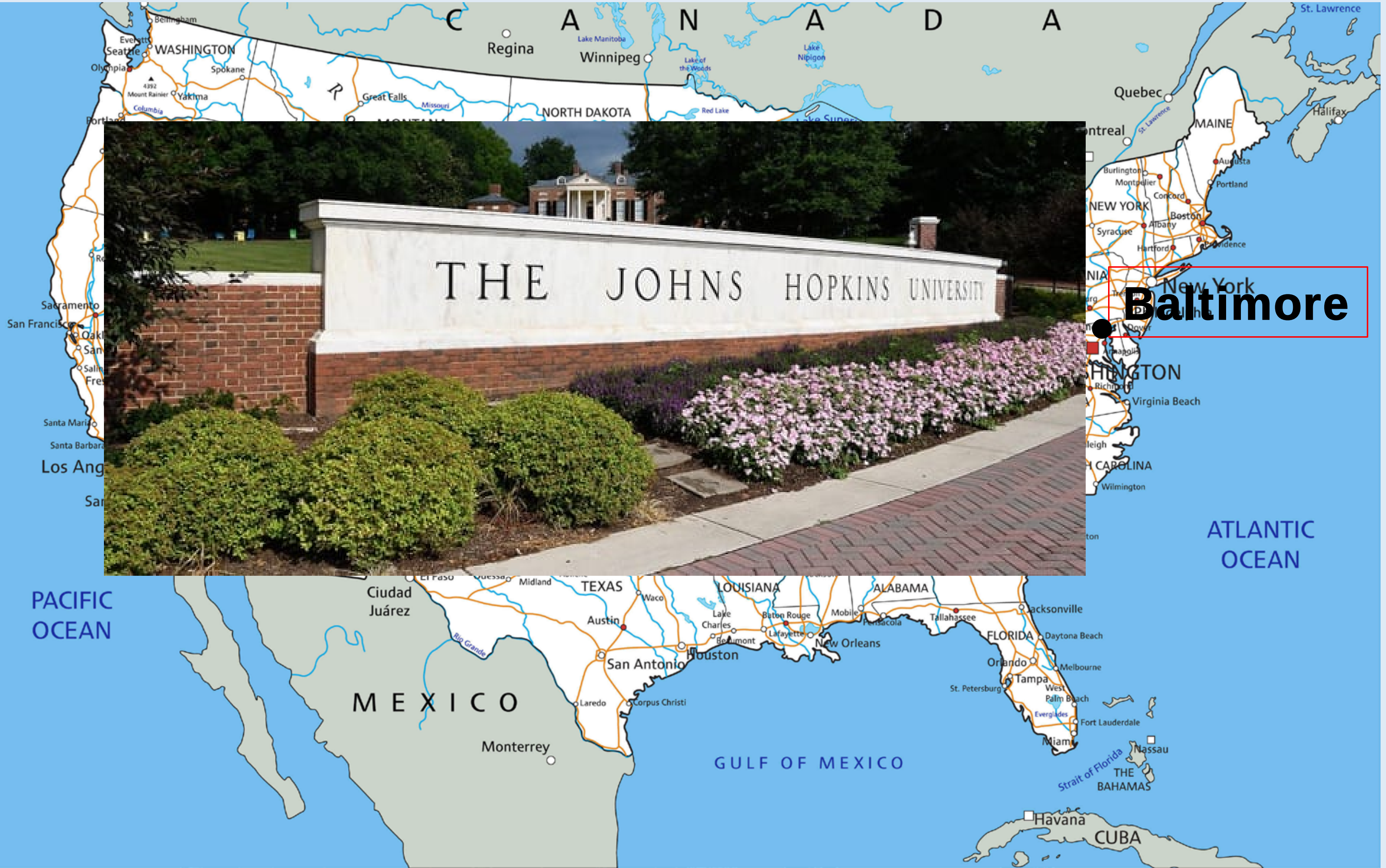
SCHMIDT FUTURES

The Cosmological Context of our Local Group of Galaxies

Rosemary Wyse

JOHNS HOPKINS UNIVERSITY

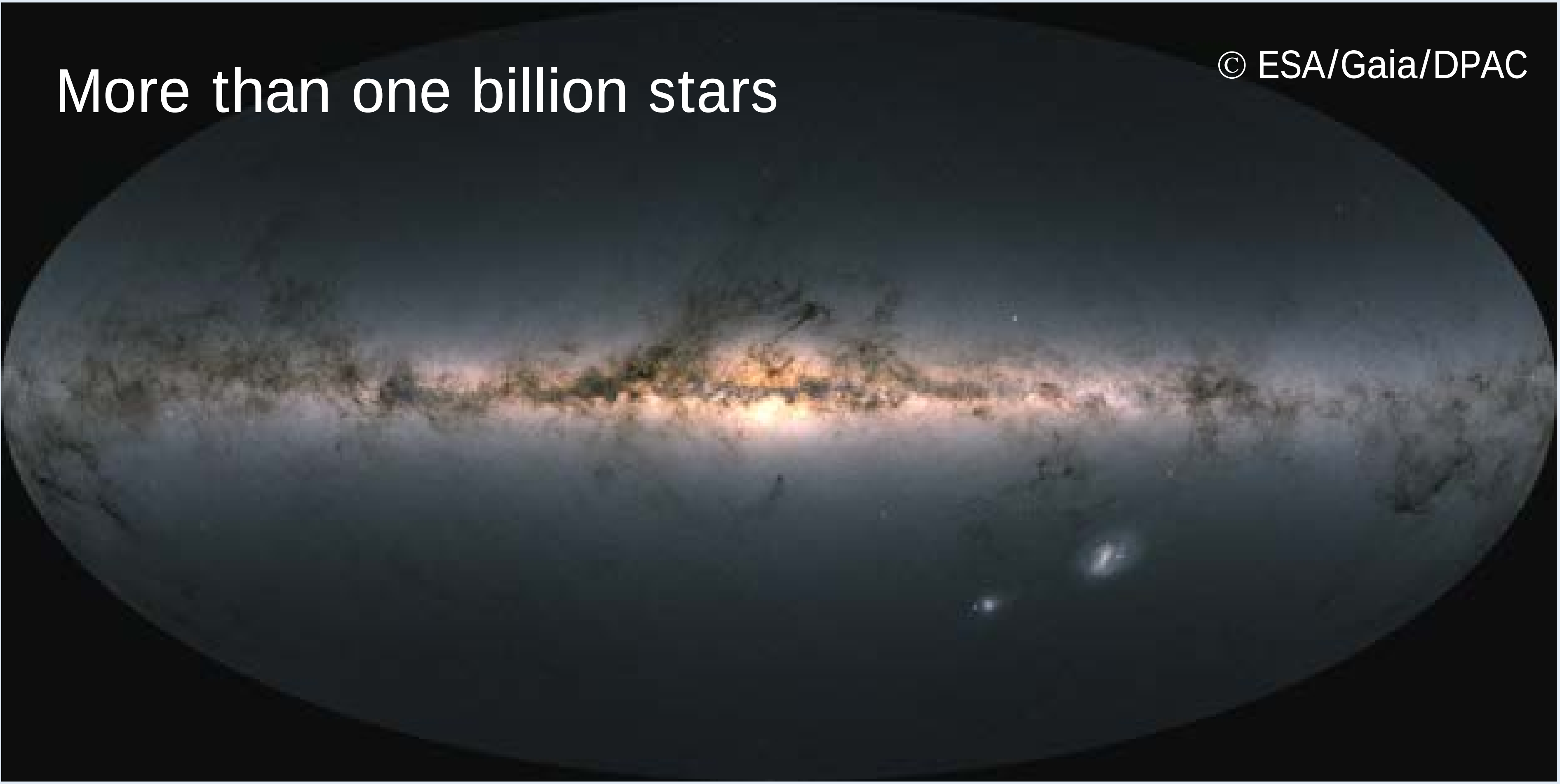
Dundee, Scotland → London → Cambridge (PhD) → Princeton → UC Berkeley → Baltimore



