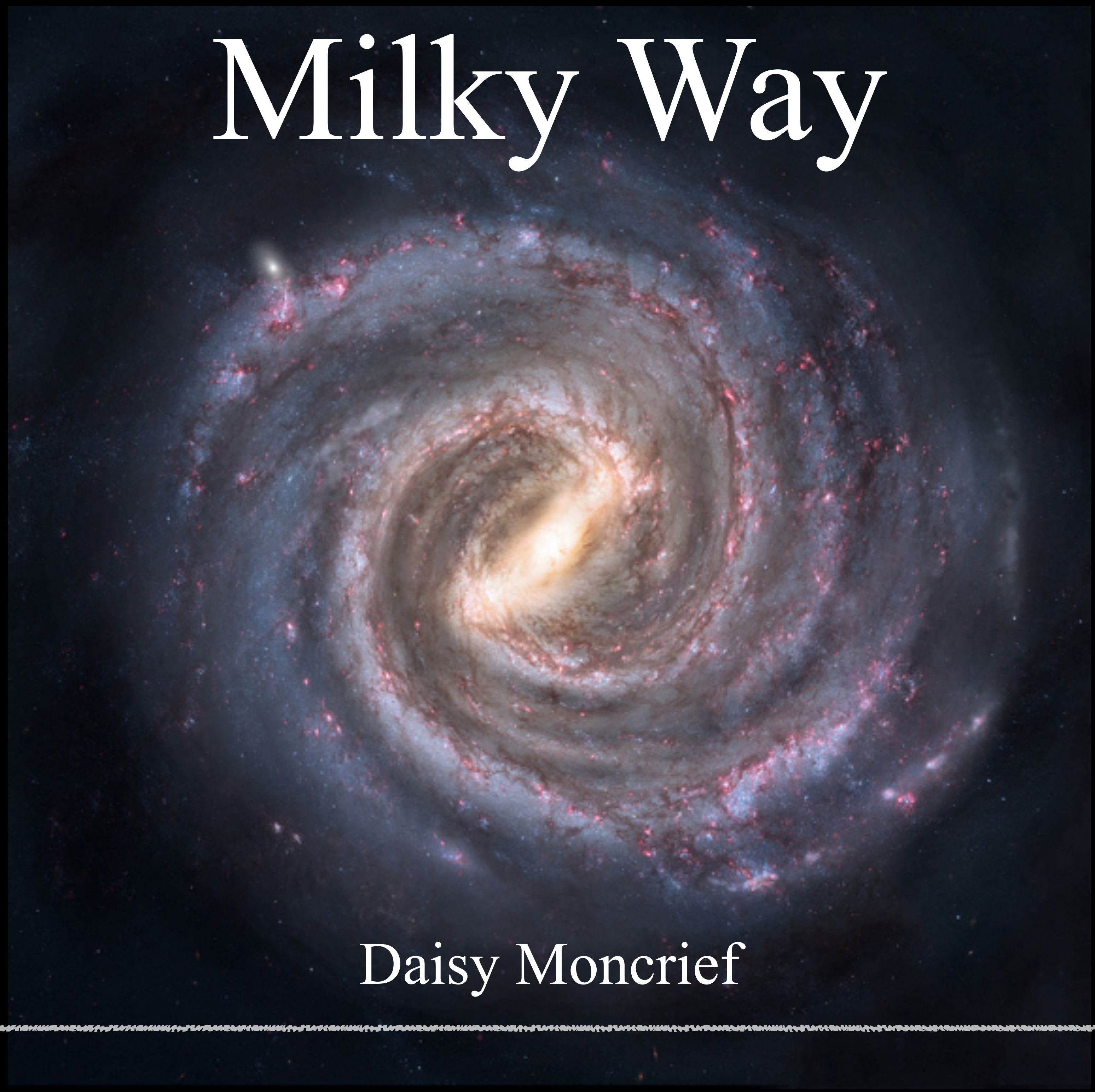
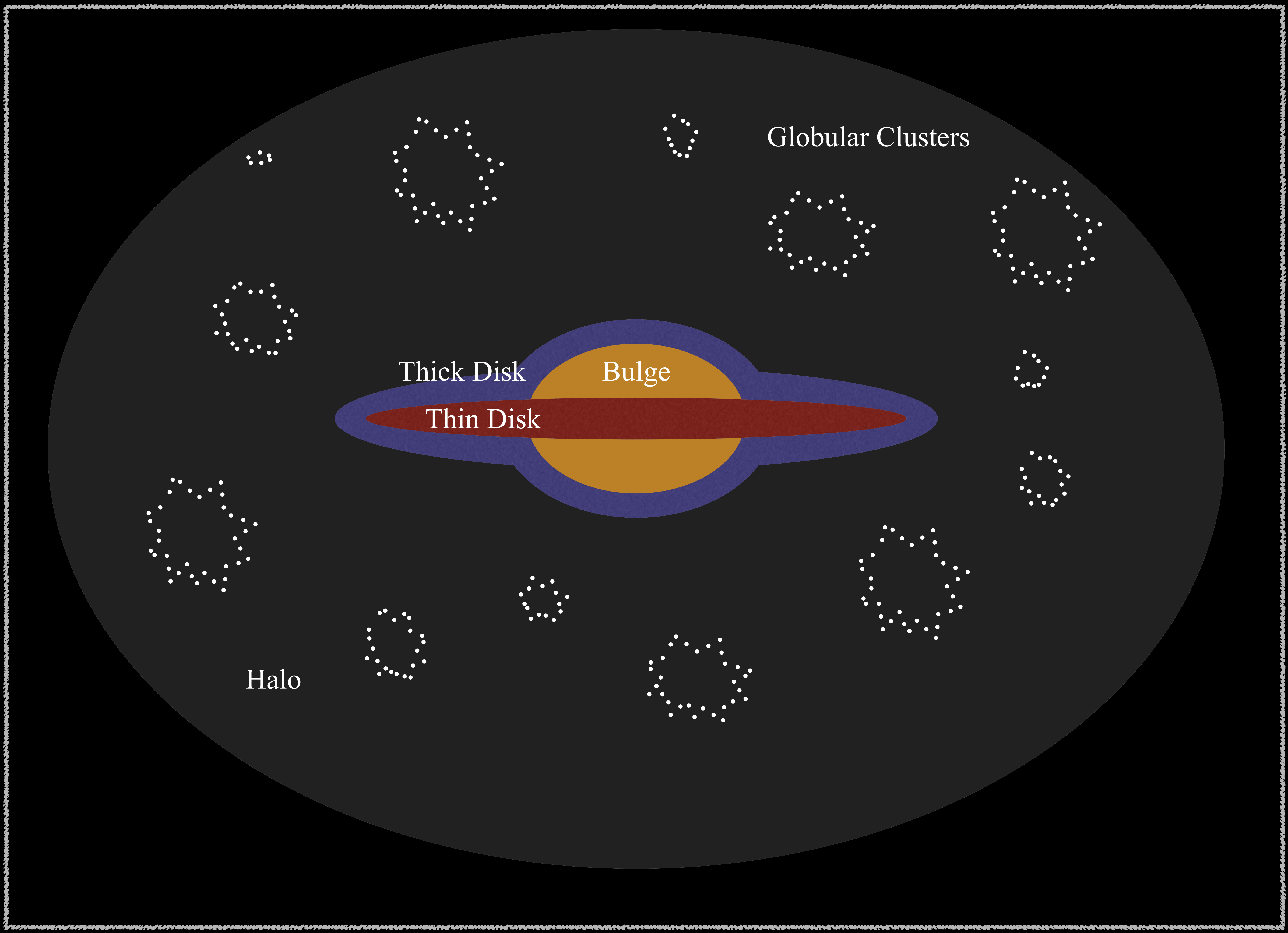
# The Formation of the Milky Way



