Galactic Archaeology

Galaxy: Stellar System dominated by Dark Matter (working defn)
↳ most of mass locked in by DM with formed stars

Dark Matter

↳ 26.8% - Dark Matter
4.9% - Ordinary Matter
68.3% - Dark Energy

Over whole universe:
Dark : Ordinary ≈ 5:1

Dark Matter Halo Formation

Assembles into enormous diffuse cloud – Halo.

Scales: DM Halo ~500 kpc (10-20 × larger than MW Disk - Visible part (stars + gas).

Time: Established early (by $z \approx 1$)

Dense lumps of DM form early / Survive to $z \approx 0$.
↳ Only interacts gravitationally, no cross section.

Question in Galaxy formation / evolution:

↳ What is Dark Matter and is it cold?:

i.e. 3D Shape, radial profile DM Distribution

How did first stars form:

Metal Free Star formation, reionisation universe, Nucleosythesis sites.

How did first galaxies form?

Massive star clusters / Supermassive black holes, Seeds of SMBH?

Challenges / Difficulties

↳ Surveying vast structures devoid of baryons and light.

Evidence for Dark Matter Halo?

Mismatched Coexistance - disagreement between dynamic / stellar radial profiles.

Our View of the Milky Way: – We are within Disk:

IR Spectrum - allows probe beyond local dust.

Bulge: Centrally Concentrated quasi-Spherical - also contains a peanut-shape bar born from disc bulge stars are mostly old and metal rich. → Early formation in short time period.

Disc: Mostly thin, flat, planar distribution of stars, gas and dust.

2 components: Old (thick / Stuby) - New (thin / extended) → More Conti
(range metalicity)

Galactic Halo: any matter far away from disc plane.

(<0.1% Galaxies mass - 99% evolution information).

Does not allow Star formation - (Phasing mixing takes very long time).

A 'record' / preserved structure,

All stars in halo are accreted from mergers of external galaxies.

Reference Frames:

1) Galactic Longitude, l and latitude, b
2) Equatorial Plane

Field of Streams:

Ghost Streams are hierachical build up of galactic halos.

Stellar Streams → There are enough stars in Stellar halo at large distances to trace dark matter halo as formed through similiar accretion / phase mixing process.
↳ very dim (only observable in local Group / Milky Way)

Streams ~ 'Delineate Orbits'

Small orbital frequencies $\xrightarrow{\text{Time}}$ large orbital phase offsets

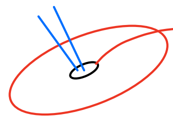
Super Massive Blackholes at Galactic Centres

SMBH accelerate particles creating jet of charged particles at near light speed.

↳ Jet narrow due to magnetic fields

Charged particles spiralling around magnetic fields

↳ emit synchrotron radiation in broad range of wavelengths.



→ SMBH jet stream have potential to do large degree damage to galaxy.

Phase Mixing – Relaxation of Galaxy Structure

During star formation, stars generated with similiar initial conditions

Initially high structure – formation / mergers

↳ Slight differ in orbital frequency → $\Delta\theta = \delta\omega \times t$ (Diff in frequency; Phase offset)

Leads to phase mixing / 'randomness'

Also responsible for tidal streams.

Differentiating Stars/Galaxies

Star → point source, delta function 'smeared by instrument'

Galaxy → Shape/Structure

} Compare flux with distance from centre

Stars in Galaxies orbit

↳ Galaxies mass is not distributed centrally as a point, as a star moves it experiences different masses

Apocentre (most distant point)

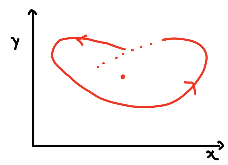
↳ 'observes/encounters' greater mass / accelerated by greater mass.

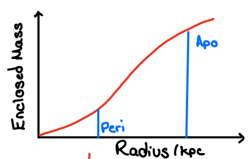
Pericenter (closest approach)

↳ 'observes/encounters' smaller mass / accelerated by greater mass.

Insufficient force to reverse / mirror trajectory.

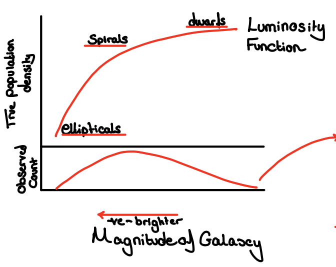
Non Keplarian orbit/motion





↳ 'Radial frequency not equal'

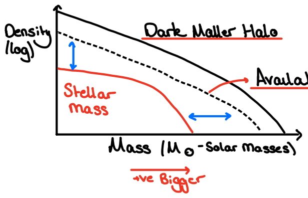
Density Distribution



→ Disagreement as 'dim galaxies' only observed for smaller neighbourhoods → Map Count/Neighbourhood size/volume

Similiar plot for stellar mass but reversed axis.