Outline

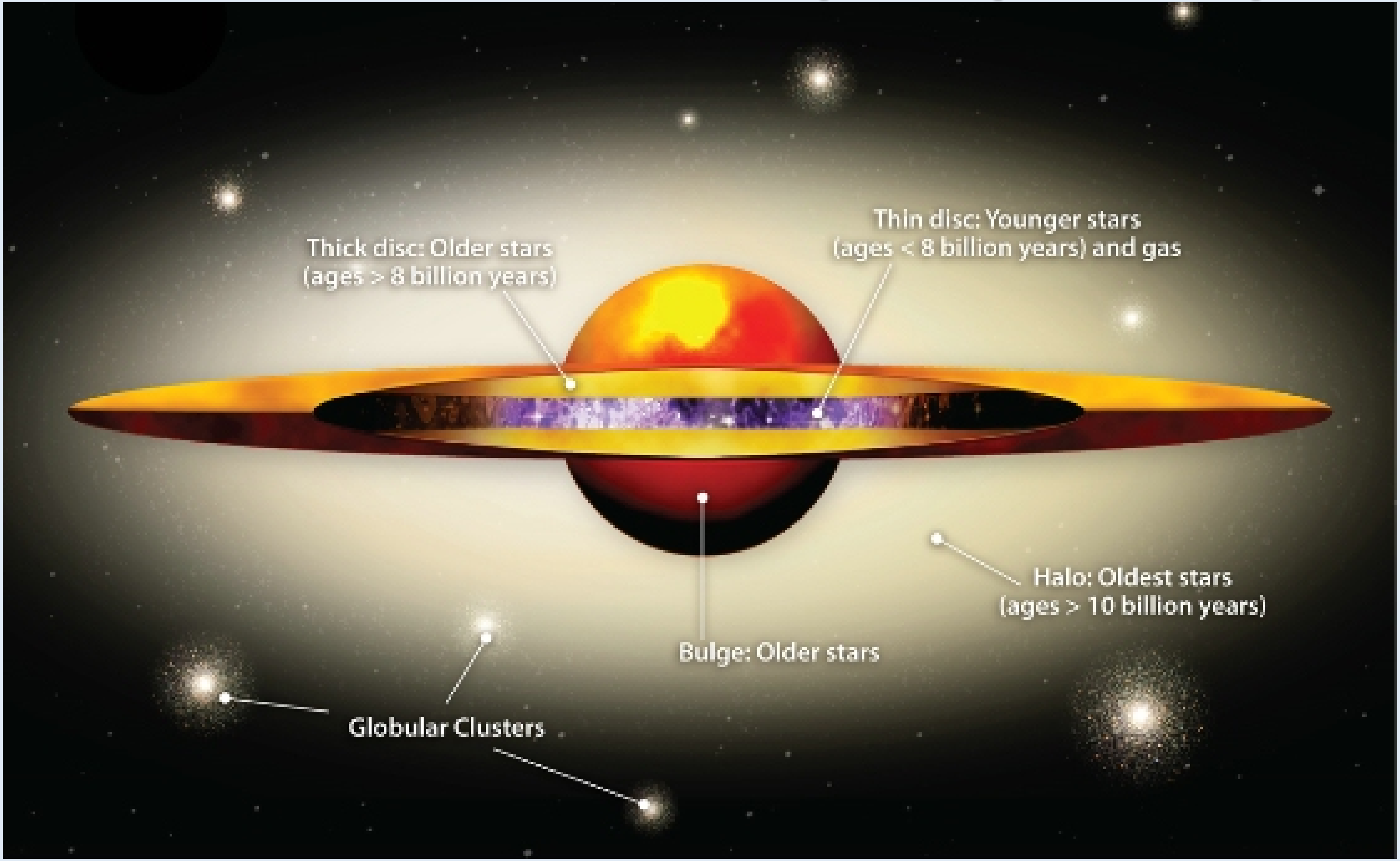
- What are galaxies?
  - What we observe and what we infer
    - Light and Dark matter
  - Galaxies of the Local Group
- How do galaxies form?
  - Cosmological structure formation and content of the Universe
- What can Local Group galaxies tell us?
  - Study individual stars – detailed information
  - Old (low mass) stars nearby formed at early epochs –> early star formation
  - Origin of the elements: we are stardust
  - Nature of Dark Matter

The Milky Way Viewed by the Gaia Satellite



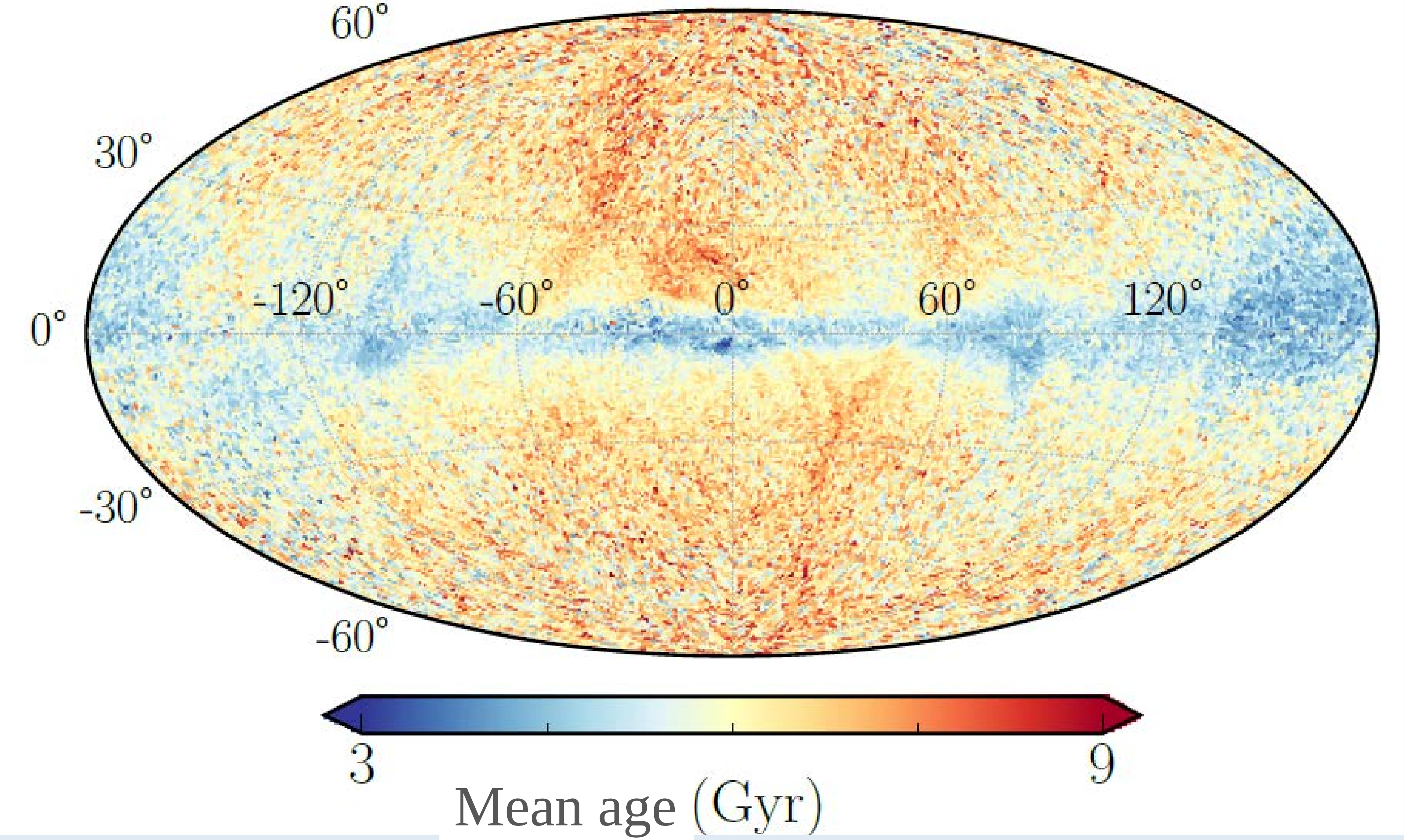
Early Data Release 3 (Dec 2020): positions and brightnesses.
Subsets have measured geometric distances and motions.

