E}{\partial V}\right)_{S,N} = \frac{\alpha}{3}\frac{E}{V} = \frac{\alpha}{3}\varepsilon$$

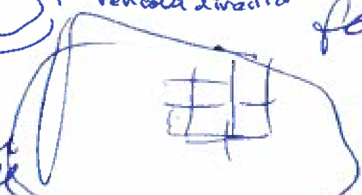
$\frac{2}{3}\varepsilon$ NR

$\frac{1}{3}\varepsilon$ ER

↑ Particles can't

Of course somehow has to prove this is a pressure — but some has

Periodic BC can be replaced by ~~zero~~ $\psi(BC) = 0$ as for infinite cubical well to some level of accuracy



← Irregular shapes can be approximated by little cubes. Low k (long wavelength) modes won't fit, but they make little contribution → More handwaving that intro QM course textbooks usually do ~~...~~ stride over tricky points — Just don't ~~mention~~ them ~~forget~~

Of course, the N(k) can be used to construct ~~fo...~~ wave packets and recover the classical picture

To conform to C; 147, 182 $P = \frac{1}{3}\int_0^\infty m v^2 \, n(v) dv$

where ~~...~~ $= \frac{1}{3}\int_0^\infty m v^2 f(v) dv = \frac{1}{3}\rho \langle v^2\rangle$

1-d or line of sight dispersion