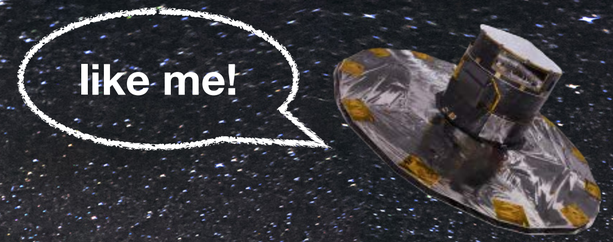
# Galactic Archaeology

## in the era of large surveys

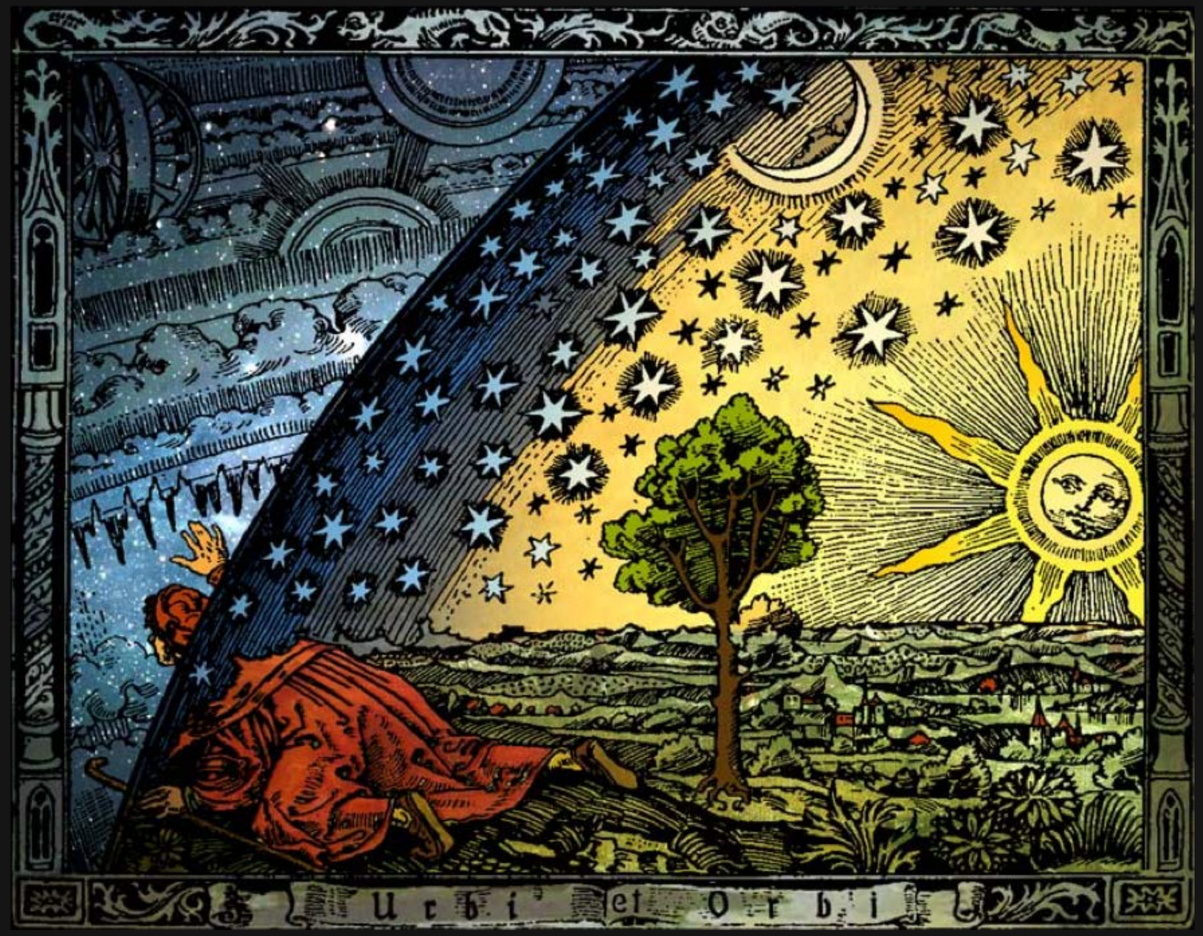





GyuChul Myeong

# Outline

- **What we want to know**
- **(Dynamical) Overview of our Milky Way**
  - Components of the Galaxy
- **Various dynamical features**
  - Kinematics & Dynamics
  - Virial Theorem
  - Orbit & Integrals-of-motion
  - Stellar stream
  - Dynamical Friction
- **Chemo-dynamical analysis**
  - Halo Structure & Substructure
  - in situ & ex situ populations
  - Chemo-dynamical view of Galactic components