Galaxies vs Their Dark Matter Halos



→ Available Baryon Mass (~5:1 ratio DM:Baryon)

↯ Large discrepencies for High Mass vs Low Mass

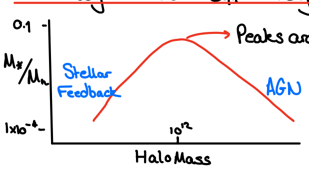
↳ Low Mass Halo – Stellar Feedback

High Mass Halo – AGN

} Supressing star formation

(produced pre collapse)

Galaxy Formation efficiency



→ Peaks around Milky Way

Decreasing Efficiency

Stellar Feedback - Low Mass Halo

↳ Small Galaxy in presence large galaxy

Induces burst of efficient star formation.

↳ large stellar winds and Supernovae (explosion young massive stars)

remove all gas - Surpressing star formation

Active Galactic Nuclei (AGN) - Large Mass Halo

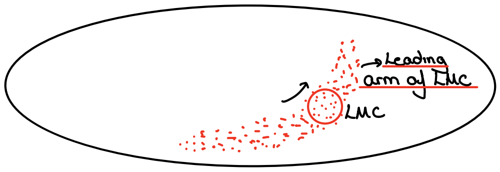
Emission from region of SMBH heats gas in galaxy

Galaxy filled with hot, ionised gas → not available for star formation

Star formation paused/completely surpressed.

Additional: Satellite Galaxies (tidal disruption)

Gravitational perturbations on orbit (analogous with stellar streams) strip galaxies of hyrogen and spread along orbit (observed by HI with radio telescope).



Stars

Chemical Enrichment of Universe

↳ Classification of stars by metallicity corrosponding to formation time.

Stars fuse elements creating higher metallicity products (nuclear fusion)

→ Supernovae release elements into interstellar medium

New stars form from enriched material → Higher Metal content. (~1.1% - Still majority H/He)

Stars Formed Early: Low Metalicity

Stars Formed Late: High Metalicity

Population III Stars (1st Gen/Primordial Stars)

First stars to form, pure H and He (No metals)

Lack of metals → Less efficient cooling → Higher gas temp

→ Greater Jeans mass → Larger/fewer gas cloud fragmentations

→ Much more massive/Short lived

Not observed directly

Population II Stars (2nd Gen)

Formed from gas enriched by Population III stars

Contains small amounts of metals

Found in Globular clusters/Galactic Halo

Population I Stars (Modern + Metal Rich)

Formed from further enriched gas

Located in disk of milky way → young star forming regions.

Stars as probes of galactic archeology

Distant Galaxies (High Redshift)

→ Directly look at galaxies from earlier universe due to fixed speed of light (dim/small)

Milky Way

→ A mixture of individual stars from different ages/origins.

Stars in disk → younger (insitu) → higher metalicities

Stars in Halo → older (acreted) → lower metalicities

Observations: Spectral absorption lines

Trace amounts of metals in stellar atmosphere absorb specific wavelengths

└→ Spectral absorption lines → Strength + number represent metalicity

Stellar Evolution

Formation of Stars:

Starting Point: Interstellar medium

Composed of a mixture of gas (of different phases) and dus

Once reaching critical density – gas begins to collapse

(often initiated by an external force such as supernovae) – Protostar

Free Fall – Gravitational Collapse

Cloud is initially optically thin – radiation escapes, no outwards force

As cloud thickens → 'optically thick'

Increase in temp → Internal pressure → Slowing rate of collapse

Protostellar Core

Density increase → Opacity increase

More trapped radiation → Temperature increase → Hydrostatic Equilibrium

Conditions sufficient for dissociation and ionisation:

$H_2 \longrightarrow 2H$ and $H \rightarrow H^+ + e^-$

As this is endothermic, absorbs energy allowing further collapse (acceleration)

Radiative core develops → Increases luminosity → Main sequence

Nuclear fusion occurs (Proton-Proton Chain)

Main Sequence Lifetime

More massive stars → Higher Mass → Higher Rate Nuclear fusion for Hydro Stat Equilib \\ Hotter More 'blue' in colour

Greater rate Fusion → Shorter Lifetime \\ Cooler - more red in colour

Death of Stars

Low Mass Stars - Red Dwarfs $(0.08 < M_0 < 0.4)$

Only sufficient mass for hydrogen fusion

Main Sequence $\xrightarrow{\text{Simple}}$ White dwarf

Intermediate Mass Stars $(0.4 < M_0 < 8)$

During main sequence → Increase in mean molecular mass/density

Hydrogen fusion begins in shells → Increase in luminosity

Red giant branches

Outer layers of stars shell undergo H fusion

Expand and cool → Increase in Luminosity, Decrease in Teff

Collapse He - Core flash

H fusion source depleted, sudden collapse

Becomes hot enough for He fusion in core

Luminosity remains constant H-shell blocks He-core radiation

Teff Increases → Asymptotic Giant Horizontal Branch

He-Shell Initiation → rapid luminosity increase:

Planetary Nebula

Outer stars expelled by shock/pulses of unstable fusion stages

White Dwarf

Inner core held up by electron degeneracy pressure

More massive Stars

Able to fuse heavier elements → C,O,Si fusion shells.

