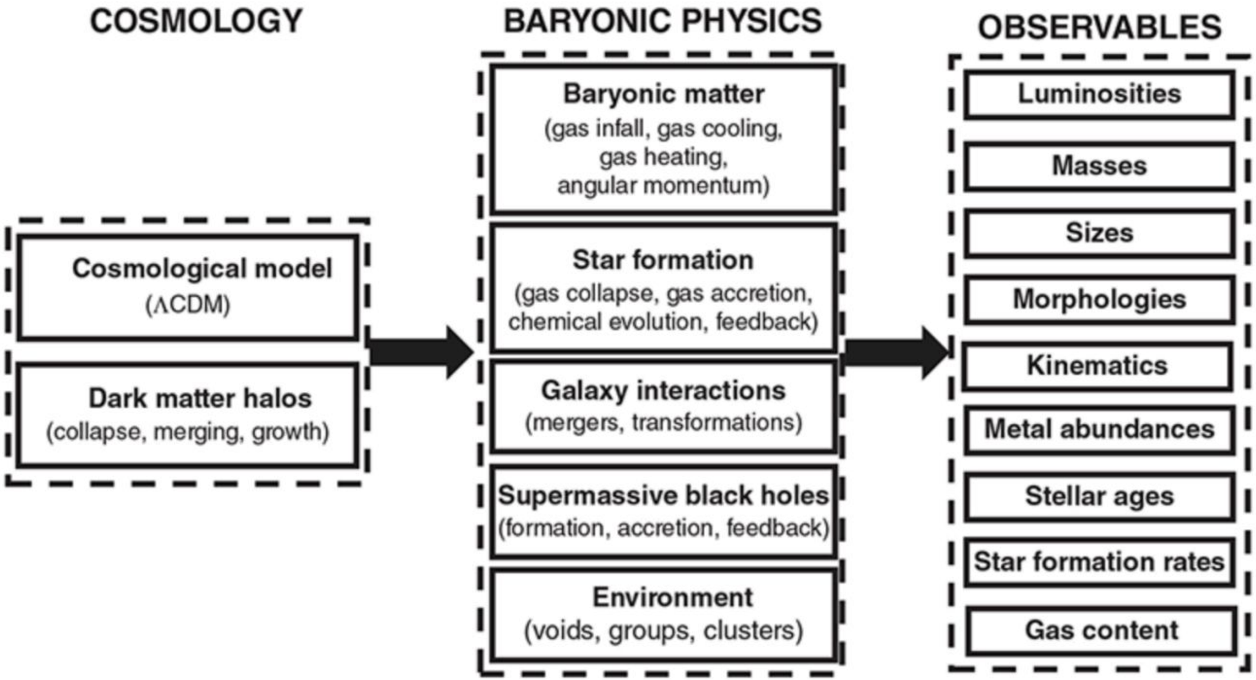
Galaxies Lec 1

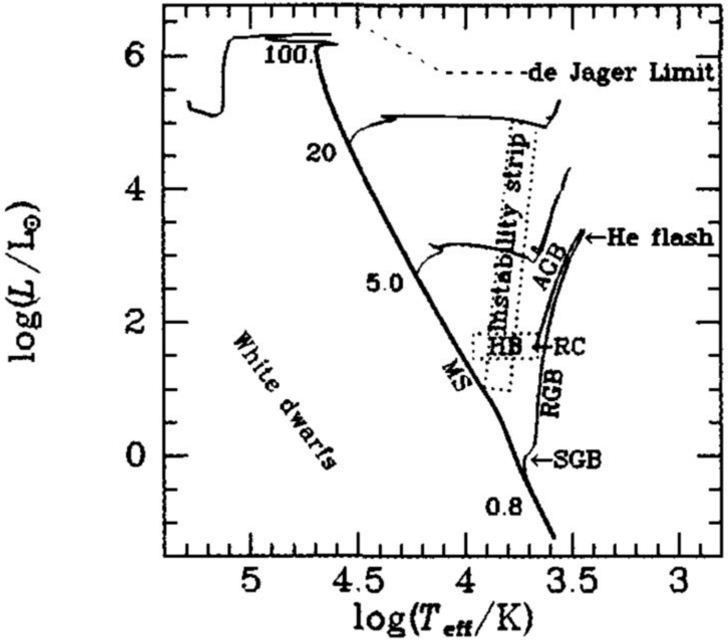
Mapping the Milky Way



This is how we study galaxies, we have foundational models of how the universe is built up, then using the physics of various "microscopic" components and predict various observables to which we then check with reality.

$$m - M = 5 \log d - 5 + A.$$

Equation for the distance modulus: m = apparent magnitude, M = absolute magnitude, d = distance and A is the dust correction for extinction



Main sequence (MS): H burning in core

Subgiant branch: transition between main sequence and red giant branch.

Red Giant Branch (RGB): H burning in shell around inert He core

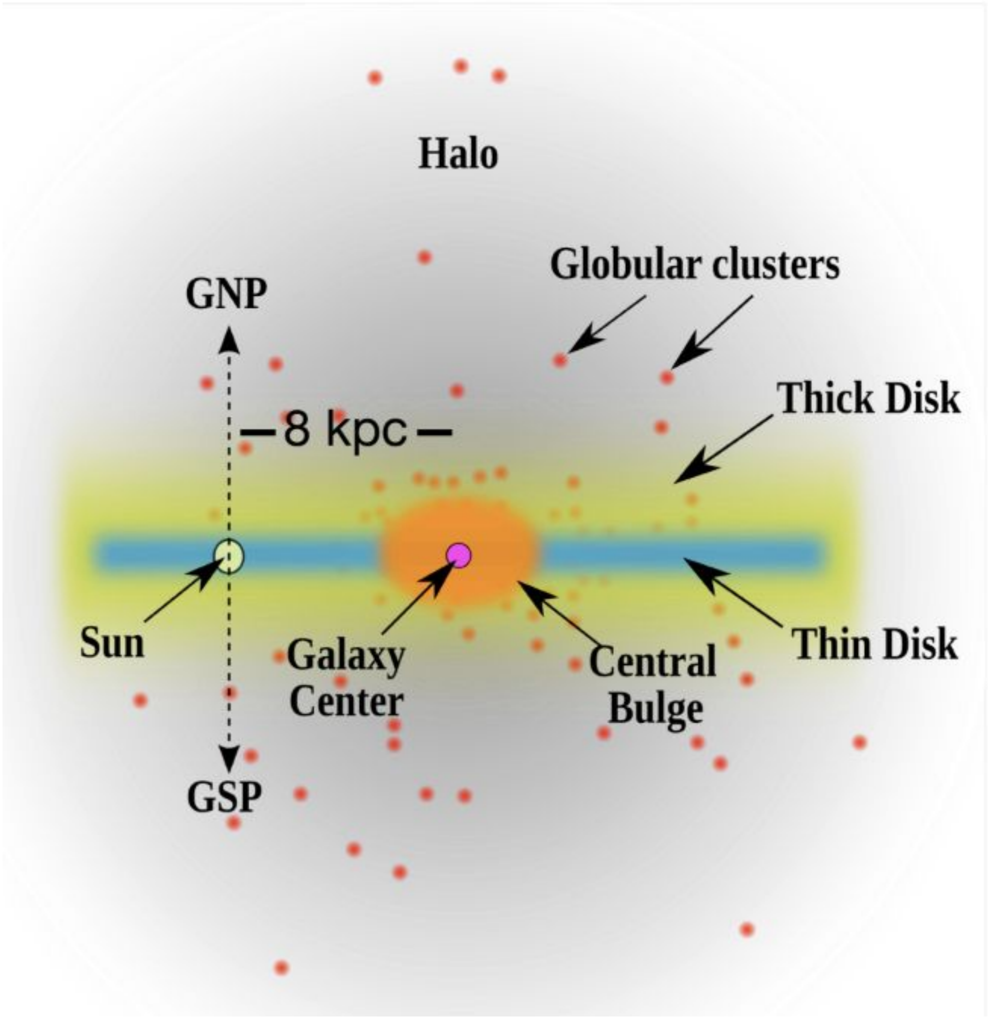
Horizontal Branch (HB): core He burning

Red Clump: core He burning stars with large convective envelopes, formed by more metal-rich stars.