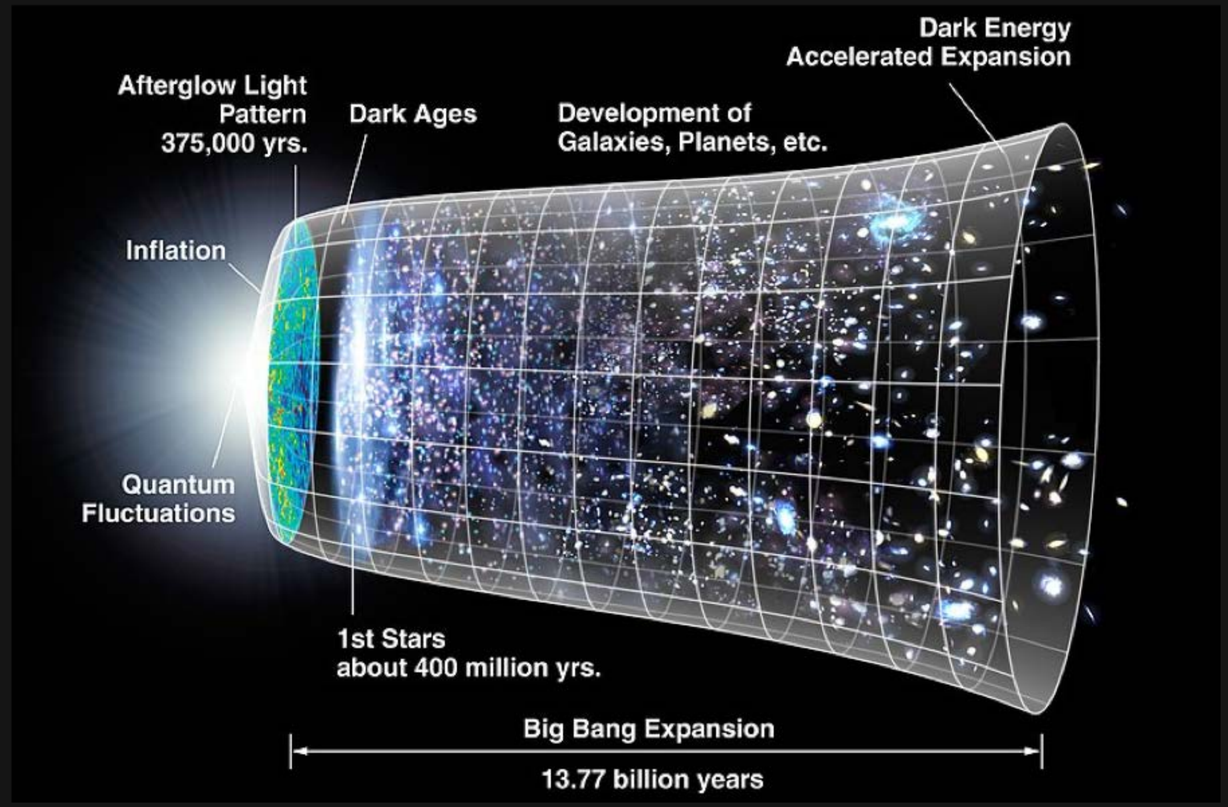


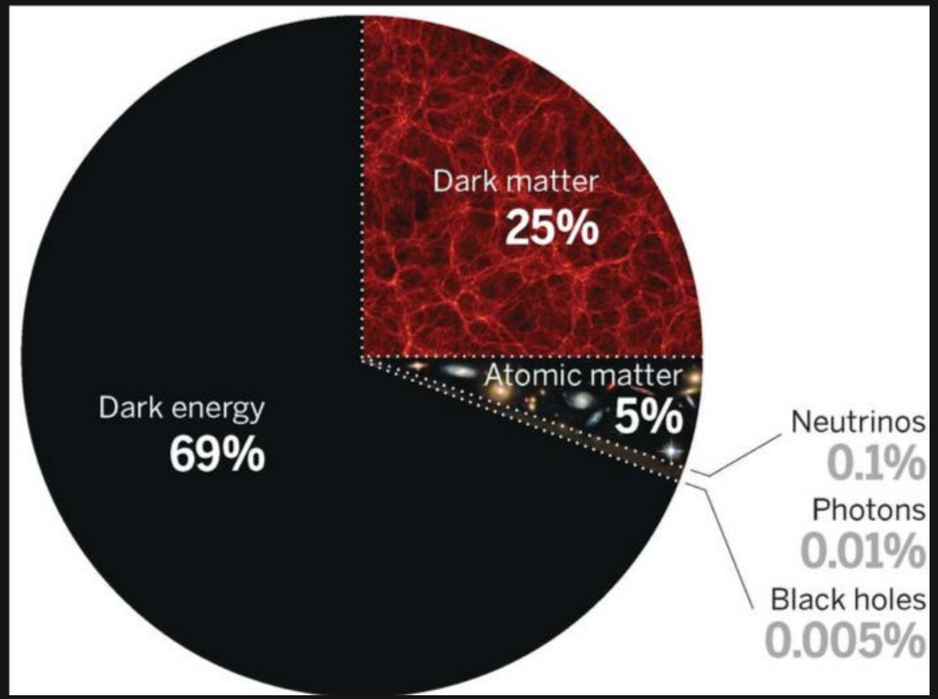
# Lecture 7

- **What we want to know**
  - Testing physics in Galactic scale
  - Milky Way as a test site
- **(Dynamical) Overview of our Milky Way**
  - Stellar Disc(s) & Spiral arms
  - Bar & Bulge
  - Stellar Halo & Streams
  - Dark Halo & Rotation curve

# Current Cosmological Model

- **Λ Cold Dark Matter Model** as the “standard” model
  - Big Bang (with inflation)
  - Dark energy and Dark matter
- The simplest model that provides a reasonably good description of the cosmos



# We want more detailed test!

- **Near-field Cosmology: ΛCDM in galactic scale**

  → Validating & Fine-tuning the ΛCDM

  → **Galactic Archaeology**

  - Detailed Galaxy formation / evolution
  - Retracing the “building blocks” of the Galaxy
  - Structural (morphological), kinematical, chemical evolution

  - Law of Gravity
    - Galactic rotation curve
  - Dark matter
    - Dark matter structures? (filaments? subhalos?)
    - Dark perturber?
    - Direct detection?

# Galactic Assembly history

- Some things to think about:
  - What are the physical processes governing the galaxy formation/evolution?
  - What is the typical timescale?
  - How well is it portrayed by the current ΛCDM picture?

✴ Milky Way provide various tracers (e.g., stars, streams, GCs) with great details & precision

→ How has the Galaxy been formed & evolved?

→ How has Galactic components (e.g., disks, bulge, bar, halo) been assembled?

→ Any traces of dark matter? Any possible constraints?

✓ Is the Milky Way atypical?

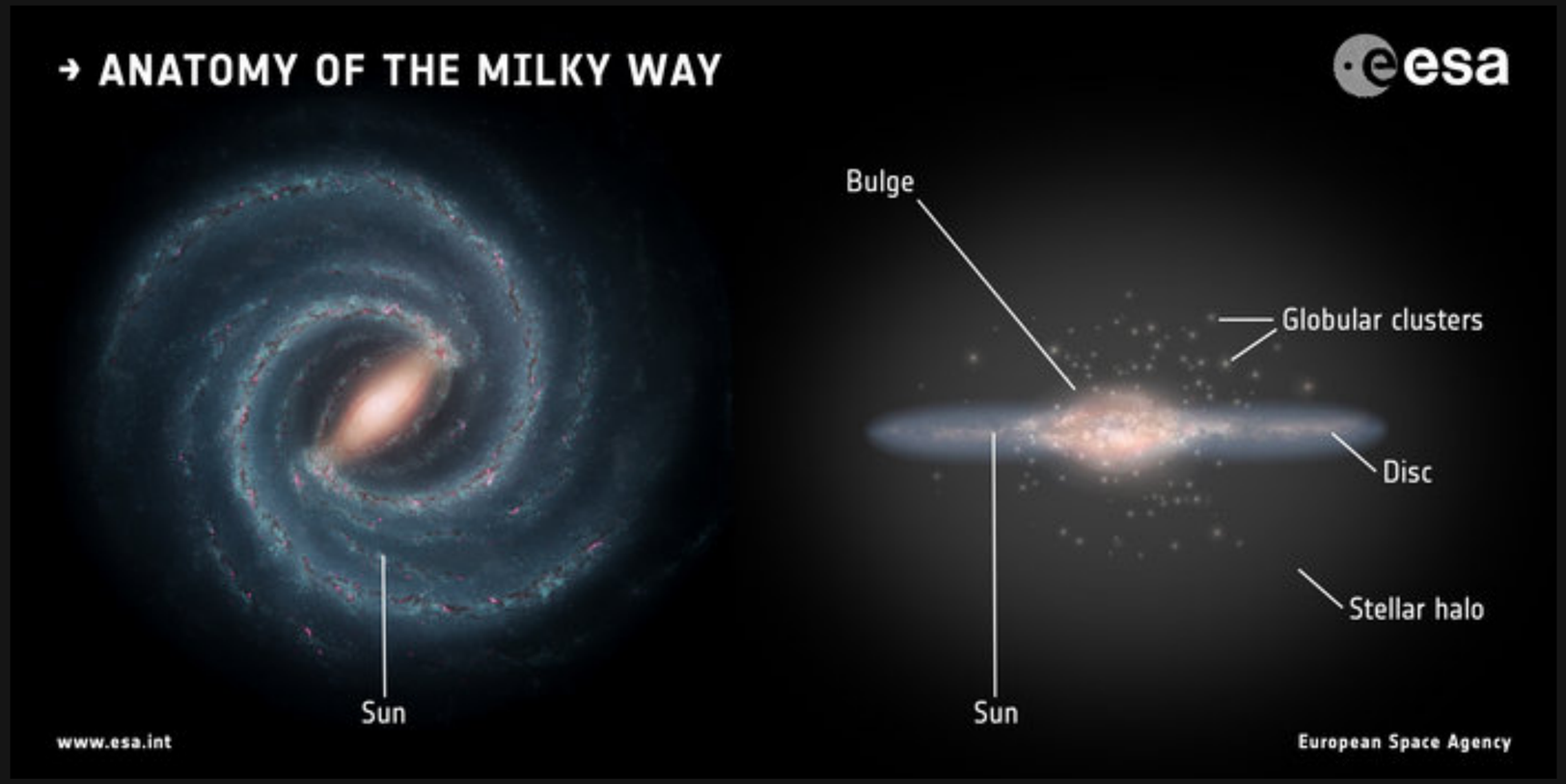
- Mass-wise not particularly: many galaxies with comparable mass (& similar morphological type)
- Assembly history-wise probably: a major merger ~10 Gyr ago, quiet since then