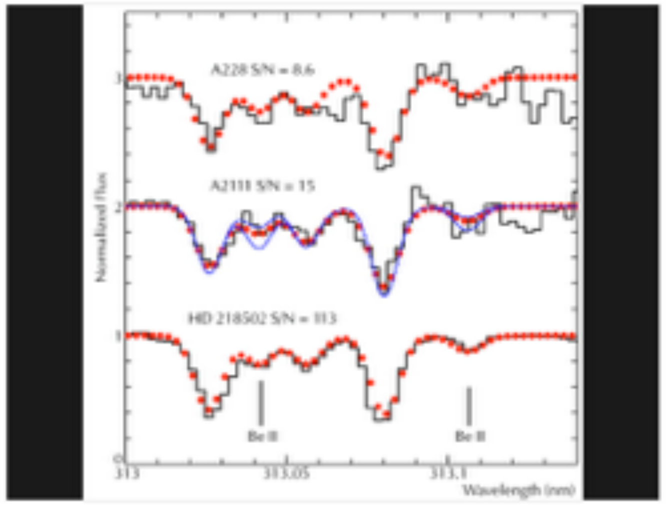
Daisy Moncrief


Globular Clusters
Thick Disk
Bulge
Thin Disk
Halo

# First Generation Stars

European Southern Observatory

## Beryllium spectral lines in three stars




Reproduction of a small wavelength region of the spectra obtained with the UVES spectrometer at the 8.2-m Kueyen telescope at Paranal of these stars (above), together with that of another nearby star, HD 218502, a field star in which the Beryllium lines are also visible (below). This star, however, is not a member of a cluster and its age is not well known. The achieved signal-to-noise ratios are indicated. The best-fitting synthetic spectra are show as red dots; in the spectrum of A2111, the blue dashed lines illustrate the accuracy of the fit - they correspond to a variation of the Beryllium content by approx. ± 50% (0.2 dex).

**Credit:** ESO

European Southern Observatory

eso0425 — Science Release

$^{4}$Be

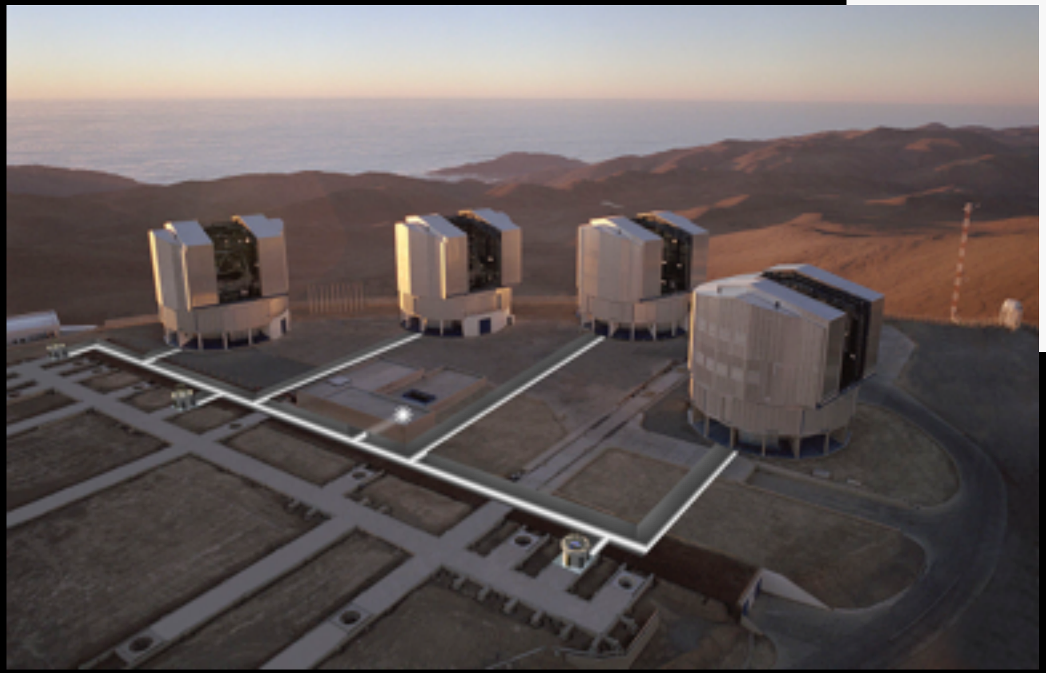
## How Old is the Milky Way ?

### VLT Observations of Beryllium in Two Old Stars Clock the Beginnings

17 August 2004

**Observations by an international team of astronomers [1] with the UVES spectrometer on ESO's Very Large Telescope at the Paranal Observatory (Chile) have thrown new light on the earliest epoch of the Milky Way galaxy. The first-ever measurement of the Beryllium content in two stars in a globular cluster (NGC 6397) - pushing current astronomical technology towards the limit - has made it possible to study the early phase between the formation of the first generation of stars in the Milky Way and that of this stellar cluster. This time interval was found to amount to 200 - 300 million years. The age of the stars in NGC 6397, as determined by means of stellar evolution models, is 13,400 ± 800 million years. Adding the two time intervals gives the age of the Milky Way, 13,600 ± 800 million years. The currently best estimate of the age of the Universe, as deduced, e.g., from measurements of the Cosmic Microwave Background, is 13,700 million years. The new observations thus indicate that the first generation of stars in the Milky Way galaxy formed soon after the end of the ~200 million-year long "Dark Ages" that succeeded the Big Bang.**