Cartoon of the Milky Way Galaxy



IoA, Cambridge

Ages estimates for ~33 million stars in Gaia DR3



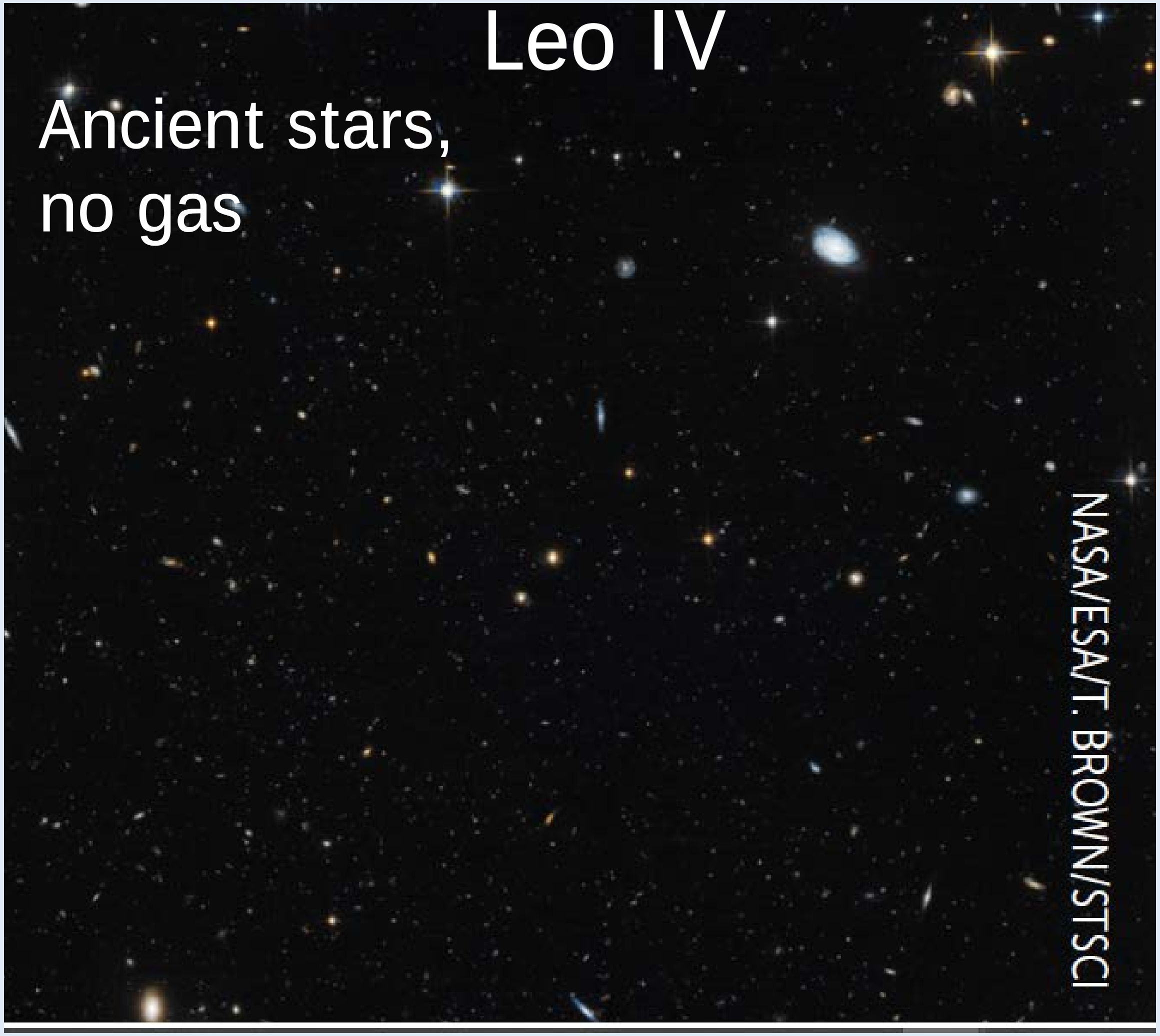
Kordopatis et al 2023

M31, the Andromeda nebula, is our nearest comparable neighbour – large disc galaxy

Moving towards our Galaxy – will collide in ~5Gyr

A Typical Dwarf Satellite Galaxy: Leo I

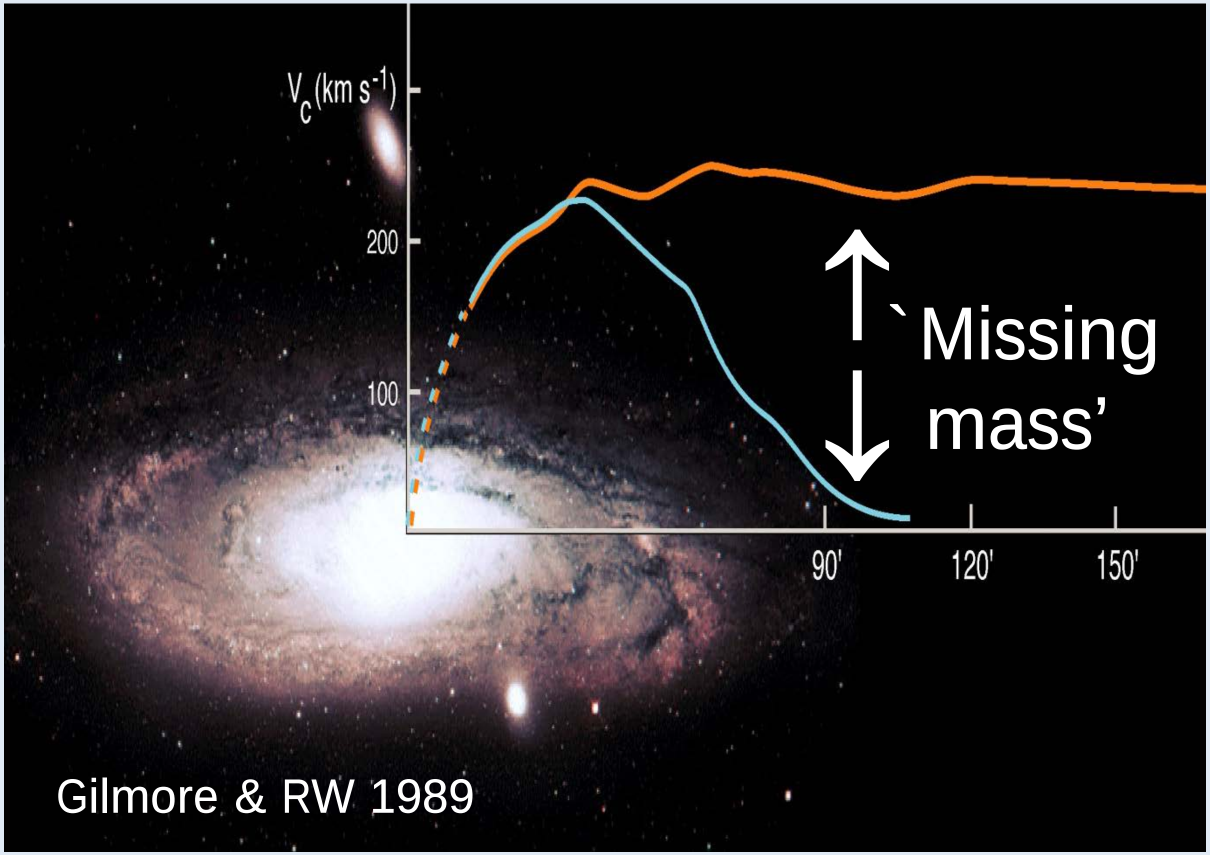
A More Typical Ultra-Faint Dwarf Satellite Galaxy:



Identified in star counts through pattern recognition: matched filter

Dark matter in galaxies detected through gravity

Flat Rotation Curve



Red: observed orbital speed of gas, as a function of distance from the galaxy's center