# Some unusual units

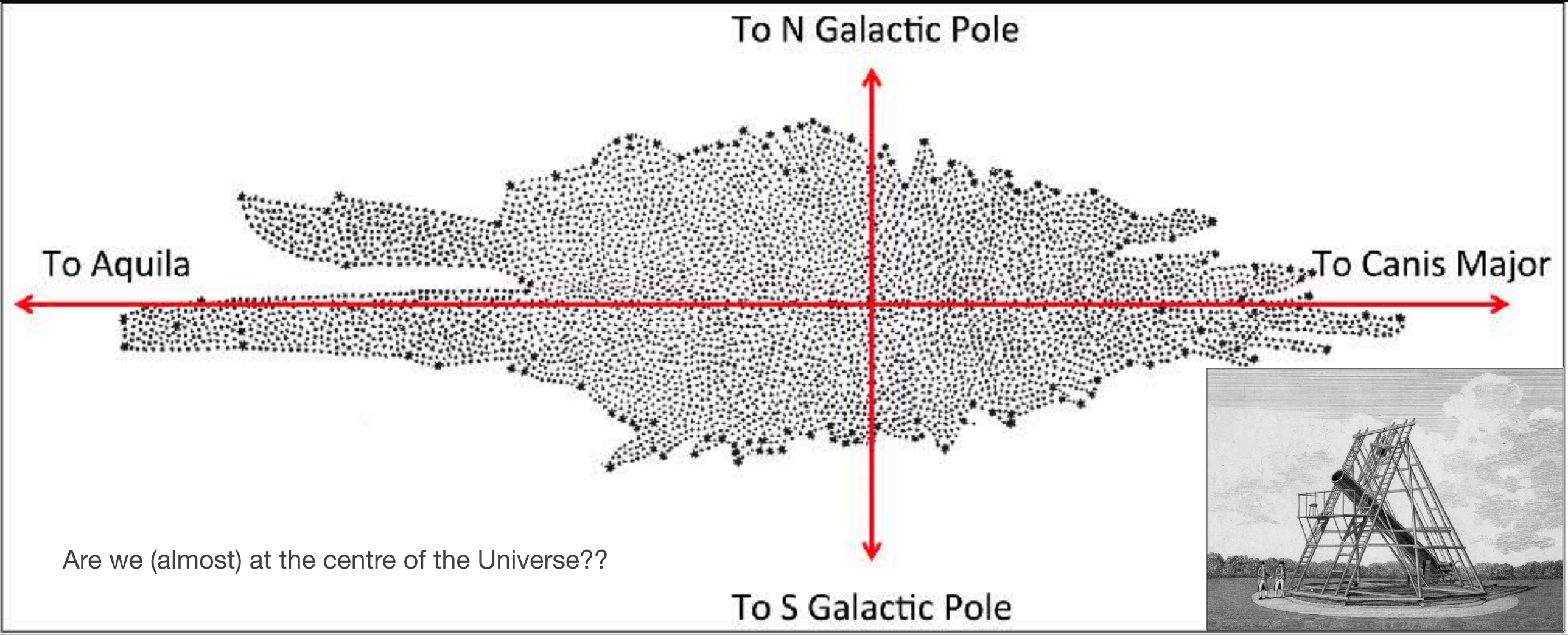
- Spatial
  - $1\,\mathrm{kpc} = 1000\,\mathrm{pc} = 3261.56\,\mathrm{ly} = 3.086 \times 10^{16}\,\mathrm{km}$
  - $1\,\mathrm{degree} = 60\,\mathrm{arcminute} = 3600\,\mathrm{arcsecond}$
- Time
  - $1\,\mathrm{Gyr} = 10^{9}\,\mathrm{yr}$
- Mass
  - $1\,\mathrm{M}_{\odot} = 1.989 \times 10^{30}\,\mathrm{kg}$

# Our Milky Way

- **A brief story…**
  - (Large) collection of stars, gas, dust, and dark matter, comprising $\sim 1.5 \times 10^{12}\,\mathrm{M}_{\odot}$ ($M_{*} \sim 6 \times 10^{10}\,\mathrm{M}_{\odot}$)
  - Gravitationally bound & orbit around the galactic centre
  - Various components: Disc(s), Bulge, Bar, Halo(s)



# Herschel's Star-gaging




Are we (almost) at the centre of the Universe??

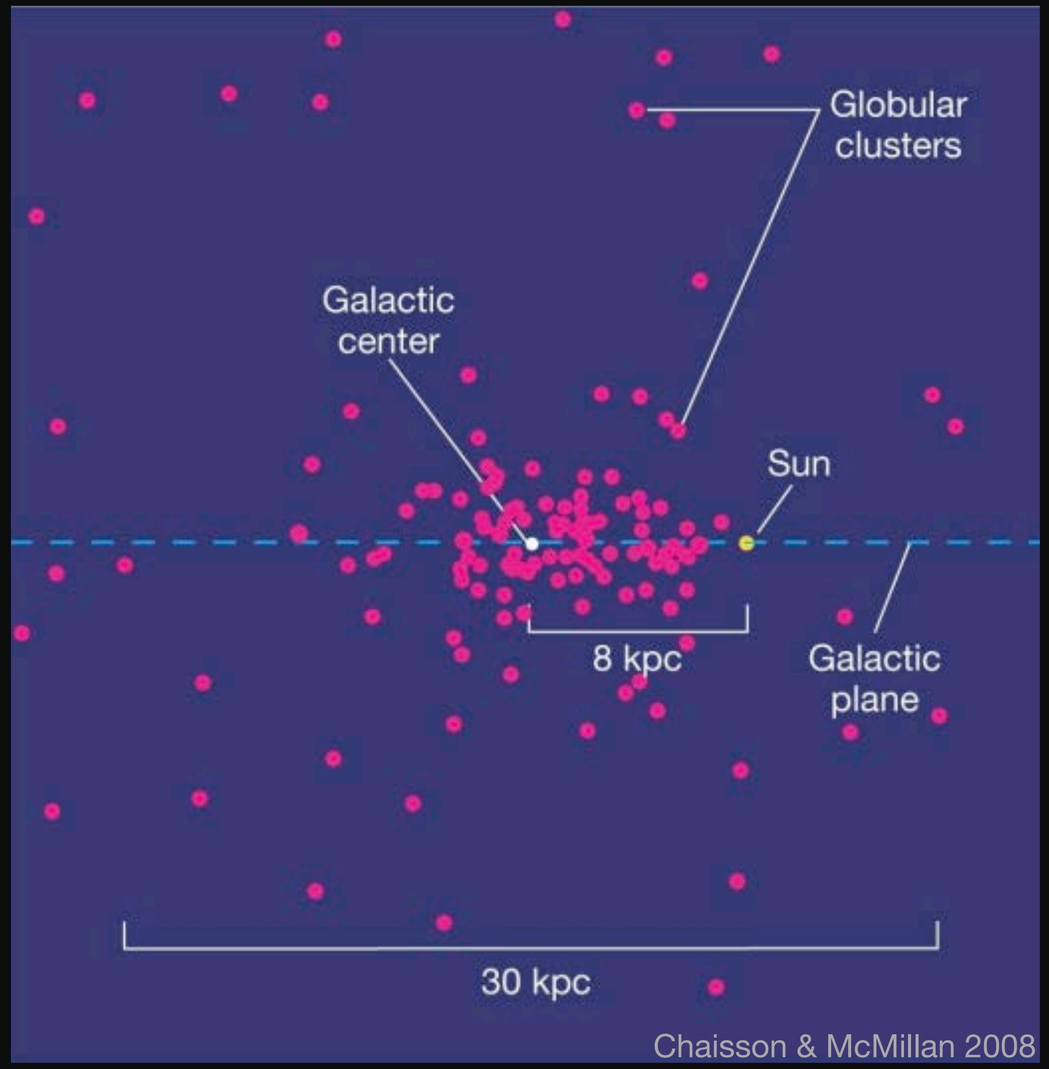
# Shapley's Cluster-gaging

- Globular clusters

  → much easier to detect (more complete)

  - observed uniformly above & below the Galactic plane
  - more concentrated towards a certain direction

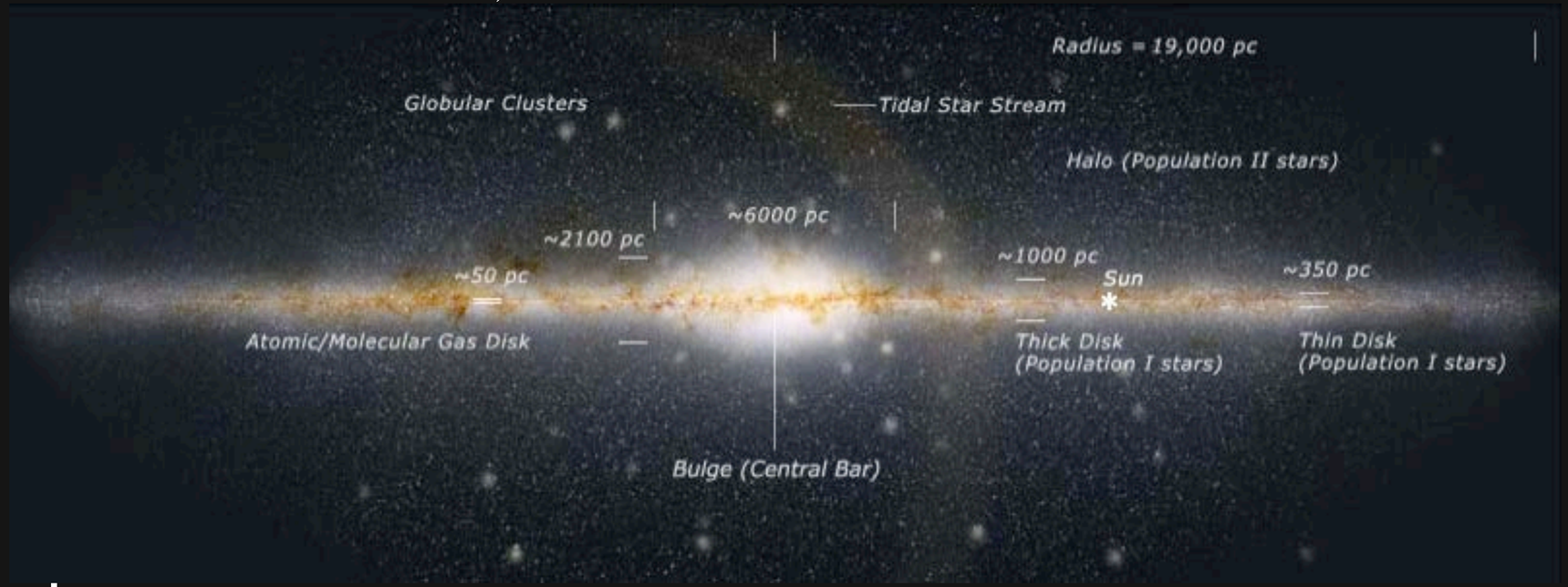
  → We are not at the centre: Shapley's estimate to be ~15kpc away from the centre (in fact, ~8.2kpc)



