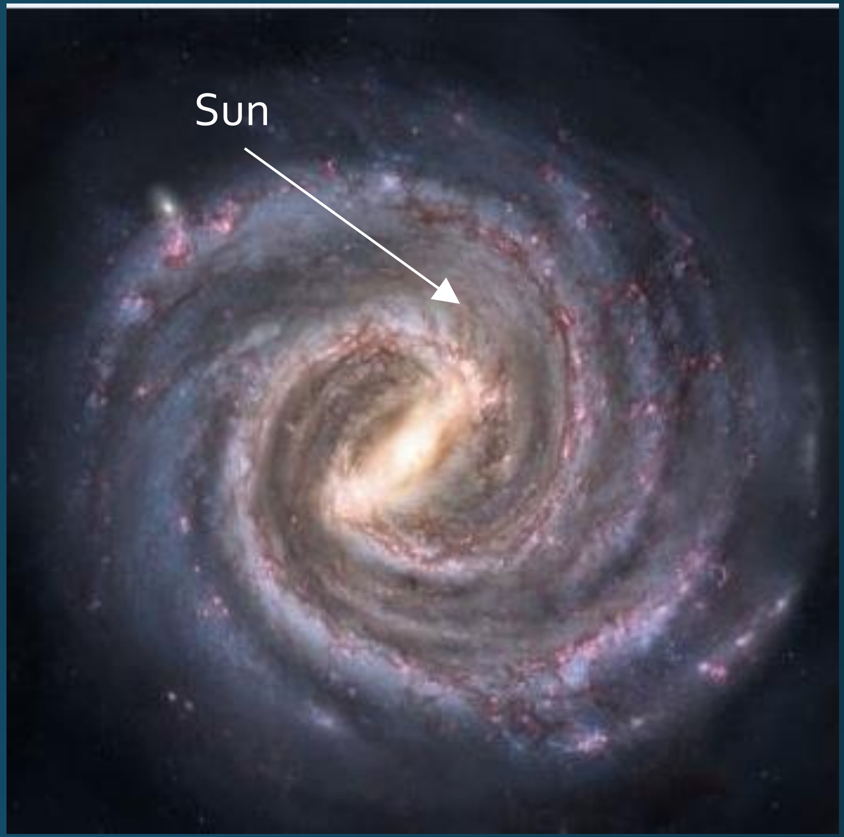
Understanding our Galaxy

James Binney, University of Oxford

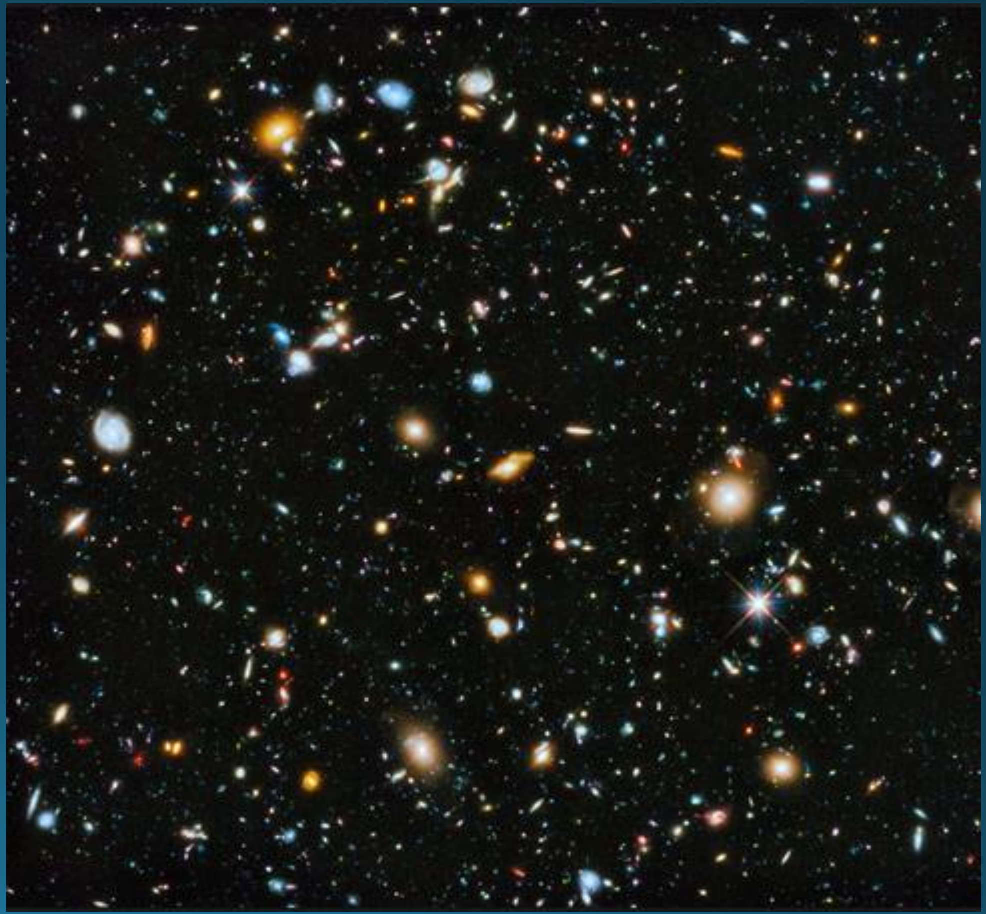
One in 100 billion stars

- Image below made by counting 100s of millions of stars imaged in infrared light to minimise impact of cosmic smoke ("dust")
- Our Galaxy closely resembles the galaxy on the right



One in > 100 billion galaxies

- This is just the part of the Universe we can see
- There's more beyond, probably infinitely more
- There must be billions and billions of civilisations out there

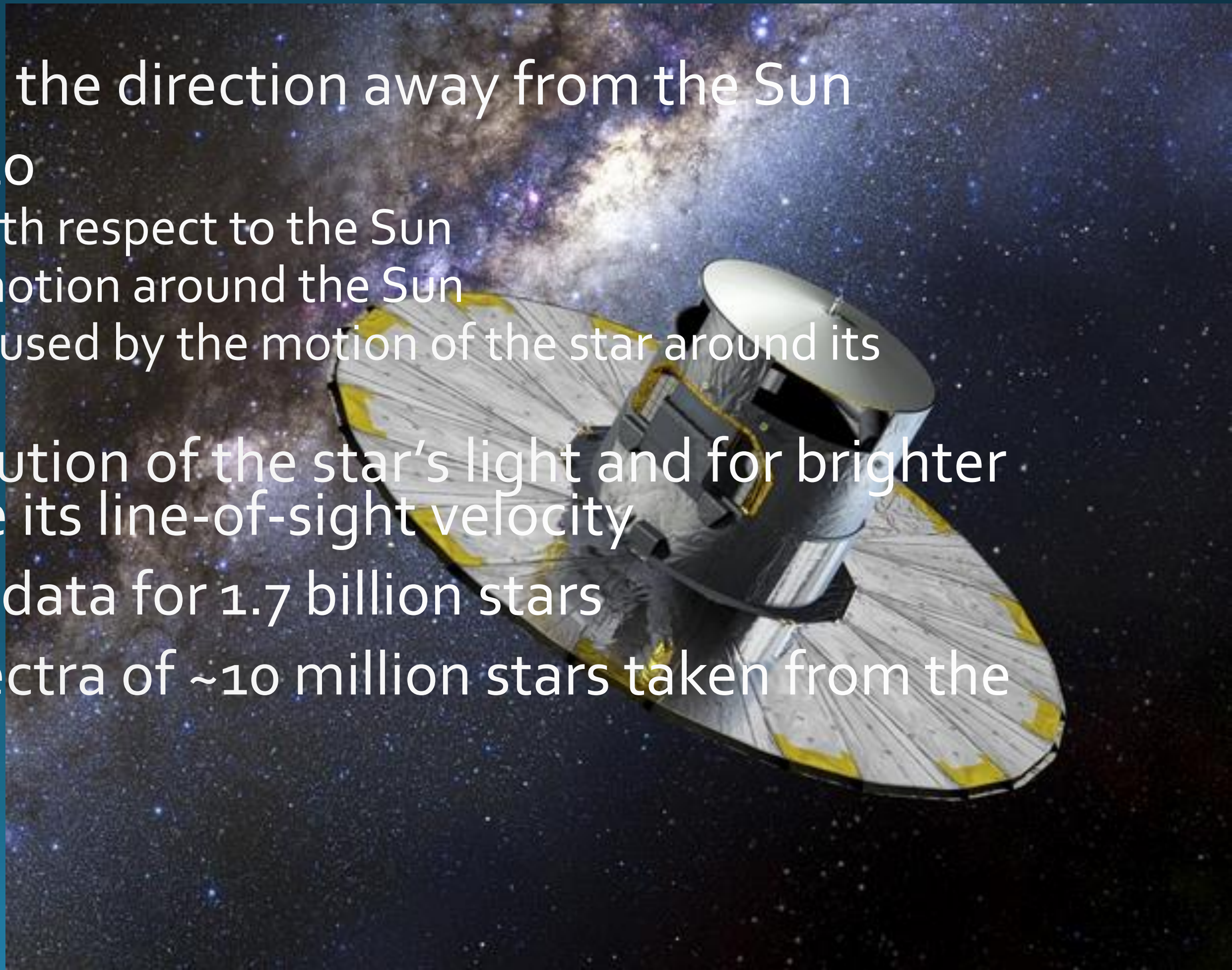


What we want to discover

- The Galaxy is a giant machine
- What are its parts & how do they fit together?
- How was it assembled?
- How does it work?
- What’s it evolving into?