https://www.eso.org/public/news/eso0425/

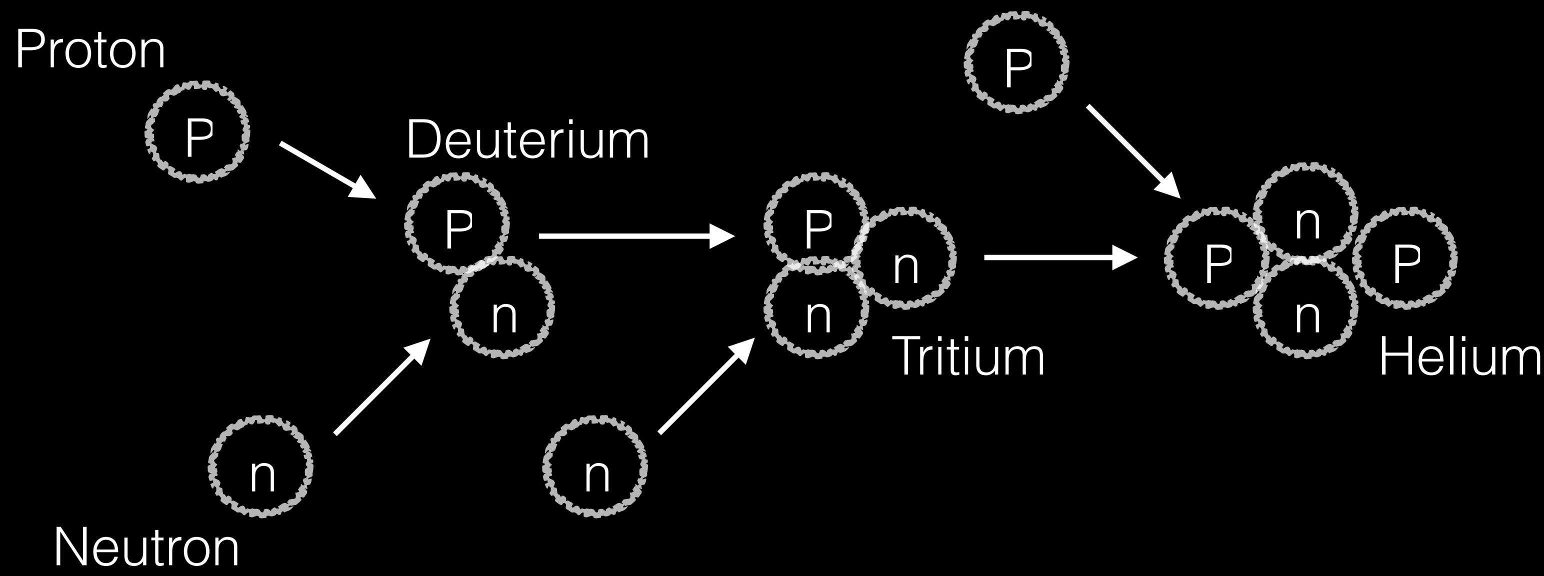


http://1.bp.blogspot.com/-Tm5JxP4EHRM/Tfy4szzDy_I/AAAAAAAADqw/FB7_xac65wI/s1600/VLT.jpg

Nuclear Fusion:
Two nuclei with low mass numbers combine to produce a single nucleus with a higher mass number.

# Star Populations

Nucleosynthesis: as the Universe cooled, protons and neutrons come together to form heavier atomic nuclei




| Population I Stars | Population II Stars |
|---|---|
| - ordered motion<br>- circular orbits in the disk plane<br>- younger<br>- more metal-rich | - random motion<br>- eccentric orbits passing through disk plane<br>- older<br>- more metal-poor |

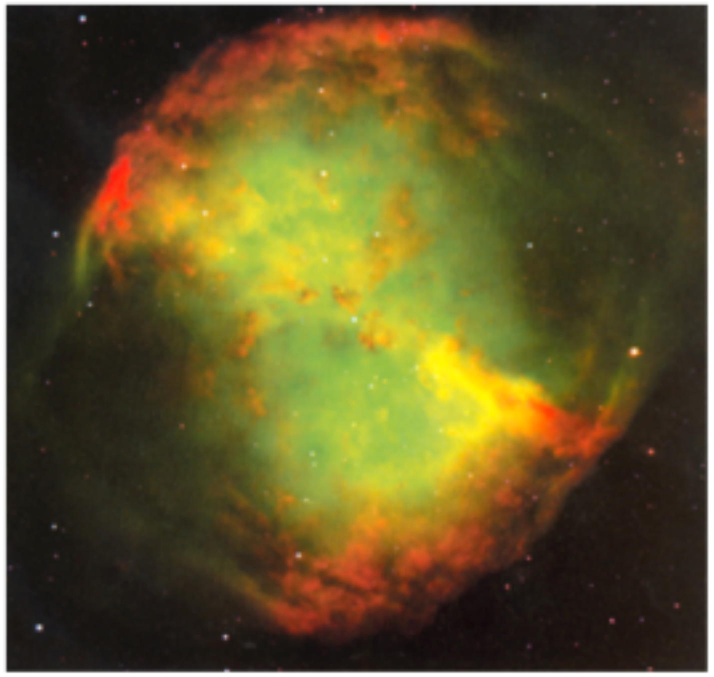
https://en.wikipedia.org/wiki/File:Crab_Nebula.jpg

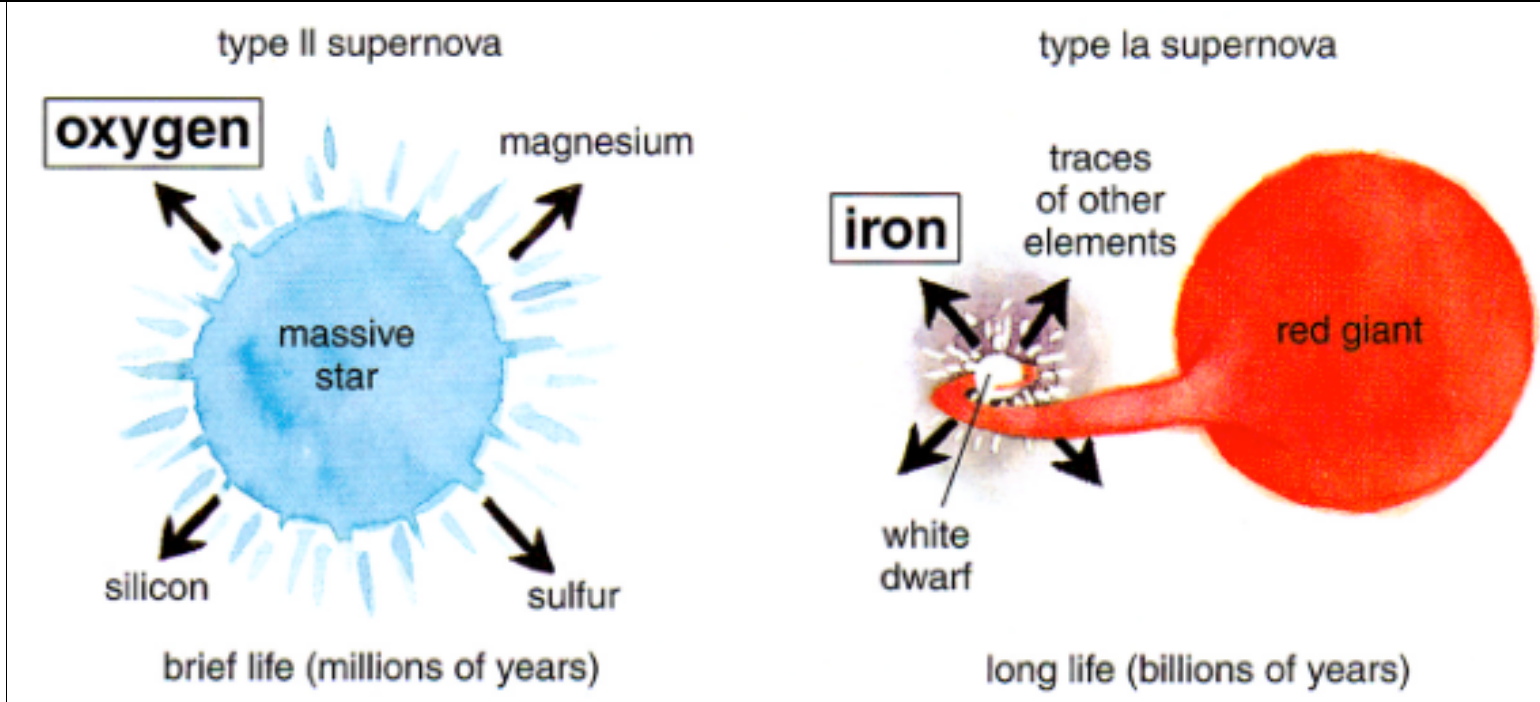
The Crab Nebula is a pulsar wind nebula associated with the 1054 supernova