Chaisson & McMillan 2008

# Stellar discs

- **A brief story…**
  - Composed of stars roughly on circular orbits with coherent rotation around the centre
  - Kinematically cold & rotationally supported! (i.e., flattened, rotating structure)
  - Density of stars drops exponentially, $\rho(R,z) = \rho_0\, e^{-z/z_0}\, e^{-R/h}$, where $z_0$ is scale height; $h$ is scale length (i.e., “scale” distance where the density drops to $1/e$)
  - Thin disc: thin (scale height, $z_{0,thin} \sim 0.3\,\mathrm{kpc}$) & more extended, younger stars
  - Thick disc: thick(er) (scale height, $z_{0,thick} \sim 0.9\,\mathrm{kpc}$), older stars



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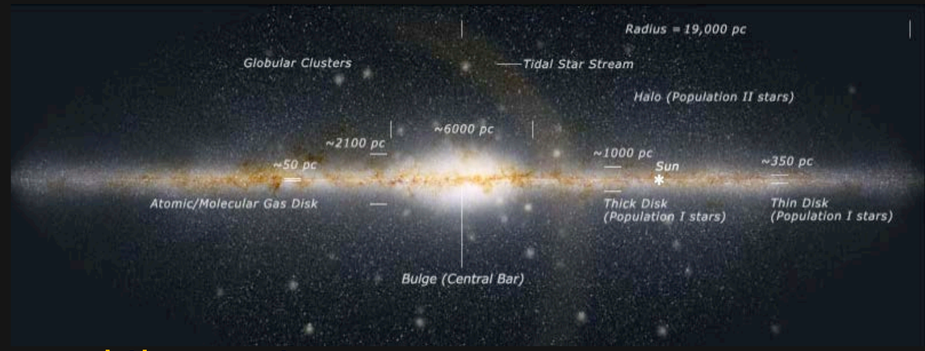


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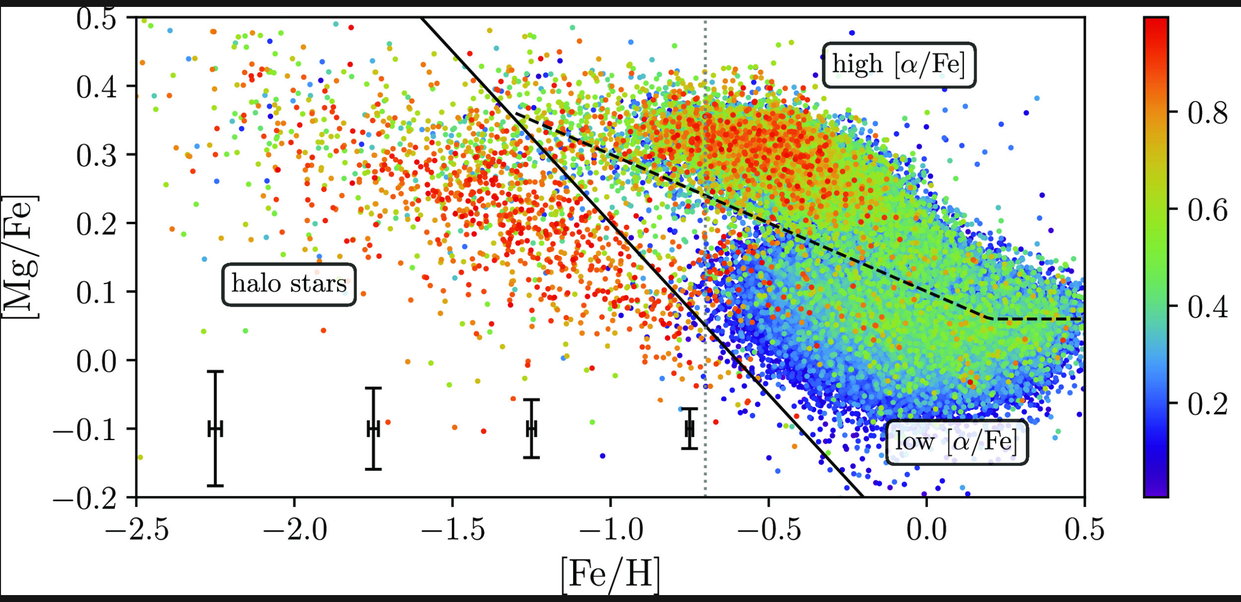
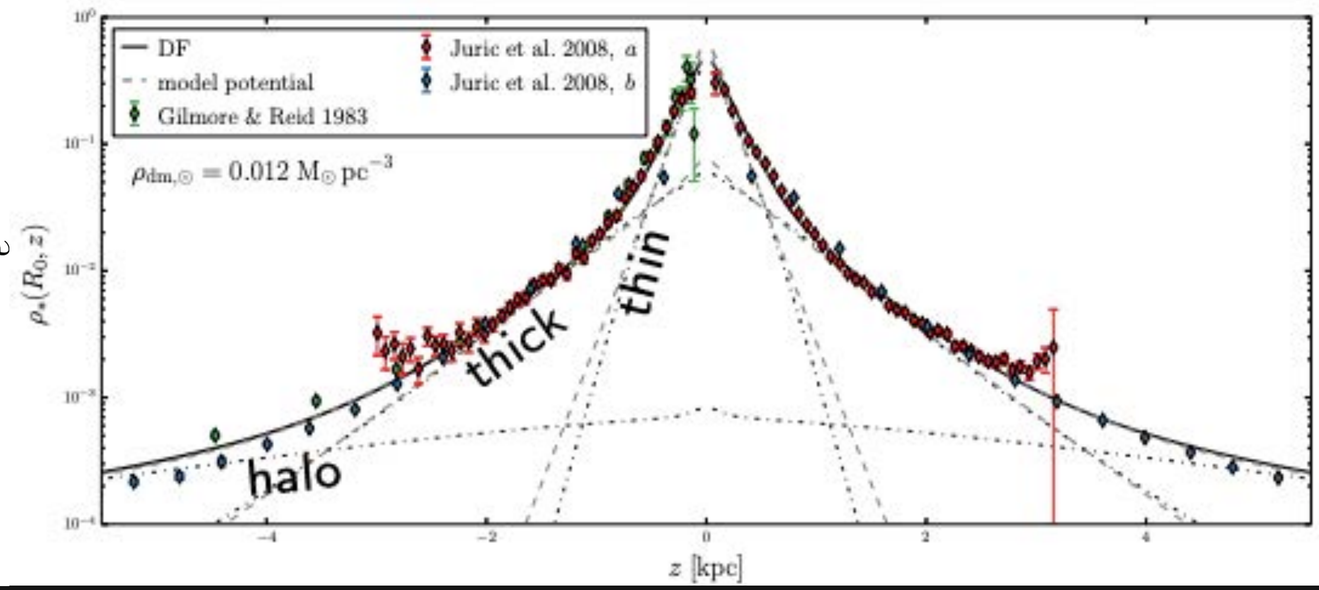
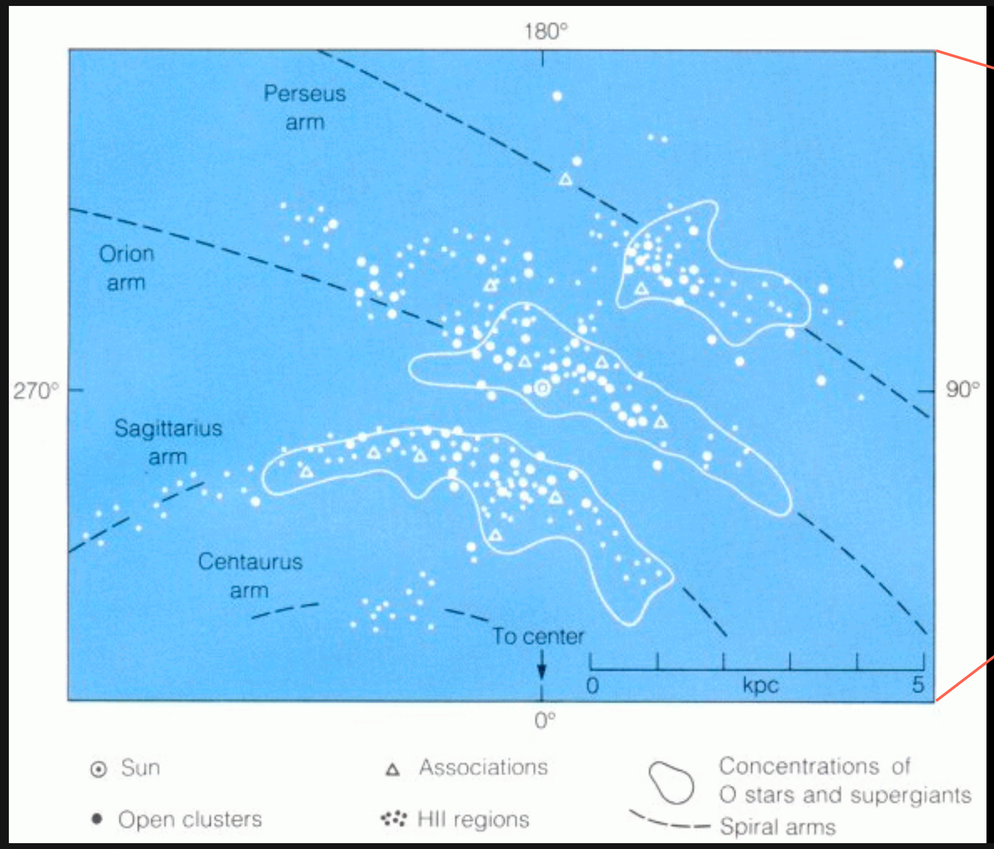
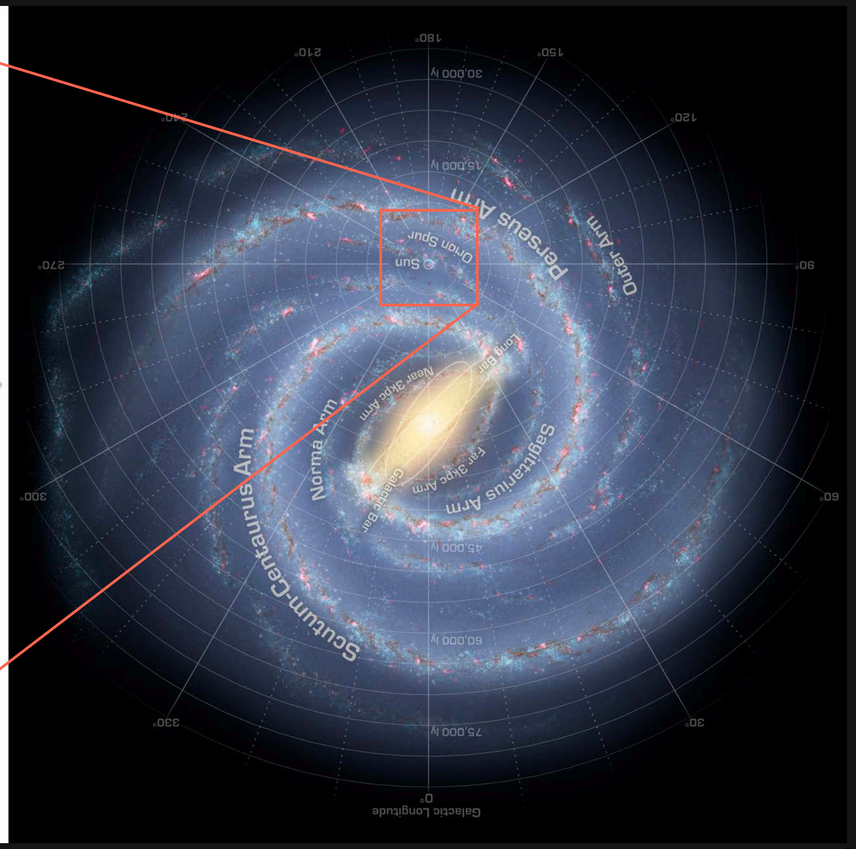