Asymptotic Giant Branch (AGB): He burning around inert C/O core

White dwarfs: stellar remnants of low-to-intermediate mass stars, cooling electron-degenerate stars.

The smallest constituents of galaxies are stellar populations. Galaxies are made of multiple SSP (simple stellar pop) born at the same time and also of the same metallicity.



The simple anatomy of the MW

- Halo
- Disk
  - Thick
  - Thin
- Bulge / Bar
- Globular cluster

We will discuss and define each individual components

Getting Luminosity Function

$$dN = \Phi(M, \mathbf{x})\, dM\, d^3\mathbf{x}.$$

luminosity function at position **x**.

d ~ 1 pc / p(arcsec)

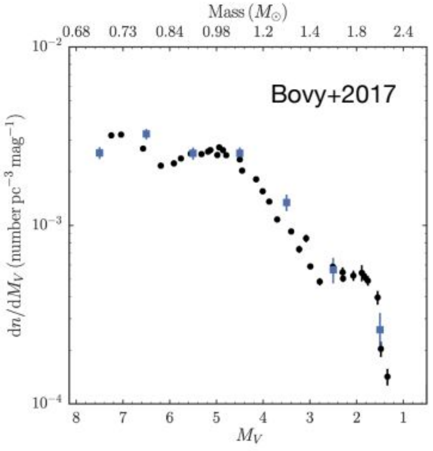
2) Get distance by parallax

1) We start by trying to get the LUMINOSITY function But this requires distance measurements…

2) Get distance by photometric parallax - > CMD and look for their color relative to solar and map that to luminosity and then get distance by measuring flux

1. Identify sample of stars
    - apparent magnitude limited sample with some m_{lim}
    - volume-limited sample in solar neighborhood (i.e. all stars in 100 pc)
2. Compute absolute magnitudes
    - use parallax distances with dust corrections.
3. Bin stars by M_V and compute number density in each bin.
    - compute volume relevant to each M_V bin.
4. Correct for selection effects.

Malmquist Bias: in a magnitude-limited survey, luminous stars will be visible over larger volumes than intrinsically fainter stars, and hence will be over-represented by number.



Classic work by Reid & Gilmore (1982)

- Photometric survey toward the south galactic pole (SGP) with i_{lim} ~ 17.0
- Pushed to M_V=+19
- Distances and absolute magnitudes determined from **photometric parallax****
- Results show luminous stars far more rare than (intrinsically) fainter stars.
- Modern methods now delivering stellar luminosity functions using Gaia parallaxes, with broadly similar results.

What do we notice about the **luminosity function**?

1) Most stars in solar neighborhood are intrinsically faint.

2) Essentially all light emitted by intrinsically luminous stars

3) Most stellar mass density in solar neighborhood contributed by low luminosity stars.

(4) Average (stellar) mass to light ratio $\Upsilon \sim 0.67\ M_\odot/L_\odot$

Getting Initial Mass Function

Getting IMF

Step 1: Measure the total stellar luminosity

  This can be done with parallax or photometric parallax

  Do volume limited sample instead of magnitude limited

Step 2: determine the initial luminosity function with some assumed constant star formation?

Step 3: Convert luminosity to a mass through a luminosity mass relation for main sequence.

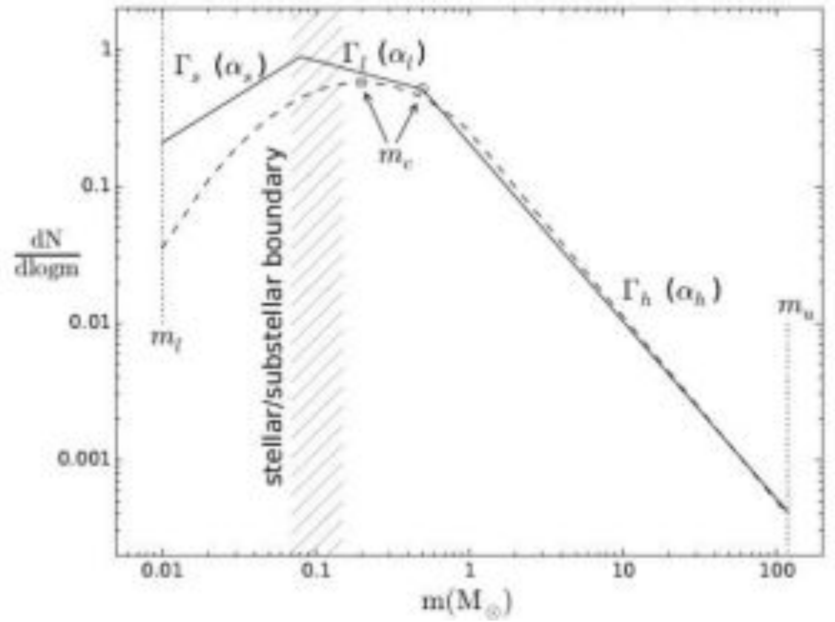
Can the IMF be assumed as universal?

No, can very in elliptical galaxies and star clusters

Bulge has top heavy

$$\xi(\mathcal{M}) \propto \mathcal{M}^{-2.35} \quad \text{(Salpeter IMF).}$$

Salpeter IMF scales down with M^-2



Stellar Populations

Observables:

1. Density / spatial distribution
2. Kinematics
3. Metallicity/chemistry
4. Age

open clusters: most stars have ages $\lesssim$300 Myr, situated near the plane of the disk.

globular clusters: most very old ($\gtrsim$10 Gyr), high above midplane in stellar halo.

SSP can be applied to:

Feature	Open Cluster	Globular Cluster
Shape	Irregular, loose	Spherical, dense
Star Count	Hundreds to thousands	Thousands to millions
Age	Young (Millions of years)	Ancient (Billions of years)
Location	Galactic Disk (Spiral Arms)	Galactic Halo
Binding	**Weak (disperse over time)**	**Strong (survive indefinitely)**
Metallicity	High (Metal-rich)	Low (Metal-poor)

Finding age of star cluster

How to determine the age of a star cluster?

1. Plot CMD of cluster

2. Fit theoretical isochrones

3. Solve for age of star cluster.

→Inform assembly history of Milky Way!

Isochrones: curve of stars of the same age but different masses to produce an isochrone, astronomers first run stellar evolution simulations (like MESA) to generate tracks that calculate how individual stars of varying masses evolve over time.

Find Main sequence turnoff points

Chemical Abundance of Stars in the Milky Way

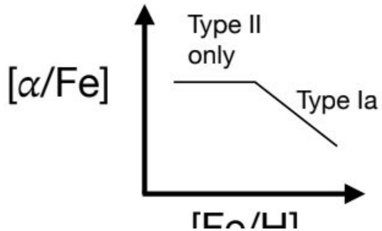
Elemental abundance ratios provide additional insight into the age/star formation history of a galaxy:

α**-elements** (O, Ne, Mg, Si, S, …) are mostly produced by core-collapse supernovae (**Type II**).

Fe-peak elements (i.e., Fe, Ni, Ma) mostly released in **Type Ia SN.**

Recall that Type II SN come from massive, short-lived stars and Type Ia SN come from binary evolution of lower mass stars, hence have a time delay (10^7-10^8 yr) with respect to the initial star formation.

The α/Fe ratio is sensitive to past star formation!



Expected abundance pattern for self-enriching stellar population (i.e. Milky Way disk)

- Older stars (low [Fe/H]) have large [α/Fe]
- Younger stars (higher [Fe/H]) have smaller [α/Fe]

Thick/Thin Disk

Vertical Distribution of stars.

Described by two separate power laws

Indicates two types of disks potentially?