Photodisintegration

Thermal photons from fusion of Si able to endothermically break apar heavier elements

Critically weaken core decreasing int pressure

Electrons absorbed by photo disint products – no e^- degeneracy pressure

↳ Free fall collapse → Strong nuclear force rebound

Supernova

Pressure / Shock wave from rebound.

Endpoints of Stars:

White Dwarfs ($< 1.4 M_\odot$)

↳ Held from collapse by electron degeneracy pressure.

Mass increase → Radius Decrease (fixed)

Central Pressure $\boxed{P_c = \frac{3}{8\pi} \frac{GM^2}{R^4}}$

Up until Chandrasekhar Limit $\sim 1.4 M_\odot$

Neutron Star ($< 2.5 M_\odot$)

Exceeds Chandrasekhar Limit – Overcomes e^- degeneracy pressure

Stops collaps by Neutron Degeneracy Pressure / Strong nuclear force.

Magnetosphere: Strong magnetic field around neutron star accelerating charged to relativistic speeds along field lines → emit radiation / observed as radio pulse

Black Holes ($> 2.5 M_\odot$)

Nothing prevents collapse → Infinitely hot/dense Singularity

Schwarzchild Radius: $\boxed{R_s = \frac{2GM}{c^2} = 2.95 \left(\frac{M}{M_\odot}\right) \text{km}}$

(Event Horizon)

Supernovae (SN)

Catastrophic stellar explosion that marks the death of a star, releasing huge energy

Enrich universe with heavier elements + shape galaxy evolution

Produce compact remnants: eg. Neutron Stars and Blackholes

Type I Supernovae

Lack Hydrogen, H in Spectra

Type Ia (Thermonuclear Supernovae)

White dwarf (Carbon-Oxygen) in a binary system accretes mass from Companion Star: → Main Seq./Red Giant: Single Degenerate Model

Another White Dwarf: Double Degenerate Model

Mass approaches Chandrasekhar Limit ($\sim 1.4 M_\odot$) and radius decreases as determined by e^- degeneracy pressure.

Increase in Density/Pressure/Temp → Critical Core Conditions

Carbon Fusion Ignites → Runaway thermonuclear reaction

$C + O \xrightarrow{\text{Explosion}}$ Heavier elements + no remnant

↳ Largely Fe, Ni → Chemical remnants
→ Also Si, S, Ca, Mn

} Iron peak elements

Relatively constant peak Luminosity → Used as Standard Candels.

Type Ib Super Novae (Stripped Envelope Core Collapse)

Massive/Shortlived Stars → Young Star forming regions

massive Stars ($> 25 M_\odot$) have such strong stellar winds they blow away outer H layers. (Wolf-Rayet Progenitor)

Binary System, Stars loose hydrogen envelope to its Companion (Roche Lobe Overflow)

Type II Supernovae

Core Collapse Supernovae

Contain H in Spectra – Progenitor retained H envelope

Type II-P (Plataeu) ($8-25 M_\odot$)

Collapse of red Supergaint (RSG), Core Collapses as fusion stops

Core Collapse Suddenly Stops → Shockwave + neutrinos

Stars thick outer H layer → ejected at High Velocities.

Ionised H expands + cools → H recombination ($p + e^- \rightarrow H$)

Process is sustained by ~100days – Plataeu in brightness

Element Production:

α elements: O, Mg, Si, Ca Formed during nuclear fusion

Low amounts Fe-Peak elements: produced in innermost region Core / Conditions extreme – trapped in Neutron Star / blackhole

Type II-L (Linear)

Similiar to Type II-P but thinner H envelope

Linear decline in brightness – Shorter recombination phase

He-rich core that remains undergoes successive nuclear burning stages

Produces α-elements: (reactions involving ^4He)

→ O, Mg, Ne (produced pre collapse)

Reaches Fe - Fusion unstable, stops and collapses

Electron degeneracy pressure fails → Core collapses → Supernovae

No H but He spectral lines

Remnants: Neutron Star or Black Hole.

Type Ic Supernovae (Stripped Envelope Core Collapse)

Similiar to 1b loose outerlayes by Wolf-Rayet Progenitor/Stellar winds

or Roch lobe overflow/binary system but larger ($>30 M_\odot$)

Loose both H and He layers. → Carbon and Oxygen remain

Collapse due Iron core instability → Shockwave

No H or He spectral lines.