# Stellar discs

- **Spiral arms**
  - Long, thin regions of stars and gas extending from the galactic centre
  - Mostly young, blue O/B stars (hot massive stars, efficient star formation) → short lifetime << galactic dynamical time
  - Can be traced with young stars, molecular clouds (e.g., Gaia provides motions for thousands of open clusters!)

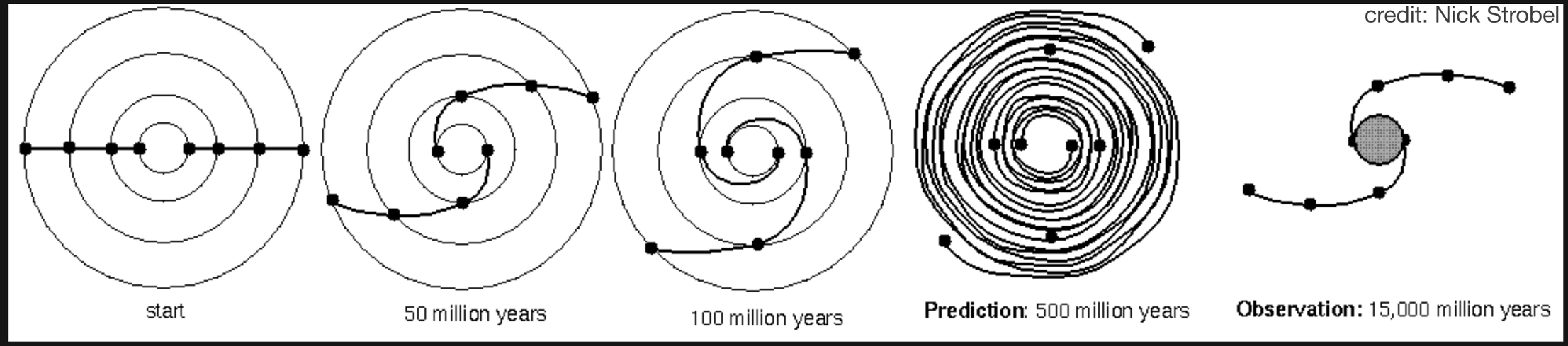


# Stellar discs

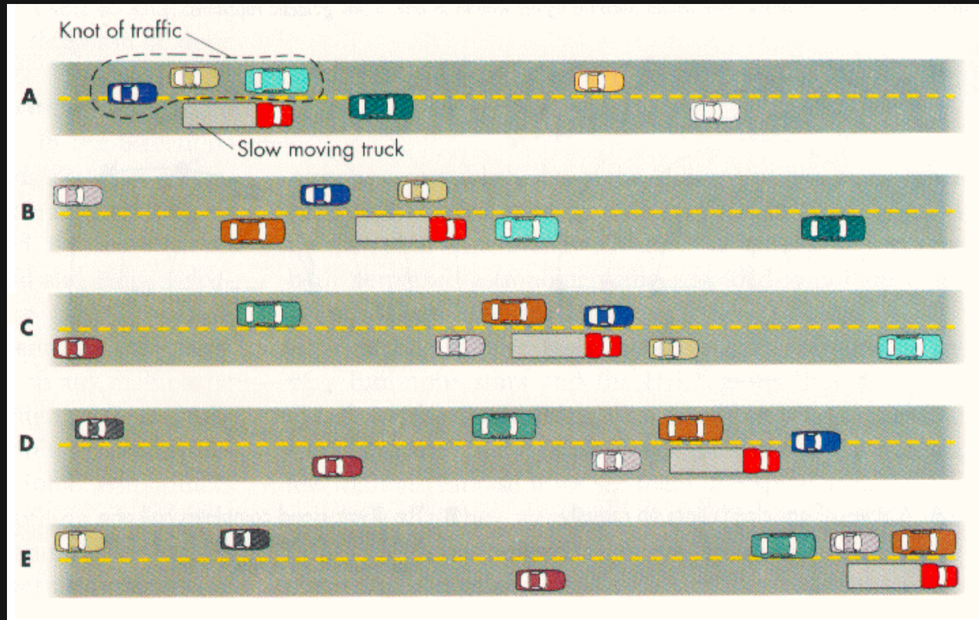
- **Spiral arms' Winding dilemma**
  - Galaxy is not rotating like a solid body
  - Spirals trail Galactic rotation
  - Differential rotation can produce spirals but quickly wind it up to tighter spirals!