Blue: predicted from Newton's laws and observed mass distribution

Large discrepancy in outer parts: dark matter halo, ~x10 in mass

$$V^2_{circular}(r) \sim \frac{GM(<r)}{r}$$

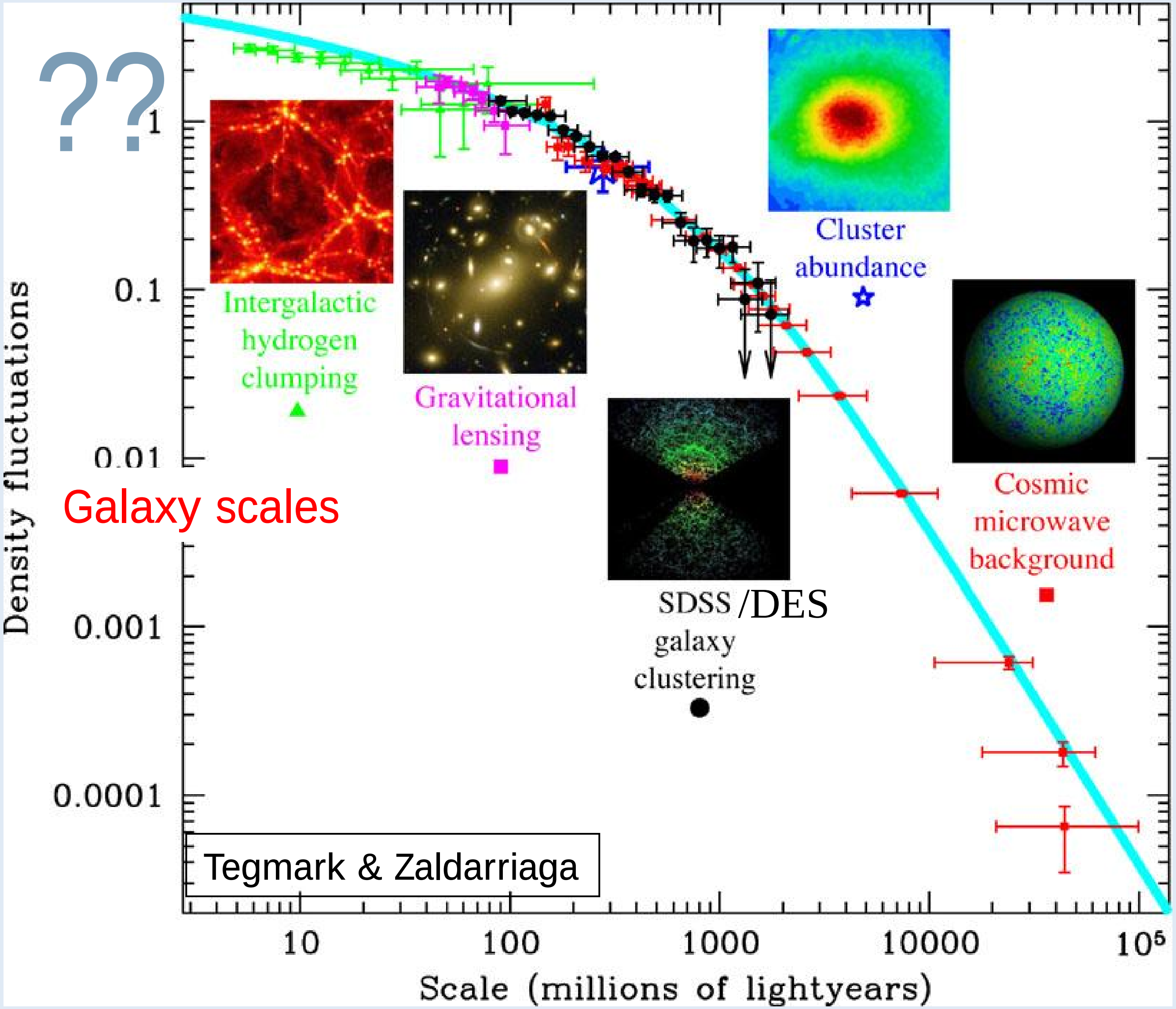
A galaxy is...

- A vast assemblage of stars, gas and ‘dark matter’ held together by gravity, dominated by dark matter
  - (ultra-faint) dwarfs are most dark-matter dominated
  - many more low-mass galaxies than high-mass ones
  - galaxies cluster: Local Group - Milky Way, M31 plus their retinues of satellites
- Cosmic star formation started ~13 billion years ago
  - stars are forming today, from gas, in galaxies
  - forms many more low-mass stars than high-mass ones
  - the most massive stars (~50 times the mass of the Sun) live for only a few million years, solar mass stars live ~ 10 billion years ~ age of the Universe
    - Low-mass stars from the early Universe are still here!
    - Counting old low-mass stars yields early mass function (e.g. RW et al 2002)

Origin of the Elements

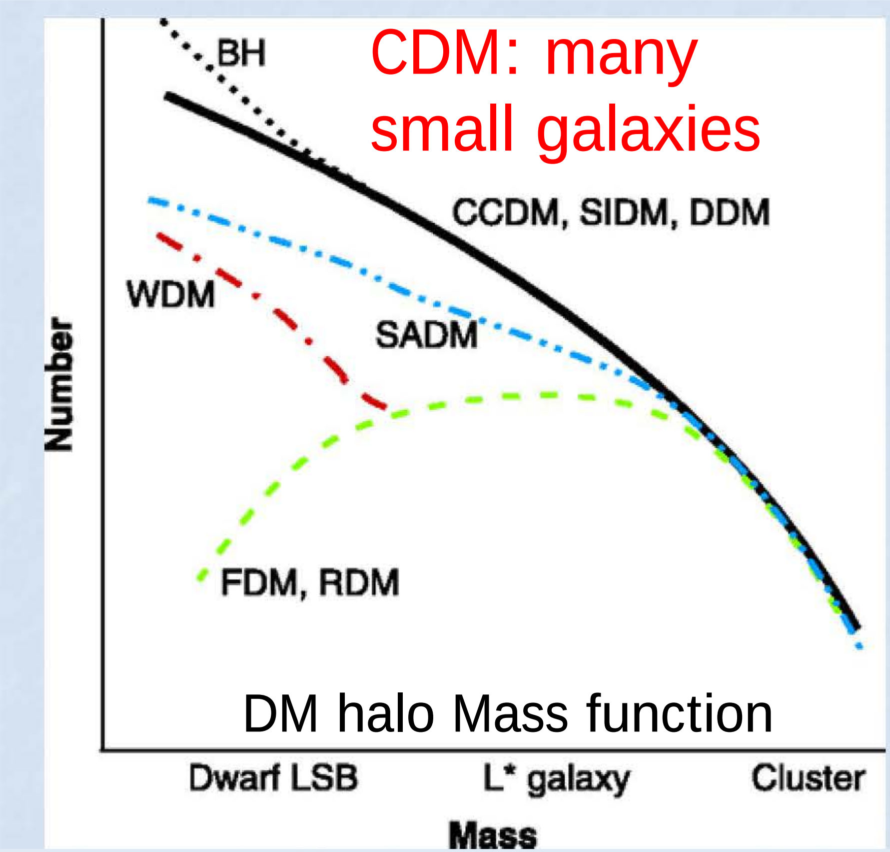
- The hot, dense conditions of the early (expanding) Universe created ~75% Hydrogen and ~25% Helium
- Stars shine through nuclear fusion in their cores, creating elements heavier than Helium → 'metals'
  - o first stars are metal-free, Big Bang creates only H, He
  - o metals ejected when stars die, in supernova explosions (also create metals, beyond 'iron peak')
  - o incorporated into surrounding gas and then into new generations of stars, metallicity increases with time
- Stars of different masses create different elements, on different timescales
  - Elemental abundance patterns measured in stars depend on mass distribution of previous generations, plus star-formation history (e.g. Gilmore & RW 1991; RW & Gilmore 1992)

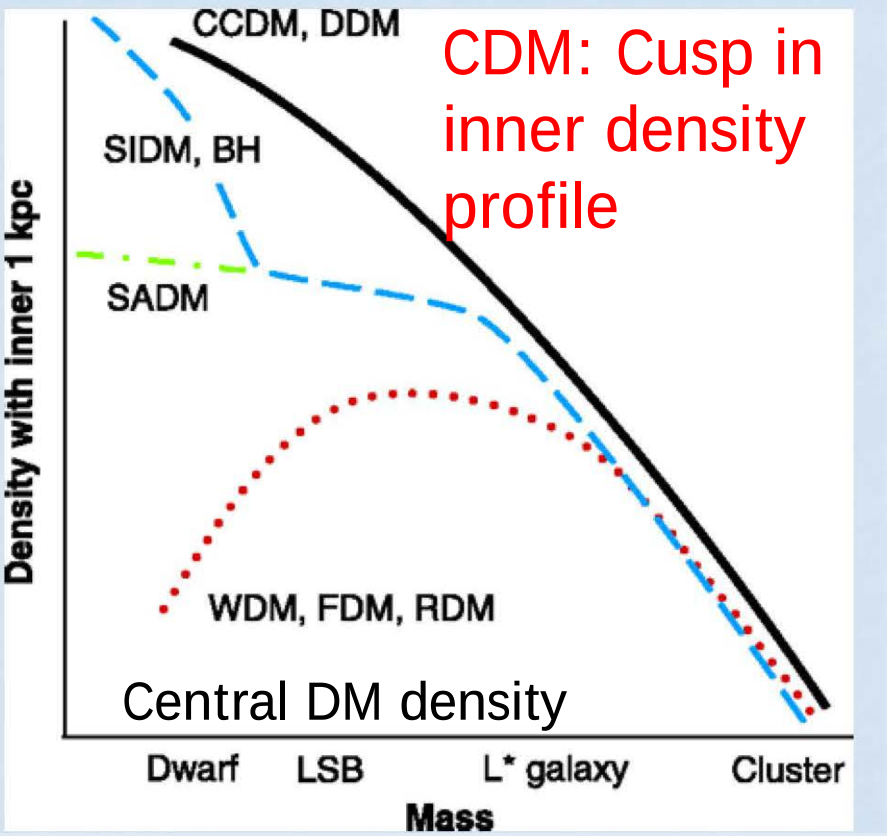
ΛCDM: impressive consistency with matter power spectrum over five orders in length scale