Produces α-elements: (reactions involving ^4He)

→ O, Mg, Ne, Si, S More advanced burning stages

Supernovae in Galactic Archaelogy

Core Collapse Supernovae (ie Type II) - α Element Factories

Show - Young, mass stars in star forming regions

→ Largely in galactic disk

Produce α-elements (O, Mg, Si, S, Ca, Ti)

Small no. Iron peaked elements, as trapped in remnants (Neutron Star/Black Hole)

High [α/Fe] Ratios

Type Ia Supernovae - Iron Factories

Older stellar populations - binary systems containing whitedwarfs

White dwarfs from low mass/long lived stars.

Produce Fe-peaked elements: (Fe, Ni, Co, Mn)

As no remnants thus excpelled/not trapped.

Lower [α/Fe] Ratios as increase Fe.

Age of Different Galactic Components:

Early Forming (ie in Halo) → More massive stars → Type II SNe active

→ High [α/Fe]

Late Forming → Type Ia Supernovae begun → Iron enrinching

→ Lower [α/Fe]

Celestial Coordinates

RA - Eastwards along Equator

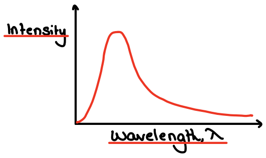
Dec - Angle with respect to Equator.

Parsec - The distance at which one Astronomical unit subtends as an angle of 1 arcsecond (1")

Colours of Stars

Near black body radiators: Colour ⟶ Tempreture

$$B_\nu(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$



Often given by B−V: brightness through red − blue filters.

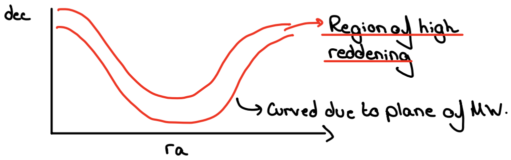
Reddening

Dust extinction: loss of light due to absorption of dust grains

Disparity in absorbtion magnitude with colour.

Blue Light - Shorter wavelength - greater absorbtion

Red Light - Longer Wavelength - Smaller absorbtion.



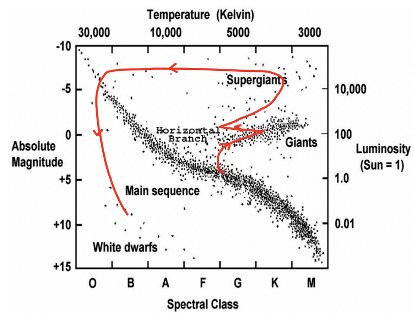
Correction: $\boxed{m_0 = m - R_m \cdot E(B-V)}$

↳ Filter Constant

Magnitude of Stars

Apparent magnitude (m): logarithmic measure of flux recieved from a celestial object at earth

$\boxed{m_1 - m_2 = -2.5\log_{10}\left(\frac{F_1}{F_2}\right)}$ F - Fluxes



Absolute Magnitude: Apparent magnitude of a celestial object if it was placed at a standard distance 10 parsecs, assuming no extinction.

$\boxed{M = m - 5\log_{10}(d) + 5}$ d - parsecs

Globular Clusters

All Stars formed at a similiar time:

Ages of Stellar Populations

Assuming all are born with same initial mass function (IMF)

Use lifetime star (larger ⟶ die faster) to work backwards

Current Mass Distribution: estimate the age of stellar population.

Chemical Spectra/Spectroscopy

Chemical Composition of Stars encoded in Stellar Spectra, in absorbtion line features.

↳ Inner Star acts a blackbody - hot stellar interior - nearly continuous spectra thermal radiation

⟶ Cooler outer layers absorb specific wavelengths - absorbtion layes

↳ Quantumn Mechanical - Atoms/Molecules have unique electronic transitions

⟶ Depth/Position of absorption lines reveal elemental abundances, ionization states and physical properties.

Viewing Chemical Spectra

Result of a combination of

⟶ black body radiation ⟶ Absorption lines ⟶ Wavelength Coverage

⟶ Instrument profile ⟶ Signal-to-noise ratio (S/N) ⟶ Spectral resolution ($R = \lambda/\Delta\lambda$)

Information gain depends on Resolution $R = \lambda/\Delta$

Sun - high S/N - $R \sim 1\times10^5$ ⟶ 67 elements

Medium Resolution - $R \sim 1\times10^4$ ⟶ 10 elements

High resolution - $R \sim 3\times10^4$ ⟶ 25 elements

Analysis of Absorption Features (1D - (Normalised) Flux vs wavelength)

→ Commonly fitted with Gaussian Profile

↳ Depth: abundances of elements

Equivelent width – width of hypothetical rectangle that has same total area as absorbtion/emission feature – where depth = continum level

Why not delta functions:

↳ QM nature would suggest a dirac delta function absorbtion feature.