[Fe/H] = log (Fe/H)– log (Fe/H)Sun

# Stars making metals

http://www.astro.caltech.edu/~george/ay20/Chiappini-MilkyWay.pdf





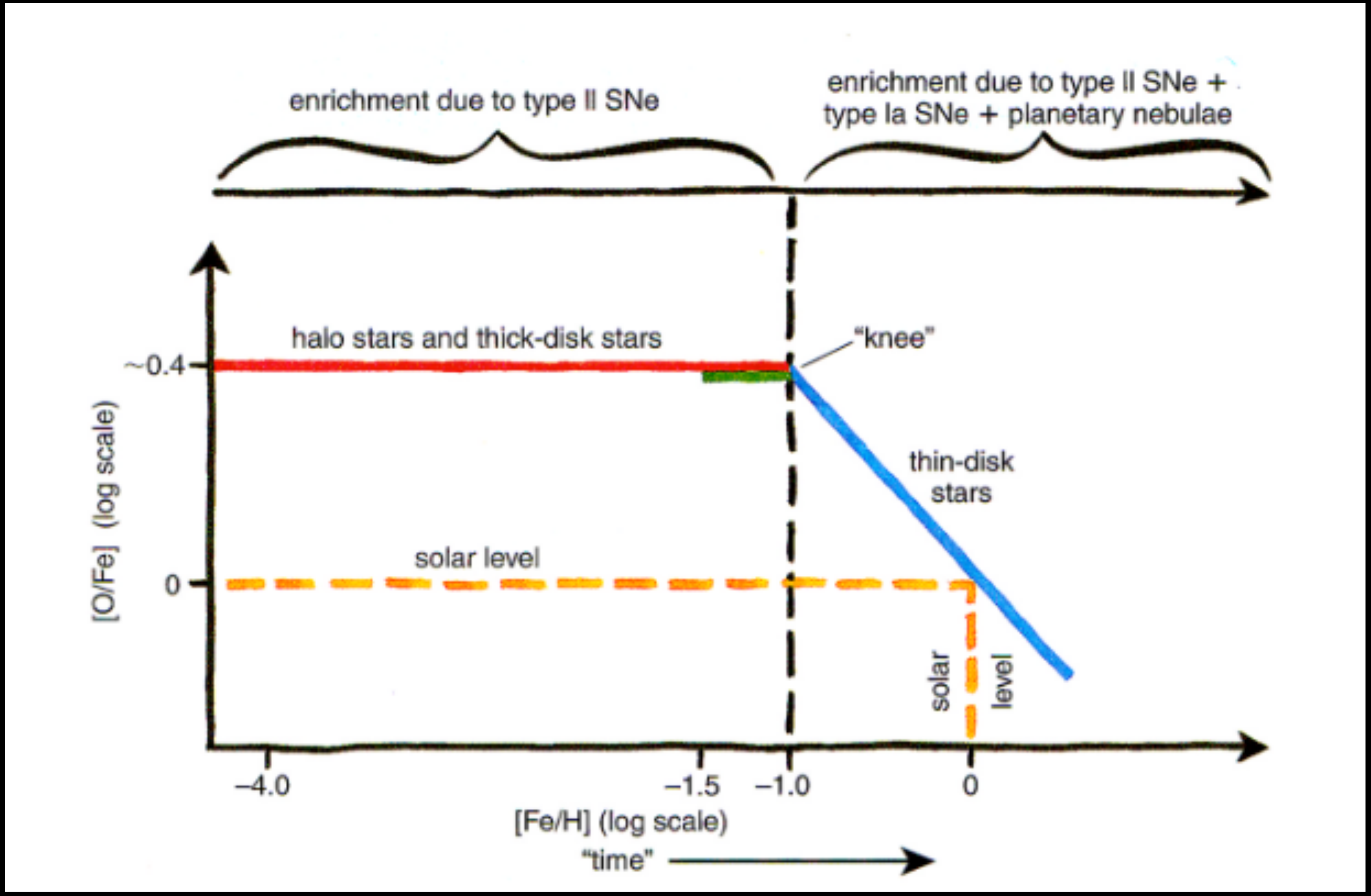

| helium-4 | oxygen | iron |
|---|---|---|
| carbon | neon | sulphur |
| nitrogen | magnesium | silicon |
| | silicon | calcium |
| | sulphur | |

Three astrophysical processes contribute to the bulk of chemicals in the interstellar medium. Planetary Nebulae (Low and intermediate-mass stars); Type-II supernova explosions (Massive Stars); Type Ia supernovae (Binary systems)

Because each of these processes takes place on a different timescale, the relative abundance of different chemical elements in a particular region of the Galaxy provides clues to the rates of star formation and the region's evolutionary history.