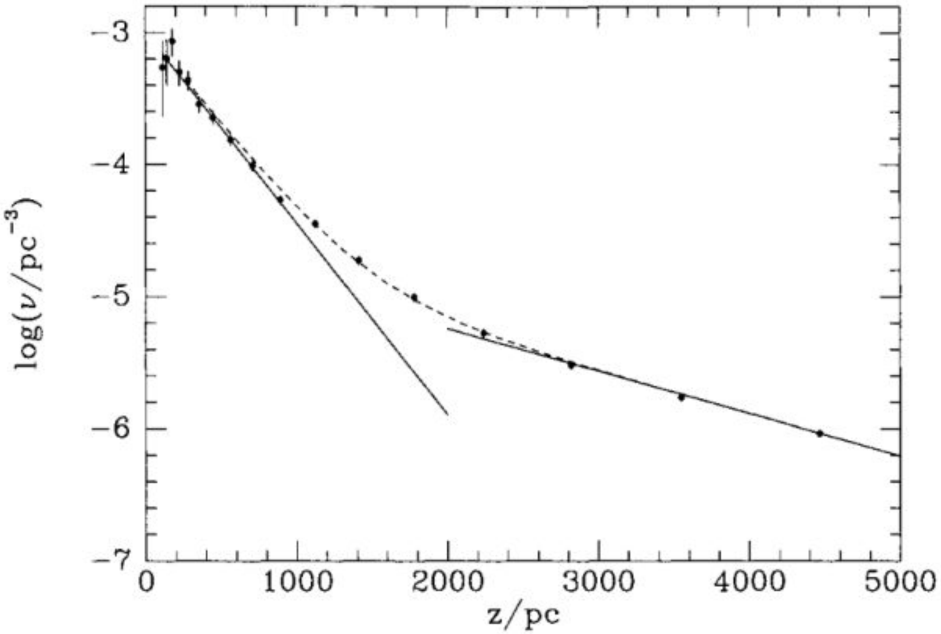


Figure 10.25 The space density as a function of distance z from the plane of MS stars with absolute magnitudes $4 \le M_V \le 5$. The full lines are exponentials with scale heights $z_0 = 300$ pc (at left) and $z_0 = 1350$ pc (at right). The dashed curve shows the sum of these two exponentials. [From data published in Gilmore & Reid (1983)]

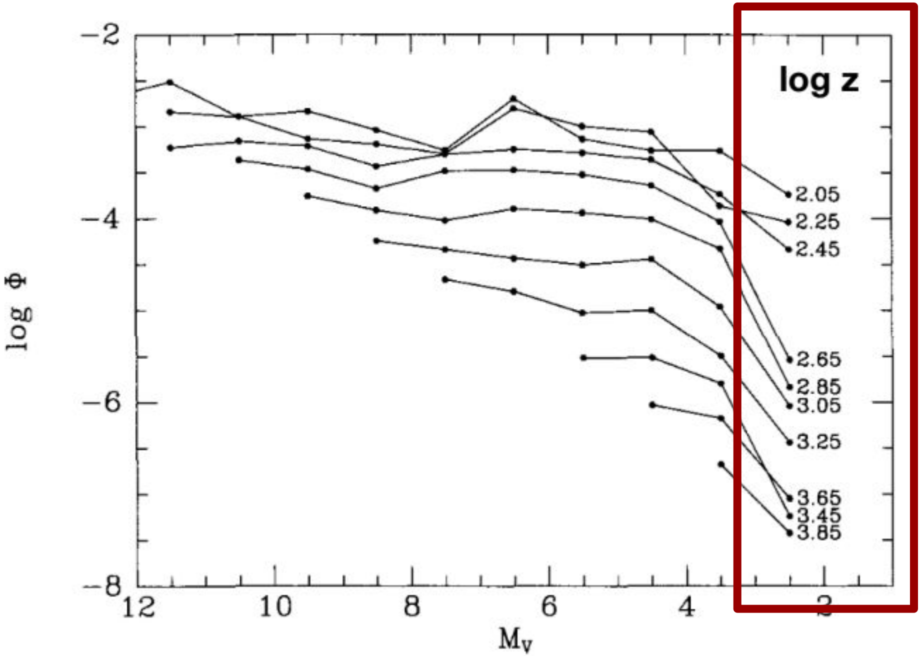


Figure 10.24 Each curve shows the luminosity function that was determined by Gilmore & Reid (1983) for the distance in parsecs from the plane whose logarithm is given at the right-hand end of the curve. Notice that the three uppermost curves fall less steeply to the right of $M_V \simeq 3.5$ than do the lower curves.

Luminosity dependence!

We see that there is a sharper drop in the luminosity meaning that those stars are likely older as we get further

Think disk => older?

Box area is younger stars

Age and Velo dispersion

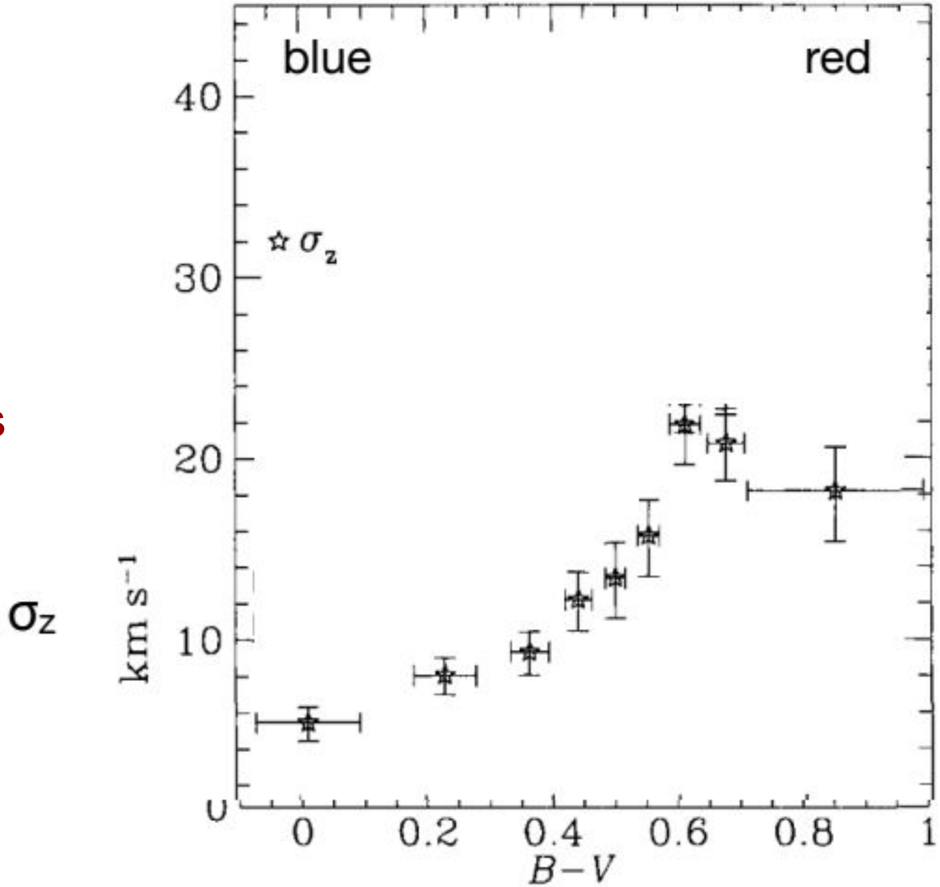
We see that stars that are redder have more velocity dispersion

1) scattering of disk stars against gas clouds

2) heating by transient spiral arms (rapidly varying gravitational potential)

3) mergers with smaller galaxies ("minor mergers")