Mechanisms of Broadening Features:

→ Instrumental Resolution

↳ Sharp spectral lines will broaden due to limitations of instrument (gratings/lenses)

Natural Broadening – Quantum

↳ Heisenberg Uncertainty principle – fundemental uncertainty to energy level ($\Delta E \cdot \Delta t \geq \hbar/2$)

Pressure Broadening

↳ High pressure enviroments, frequent collisions which perturb energy levels

Doppler Broadening

↳ Random motions of atoms in stellar atmosphere → some relatively blue/red shift – Gaussian broadening

Equivalent Widths to Abundances

Requires Effective Tempreture, Teff

↳ Tempreture of blackbody that emits same energy/unit area

$L = 4\pi R^2 \sigma T_{eff}^4$

Surface Gravity, Log g

↳ Measure of gravitational acceleration at stars surface

$g = \frac{GM}{R^2}$ Affects pressure and thus line broadening

Spectra Effects

Tempreture

↳ blackbody radiation shape ($\lambda_{max} \propto 1/T_{eff}$)

Ionisation State – higher degree ionisation, less spectral features as e^- no longer in discrete energy levels.

Surface Gravity

↳ Higher gravity, higher atmospheric pressure, greater line broadening

Also effects ionisation balance (promotes neutral atoms)

Metalicity

↳ Stronger metal absorbtion lines, Increase in features

(Also effect ionization equilibrium)

Stellar Velocity

↳ Systematic shift in wavelength – red/blue shift

Elemental Abundances

↳ $\boxed{\left[\frac{X}{H}\right] = \log_{10}\left[\frac{N_x}{N_H}\right] - \log_{10}\left[\frac{N_x}{N_H}\right]_\odot}$ [Fe/H] - Common benchmark

Fe - easy to measure, scales with overall metalicity

H - mostly constant

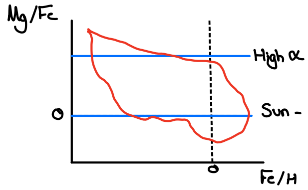
Elemental abundances given relative to iron [x/Fe] - reveals neiches in star formation history

↳ Fe produced both core collapse (SNe II) and Type 1a SNe

Mg/Fe → Traces α elements (Mg, Si, Ca, O) from SNeII - Massive Stars in early Universe

Old Stars - Lower [Fe/H] - early universe

- Higher [α/Fe] - Type II Contributed more than Type Ia



Efficients vs Inefficient Star forming Enviroments

Efficient.

High gas density - rapid formation → Massive Stars

Frequent and Strong SNe II - α-enrichment before

Fe from Type Ia can accumulate → High [α/Fe]

↳ Takes longer due to low mass → White dwarf

→ Type Ia Supernovae.

Inefficient

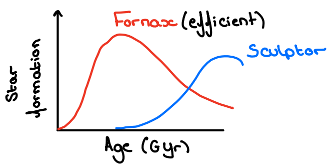
Lower gas density - Slow formation - Less massive - Less SNeII

Timescale allows contribution from Type Ia → Lower [α/Fe].

Less α elements by time Type Ia occour.

Dwarf Galaxies

↳ Relatively isolated/simple Systems.



Fornax

↳ Efficient/Early Star formation

Greater no. Type II Supernovae/Chemical enrichment occour before Type Ia begin

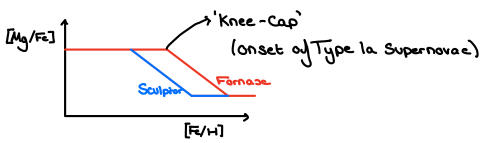
later rebalance of equilibrium (alpha knee)

Sculptor

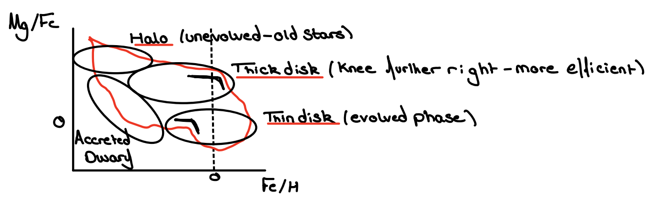
↳ Inefficient/Delayed star formation.

Less Type II supernovae/Chemical enrichment before Type Ia begin

Earlier rebalance of equilibrium (alpha knee).



The Milky Way's (Mg/Fe vs Fe/H)



Galactic Assembly History:

↳ Milky way provides tracers - Stars Streams, Globular Clusters

↳ Typical mass and morphology

Atypical: major merger ~10 Gyrs ago.

Role of globular Clusters:

Small dense regions 10^5-10^6 Stars of low mass, old stars

Observed uniformly above and below Galactic plane

Easier to Study at longer distances.