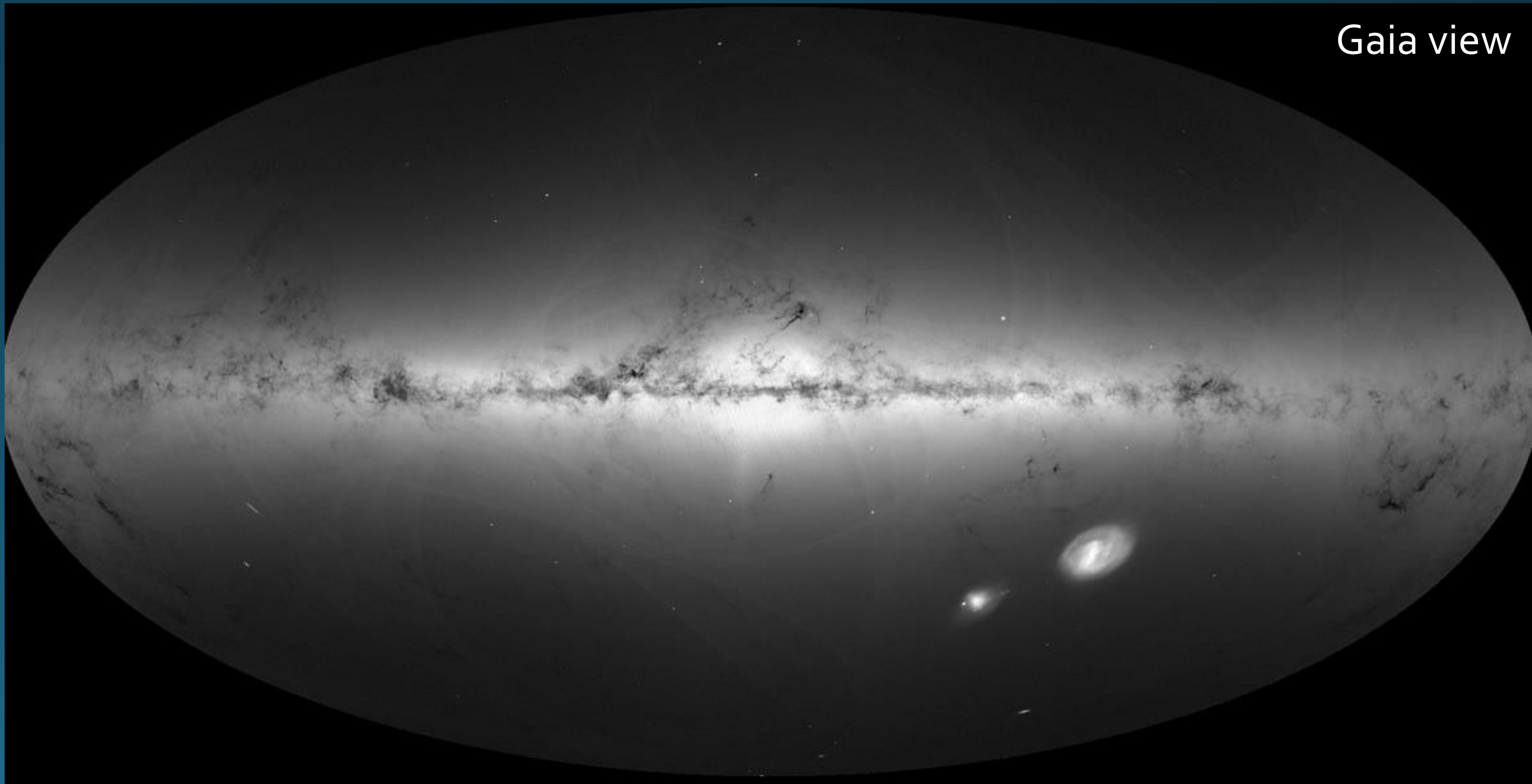
Now's the time to answer questions

- Since July 2014 Gaia has been plotting the motions across the sky of ~ 2 billion stars
- It's located 2,000,000 km from Earth in the direction away from the Sun
- We decompose the track on the sky into
  - a straight line caused the star's velocity with respect to the Sun
  - a 'parallax' ellipse caused by the Earth's motion around the Sun
  - and, if it's a binary star, a second ellipse caused by the motion of the star around its companion
- Gaia also measures the spectral distribution of the star's light and for brighter stars uses the Doppler shift to measure its line-of-sight velocity
- In April 2018 ESA released astrometric data for 1.7 billion stars
- These data vastly enhance value of spectra of ~10 million stars taken from the ground