Galaxy Scales Reveal Nature of Dark Matter

Ostriker & Steinhardt

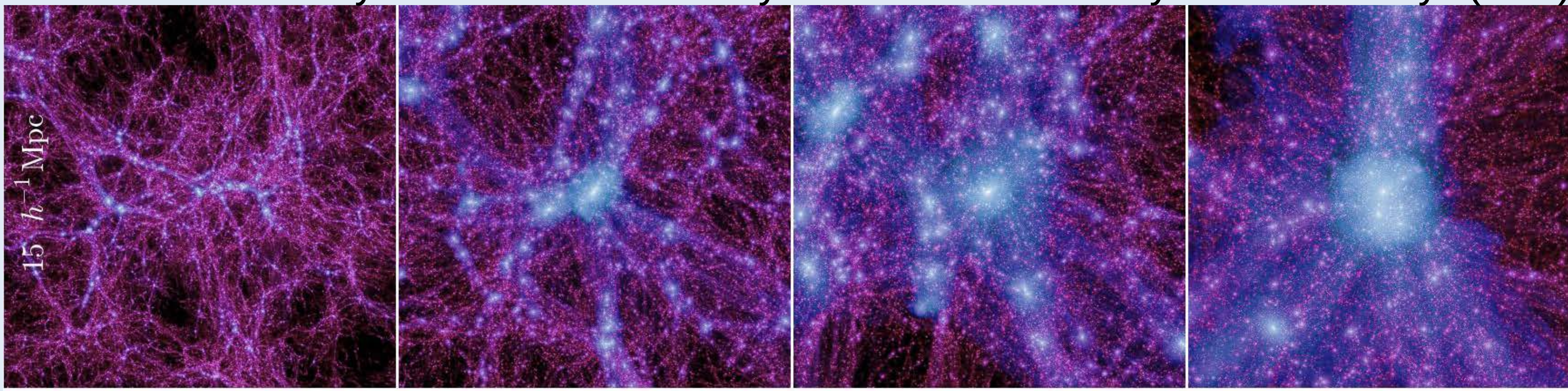




Use Local Group galaxies as tests of theory! Can study individual stars → motion, chemical abundances...

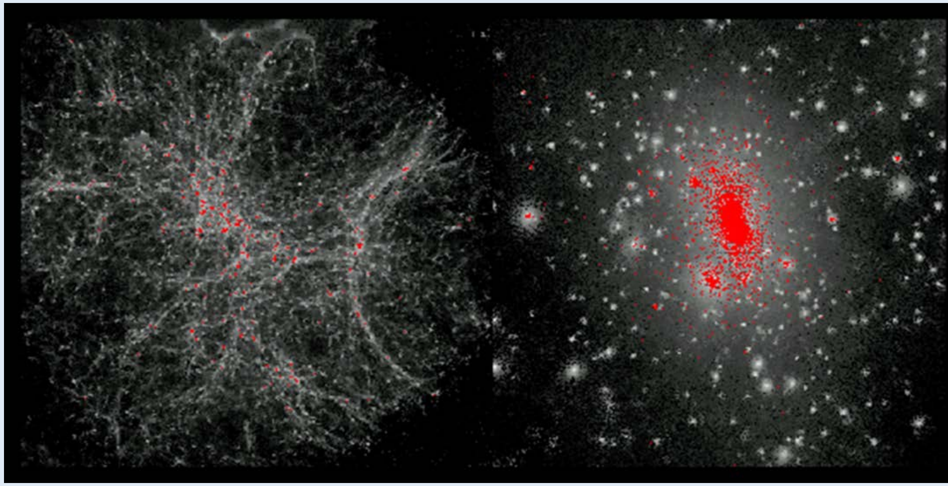
Cold Dark Matter predicts small galaxies form first, merging to form successively larger systems

Time → t=1 Gyr 3Gyr 6Gyr 13.7 Gyr (now)



- Active merger history for typical Milky Way size haloes
- Much surviving substructure & streams within the Galaxy
- Many satellite 'galaxies'

0.5Gyr 13.7 Gyr (now)



Boylan-Kolchin et al 09
Moore et al 1999

Dark-matter only, N-body simulations - need to model baryonic physics

Galaxy-scale Challenges for ΛCDM

ΛCDM extremely successful on large scales but....

- \`Missing satellites' – theoretical predictions of many more low-mass dark haloes than visible satellite galaxies around the Milky Way (Moore et al 1999; Klypin et al 1999) – numbers perhaps now OK but spatial distribution, stellar pops are not
- 'Too Big to Fail' – predictions of massive dark sub-haloes of Milky Way mass dark haloes that should form stars but are not visible (Boylan-Kolchin et al 2011, 2012)
- 'Core vs Cusp' – predictions of rising dark-matter density profile to central regions whereas cores are often favoured (e.g. Gilmore, Wilkinson, RW et al 2007; Walker & Penarrubia 2011; Oh et al 2015; Read et al 2016; Santos-Santos et al 2020)
- Bulgeless disk galaxies and old thick disks – predictions of active merger histories lead to massive bulges and young thick disks, at odds with observations (e.g. Toth & Ostriker 92; RW 01)

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Baryonic Physics or Dark Matter Physics?

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Stellar populations – kinematics, spatial distribution, ages, chemistry, IMF – are critical to deciphering Galaxy formation and the nature of dark matter

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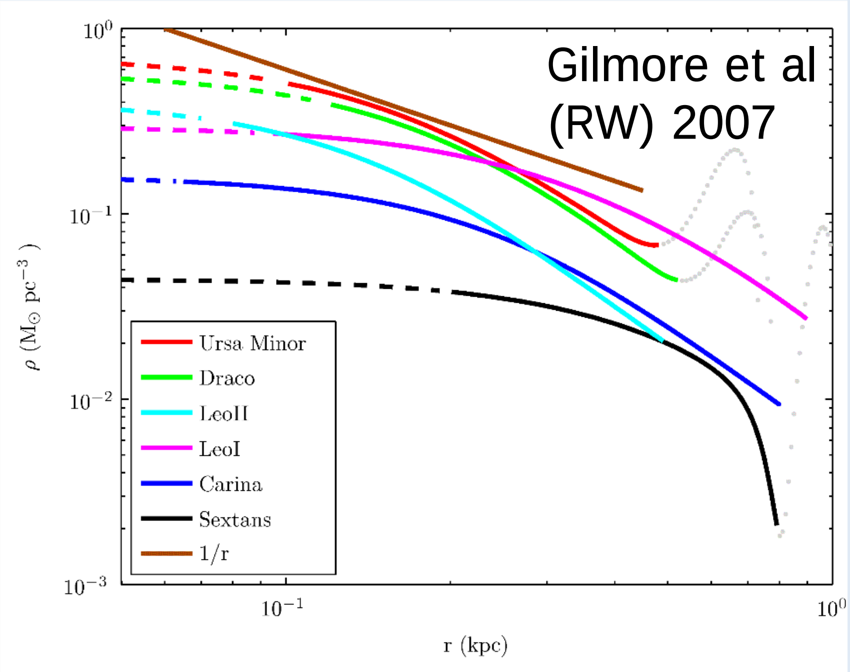
The Fossil Record: Galactic Archaeology

- Studying low-mass stars of all ages nearby allows us to decipher the evolution of the host galaxy
  - There are copious numbers of stars nearby that have ages $\gtrsim$ 10 Gyr : formed at redshifts > 2
    - 'cosmic noon' when global star formation rate peaked
  - Retain memory of initial/early conditions: surface chemical abundances (gas from which they formed), orbital dynamical quantities e.g. energy and angular momentum → clustering in chemical+kinematic/dynamical phase space
- Complementary approach to galaxies at high redshift
  - Snapshots of different galaxies at different times *vs* temporal sequence of typical system(s)
  - Individual stars can break degeneracies of integrated light e.g. age/metallicity

Cored Density Profiles: Dark Matter Physics or Baryonic Physics?