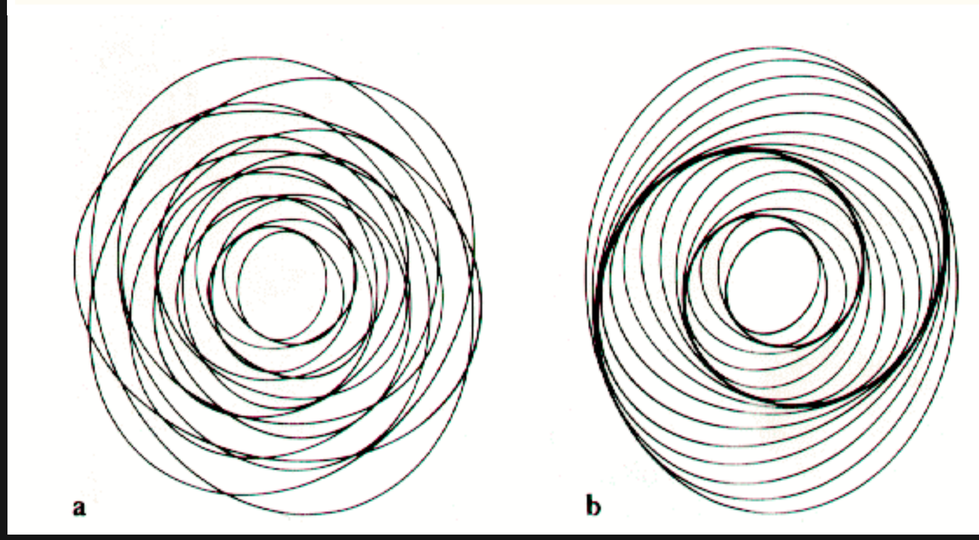
    → This clearly is not what we see… this is not how the spiral arms are supported



# Stellar discs

- **Spiral arms and Density wave theory**
  - Imagine a slow moving vehicle causing a local traffic jam…
  - Slow orbiting gas cloud in the arm builds up overdensity in the region
  - Exerting gravitational influence on local stars and gas orbiting the Galaxy
  - Density patterns move… a wave of overdensity moving through the disc
  - Concentration of gas → triggers star formation → HII regions and young star clusters → drift out from the spirals over the time
  - But what forms such density waves in the disc in the first place?



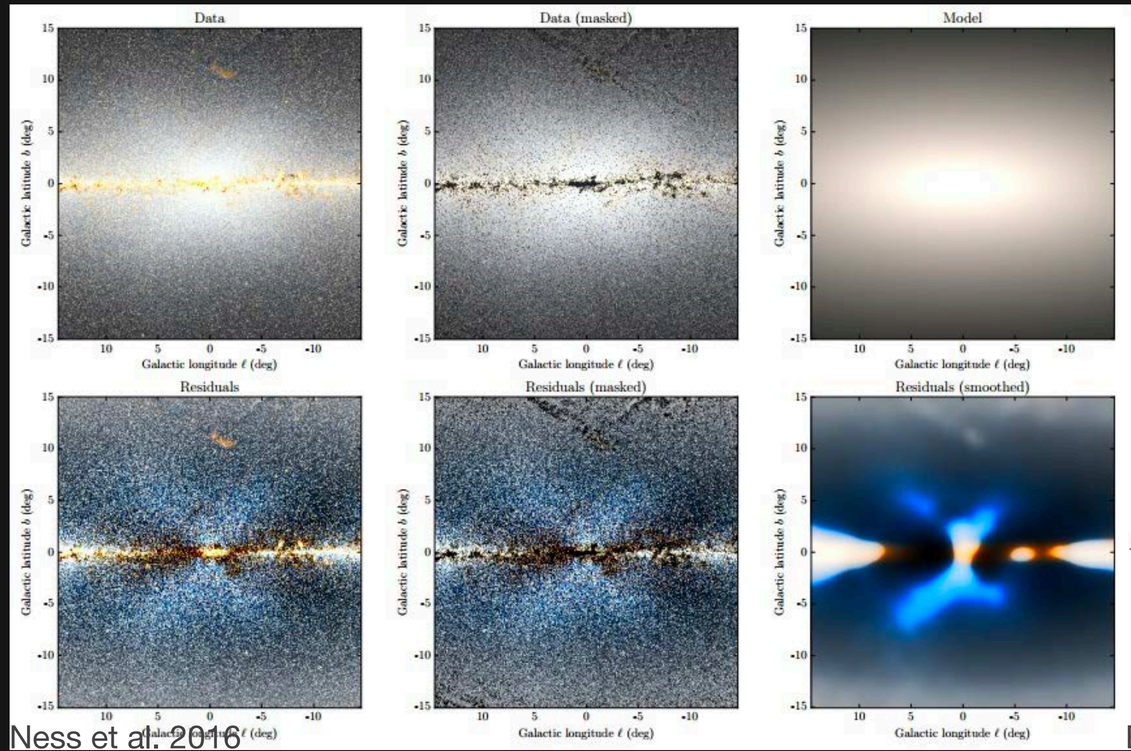



# Bar & Bulge

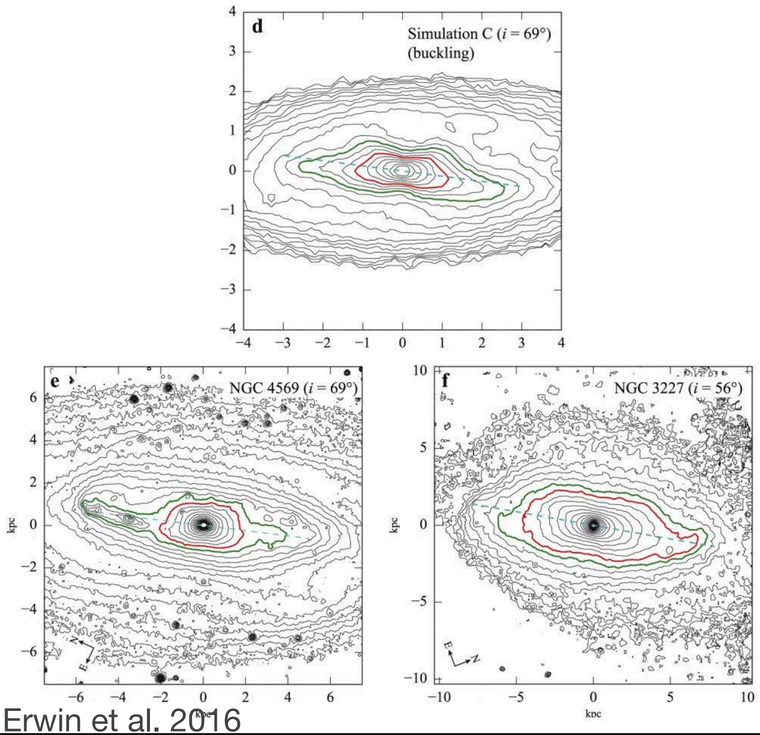
- **Bar**
  - Commonly found in spiral galaxies including the Milky Way
  - Forms through (pre-existing) Disc instability → various scenarios (e.g., a galactic merger event?)
  - Stars stay in the bar and move along the bar! → not a density wave!
    - Gas can lose angular momentum, compressed at the edge of the Bar
    - Funnels gas along the bar, all the way to the galactic centre → can fuel the inner MW
    - Can be the driver of a density wave in the disc
  - Bar grows/disappears, and rotates too! → pattern speed ($\Omega_B \sim 32\,\mathrm{km\,s^{-1}\,kpc^{-1}}$)