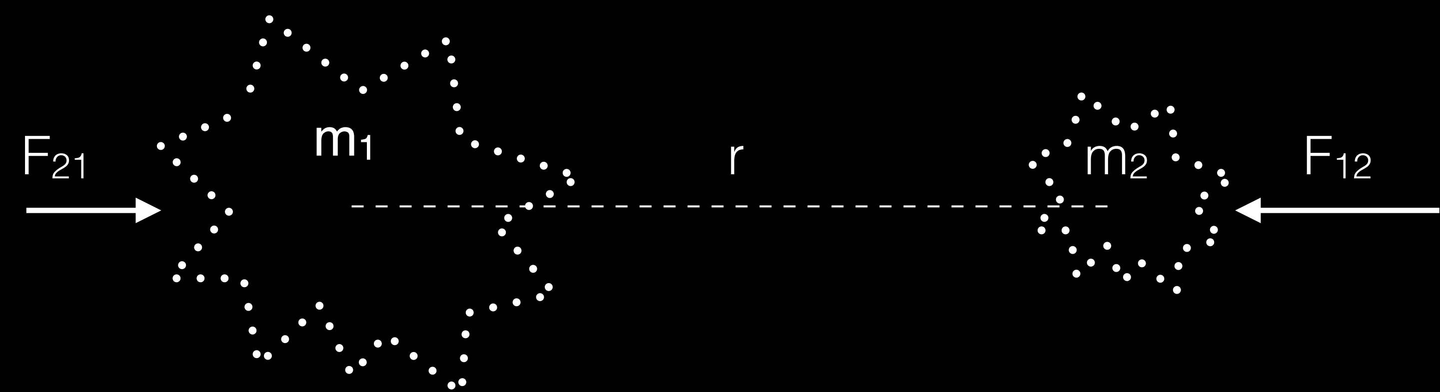
# Chemical Evolution of the Galaxy

http://www.astro.caltech.edu/~george/ay20/Chiappini-MilkyWay.pdf



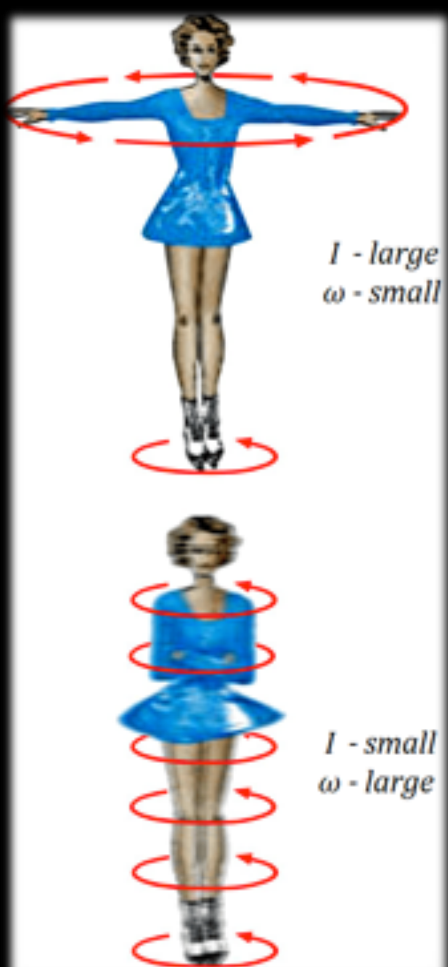

The general metallicity of the Galaxy [measured by the abundance of iron (Fe), compared with hydrogen (H)] increases with time.

# Halo and Disk Separation



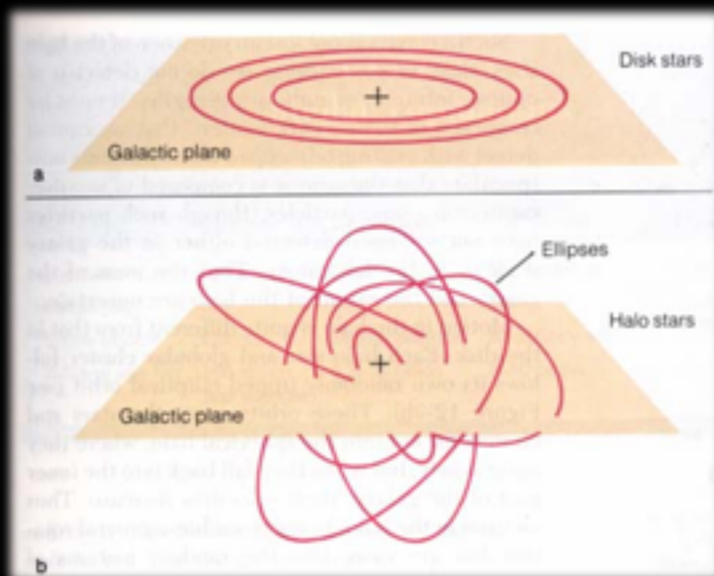

$$F_g = G\frac{m_1 m_2}{r^2}$$

Rotational velocity (V)
Vertical velocity (W)
Radial velocity (U)




$$L = I \times \omega$$

Angular Momentum — Moment of Inertia — Angular Velocity




The halo and the bulge tend to consist of low-angular-momentum stars, whereas the thick disk and the thin disk typically contain stars with a high angular momentum. Since angular momentum is conserved, these distinctions reflect the intrinsic characteristics of the gas from which the stars evolved. So these galactic components must have originated from separate clouds of material with different angular momenta. (Rosemary Wyse)

http://www.daviddarling.info/encyclopedia/A/angular_momentum.html

https://web.njit.edu/~gary/202/Lecture24.html

# Galactic Disk

| Thin Disk | Thick Disk |
|---|---|
| - site of gas, dust, star formation<br>- small scale height (300pc)<br>- high stellar density<br>- small velocity dispersion<br>- clear abundance gradient<br>- ordered rotation | - Older Stars (10-12 Gyr),<br>- More metal-poor stars (metallicity 0.5 - 1.0 dex)<br>- lower stellar density<br>- larger scale height (1000pc)<br>- larger velocity dispersion (40km/s)<br>- No obvious vertical abundance gradient<br>- ordered but slower rotation<br>- surface brightness ~ 10% of thin disk's |

Predictions:

– Stellar disks should generically form from the inside out.

– No major merger since a redshift of $z \simeq 1$.

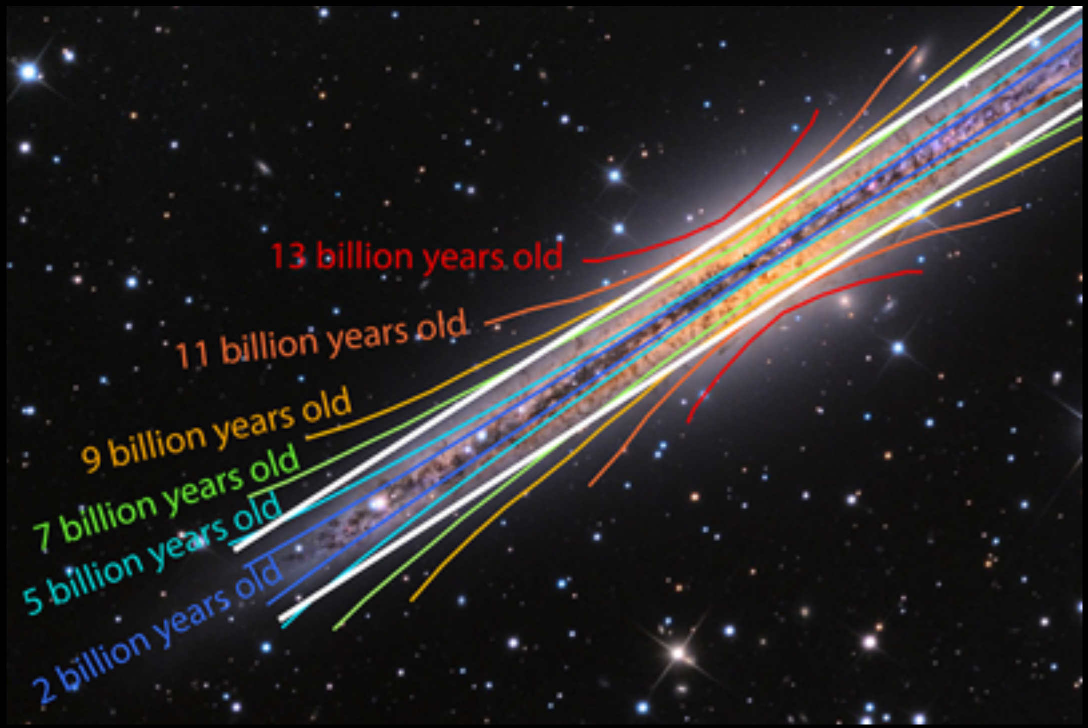
– The luminosity- or mass-weighted radial stellar density profiles at late epochs resemble exponentials.