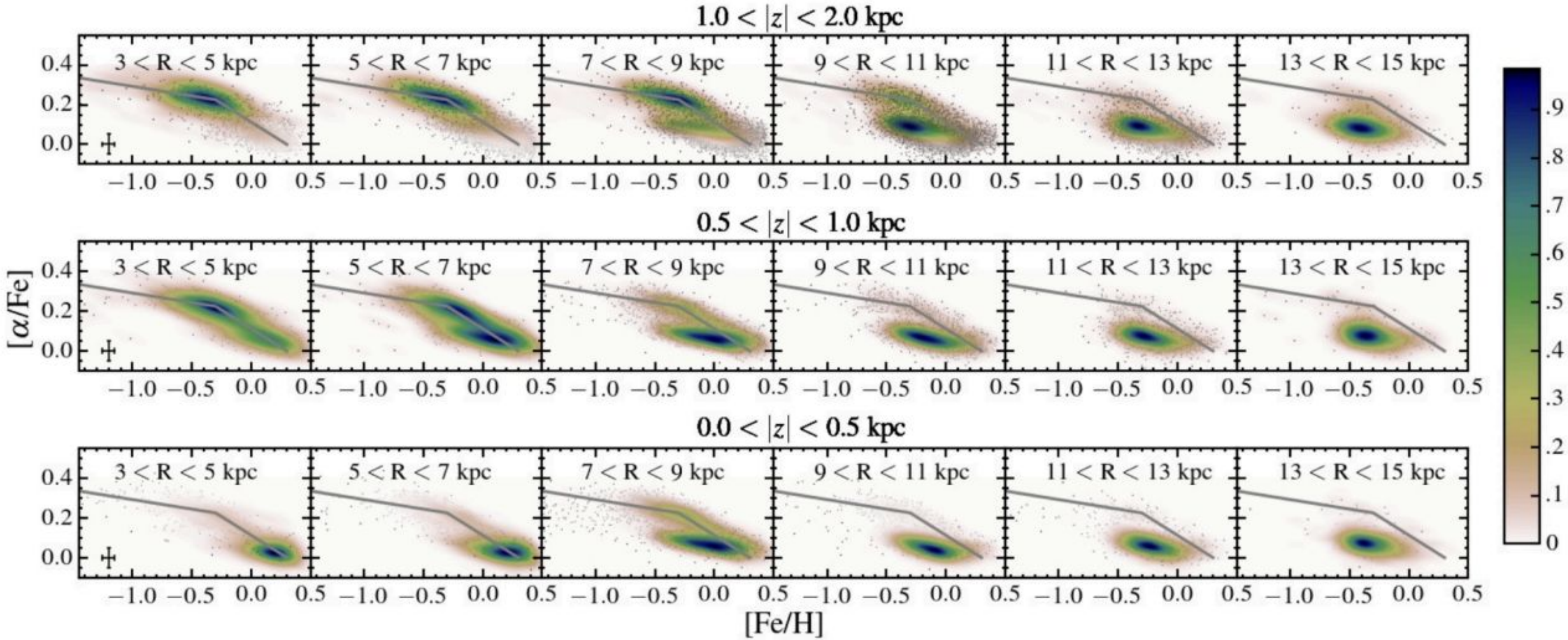
Dehnen & Binney 1998



Chemical Differences

Furthest

Closest



Furthest away have clear Higher sequence -> BURSTY

If the larger [α/Fe] sequence is associated with **thick disk**, we should see variations in the abundances with vertical height. Is that apparent?

Yes! The higher [α/Fe] sequence is more common at large vertical heights, where the thick d dominates — indicates thick disk formed bulk of its stars early before Type Ia enrichment.

Now commonplace to identify thick disk stars by large [α/Fe] ratios, a process called **chemical tagging.**

- Current measurements indicate that the thick disk has a smaller scale length than the thin disk
    - R_0^t=4.2 kpc (thin)
    - R_0^T=2.7 kpc (thick)
    - recall radial density distribution follows exponential profile ($\rho \propto \exp(-R/R_0)$), characterized by scale length R_0
- Density profiles can be integrated to get the total stellar mass in both components
    - $M_\bigstar \sim 4 \times 10^{10}\, M_\odot$ (thin)
    - $M_\bigstar \sim 5 \times 10^{9}\, M_\odot$ (thick)
    - thin disk dominates stellar mass (~85% total mass in disk)

What is the origin of the thick disk?

1. Stars formed in thin disk and heated vertically by mergers with other galaxies (>10 Gyr ago, similar to age of stars in thick disk), close encounters with satellites.

2. Thick disk stars form \`in-situ’ during burst of star formation early in Milky Way’s history, larger turbulence at early epochs can lead to larger scale heights for disks.

3. Thick disk stars formed in satellite galaxies, deposited stars into thick disk when disrupted by tidal field of thin disk.

Inside-out disk growth: inner regions appear to form first, with outer disk growing later.

- supported by metallicity and age gradients.
- outer disk is lower metallicity, younger ages: more recently building up from metal poor gas
- chemical evolution has proceeded differently as a function of radius: gas remains metal poor in outer disk for longer.

Timescale of thick disk formation, disk heating

- The older stars in the Milky Way (>8-10 Gyr) appear to have larger scale heights (thick disk).
- Age velocity dispersion relation + asymmetric drift indicates old stars have been heated more than younger stars. Heating can be external (mergers) or internal (interaction with spiral arms, gas clouds).
- The α/Fe ratios indicate a rapid formation for the early (thick) disk, prior to significant enrichment from Type Ia SN.

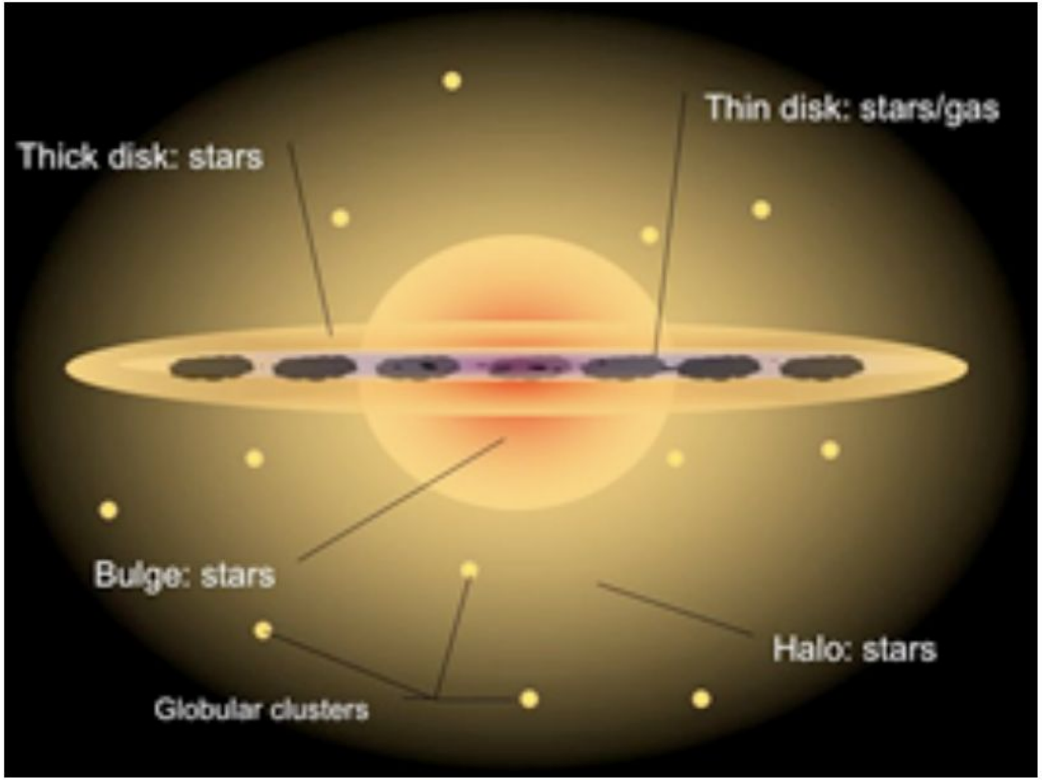
Role of Mergers in Disk Properties

- MW is thought to undergo a merger with a large galaxy 8-11 Gyr ago.
- This event heated stars formed in the MW prior to this event, contributing to thick disk.
- Supported by fact that oldest, high α/Fe stars have very low angular momentum, as expected for a population that experienced disk heating.

Radial Migration

- Spread in metallicity at given age can be explained by radial migration of stars.
- Weakens metallicity gradient and contributes to scatter in metallicity in solar neighborhood.

Stellar Halo



stellar halo is an extended, diffuse, and low-surface-brightness component of a galaxy that surrounds the central disk and bulge. Far away but still bounded.

Classical formation picture: halo is a smooth envelope of stars that formed in-situ during the initial collapse

Alternative view: stellar halo is built up from accreted galaxies, based on metallicity spread in globular clusters at large radii.