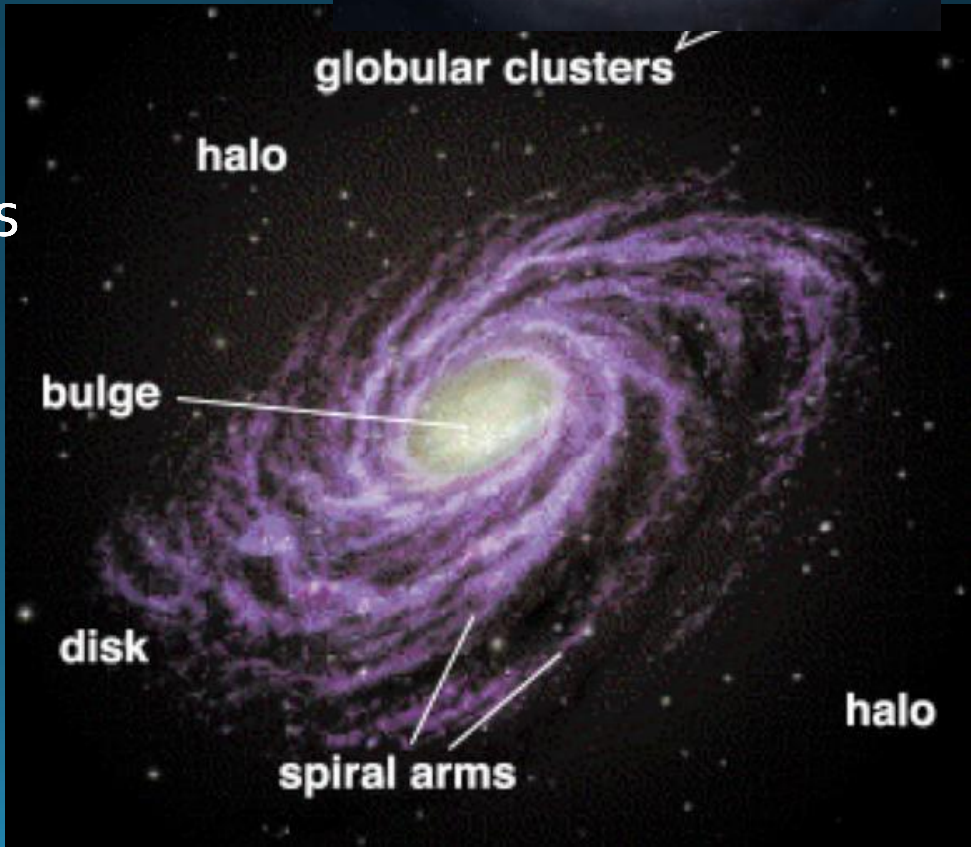
Gaia's sky

- Every star an equal point
- Obscuration by dust evident

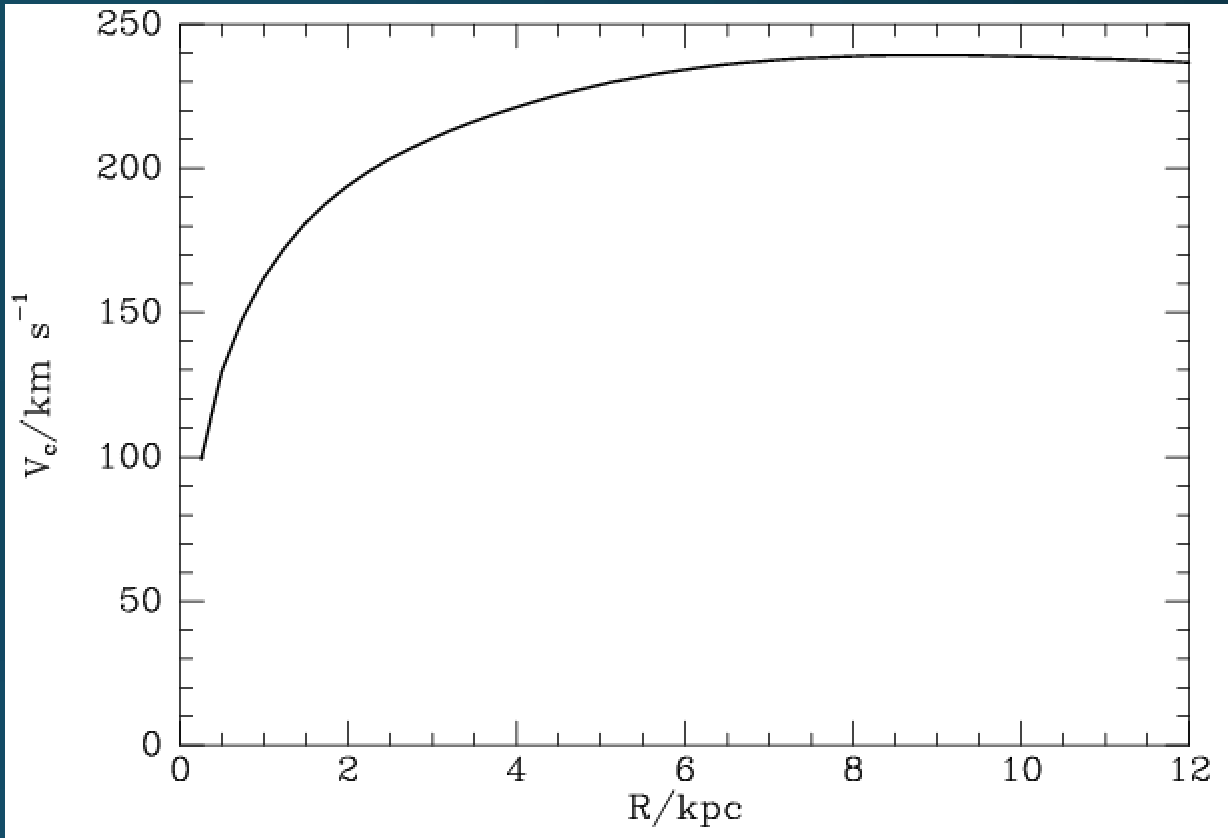


Basic facts

- The Sun is part of a disc of stars & gas
- It sits R_0= 8.2 kpc = 25,000 light years from the Galactic centre (GC)
- It moves on a nearly circular orbit at 250 km/s
- But even at this speed needs 200 million years (200 Myr) to go round
- The Sun must be held in its orbit by a gravitational field generated by the matter closer to the GC than the Sun
- What generates that field?

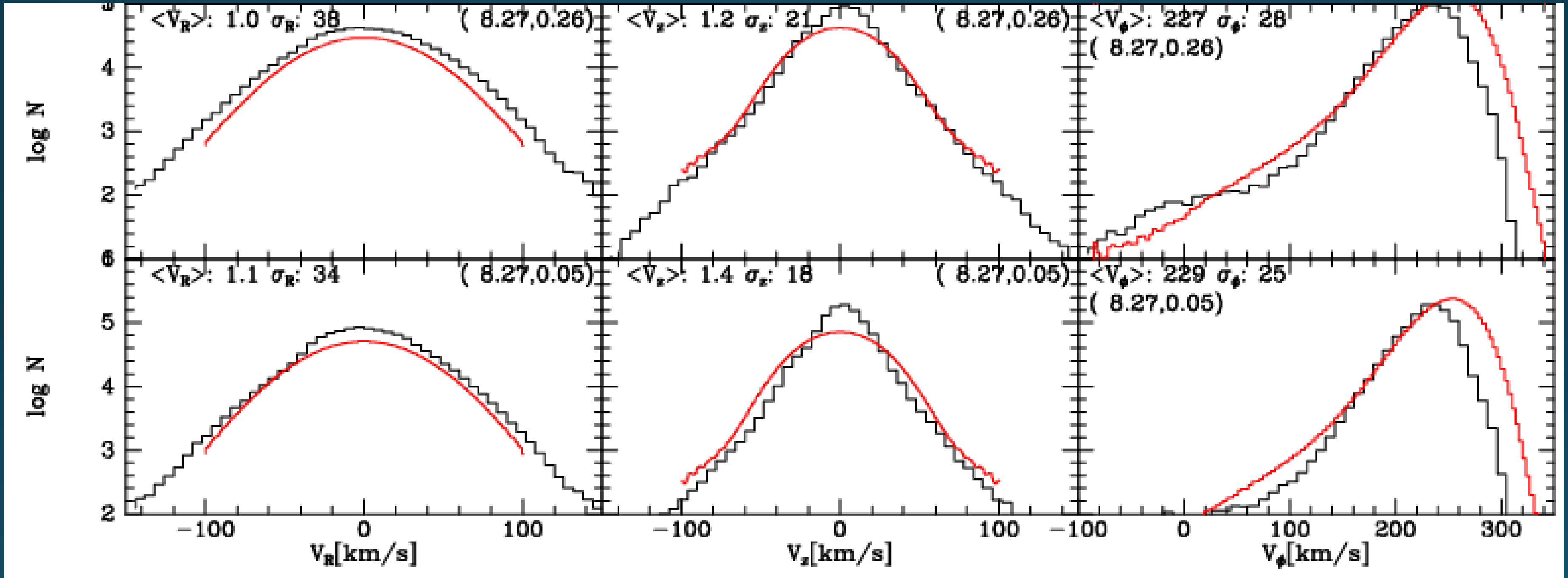


Mass distribution



- Measurements of the 21 cm line of H and the 2.6 mm line of CO from interstellar space enable us (via Doppler effect) to determine the rotation curve $V_c(R)$ for $R<R_o$
- We find that V_c rises with R & then becomes flat
- From Newton's law $g = GM/R^2$ so $V_c^2 = GM/R$ this implies that M grows at least as fast as R – the mass of the Galaxy is *extended*

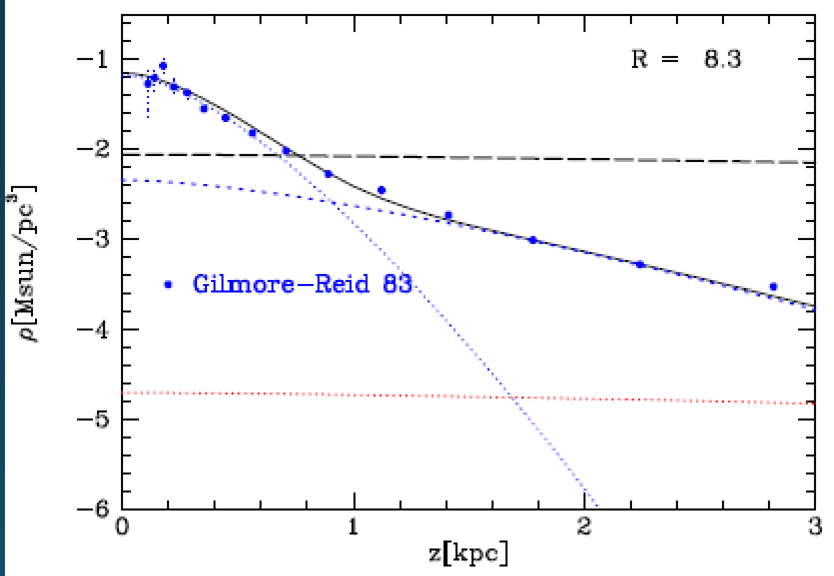
Circular speed from Gaia stars

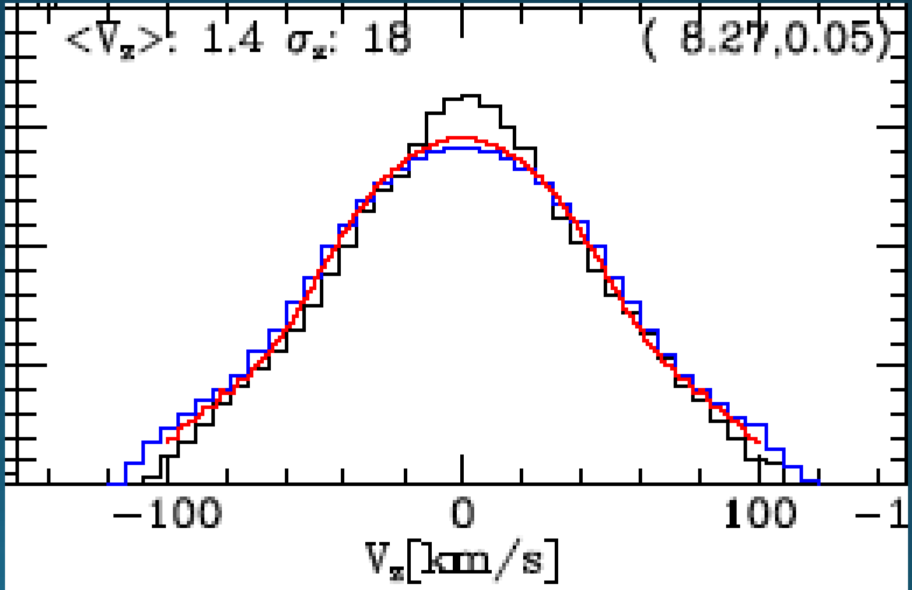


Weighing the disc 1

- Stars oscillate above & below the Galactic plane
- The vertical force that drags a rising star back towards the plane comes mostly from the disc
- So from (i) the distribution of velocities of stars as they cross the plane and (ii) the way the star density decreases with distance from the plane, we can find the local surface density of the disc: ~ 50 $M_\odot/pc^2$