– Characteristic disk thicknesses or vertical temperatures of 400 pc and $\sigma_z \simeq 25$ km $s^{-1}$ are plausible.

– Variable material infall. It is rare that one particular infall or heating event dominates.

– Non-axis symmetries resemble bars and spiral arms. Through resonant interactions, these structures may have an important influence.

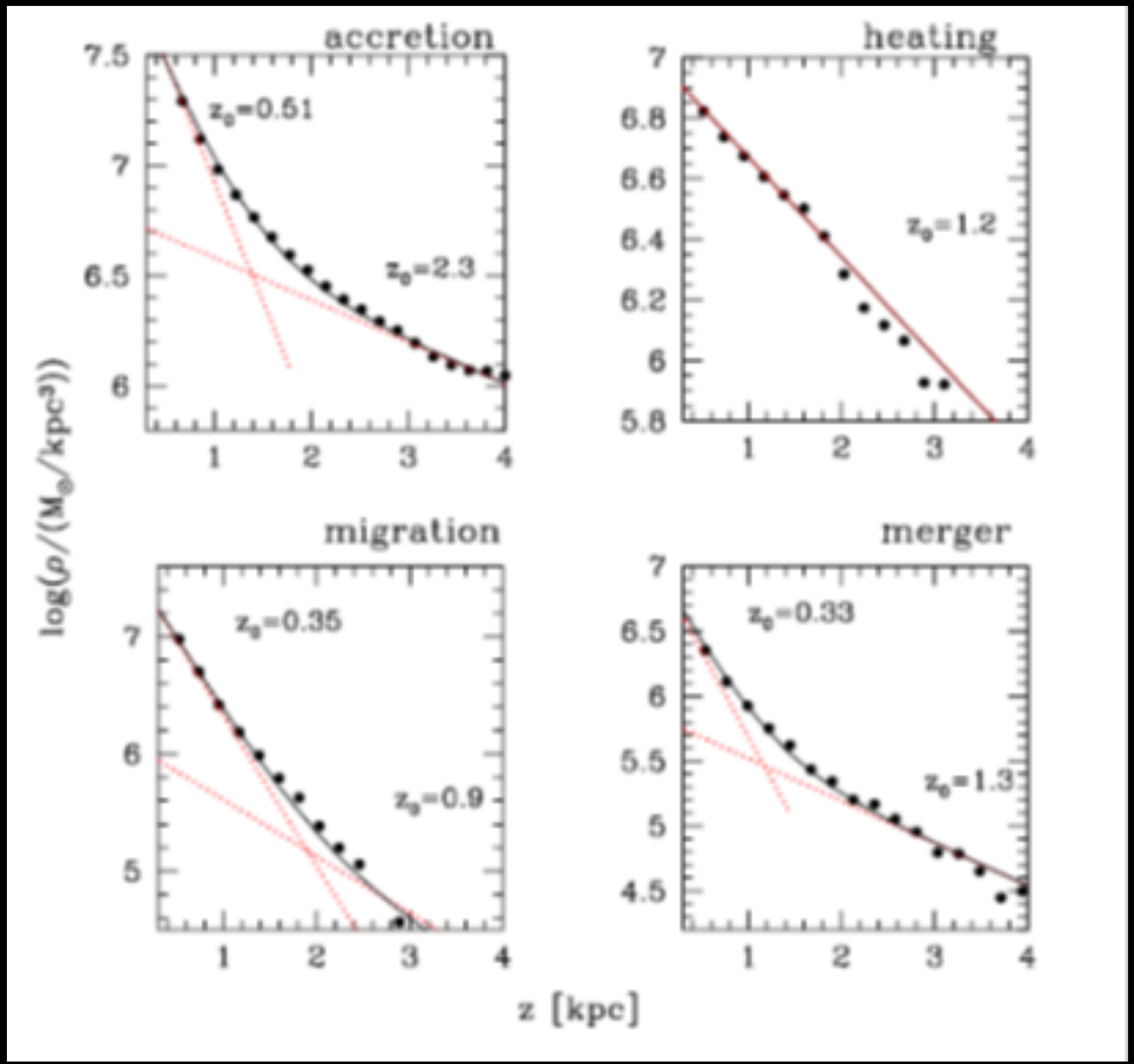
# Thin and Thick Disk Formation Possibilities




The Milky Way analog galaxy. Overlaid are colour curves that show the flares from groups of stars with similar ages. When all stars are put together, the disk has constant thickness, shown by the straight white lines.

**Thin Disk Evolution:**

The relation between the stellar age and the mean metallicity and velocity dispersion are the fundamental observables that constrain the chemical and dynamical evolution of the Galactic thin disk.



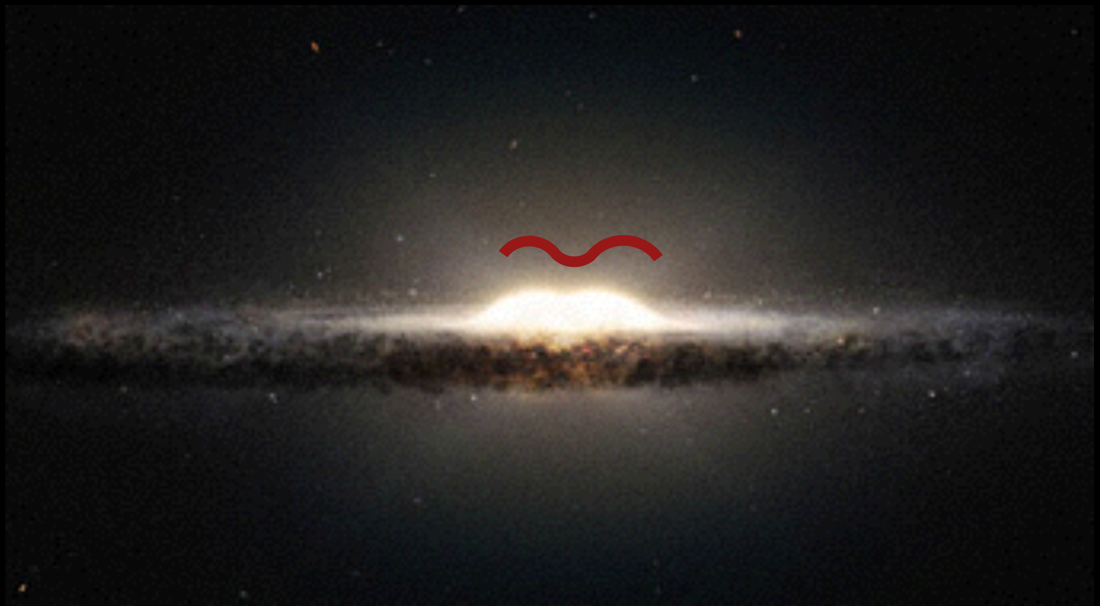

**Thick Disk Evolution:**

- A gas-rich merger followed by star formation
- Accretion from disrupted satellites (stars) on preferential directions (Abadi et al. 2003)
- Heating of early thin disk by accretion of a massive satellite
- Radial Migration: stars from the inner disk migrate out to larger radii