Inner disk: Insitu stars heated from GSE

Outer disk: ex-situ stars from accretion

Globular Clusters

Definition: A globular cluster is a massive, spherical collection of stars that orbits a galactic core as a satellite. They are among the oldest known objects in the universe and are tightly bound by gravity - **10^4 - 10^6M dense!**

- **High Mass to light ratios: 1 ≲ M/LV ≲ 4** meaning not dominated by Dark Matter

- Core radius between 0.1 and 4 pc
- Truncation radius between 20 and 70 pc

- •Typical line-of-sight velocity dispersions range from σr~1 -10s km s-1

- **Low metals** (fit isochrones - position/slope of horizontal branch (and red giant branch) in CMD dependent on metallicity.
- **Metal gradient** -“richer” globular clusters tend to be in thenner halo, while the outer halo tends to be more metal poor.

Multiple Stellar populations
Split CMD with 2nd-generation stars very different metallicities from field stars in Milky Way.
Cannot be formed from 1 population of polluters since the mass required is not enough - unsolved?

1. The (high pressure) ISM conditions at high redshift produce dense clusters.

2. The clusters are tidally disrupted by dense gas concentrations in the disks of high redshift galaxies. Most low mass clusters removed.

3. Destruction continues until clusters migrate out of the disk into the halo of their host galaxies

Field Stars

How to find them:

1. **MSTO**
   a. They are the most numerous type of bright star in an old population. If you want to make a detailed density map of the halo you use these because there are millions of them.
2. **Blue Horizontal Branch**
   a. Old, hot stars burning helium in their cores.
   b. They are Standard Candles. They have a very specific brightness. If you find one, you know exactly how far away it is.
3. **Mtype giants**
   a. They are extremely bright. They allow us to detect the halo out to extreme distances (100kpc+), where MSTO stars would be too faint to see

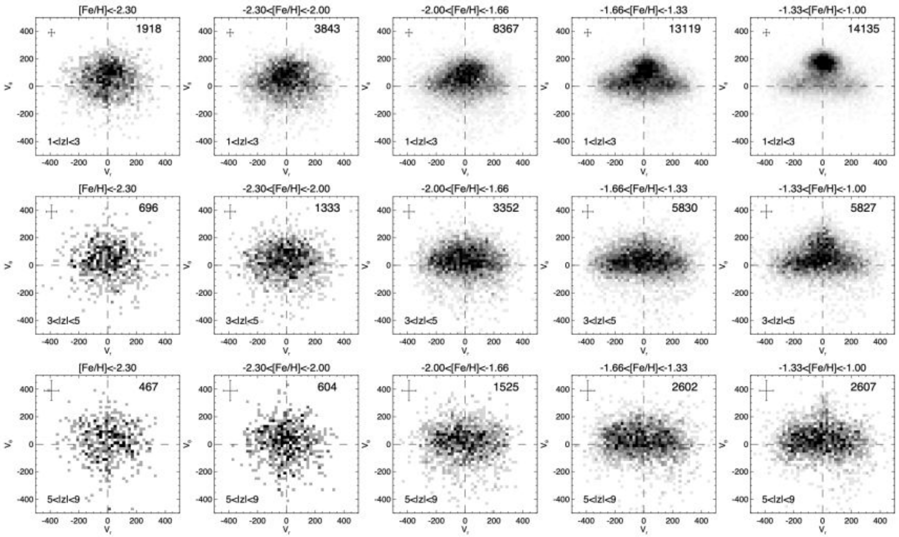
Identifying them:

- Kinematics (if they are high rel velo?)
- Metalicitiy (metal poor)
- Color cut for blue and bright stars? (Blue horizontal branch since its older)

Gaia Sausage inner halo

- Tightly bound phase space, correlated to metals
- Are alpha and Fe poor suggesting was accreated

Belokurov et al. 2018 (see also Helmi et al. 2018)



Inner / Outer Halo

Outer Halo (~13.5 Gyr): This region is populated by debris from the very first tiny dwarf galaxies that the Milky Way cannibalized. Because these dwarfs were small, they stopped forming stars very early, so their "fossils" are extremely old.

Inner Halo (~11.5 Gyr): This region is dominated by the debris from the **Gaia-Sausage-Enceladus merger.** Because this was a massive galaxy, it was able to keep forming stars for longer before it crashed into us. Therefore, the stars it dumped into our inner halo are slightly "younger"

Observation:
The Broken Density Profile -> two halos
The Alpha-Bifurcation -> two halos
The "Sausage" Plot -> inner halos

Inflow: A dwarf galaxy brings in both field stars and globular clusters.

Destruction: The dwarf galaxy is destroyed, turning its bulk stellar mass into Halo Field Stars.

Survival: The dense Globular Clusters survive as independent satellites.

Decay: Over billions of years, the GCs slowly dissolve, leaking stars that become new Field Stars.

Practice Problem

In Class Work — Globular Clusters, Proper Motions, and Parallax

1. (a) Estimate the density of stars in the core of 47 Tuc.

   You may assume that 10% of the luminosity is associated with stars in the core.

   To convert to a stellar mass, you may assume a mean IMF for the globular cluster of M^*/L_V=1.5. *How does this ratio compare to the mean value found in the solar neighborhood? Why is there a difference?*

Cluster		d (kpc)	[Fe/H]	M_V (mag)	L_V ($10^3 L_\odot$)	r_c (pc)	r_t (pc)	σ_r (km s^{-1})
NGC 5139	ω Cen	5.2	−1.6[a]	−10.2	1100	4	70	20
NGC 104	47 Tuc	4.5	−0.71	−9.5	500	0.5	50	11
NGC 7078	M15	10.8	−2.15	−9.3	440	<0.01[b]	85	12
NGC 6341	M92	8.5	−2.15	−8.3	180	0.5	35	5
NGC 7099	M30	9.1	−2.13	−7.6	95	<0.1[b]	45	5
NGC 6121	M4	1.73	−1.2	−7.2	60	0.5	25	4
	Pal 13	24.3	−1.9	−3.8	3	0.5	>50	0.6–0.9
NGC 1049	Fornax 3	140	−2.0	−7.8	100	1.6	>50	9

   You may assume a mean <m*> ~ 0.3 $M_\odot$ (recall mean stellar mass is very low).

   Compare your answer to the number density of stars in the Solar neighborhood (0.2 stars pc^{-3}).

2. Consider a main sequence turnoff star with M_g ~ 4 with tranverse velocity typical of the Milky Way halo (~100 km s^{-1}). For distances of 10 pc, compute the (i) apparent magnitude in g-band, (ii) true parallax, and (iii) proper motion, (iv) signal-to-noise ratios for parallax and proper motion.

You may assume parallax uncertainties of 0.4 mas and proper motion uncertainties of 0.4 mas yr^{-1}.

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Compare your answer to the number density of stars in the Solar neighborhood (0.2 stars pc^{-3}).

mass density = (0.1*500x10^3*1.5)/(4*3.14*0.5 pc ^3)

n ~ mass density / 0.3 ~ 10^5 stars pc^{-3}
much larger than the density in the disk near the solar neighborhood! expect different dynamical effects.

2. You should find g=19, parallax = 0.1 mas, μ=100/(4.74*d(pc))=2.1 mas/year

Note, 4.74 comes from converting km/s to arcsec/yr at 1 pc.

So SNR on parallax is SNR = 0.1 mas/0.4 mas = 0.25

But the proper motion SNR = 2.1 mas/yr / 0.4 mas/yr = 5

So you should get a meaningful measurement of proper motion, not parallax

Bulge / Bar

Classical bulge: most stars originate in a short phase of star formation when universe was a few Gyr old.

Pseudo-bulges: stars form in disk over a more extended time and bulge results from secular evolution of disk, driven by development of bar Several modes of bulge formation.