Weighing disc with Gaia stars



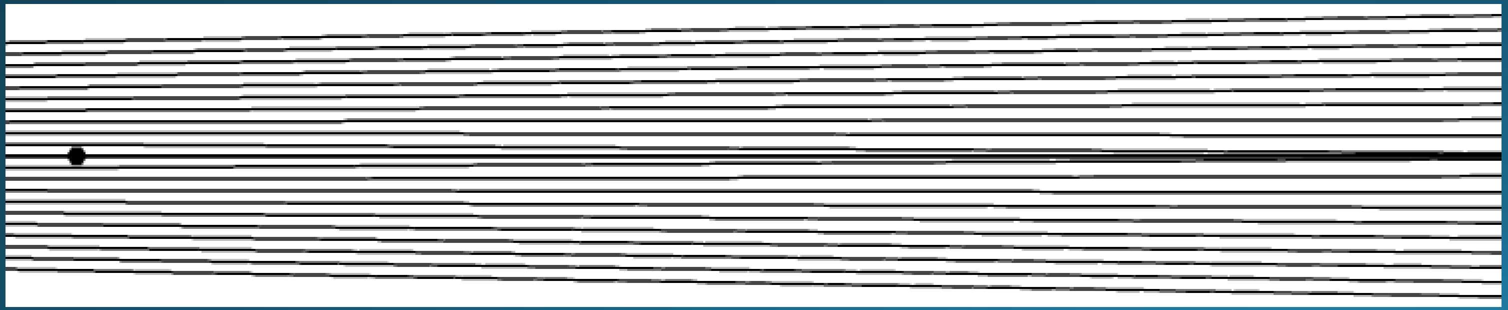


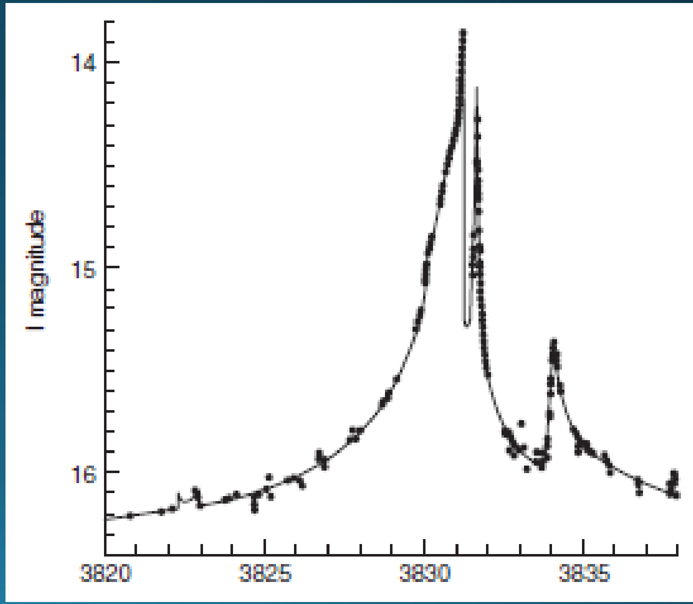
Weighing the disc 2

- By counting stars as we look towards the GC we estimate how the surface density decreases with increasing R [Σ~ exp(-R/2.5 kpc)]
- Now we can compute the gravitational force on the Sun from the disc
- It's less than half of what's required to keep the Sun on its orbit
- Observations of external galaxies lead to the same conclusion: the stars and gas don't generate enough gravity to explain the speeds at which stars & gas at R ~ 10 kpc orbit
- Is the extra gravity contributed by particles we cannot see – "dark matter"?

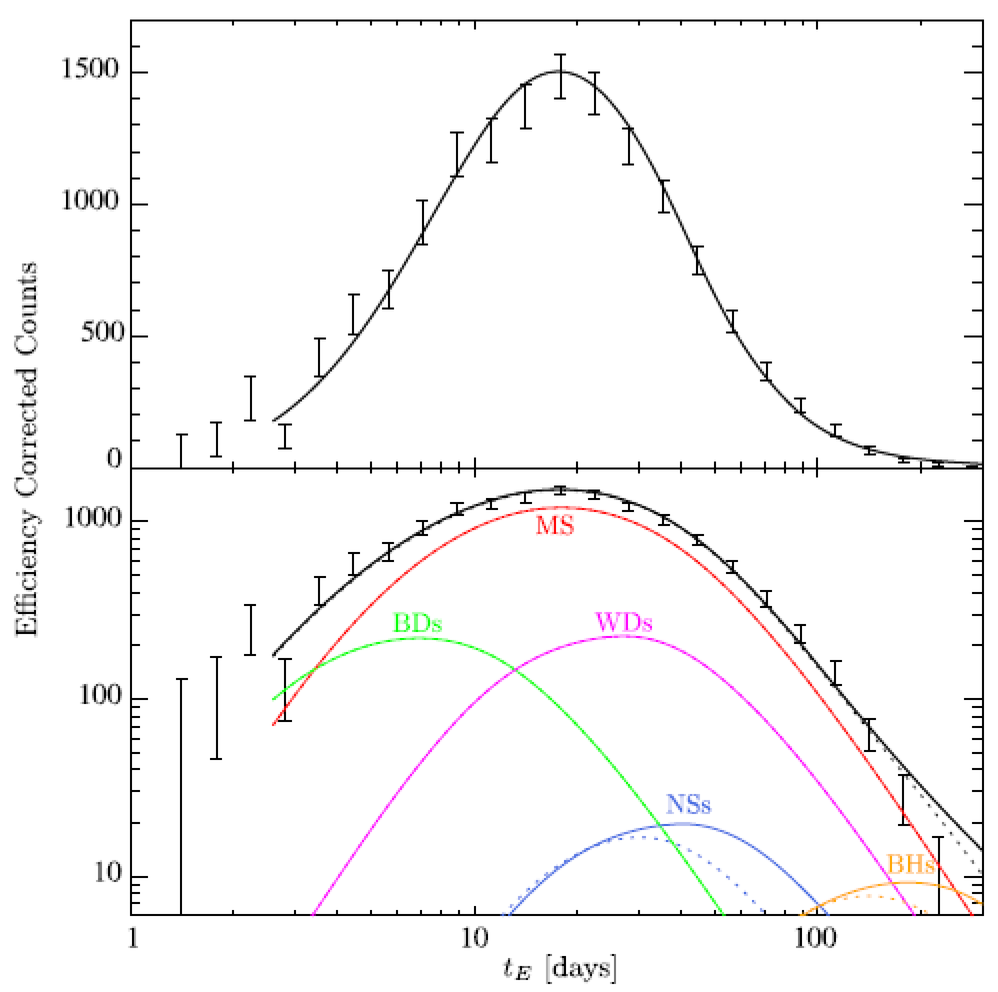
Weighing the inner Galaxy

- Light is deflected by a gravitational field just as it is by glass
- A faint star or planet sometimes comes between us and a distant star, focusing the light of the background star into our telescope
- Background star brightens for some days
- P(star is lensed) $\propto$ surface density of matter in a slab across line of sight
- Massive stars produce a few, long-lived lensing events
- From the frequency & duration of events we can determine the density contributed by all stars and planets
- Result: nearly all the force at $R \leq 3$ kpc comes from stars





Duration of microlensing events



Wegg + 2017

Dark halo

- So stars dominate the Galaxy's gravitational field near the GC, and become less important with increasing R
- Dark matter dominates the gravitational field through the huge volume 8 kpc < R < 100 kpc
- So we think that ~ 95% of the Galaxy's mass is contributed by particles we can only detect by their gravity
- Most of these particles lie at $R > R_0$ and do not affect us
- But locally they contribute 0.01 $M_\odot/\mathrm{pc}^3$ and we think they are streaming right through the Earth (& us!) at the rate of ~ 100,000 per cm^2 per second!

How was the Galaxy assembled?

- We have a theory - ΛCDM
- We know
  - The equations (laws of physics)
  - The initial conditions (CMB: echo of the Big Bang)
- In principle we could compute the evolution of the Universe to its current state
- People try to do this, but it's way too hard: the physics plays out on too wide a range of scales for even the biggest computers
- There are 2 possible workarounds:
  - Observe galaxy formation at great distances and thus far into the past
  - Observe nearby galaxies in exquisite detail and do what a detective does: figure what happened from tiny clues

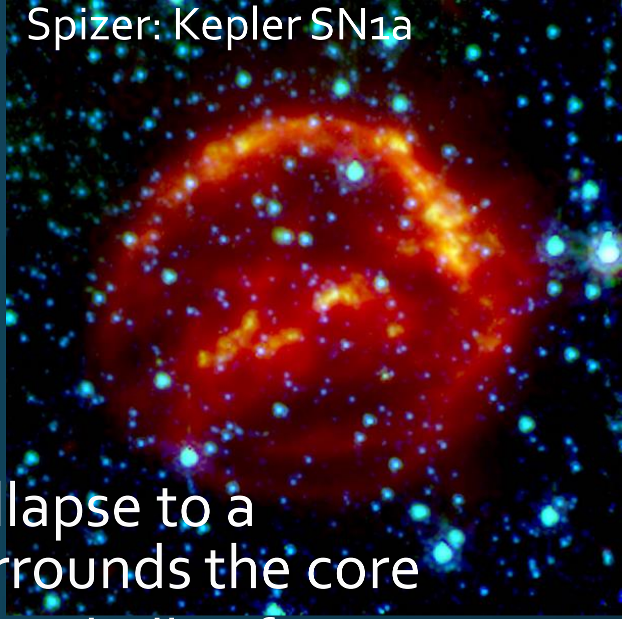
Galactic archaeology

- We can’t compute the emergence of life on Earth
- We can’t observe it happening on distant planets
- But we know how it did because in the 19th c people pieced together the story by minutely observing rocks
- That’s what we aim to do for our Galaxy and neighbouring galaxies