Constituent parts of Milky Way:

Stellar Disks:

↳ Composed of stars on circular orbits + coherent rotation about centre

Kinematically Cold (flattened, rotating structure)

↳ Rotationally Supported - Supported by Centrifugal forces → Alternative: Pressure Supported System (Stellar Halo)

↳ Can be studied with rotation curved

Density of Stars: $\boxed{\rho(R,z) = \rho_0 e^{-z/z_0} e^{-R/h}}$

Thin Disc: $z_{0,thin} \sim 0.3$ kpc, extends further in R

young stars

Thick Disc: $z_{0,thick} \sim 0.9$ kpc, extends less far in R

Older Stars.

Alternative: Pressure Supported System (Stellar Halo)

Rely on random motions of stars for stability

Stars do not follow a well defined rotation but randomly orientated velocities (in 3D)

↳ Characterised by velocity dispersion - σ

Theory: Analogous with a hot gas with thermal pressure

Stellar velocity dispersion ≈ pressure

↳ Jeans Equations (link mass, velocity dispersion, gravity)

Virial Theorem (equilibrium gravitationally bound system)

↳ $2K + U = 0$

Rotation Curve invalid - Studied by velocity dispersion.

Spiral Arms (Disk Galaxies)

↳ Long, thin regions stars extending from galactic centre.

Mostly young, blue stars (hot massive), Efficient star formation → Short, lived

Spiral Arm Winding Dilemma:

Galaxies - differential rotational (period)

IF: Spirals fixed star population: wind up over time → tighter, tighter spirals

↳ Spirals quickly indistinguishable. (winding timescale)

Solution: Density Wave Theory

↳ regions of higher mass concentration that move through galactic disk.

→ 'Slow moving density wave' compresses material in its path (temp increase in density)

Stars born in spirals - move away over time.

Bar and Bulge:

↳ Elongated stellar structures form due to disk instabilities (internal dynamics vs external interactions)

Not density waves - fixed composition of elongated orbit stars

Can drive density waves of spiral disk.

Dominant source of gravitational attraction.

Stellar Halo

↳ Supported by velocity dispersion (pressure supported)

Low stellar density of old/metal poor stars

Direct reflection of Assembly History

↳ mainly formed by extra galactic materials

from hierarchical accretion/merger.

Field of Streams

Halo has significant substructures

↳ dynamical evolution - Stellar streams → leading and trailing arms trace orbital path.

Long Relaxation time (well maintained kinematics reflect initial conditions)

Dark Halo

↳ Most dominant component of the Galaxy ($\sim 10^{12} M_\odot$)

Evidence

→ Non Keplerian galactic rotation curve

Stellar streams sensitive to mass distribution

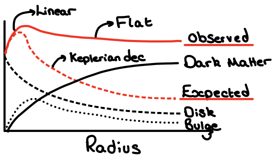
Gravitational lensing

→ Temp of X-ray gas in galaxy clusters

CMB fluctuations

Requirement for large scale structure formation and evolution.

Galactic Rotation Curve



Assuming a Spherical mass distribution:

$$\boxed{M(r) = \int 4\pi r^2 \rho(r)\, dr}$$

For an object in circular orbit ($V_z, V_R << V_\phi$)

Centripetal ≈ Gravitational

$$\frac{m V(r)^2}{r} = \frac{G M(r) m}{r^2} \longrightarrow \boxed{V_{circ}(r) = \sqrt{\frac{G M(r)}{r}}}$$

Expected Rotation Curve:

Near Galactic Centre:

Constant density $\rho(r) \sim$ const

$$M(r) = \frac{4}{3}\pi r^3 \rho \qquad \boxed{V_{circ}(r) = r\sqrt{\frac{4}{3}\pi G \rho}}$$

$V_{circ}(r) \propto r$ ⟶ Linear increase with radius near centre

* Only holds for very inner region of galaxy.

Far from the Centre

Mass treated as internal point mass.

$$M(r) \sim \text{const} \qquad \boxed{V_{circ}(r) \propto \frac{1}{\sqrt{r}}}$$

Keplerian Decline ⟶ Not obser

∴ Very different from what is observed.

Visible mass does not match observed dynamics.

Observed Rotation Curve:

$$V_{circ}(r) = \sqrt{\frac{G M(r)}{r}} \sim \text{Const} \longrightarrow \boxed{M(r) \propto r}$$

Determining density profile

Consider $\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha} \longrightarrow V_{cir}(r) = r^{1-\alpha/2}\sqrt{\frac{4\pi G \rho_0 r_0^{\alpha}}{3-\alpha}}$, with $\alpha < 3$ using $M(r) = \int_0^r 4\pi r^2 \rho(r)\, dr$

$V_{circ}(r) \sim$ const: ⟶ $\alpha = 2$: $\rho(r) \propto r^{-2}$

Overall:

At Small galactic radius : Baryonic/Stellar Matter

At Large galactic radius: Dark matter dominates.

Dark matter

Non-Collisional, Non-Interacting EM/Strong Force.