Credit: Adam Block, Mt. Lemmon SkyCenter, University of Arizona / Ivan Minchev, AIP
https://phys.org/news/2015-04-riddle-galactic-thinthick-disk.html

http://slideplayer.com/slide/10785059/

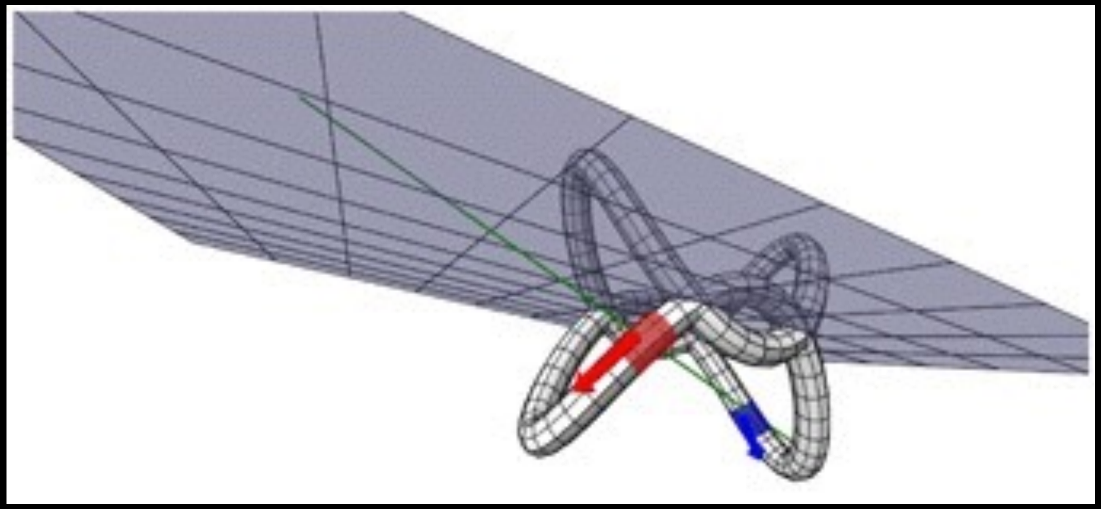
# The Bar, the Bulge, and the Black Hole



An extra-galactic alien view of the Milky Way shows a peanut-shaped bulge of stars at its centre.

http://www.skyandtelescope.com/astronomy-news/new-3d-maps-of-milky-ways-bulge/

| Bulge Properties |
| --- |
| - ~20% of the Milky Way's luminosity<br>- Bulge stars ~ circular orbits, large random velocities, mean rotational velocity ~100km/s |



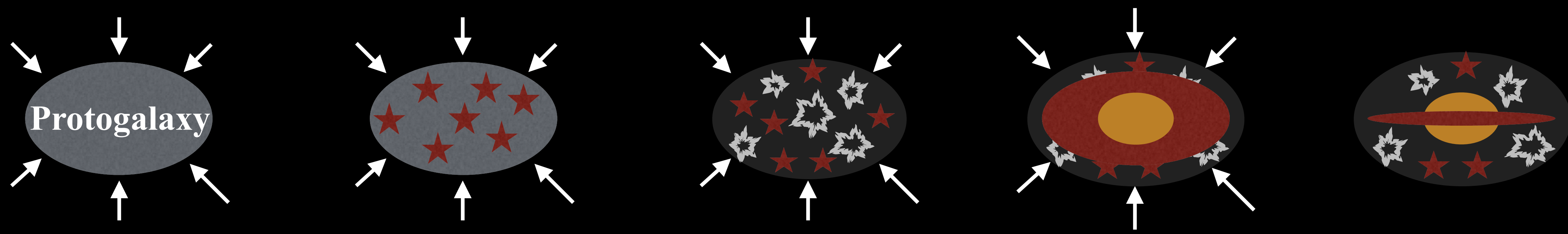
This sketch shows two such banana-like trajectories, outlining the peanut-shaped bulge. Courtesy Sergio Vásquez

Wegg: "Much of the physics of buckling or bending instability is due to what is known as the 'firehose instability. When the water flow from the hose is high, it will violently throw itself from side to side . . . The stars moving rapidly along the initially thin bar are like water travelling quickly through the fire hose."

"red clump" giants = cool horizontal branch stars that burn helium rather  than hydrogen in their cores

# Simplified Summary (ELS Model)

- based primarily on large scale gravitational forces; chemical compositions of stars; the rate at which stars are born and die; the rate at which the elements are produced by stars.




Spherical cloud of metal-poor gas born collapsing towards it’s centre

Metal-poor stars form as cloud collapses. Supernovae of this first generation produce a new generation of stars which contain metals.

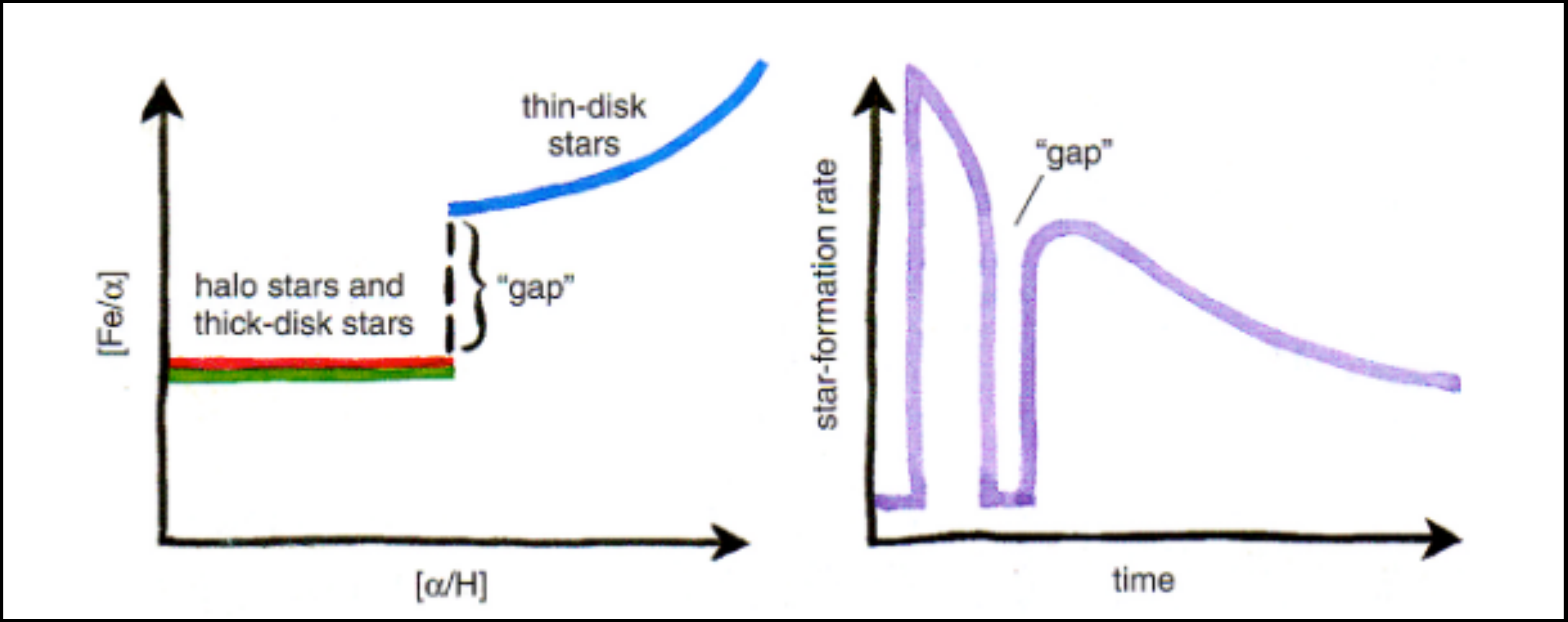
Stars follow eccentric orbits around centre of galaxy to maintain kinematic properties of the gas. Halo and Globular Clusters form.