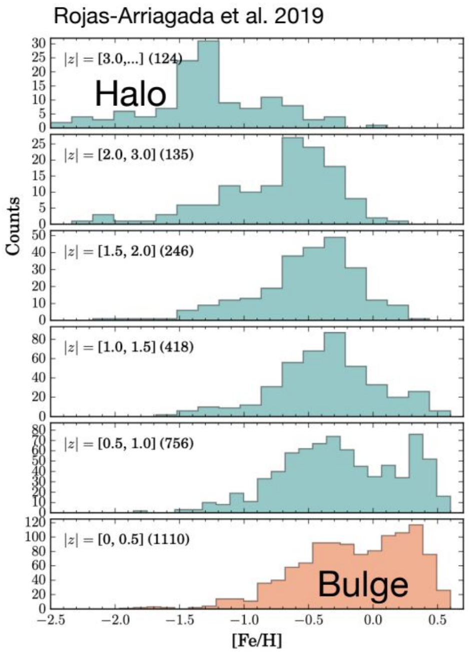
The Galactic bulge is now understood to be primarily a "pseudobulge" formed via **secular** evolution, where gravitational instabilities in the Milky Way's disk created a central **bar** that subsequently buckled, scattering stars vertically into a characteristic **boxy/peanut or X-shaped** structure. This formation scenario is supported by near-infrared star counts that penetrate dust to reveal the X-morphology and long bar , as well as kinematic data showing cylindrical rotation and microlensing age-dating that identifies the dominant metal-rich population as intermediate-age stars originating from the disk. While a small (<25%), ancient, metal-poor "classical" component likely formed through early rapid star formation , the chemical and dynamical evidence overwhelmingly points to the bulge being built up largely from the disk itself.

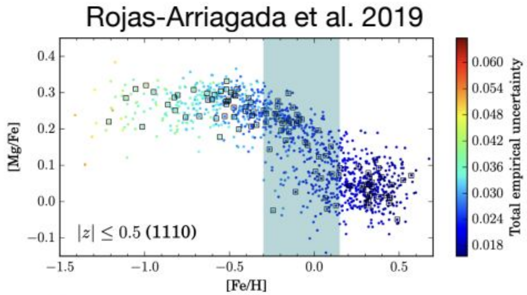
Metallicities

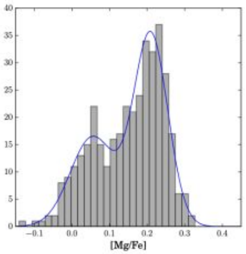
Suggests a mixture of stellar populations in the bulge. How would you explain?

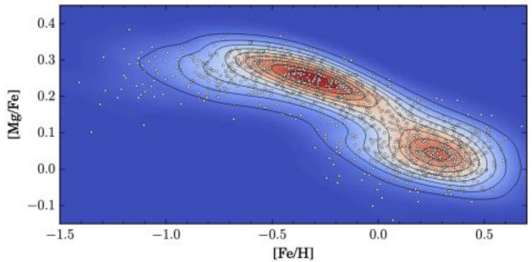
•Metal poor stars = early burst of star formation.

•Metal rich stars = secular evolution of early disk



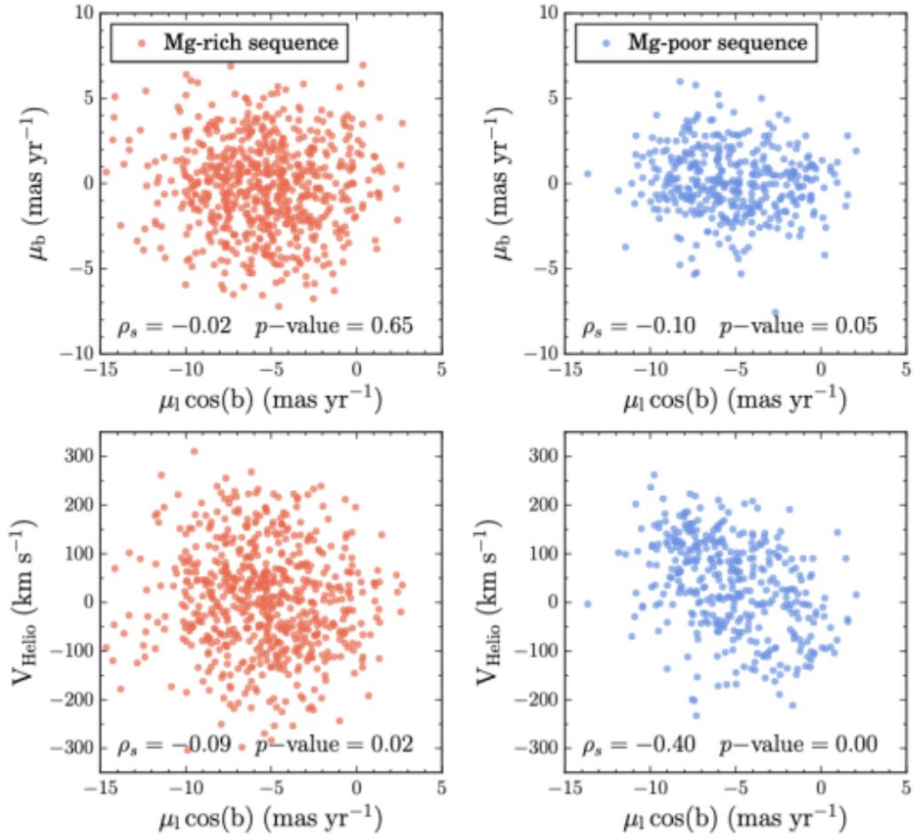






Kinematics

Different in the two bulge sequences!
• The metal rich+small α/Fe stars appear to be kinematically "colder" in the vertical direction, as would
be expected for a population that originated in disk and
entered bulge by secular evolution.

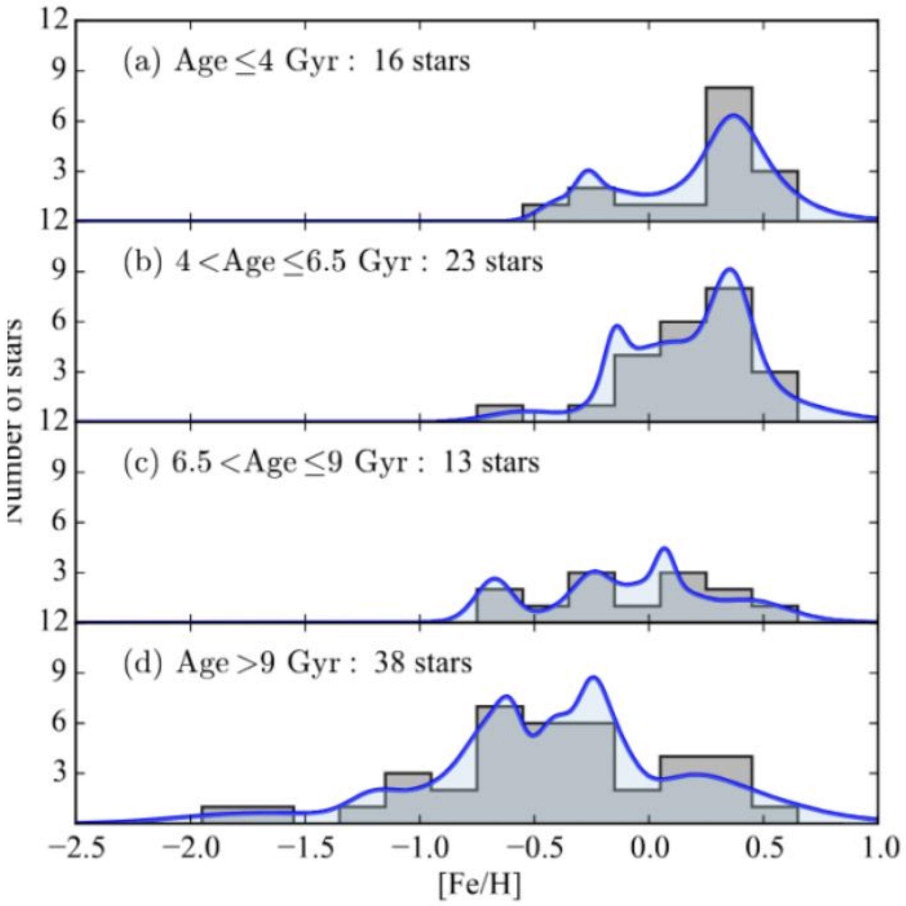


Age

MSTO - needed to get age is hard because of dust and can be faint.