- Measured motions of stars or gas + Newton's Laws give cored present-day profiles



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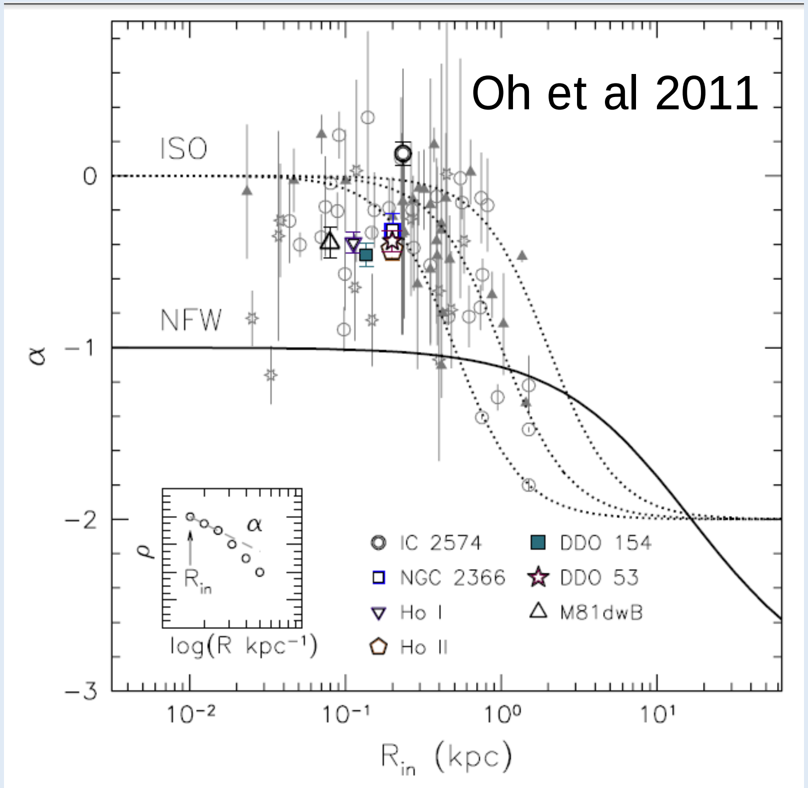

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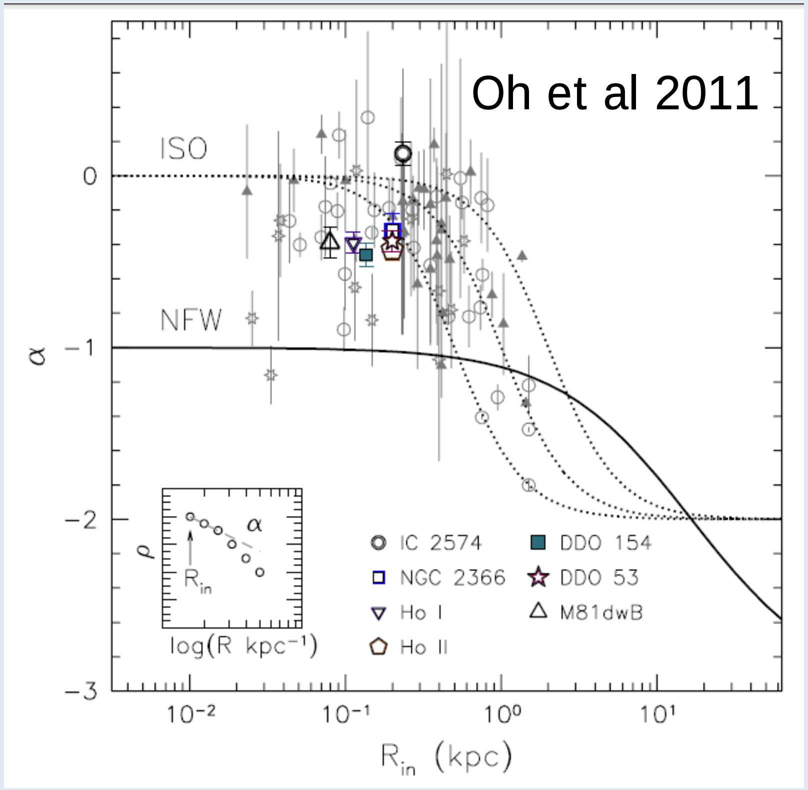

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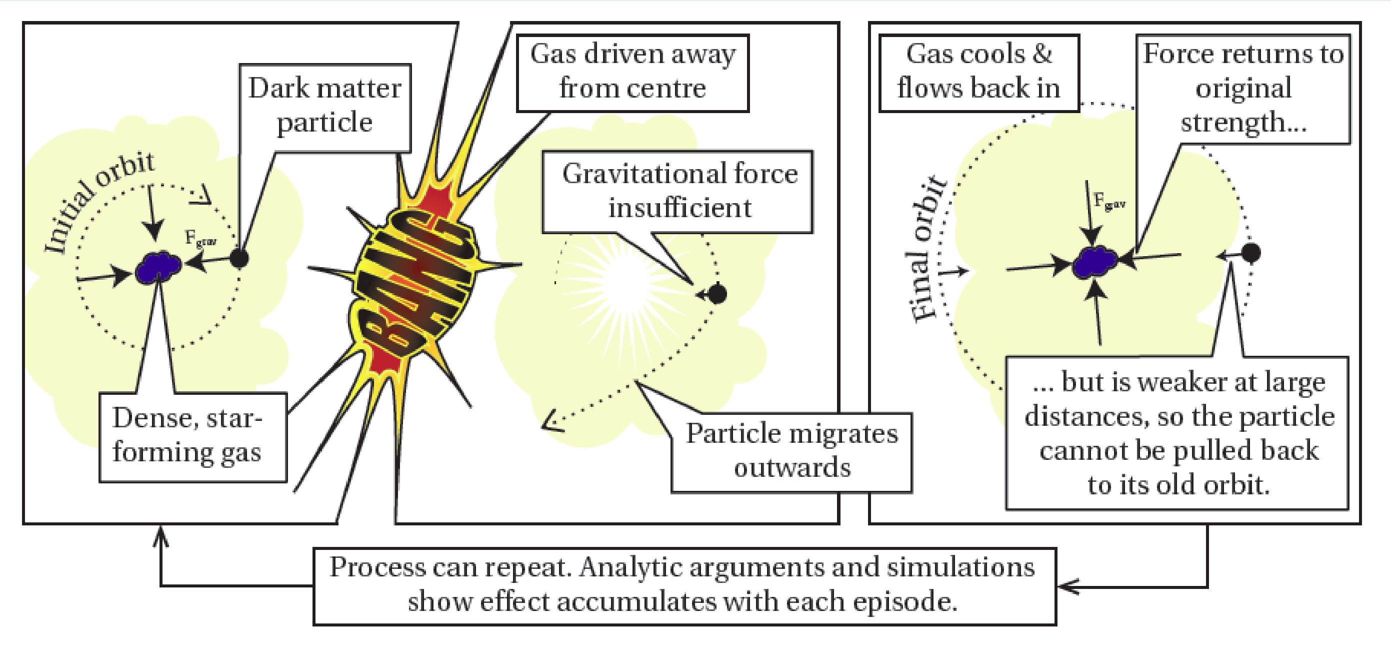
Gravity is the only force between dark matter and baryons