Dissipative collapse causes contracting cloud to lose energy to heat. Rotational speed increases due to conservation of angular momentum. New stars, gas and dust fall inwards as disk forms.

Cloud collapses along rotational axis and becomes flatter. Disk formed. Gas in disk is metal-rich.

https://www.youtube.com/watch?v=n0jRObc7_xo

# Contradicting Evidence




http://www.astro.caltech.edu/~george/ay20/Chiappini-MilkyWay.pdf

Observations by Raffaele Gratton, of the Astronomical Observatory of Padova, Italy, and his colleagues, suggest that the rate of star formation decreased suddenly in the solar neighborhood fairly early in the Galaxy's evolution. A gap in the relative abundances of iron and the alpha elements (Left), such as oxygen, is interpreted as a period during which the star-formation rate in the Galaxy decreased (right)

# The Future of our Milky Way

"All galaxies start off small and grow by collecting gas and quite efficiently turning it into stars. Then every now and then they get completely cannibalised by some much larger galaxy."

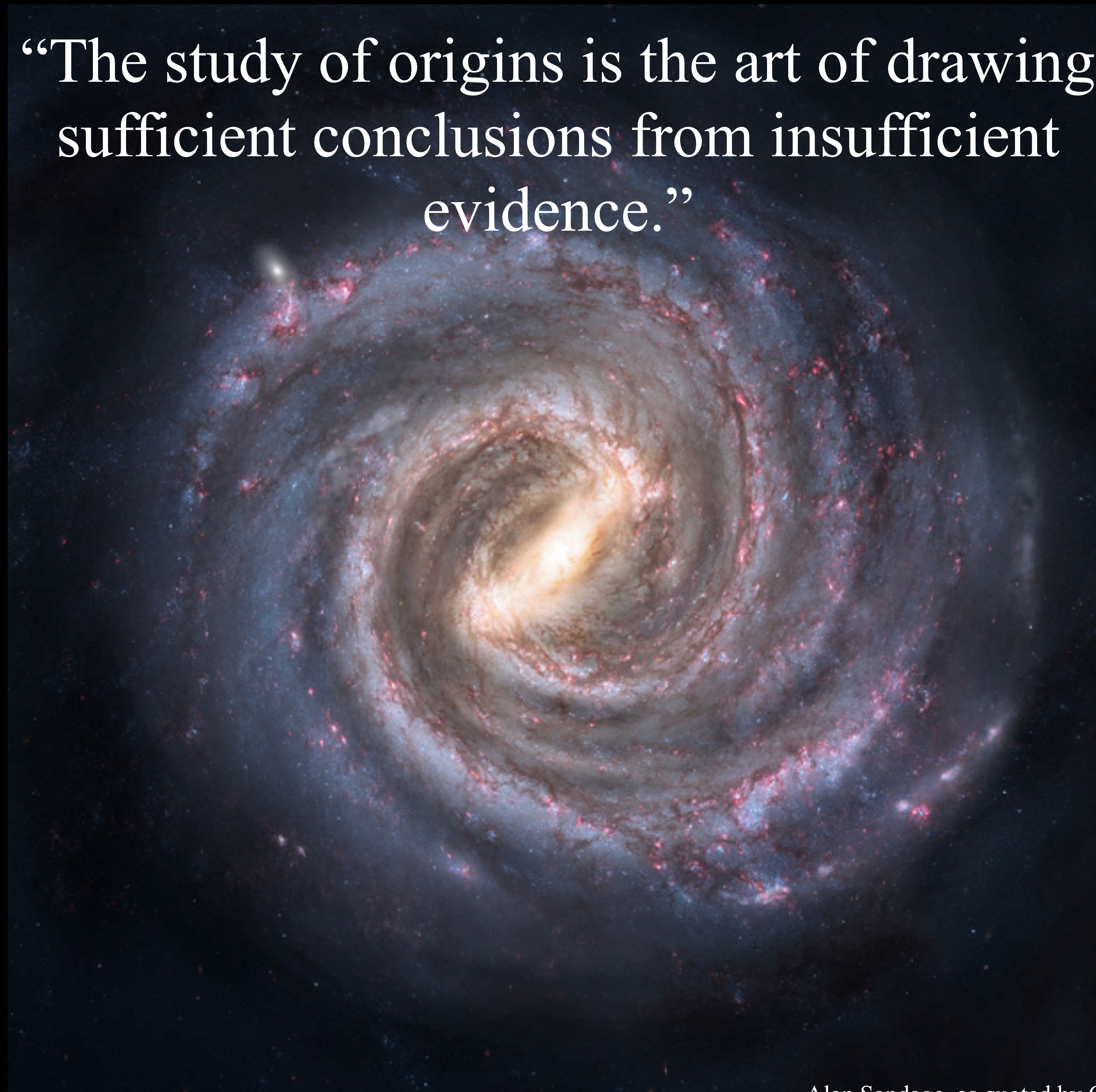
Dr Aaron Robotham

Galaxy Evolution Explorer image of the Andromeda Galaxy.

GAMA | ICRAR International Centre for Radio Astronomy Research

Merging galaxies from the Galaxy and Mass Assembly (GAMA) Survey

https://www.youtube.com/watch?v=IOasNeWWAQc




Alan Sandage, as quoted by Chiappini op cit., p. 515

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# Sources Used


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General Information about the Thin and Thick Disk:
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Mapping the Milky Way’s Bulge:
http://www.skyandtelescope.com/astronomy-news/new-3d-maps-of-milky-ways-bulge/

Beryllium Observations to work out the age of the Milky Way:
http://www.eso.org/public/news/eso0425/