Microlensing: This transient brightening makes a faint MSTO star in the Bulge briefly bright enough to be observed

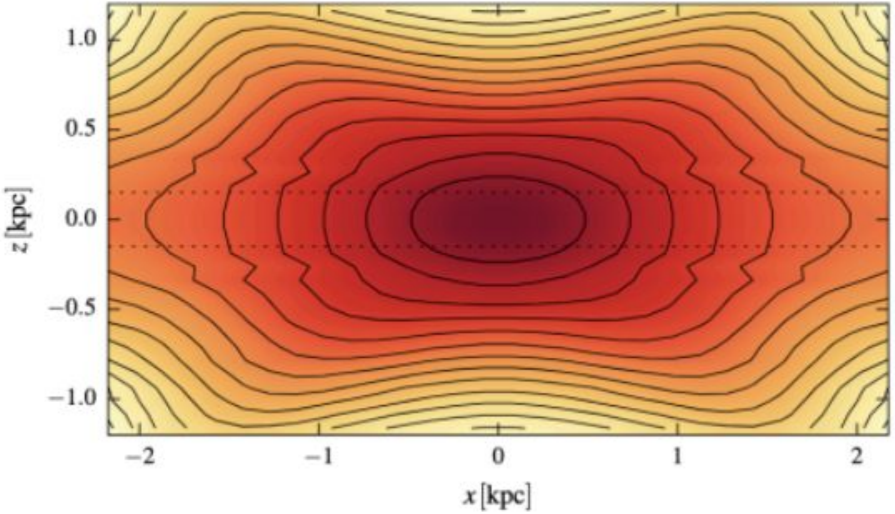
Observation: Suggests several episodes of star formation for bulge stars — metal poor component is old, perhaps formed in early burst of star formation.



Secular Evolution

These non-axisymmetric structures will create torques on stars and gas, transferring angular momentum outward. Stars and gas can begin to fall inward. Secular evolution

Orbits of the stars are altered! — they gain vertical energy (due to a buckling instability). The net result is a “boxy/peanut-shaped” distribution of stars in the central regions.



Conclusion:

The majority of bulge strs in the Milky Way are part of a boxy/peanut structure, corresponding to the inner regions of the Milky Way bar. These stars appear to be metal rich, with intermediate ages. These data corroborate the idea that the bulge is primarily built up by secular evolution (i.e., a pseudobulge).

There is an old and metal poor component with different morphology and kinematics. The origin of this component remains unclear — could be explained as a classical bulge, formed via star formation in a burst of star formation early in the history of the Galaxy. Present models suggest this component is a small fraction (<25%) of the total bulge mass (see Bland-Hawthorn & Gerhard 2016).

Innermost cluster

The Nuclear Star Cluster (NSC) is a distinct, extremely dense structure of stars occupying the innermost 5–10 parsecs of the Milky Way, with a total mass of roughly $1.8 \times 10^7 M_{\odot}$ centered on the supermassive black hole, Sgr A*.

Unlike the bulk of the bulge, the NSC shows **evidence of continued star formation**, hosting a mix of predominantly old stars (>5 Gyr) alongside a surprising population of young, massive stars (the "S-stars") orbiting within arcseconds of the black hole.

Observations of this region rely entirely on infrared Adaptive Optics (AO) to penetrate the 7+ magnitudes of dust extinction and resolve individual stars in such a crowded environment; these data reveal a broad range of metallicities and specific abundance anomalies (such as high sodium), suggesting the cluster formed via a "hybrid" scenario of in-situ starbursts fueled by inflowing gas and the accretion of globular clusters that spiraled into the center via dynamical friction.

Rotation Curves

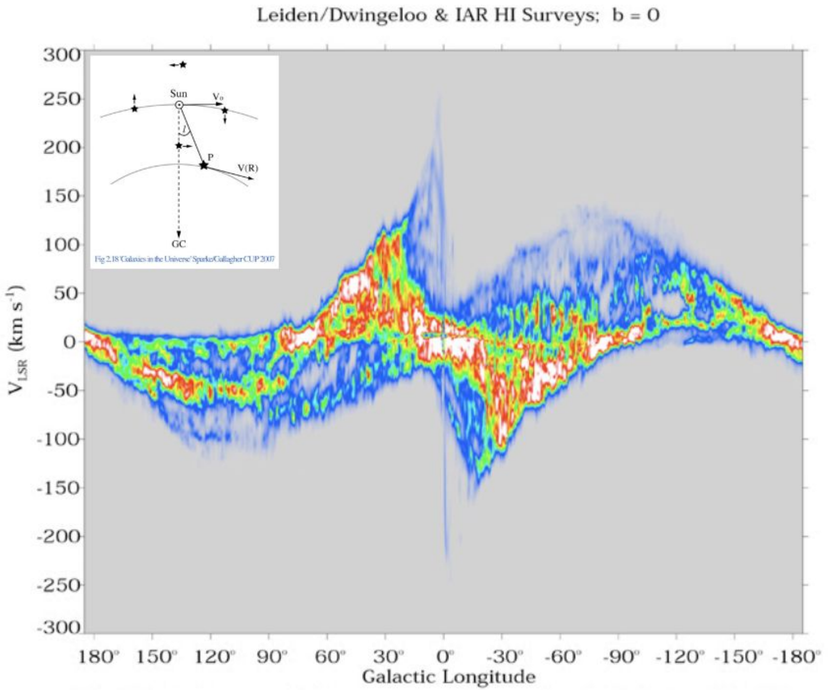
A rotation curve is simply a plot of Orbital Speed (V) vs. Distance from Center (R).

X-Axis (Radius): Distance from the Galactic Center (usually in kpc). The Sun is at R ~ 8 kpc.

Y-Axis (Velocity): The speed at which stars/gas are orbiting (km/s).

The Points: The data points (often with error bars) show the measured speeds of gas clouds or stars at various distances.

The Lines: You will often see a solid line (the total fit) and dashed lines representing the contributions from different components: the Bulge (inner peak), the Disk (middle), and the Halo (outer).



Tangent point Concept: When we look along a specific line of sight (galactic longitude l), our view passes through gas clouds at many different distances. However, the gas cloud located at the Tangent Point (the point where our line of sight is closest to the Galactic Center) has a unique property: its velocity vector is pointing directly away from us (or towards us) parallel to our line of sight.

Interstellar Medium

ISM Phases:
cold neutral medium, => Mass dominates
Hot Ionized => dominates volume

Table 2.4 A 'zeroth-order' summary of the Milky Way's interstellar medium (after J. Lequeux)

Component	*Description*	*Density* (cm^{-3})	*Temperature* (K)	*Pressure* (p/k_B)	*Vertical extent*	*Mass* ($\mathcal{M}_\odot$)	*Filling factor*
Cold clumpy gas	Molecular: H_2	>200	<100	Big	80 pc	$(2) \times 10^9$	<0.1%
	Atomic: HI	25	50–100	2 500	100 pc	3×10^9	2%–3%
Warm diffuse gas	Atomic: HI	0.3	8 000	2 500	250 pc	2×10^9	35%
	Ionized: HII	0.15	8 000	2 500	1 kpc	10^9	20%
HII regions	Ionized: HII	1–10^4	~10 000	Big	80 pc	5×10^7	Tiny
Hot diffuse gas	Ionized: HII	~0.002	$\sim 10^6$	2 500	~5 kpc	(10^8)	45%

Heating Mechanism:

-Cosmic ray hits atom, ejecting electron. => Ionization
Process: High-energy cosmic rays collide with atoms (mostly hydrogen), ionizing them. Heating: This energetic electron collides with surrounding particles, transferring roughly 10 eV of its energy as heat to the gas. Where it dominates: This is expected to be the dominant heating source in **dense molecular clouds.**

-Photoelectric effect Dust
Process: Ultraviolet (UV) photons with energies greater than ~5 eV strike interstellar dust grains. -photoelectric effect. The ejected electron carries away kinetic energy which is shared with the surrounding gas via collisions. This provides a heating rate much higher than cosmic rays and is the dominant heating process for the **Cold Neutral Medium (CNM)** and **Warm Neutral Medium (WNM).**

-Photoionization of Atoms
HII regions (ionized hydrogen) and the Intergalactic Medium (IGM)

-Shock heating
Heating: The shock wave converts the bulk kinetic energy of the moving gas flow into thermal energy (random particle motion). This mechanism can heat gas to extreme temperatures (~10^7 K) and is the origin of the **Hot Ionized Medium.**

Cooling Mechanism:

1. Collisionally Excited Line Emission (The Main Mechanism)
A gas particle (like a free electron or a hydrogen atom) collides with another atom (or ion).