A key entanglement

- The Big Bang left H, He and tiny traces of Li
- The C, O, N, .. we are made of, and the Al, Fe, Cu, etc that industry uses were made in stars that died before the Sun formed 4.5 Gyr ago
  - So the chemical composition of interstellar gas and newly born stars has evolved with the Galaxy
- Also evolving: the orbits of stars
  - Stars form on nearly circular orbits in the Galactic plane and evolve to more eccentric orbits that oscillate further & further above & below the plane
- So chemistry & kinematics are *correlated*

Supernovae

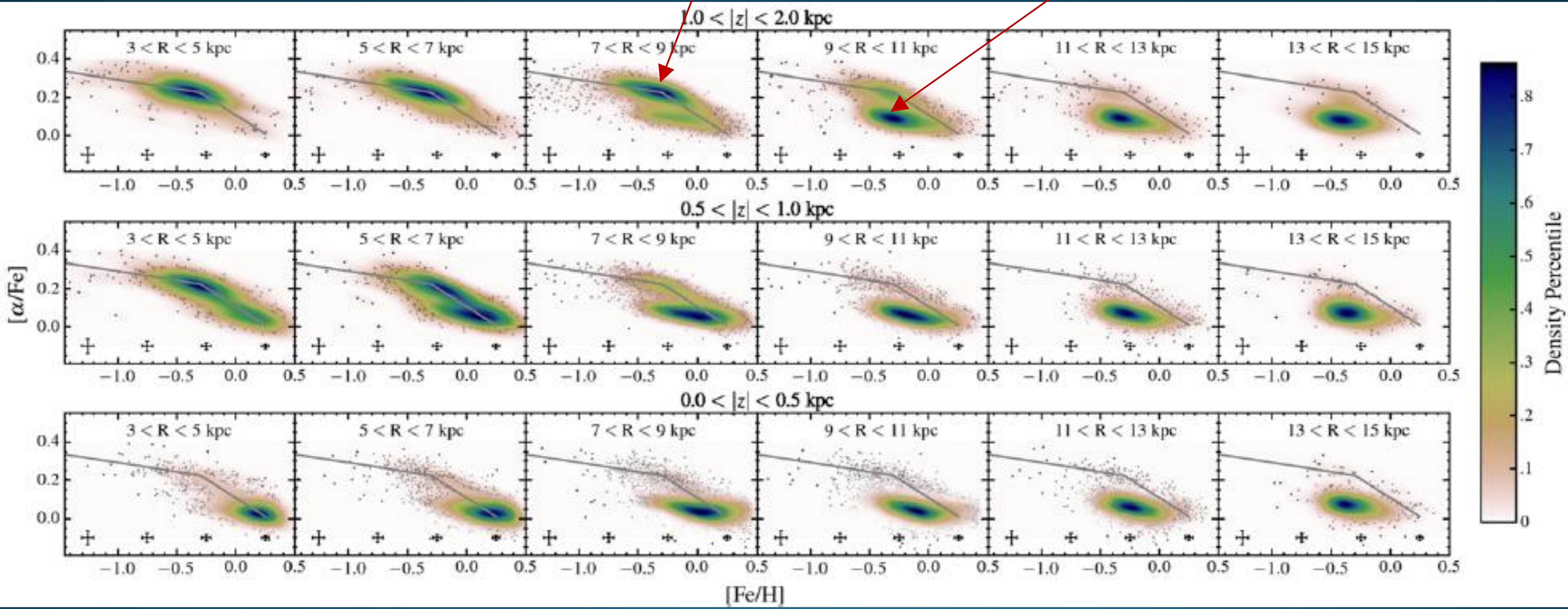


- There are 2 main types of supernova
  - Stars with initial masses >$8M_\odot$ evolve dense cores that collapse to a neutron star or black hole, ejecting most of the gas that surrounds the core
  - Stars with smaller masses evolve quietly to white dwarf stars: balls of C and O about the size of Earth with a mass of ~$0.8M_\odot$
    - This ball occasionally blows up as a thermonuclear device
    - In ~ millisecond most of the C and O are synthesised to Si and then Ni and Fe with the release of enormous energy
    - Most of the Ni quickly decays to Fe, so ~ 0.7 $M_\odot$ of Fe is injected to interstellar space
- The bottom line:
  - Stars with masses M>$8M_\odot$ quickly (<100 Myr) synthesize C, O, N, Si
  - On >1 Gyr timescale other stars with M<$8M_\odot$ synthesize lots of Fe

2 sequences

Thick disc

Thin disc



C

Mg

Fe

Hayden + 2015

Formation of the thin disc

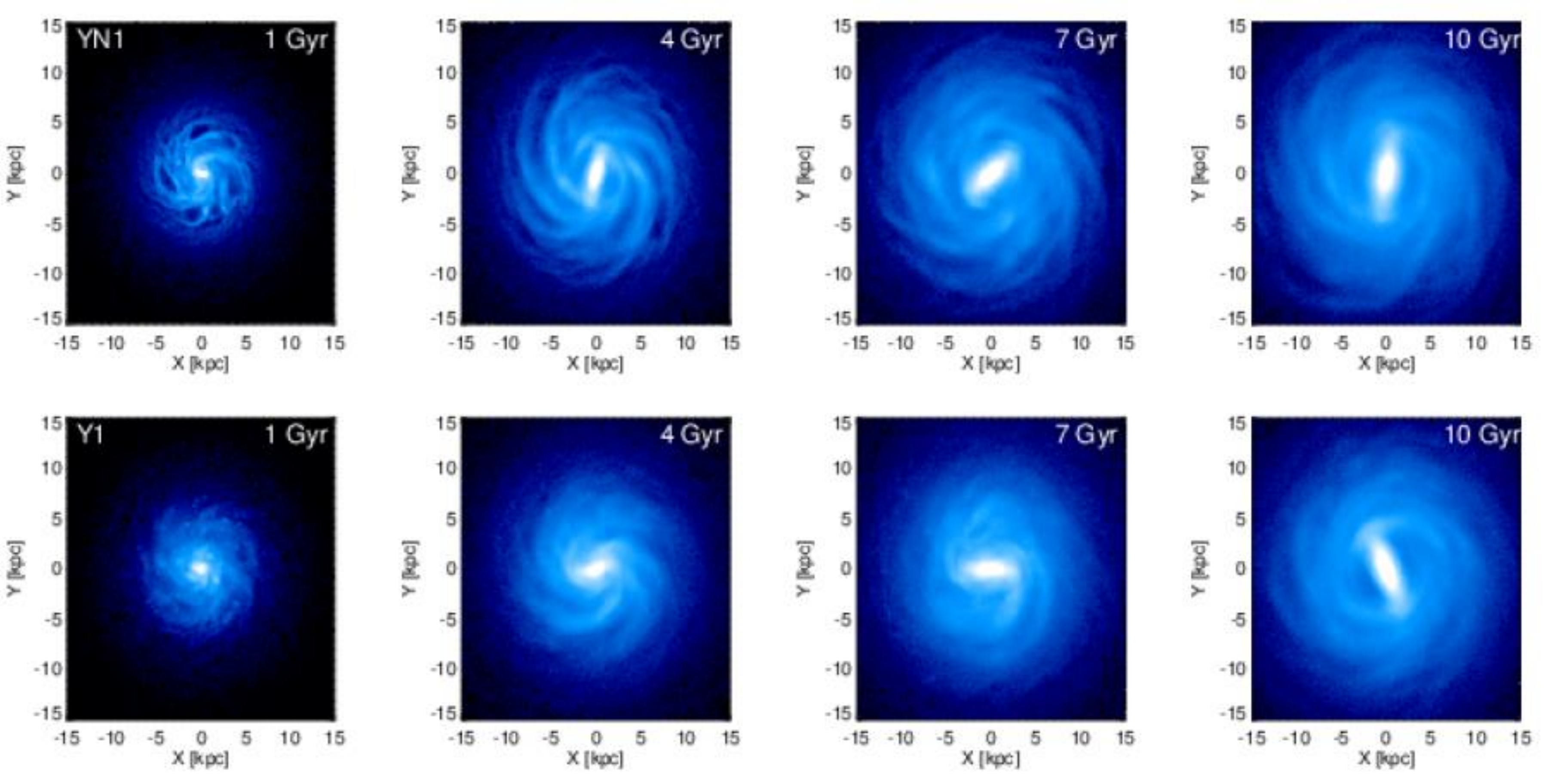
Aumer + 2016, 2017

- N-body simulations with ~10^7 particles
  - disc growth over 10 Gyr in pre-formed dark halo
- Associate with star formation a mass spectrum of short-lived Giant Molecular Cloud (GMC) particles M~100,000 Msun
  - Grow for 25 Myr, constant M for 25 Myr, then vanish