# Bar & Bulge

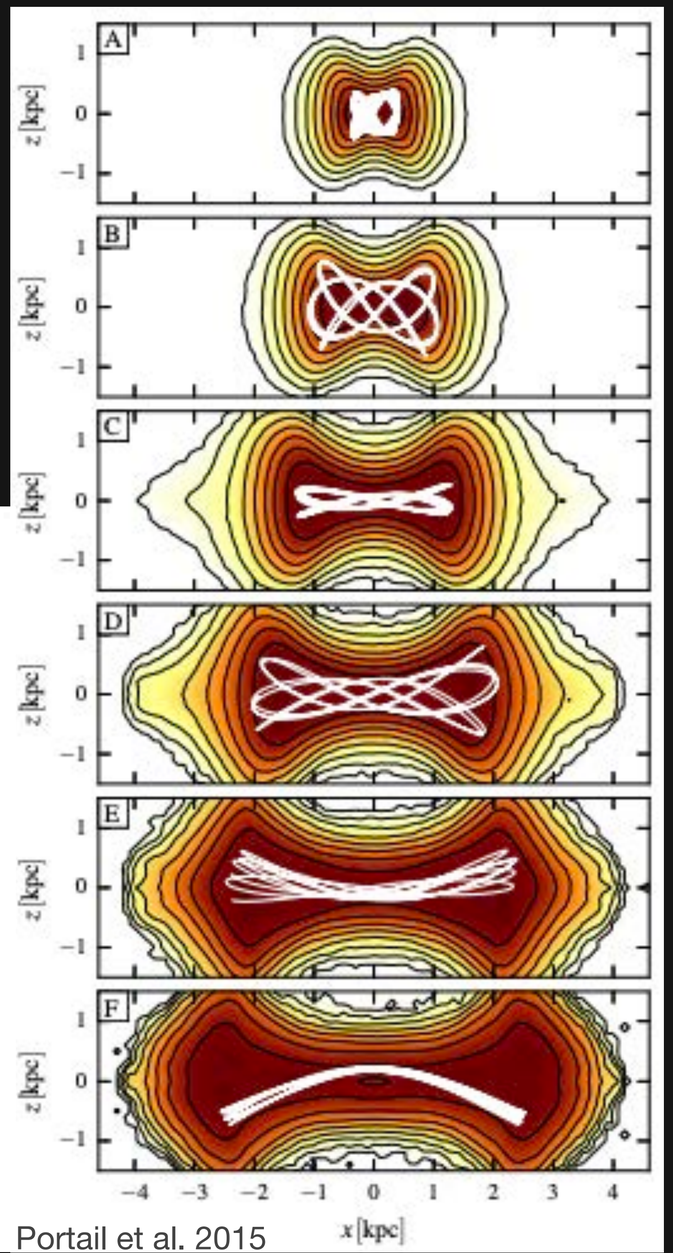
- **Boxy/Peanut bulge**
  - Also commonly found; Observational evidences in the MW (incl., double red-clumps!)
  - Dynamical origin from the (pre-existing) Bar
  - “Buckling” as a result of the tension the Bar experiences from its ends




Ness et al. 2016




Erwin et al. 2016




Portail et al. 2015

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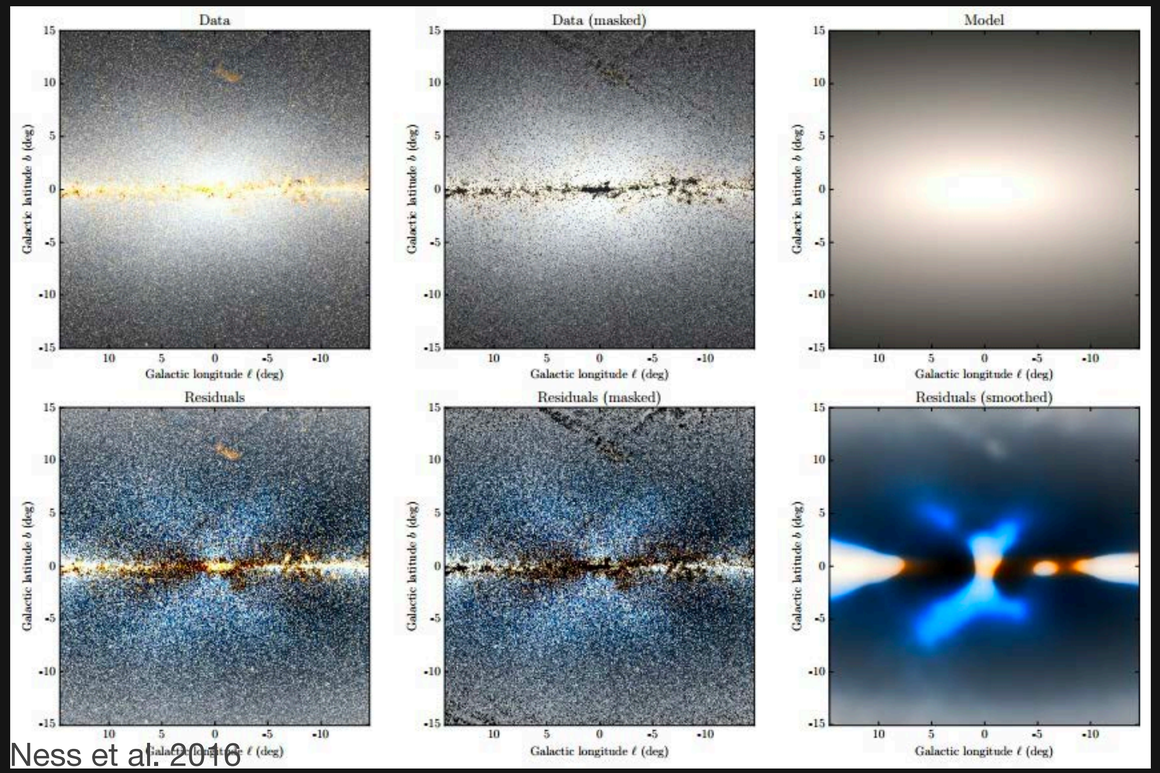


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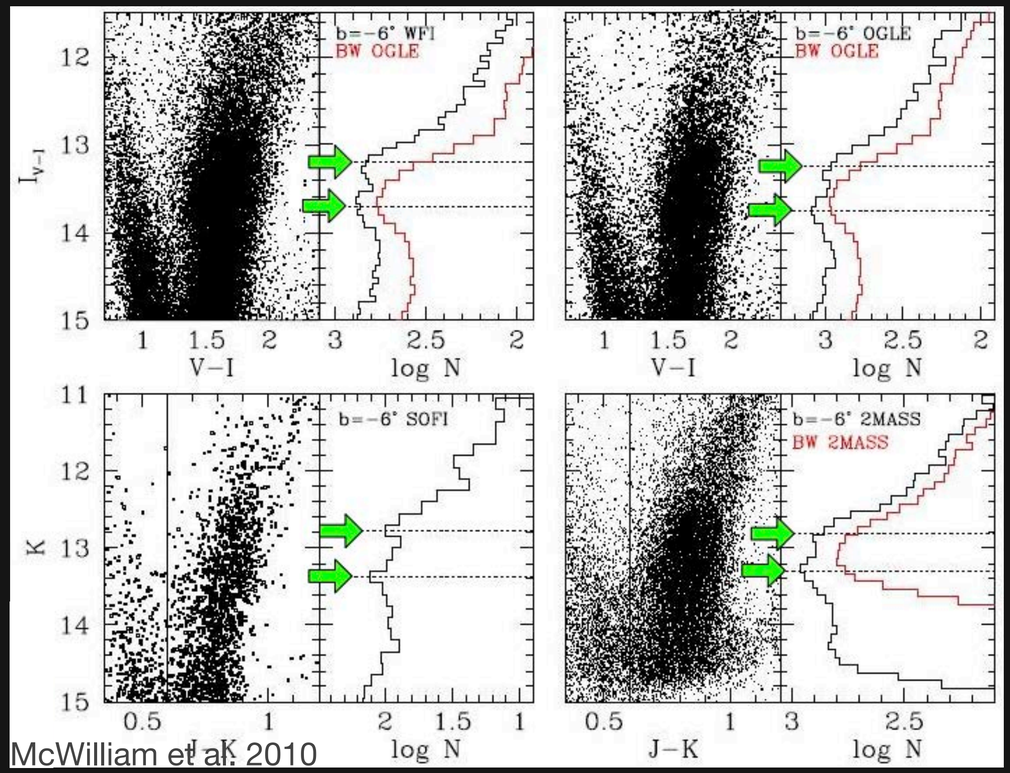
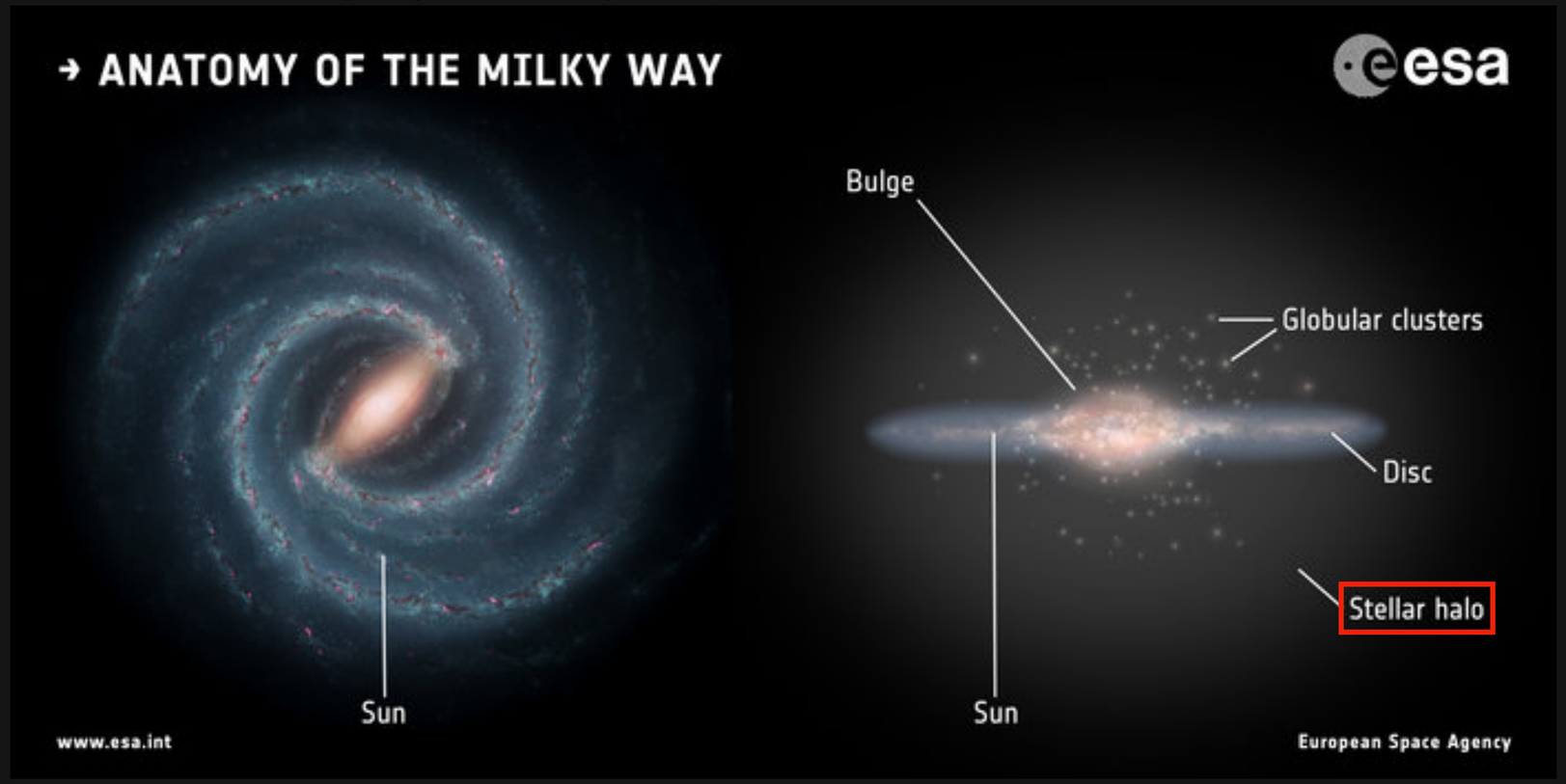