2. Cooling by "Fine Structure" Lines (Low Temperatures)
Instead, cooling relies on "metals" (elements heavier than Helium) with very small energy gaps called "fine structure" levels.
[CII] Emission (Carbon): This is the dominant coolant for neutral gas.
[OI] Emission (Oxygen): Oxygen is neutral, but its energy gap corresponds to $T \sim 228$ K. It becomes a significant coolant at slightly warmer temperatures

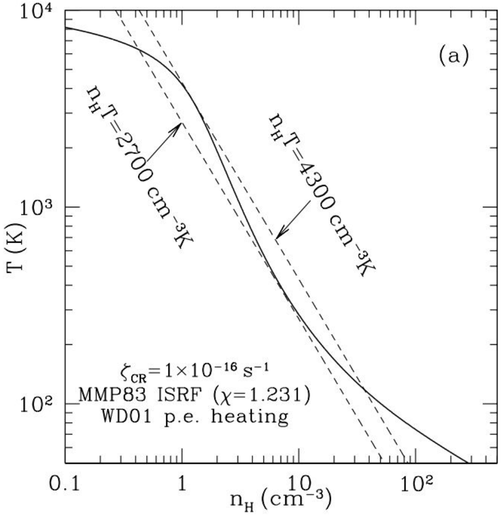
3. Lyman Alpha Cooling (Intermediate Temperatures)
At temperatures around $10,000$ K (Warm Neutral/Ionized Medium),

4. Hot Gas Cooling (High Temperatures)
Metal Lines: Collisional excitation of highly ionized metals (like OIII, CIV, OVI) dominates cooling up to 10^6 K6.
Recombination: **Free** electrons are captured by protons (or other ions). As the electron cascades down through energy levels, it emits photons7777.
Free-Free Emission (Bremsstrahlung): At very high temperatures ($T > 10^6$ K), cooling is dominated by free electrons being decelerated by the electric fields of ions, emitting radiation directly without being captured8.

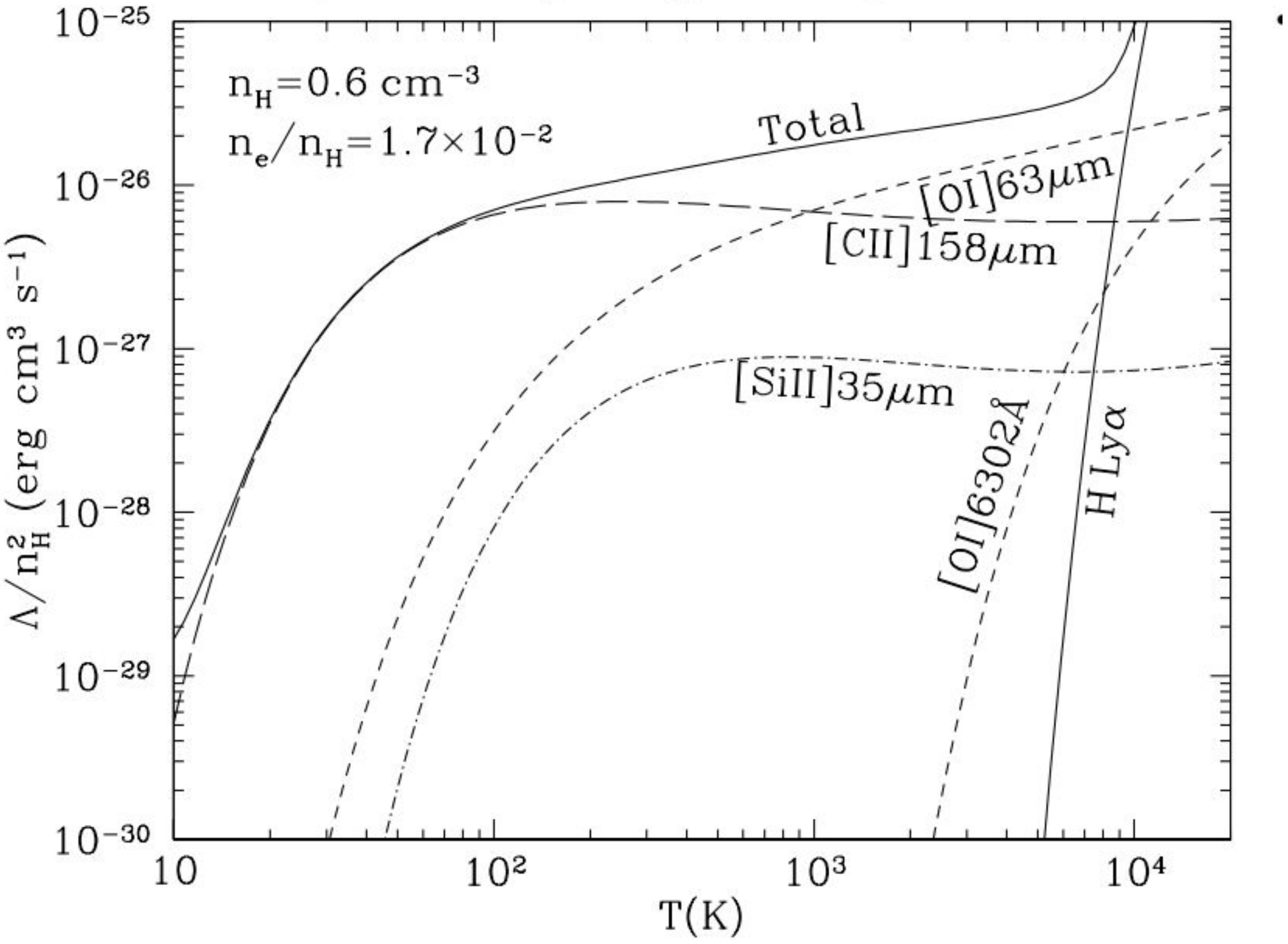
Cooling Mechanism:

Temperature dependence

n^2Λ(T)=nG



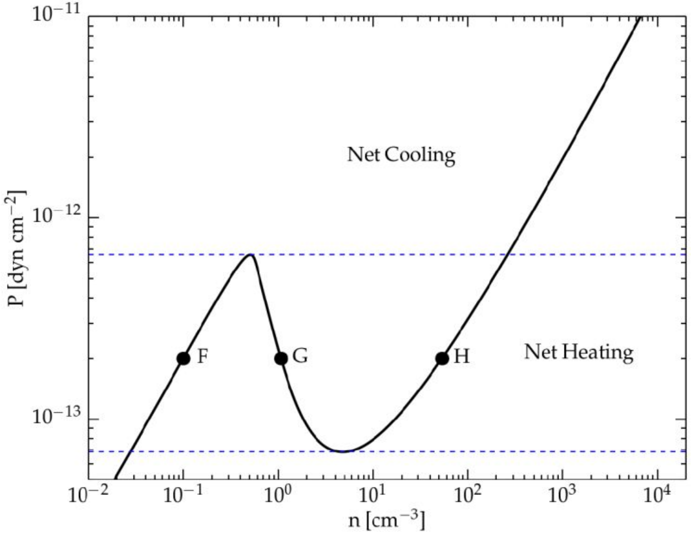
Cooling curve for (mostly) neutral gas in ISM.



Cooling Mechanism:

Temperature dependence

n^2Λ(T)=nG



- **1. Point F.** What happens if you heat gas at that point while keeping pressure fixed?
  - Number density must go down. Gas moves to cooling part of diagram. Reverts back to equilibrium.
- What happens if you cool gas at fixed pressure?
  - Number density goes up. Gas moves to heating part of diagram. Reverts back to equilibrium.
- This is a stable phase of the ISM!
- **2. Point H.** Same as Point F. Stable!
- **3. Point G.**
  - Number density again goes down, but this pushes you into a heating part of the diagram. Unstable!
  - And if you cool at fixed pressure?
  - Number density goes up, moves to cooling part of diagram. Unstable!
  - This is an unstable phase!