From spiral structure -> bar

No GMCs

With GMCs

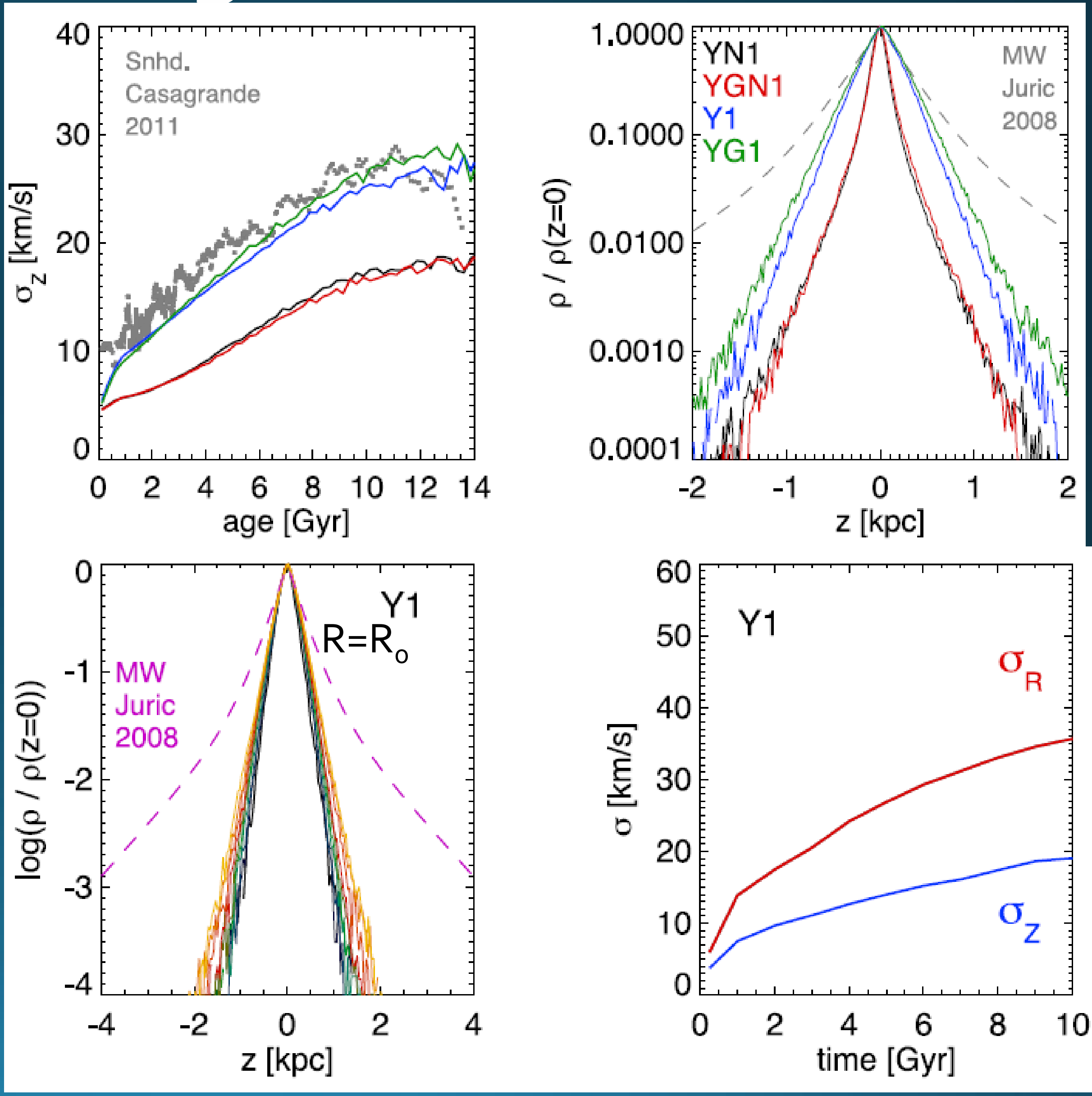


Aumer et al 2016

Basic results: GMC heating

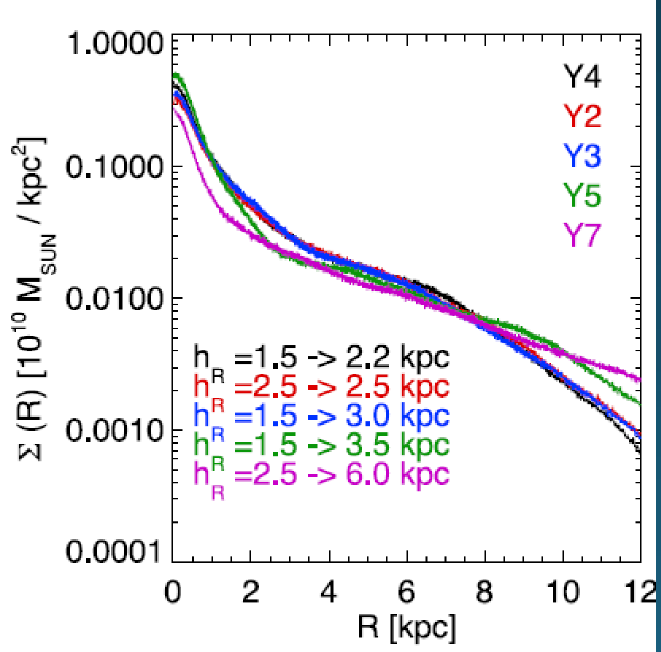
- With GMC particles included, discs just like MW's thin disc emerge

R=R$_o$

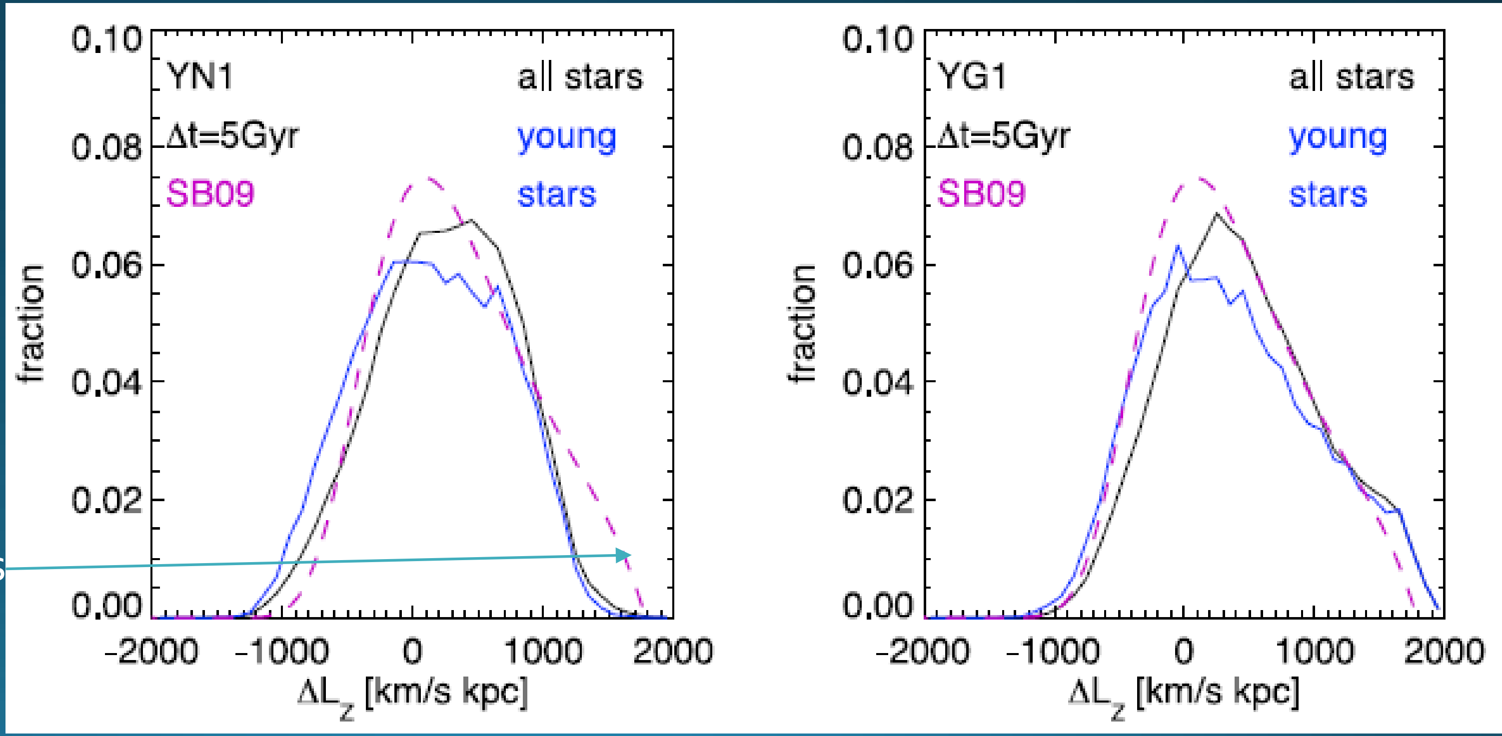


Basic results: radial shuffling

- Spiral arms cause abrupt changes in L_z of stars (Sellwood & B 2002)
- Final radial surface-density profile barely related to profile of star formation
- In Nbody simulations stars migrate at ~ rate required by Schoenrich & B (2009) to model chemical composition of the solar neighbourhood
  - Insensitive to details
  - Bar limits ΔL_z in Solar nhd because stars don't escape bar