McWilliam et al. 2010

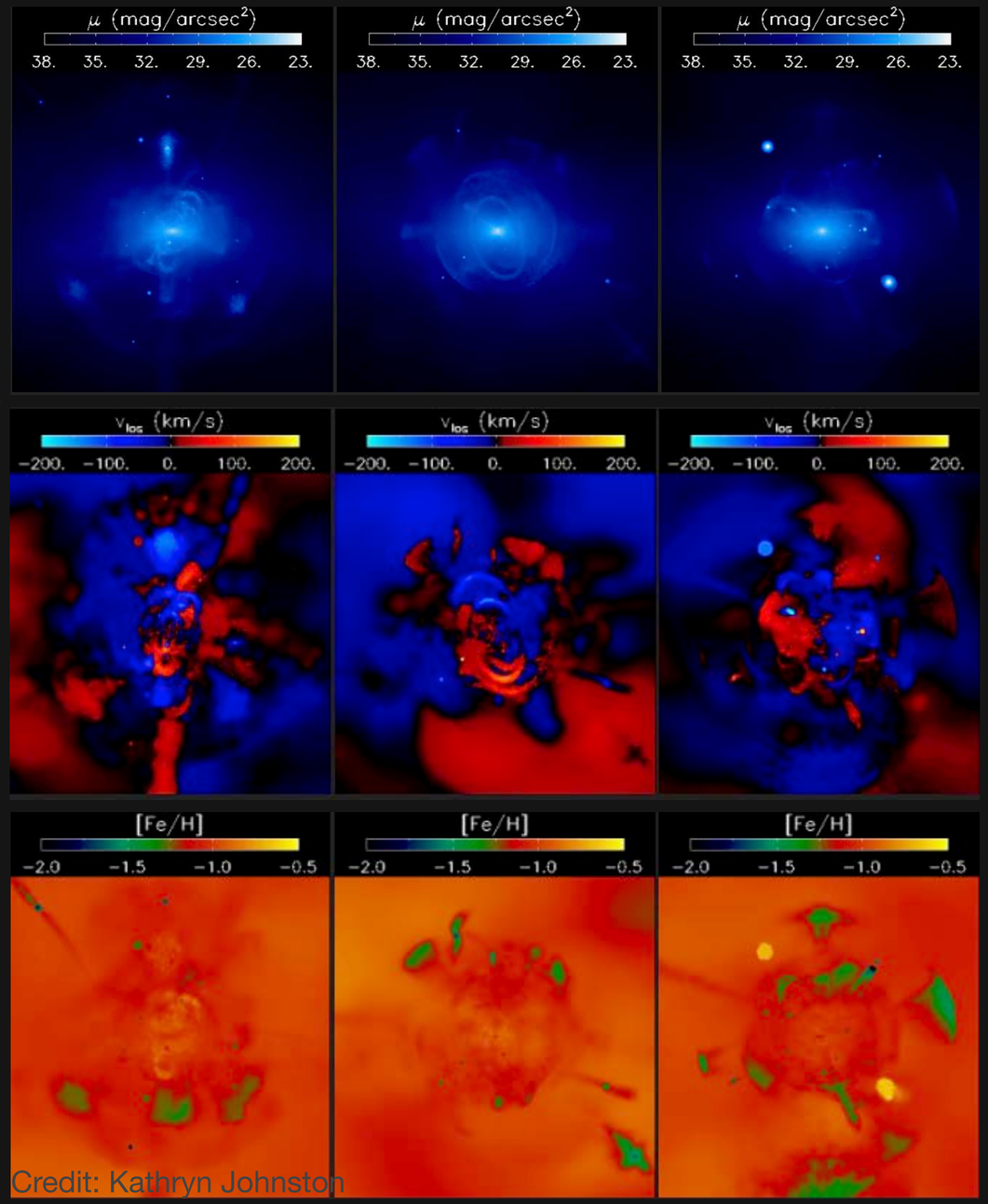
# Milky Way's Stellar Halo

- **A brief story…**
  - (mostly) Old, (mostly) metal-poor stars
  - Very low stellar density, $\sim 10^9\,\mathrm{M}_\odot$ ( ~1% as globular clusters, rest as field stars)
  - Supported almost entirely by velocity dispersion



# Stellar Halo

- **Interesting Origin!**
  - Mainly formed by **extragalactic** materials from hierarchical accretion/merger in the past!
- Structure / substructure → direct reflection of the assembly history
- Excellent tracer for dark matter halo to large Galactic radii
- Possible to obtain full 6-dimensional phase space & various chemical abundance information



Credit: Kathryn Johnston

# The Birth of Stellar Halo

- Dissipative collapse of gas? (Eggen, Lynden-Bell & Sandage 1962)
  - Older stars possess more eccentric orbit (but heavily biased sample…)
  - Rapid, radial (free-fall) collapse of gaseous contents toward the galactic centre
    → smooth spheroidal distribution?
- Hierarchical mergers/accretions of extragalactic fragments?
  (e.g., Searle & Zinn 1978; Lynden-Bell & Lynden-Bell 1995; Abadi et al. 2006)
  - Metallicity abundance of outer halo globular clusters (less biased sample…)
    → independent of Galactocentric distance
  - ΛCDM simulations
    → galaxy formation by accretion of numerous low mass fragments
  - Tidal disruption of accreted satellites (*ex situ*!)
    → stellar streams

# Field of Streams

- Halo is full of substructures
  - Satellite body orbiting the host → dynamical evolution (tidal disruption)
    - e.g., stellar streams → leading and trailing arms roughly tracing the orbital path
  - Long relaxation time
    - present day kinematics more likely to reflect their initial condition
  - Large all-sky surveys revealed the "Field of Streams" (Belokurov et al. 2006)
    - mostly found by analysing the spatial coherence of member stars
    - many more to be found with deeper survey