↳ No pressure, friction, discipation of energy.

Virial Theorem:

Derivation:

Moment of Inertia of System: $\boxed{I = \sum_i^N m_i x_i \cdot x_i = \sum_i^N m_i x_i^2}$

Kinetic Energy, K $K = \sum_i^N \frac{1}{2} m_i \dot{x}_i^2$

1st Derivative: $\boxed{\dot{I} = 2\sum_i^N m_i x_i \dot{x}_i}$

Potential Energy, U $U = \sum m_i \ddot{x}_i \cdot x_i$

2nd Derivative: $\boxed{\ddot{I} = 2\sum_i^N m_i x_i \cdot \ddot{x}_i + 2\sum_i^N m_i \dot{x}^2}$

$\ddot{I} = 2\langle U \rangle + 4\langle T \rangle$

↳ For a system at dynamical moment of inertia

↳ $\langle I \rangle \sim$ const, $\langle \ddot{I} \rangle = 0$.

Virial Theorem: $\boxed{2\langle T \rangle + \langle U \rangle = 0}$

Use Cases:

Systems of Stars at Steady equilibrium State

↳ macroscopic properties constant wrt time

Elliptical Galaxies, Globular Clusters. (evolved)

Not valid for: Merging galaxies, Star Clusters (newly formed).

Structural Views.

↳ Spatial distribution

Current Kinematics.

More 'dynamic' Perspective.

↳ Orbital Parameters. (energy, eccentricity, inclination).

Action angle variables.

↳ Angle variables (θ): Position of object along its orbit for given t. (0-2π) → Should I not add these as my parameters in GMM.

↳ Affected by Phase mixing.

Action Variables (J): Shape and type of the orbit (integrals of motion)

↳ Constants of motion for closed, periodic orbits.

Radial Action, J_R:

↳ How far a star moves wrt galactic centre (radial oscillations).

Azimuthal Action, J_ϕ

↳ Angular momentum, L_z around galactic center. (motion in orbital plane)

Verticle Action, J_θ

↳ Measures motion above and below galactic plane (J_z)

Adiabatic Invariance.

↳ Action Variables remain constant wrt evolution of galaxy. Look into this a little more.

Some what uneffected by phase mixing.

Dynamical Features

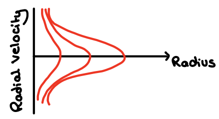
Stellar Orbit:

↳ Hamiltonian Mechanics:

Describe state of system using canonical coordinates- (position, q, momentum, p) - Phase Space

Hamiltonian: $H(p,q) = T + V = \frac{p^2}{2m} + V(q)$ Total Energy: Kinetic + Potential

Time Evolution: $\frac{dq}{dt} = \frac{dH}{dp}$, $\frac{dp}{dt} = -\frac{dH}{dq}$



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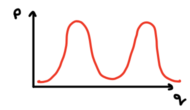


Orbital parameters

Energy (Total): $E_{tot} < 0$: bound

$E_{tot} > 0$: unbound

Angular Momentum: Cross product position and momentum

$L = r \times p$

Eccentricity: How much the orbit deviates from a perfect circle:

$\boxed{e = \frac{r_{max} - r_{min}}{r_{max} + r_{min}}}$ 0 (circ) ⟶ 1 (elliptic)

Inclination: tilt of an orbital plane from the reference (galactic) plane

$\boxed{i = \arccos \frac{L_z}{|L|}}$ 0°: Prograde

180°: retrograde- Spinning in opposite direction.

Can view milky way as a collection of 'orbits'

Stellar Streams

Consider satellite system containing stars within its own gravitational potential, Φ_s - orbiting host galaxies gravitational potential, Φ_h : Individual Stars $\Phi = \Phi_h + \Phi_s$.

Effective Potential: $\boxed{\Phi_{eff}(x) = \Phi(x) - \frac{1}{2}|\Omega \times x|^2}$ ⟶ Lagrangian (saddle) Points: $\frac{\partial \Phi_{eff}}{\partial x} = 0$

Tidal Radius: (gravitational boundary of satellite system)

$\boxed{R_t \approx R_0 \left(\frac{M_s}{3M_h}\right)^{1/3}}$

↳ Stars outside radius no longer bound to home.

Evolve across the orbits: R_0 and M_h

Two lagrangian points are main exit points.

Stellar Streams orbit not only incodes information on two features but also perterbing/modifying encounters - i.e. LMC.