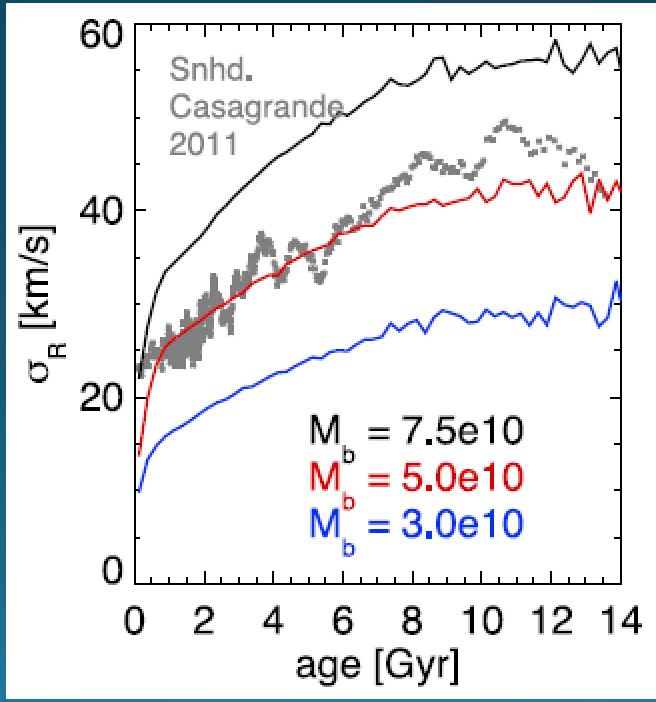


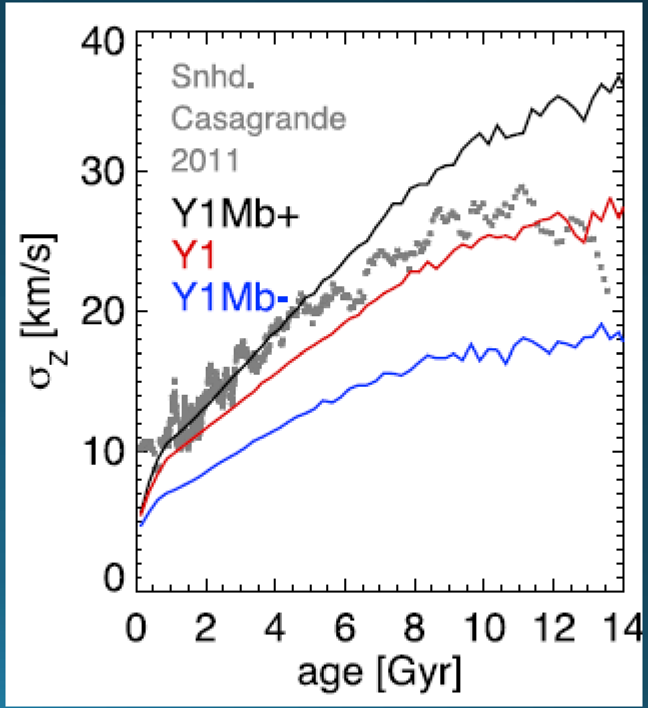
Bar suppresses migration



ΛCDM ok!

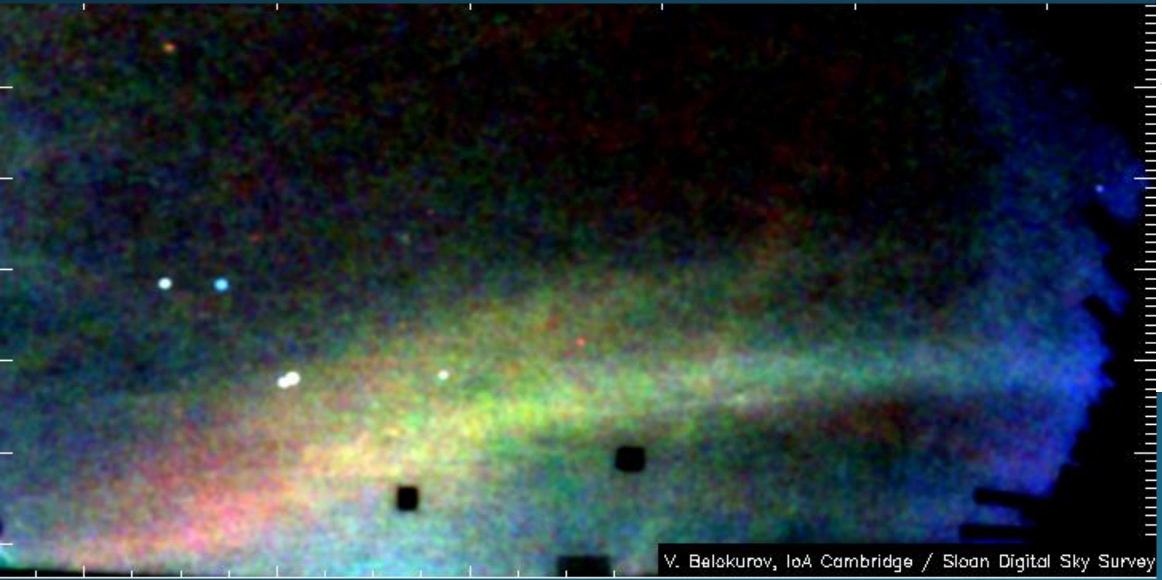
- Amplitude of non-axisymmetries depends on
  - Fraction of gravitational force from disc rather than dark halo
  - Number density of GMCs
- If ratio of disc and dark halo masses shifted from cosmological prediction, match to data spoiled



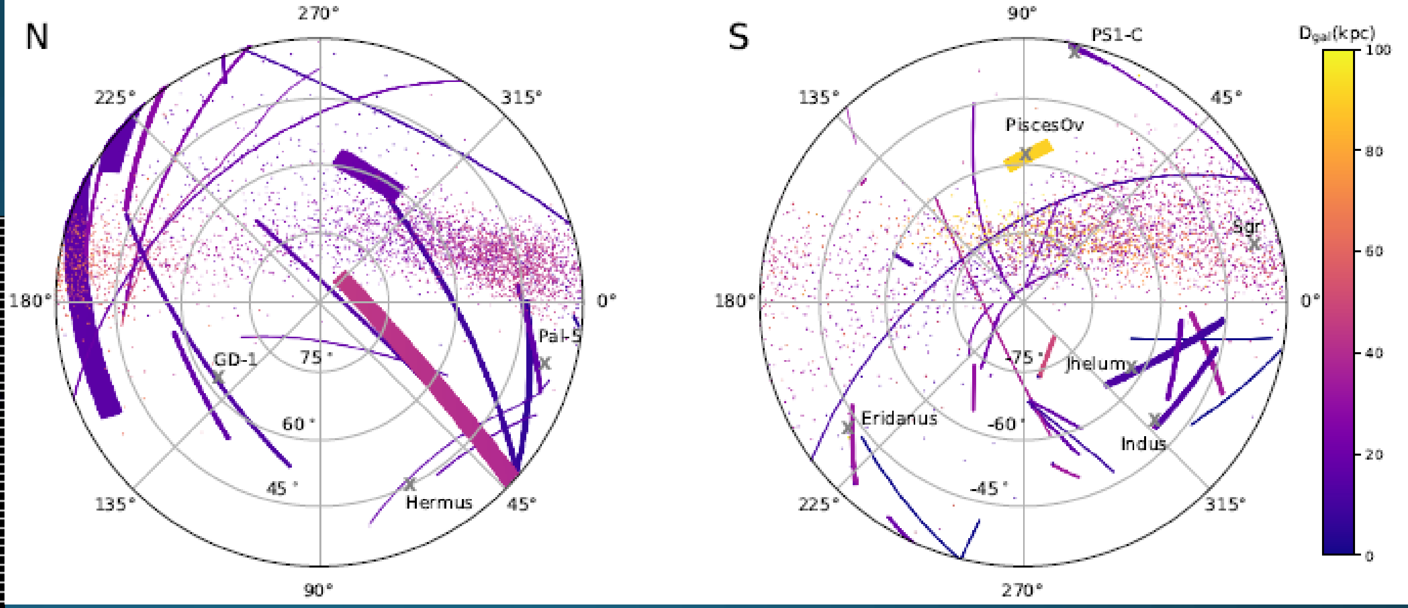


Fine structure in the stellar halo

- Globular clusters and dwarf galaxies tidally stretched into streams
- Part-digested lunch!