Massive stars also create new metals – trace past star formation



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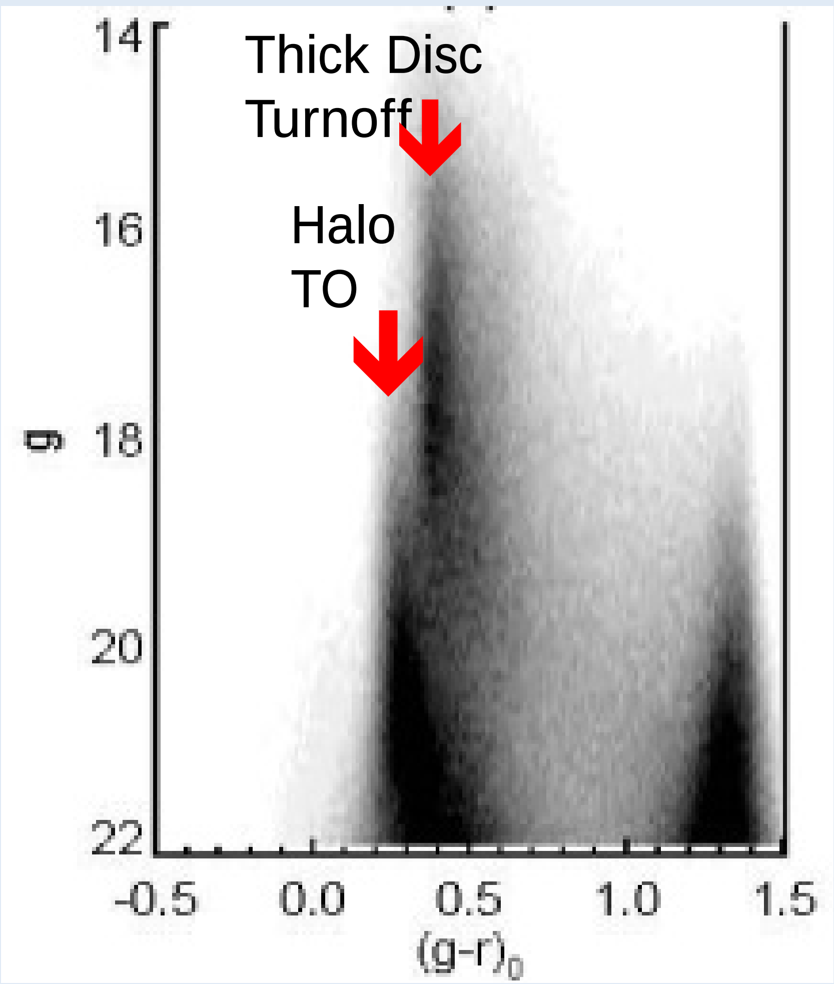
- Need large samples of stars in dwarf galaxies with both kinematics and chemical abundances

Quiescent Merger History of the Milky Way

- Star counts at intermediate latitudes show two well-defined main-sequence turn-offs, corresponding to old, metal-poor populations, stellar halo and thick disk (redder, more metal-rich)



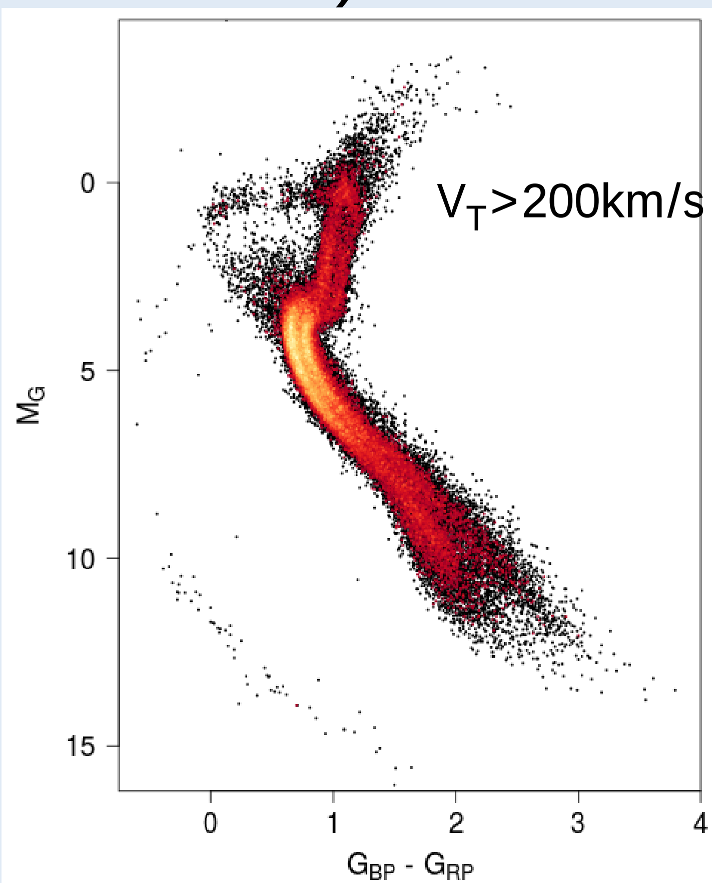
Spectroscopy → [Fe/H] ~ -1.5 for halo, -0.5 thick disk

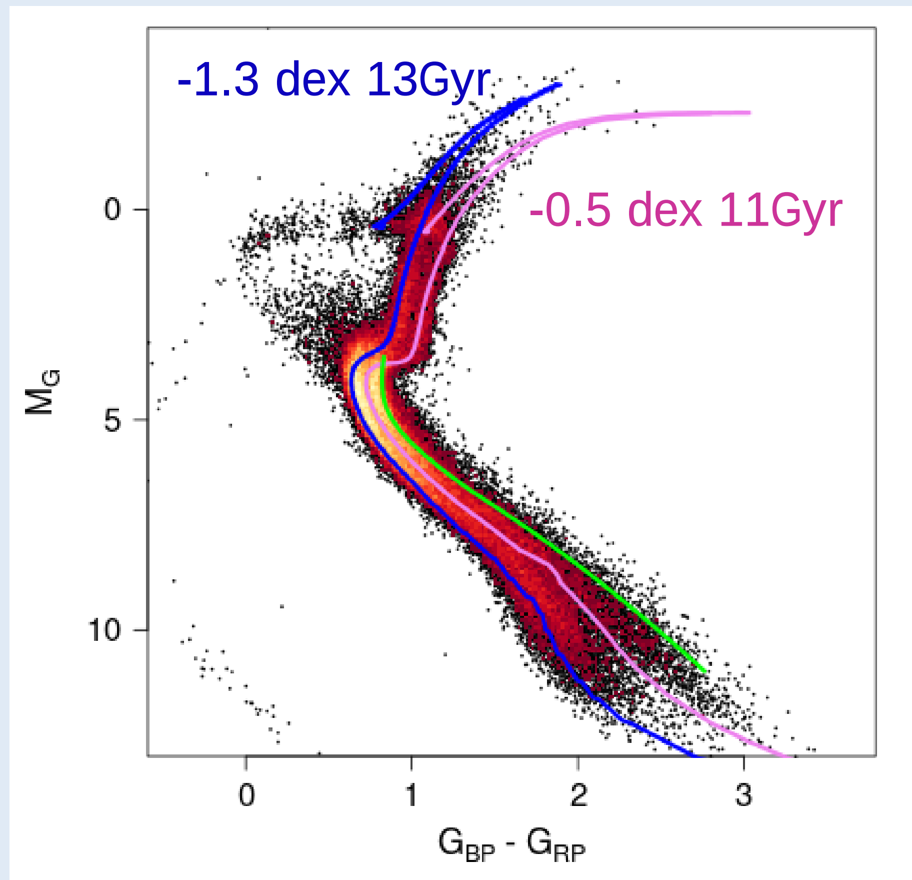
Derived mean age for thick disk stars ~ 10-12Gyr - this is lookback time for last significant merger event

Jayaraman, Gilmore, RW et al, 2013
cf Gilmore et al 1985; Gilmore & RW 1987

The Gaia Era – Distances!