Chemo-Dynamical View

Chemical

↳ Chemical abundances of a star reflect its formation enviroment.

each element traces different nucleosythesis

Comparable age and chemical composition ⟶ Common / Similiar origin

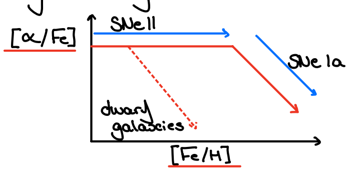
Depend on: main ISM polluter (Ia SNE vs II SNE)

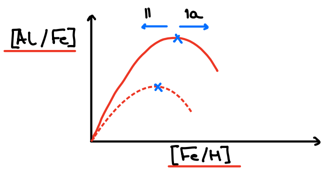
↳ Depend on:

↳ Delay time in star formation / Self-enriching rate

Depend on:

↳ Mass of host galaxy





Merger Event: GS/E.

Chemo-dynamical dichotomy in Halo

Metal Poor Halo.

more isotropic (sum earlier smaller accrettions)

Velocity Anisotropy, β ⟶

Sharp transition at nearly isotropic to extremely radial.

Metal Rich Halo

Extended J_R and J_ϕ - radial anisotropy.

Radial infall of massive satellite.

MW Halo population

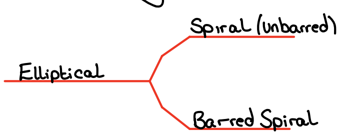
↳ Show distinct alpha abundance trends from other galaxies (halo's α-knee)

Galaxies in the Local Universe:

Galaxy Formation and Evolution:

Galaxies: Systems of billions of stars, gas, dust and dark matter halo bound by gravity

Hubble Tuning Fork (not an evolutionary sequence)



Early Type Galaxies: Ellipticals (+ lenticulars) - Redder

Late Type Galaxies: Spirals (Barred + Unbarred). - Bluer

Early Type Galaxies (Elliptical)

↳ Older Population - Redder in Colour

Little current star formation

No dust present

Pressure Supported System

Light Distribution:

Vaucouleurs $r^{1/4}$ law (Sersic Index, $n = 4$)

Later Type Galaxies (Spiral)

↳ Younger Population - Bluer in Colour

Currently undergoing star formation.

Dust present.

Rotationally Supported System.

Light Distribution

Exponential (Sersic Index, $n = 4$)

Sèrsic Profile: $\boxed{I(R) = I_e \exp\left\{-b_n\left(\left(\frac{R}{R_e}\right)^{1/n} - 1\right)\right\}}$ n - Sersic index

Formation of Early Type Galaxies

Theories

1) Monolithic Collapse: ETGs form from a Collapse of Single giant gas Cloud
2) Spiral Mergers: ETGs result from merger of 2 Spirals
3) * Hierarchical Assemble: (gradual gas accretion and multiple mergers).
   ↳ Phase 1) in Situ Star formation
   Phase 2) Growth in mass and Size by minor mergers.

Formation of Late type Galaxies:

Smoother history than ETGs

Growth through accretion of cold intergalactic ga

Galactic Environments:

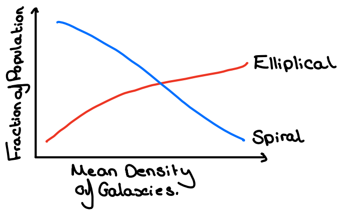
Galaxy properties depend on the enviroment

↳ Spirals dominate the field.

↓

Ellipticals dominate in clusters

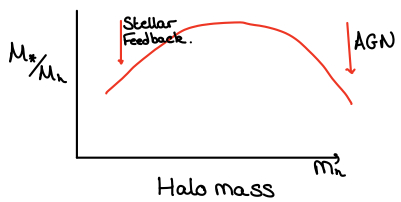
{ Decrease in Star formation rate in denser environments - 'Quenching'



Quenching Star Formation

Previously: Internal (Mass) Quenching

Stellar Formation Efficiency



Enviromental Quenching

↳ Ram Pressure Stripping

As galaxy moves through a dense intracluster medium, pressure excerted by hot gas strips away its own cold gas.-not gravitational (jelly fish Structure)

Galaxy Harrasment

High Speed encounters between galaxies in a Cluster cause repeated gravitational perturbations - leading to gas Loss

Starvation

Upon entry to cluster enviroment, Supply of fresh gas from cosmic webb is cut off.

Interaction with Cluster potential

Infalling galaxies acted on by Clusters potential, altering internal dynamics.
May lead to gas compression triggering short burst of Star formation and thus gas depletion

Seculuar Evolution

Slow/gradual internal evolution of galaxies driven by internal processes (other than external mergers and enviromental effects).

Ie Redistribution of angular momentum.

Galaxy Mergers (more detail)

Tidal Features: Stars and gas Stripped from their galaxies due to gravitational forces.

- Tidal tails: from major mergers ~2Gyr
- Streams: from minor mergers ~2-3Gyr
- Shells: Intermediate mass radial mergers

Short lived:

Tidal features rapidly phase mix after a few Gyrs

Isolated: Become part of extended Stellar halo

In Clusters: Mix into faint / diffuse component not tidally bound to given galaxy: Intercluster Light (ICL)

Show an insight to:

Late assembley history of galaxies. (recent)