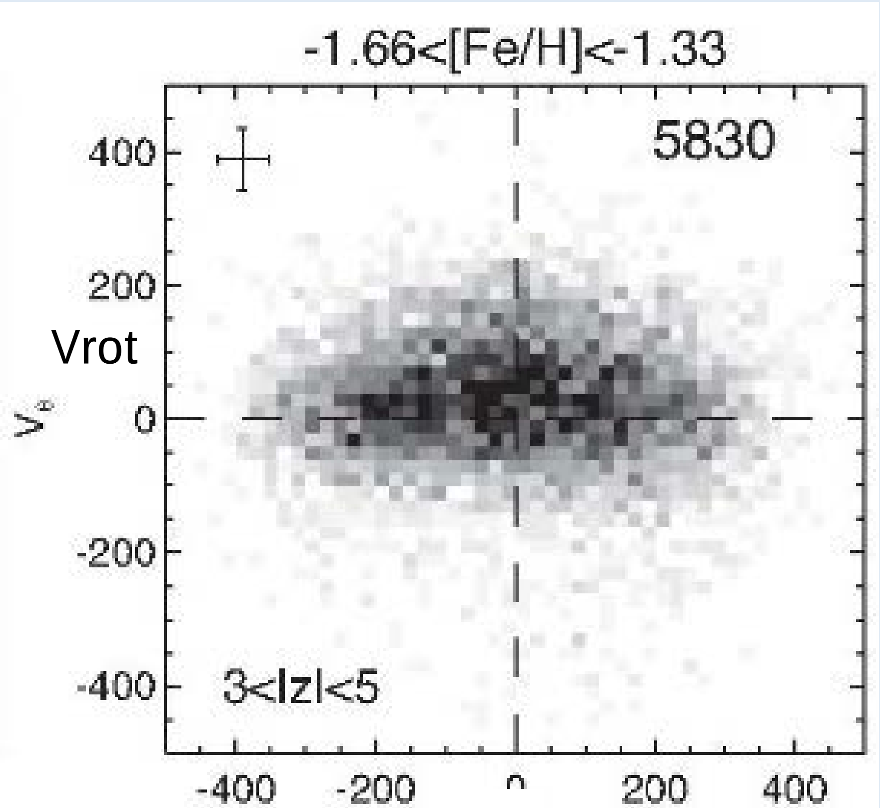
- Apparent brightnesses to intrinsic brightnesses
- Double old main sequence turn-off seen in exquisite detail in high transverse-velocity stars (Babusiaux et al 2018) – stellar halo and (high-vel tail of) thick disk

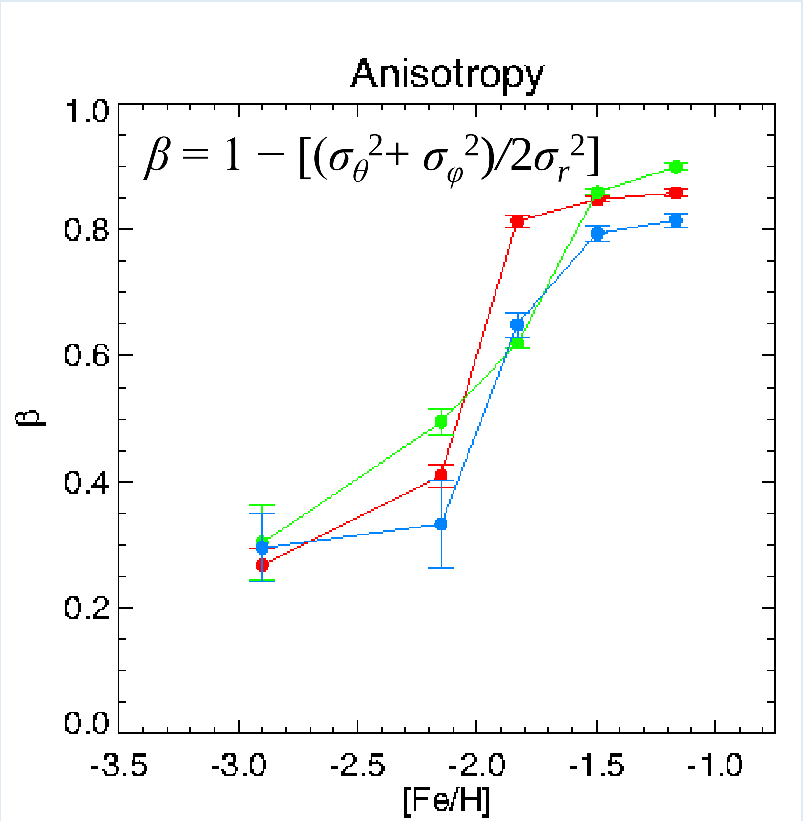




The Gaia + SDSS Era

- Very radially anisotropic prograde (mean V-rotation ~ 30km/s) component dominates metal-rich ([Fe/H] > -1.7) inner stellar halo, interpreted as debris from fairly massive early merger, $M > 10^{10} M_{\odot}$ – the Gaia Sausage (Belokurov et al 2018)
- Merger dated to 8-11Gyr ago – epoch of (thick) disk formation

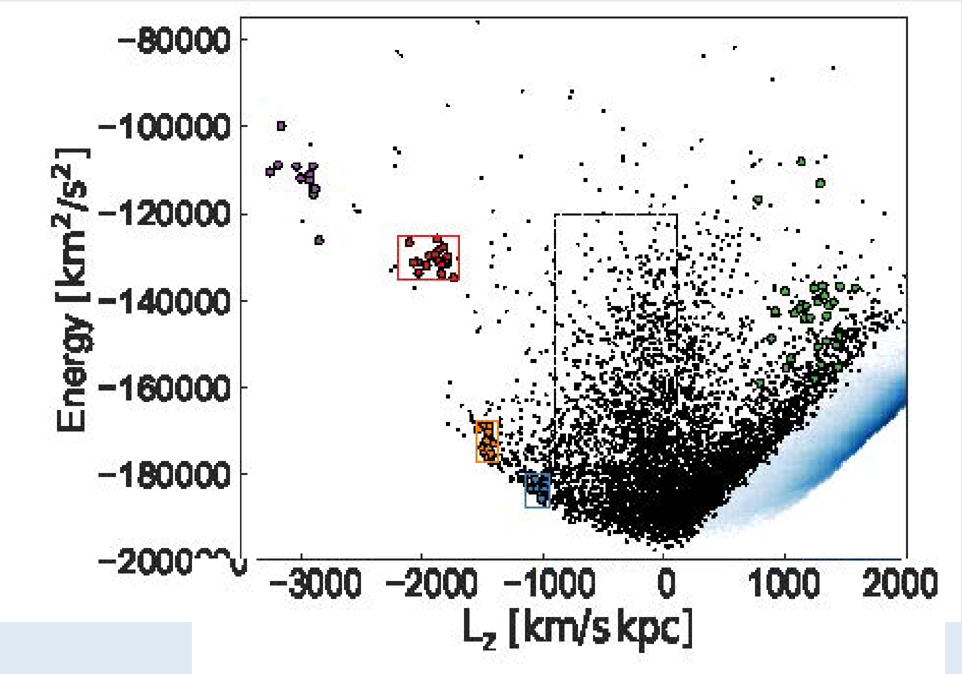




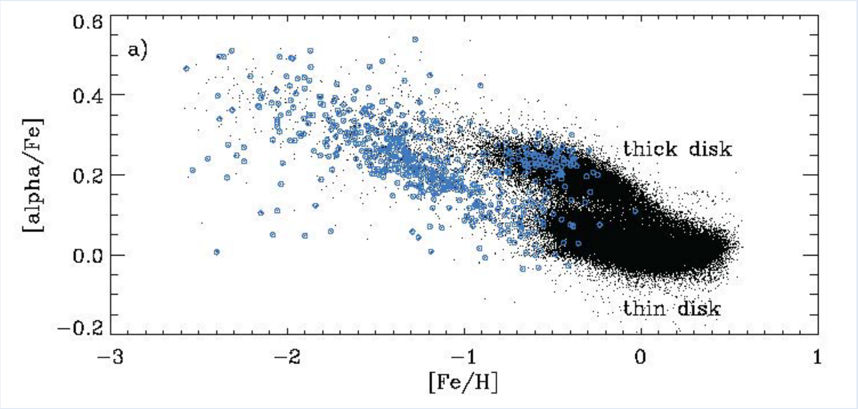
Proper motions from SDSS-Gaia DR1

The Gaia Era

- Mildly Retrograde substructure identified in 6D kinematic phase space for local halo stars in Gaia DR2 (Koppelman et al 18)



- Cross-correlate with APOGEE elemental abundances – low-alpha sequence `accreted' (Helmi et al 2018)



- Debris from a massive (1:5) satellite Gaia Enceladus on a retrograde orbit, that heated pre-existing thin disk to form thick disk, ~ 10Gyr ago (Helmi et al 2018; cf RW 2001, RW et al 2006)

The Near Future of Galactic Archaeology

- Comprehensive testing of ΛCDM and other types of dark matter
- Need simulations of galaxy formation and evolution to make predictions
- Need large samples of stars with spectra, giving line-of-sight velocities and chemical abundances, for each of Milky Way, M31 and representative satellite galaxies
  - On-going minor merger with Sagittarius dwarf galaxy: opportunity for detailed study of reaction of Milky Way disc
    - Galactoseismology
  - Interaction with Large Magellanic Cloud: causing modes in both dark and light matter

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- Machine-learning to maximise science return