Belokurov + 2006



Malham + 2018

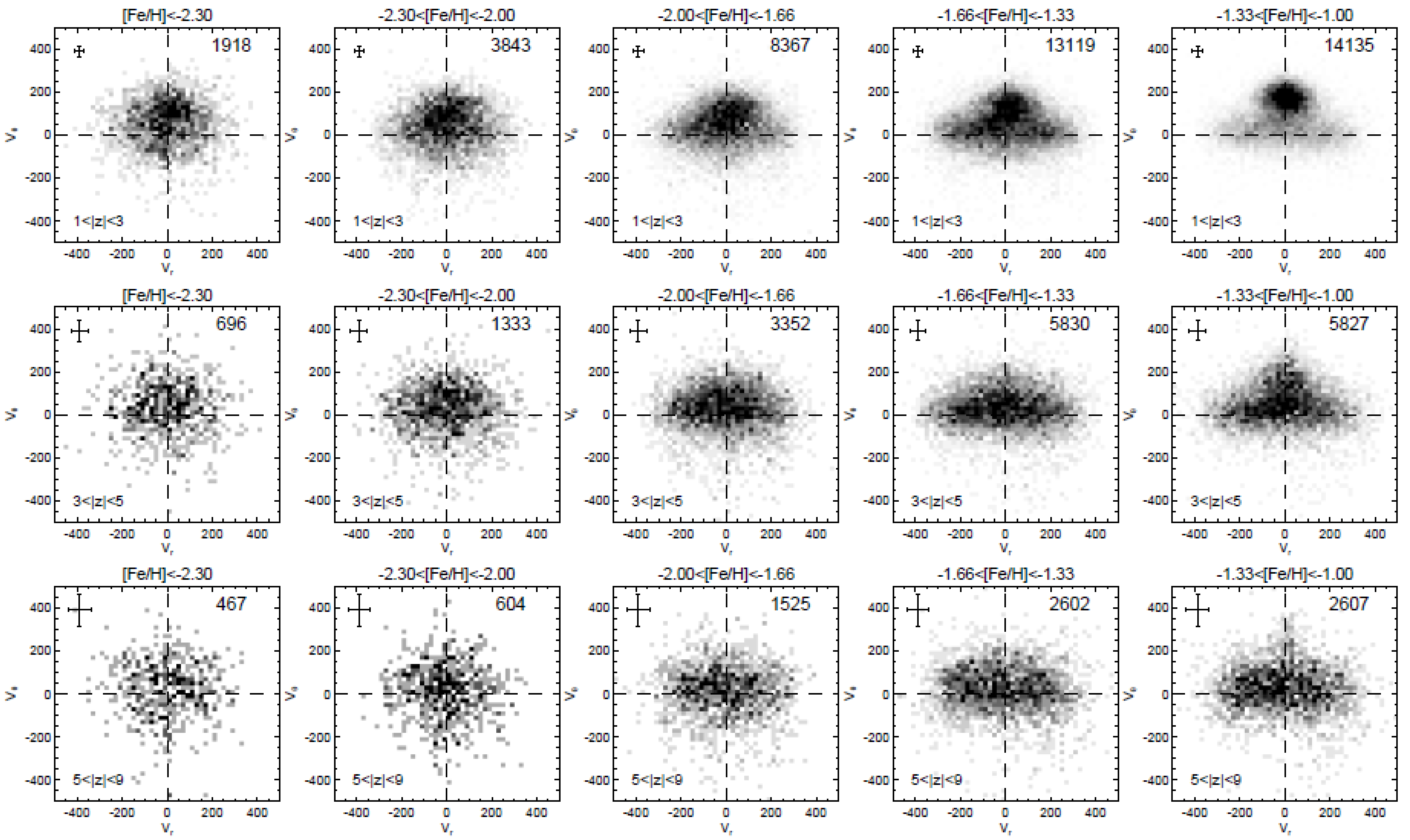
A brief history of our Galaxy

- In ~ first 2 Gyr gas falls rapidly on the Galaxy, so it is gas rich
- Stars form rapidly from abundant gas
- Chemical evolution is rapid
- Another galaxy falls in & merges
- As it merges stars are knocked onto more eccentric & inclined orbits
- The thick disc has formed
- Over the rest of cosmic time the thin disc accumulates quietly and stars become richer in Fe
- Scattering by spiral arms & giant gas clouds gradually moves stars to more eccentric and inclined orbits – the disc 'heats'

Ancient merger?

[Fe/H] ->

Z



Issues we're working on

- Was the thick disc really made when a merging galaxy scattered the stars of an old thin disc?
  - Perhaps in the confused early Gyr stars formed in gas clouds before they had settled to nearly circular orbits
- Why do stars & gas form only ~5% of the mass of the Galaxy
  - the cosmic mix implies it should be 20%
  - The remaining 15% seems to have been ejected to intergalactic space or forms a hot halo around the visible Galaxy
- How does the Galaxy acquire gas so it can grow (the thin disc)?
- Like most spiral galaxies, we have a bar – when did it form? How is it changing the disc & dark halo?
- Stars migrate through the disc: where did the Sun form?
- How does our Galaxy fit into the cosmic picture?
  - How are we related to irregular galaxies, lenticular galaxies, elliptical galaxies, etc..?
  - What happened at z>2

Our ambition

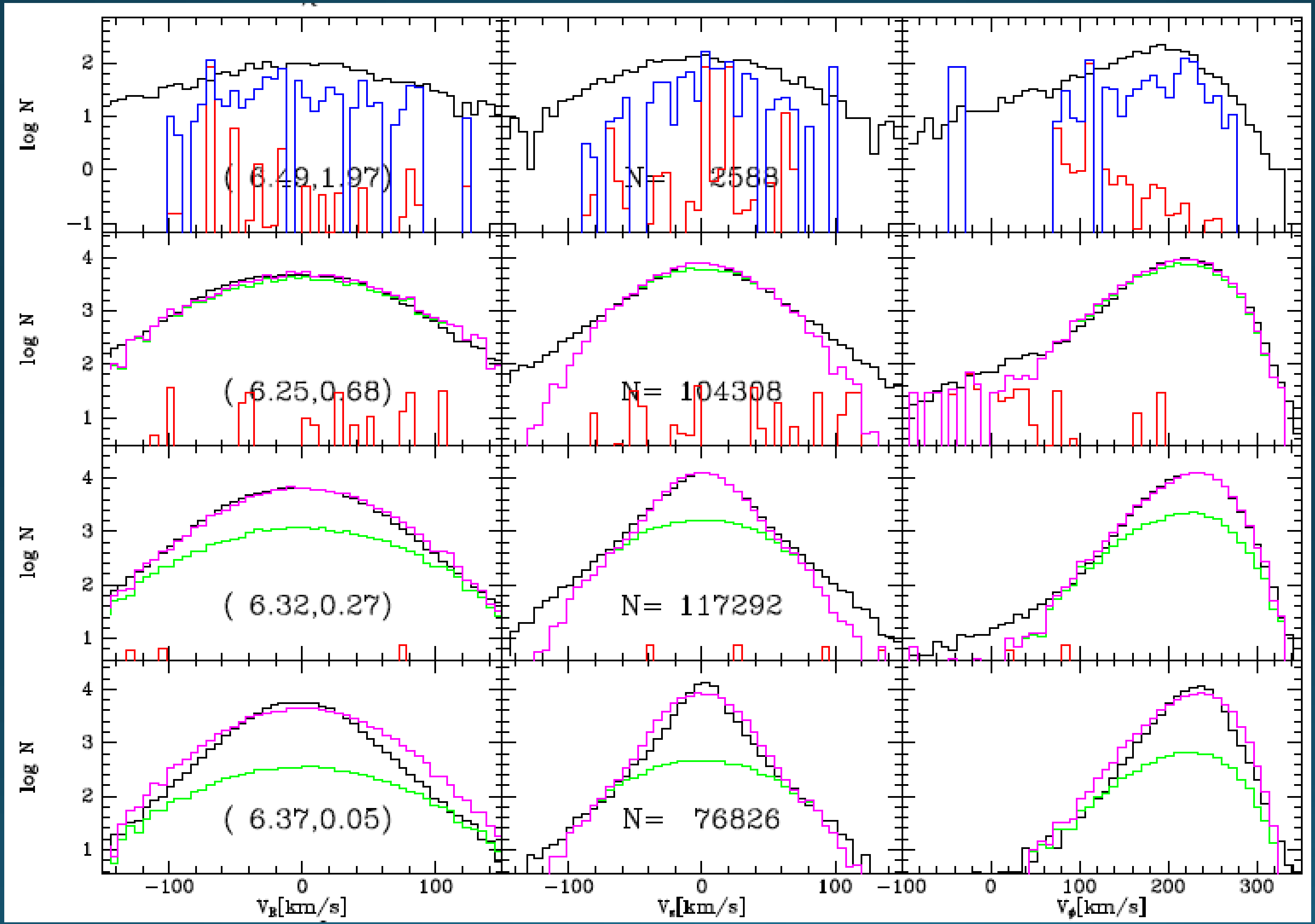
- To synthesize these data into a 'working' computer model of our Galaxy that will encapsulate all we understand about this object
- The synthesis will take into account
  - Measurement errors
  - The observational bias towards nearby and luminous stars
- The model must include
  - all the different types of star (young/old, metal-rich/poor, luminous/faint/dead)
  - Interstellar gas (which obscures from Gaia's view many important places)
  - Dark matter

Conclusions

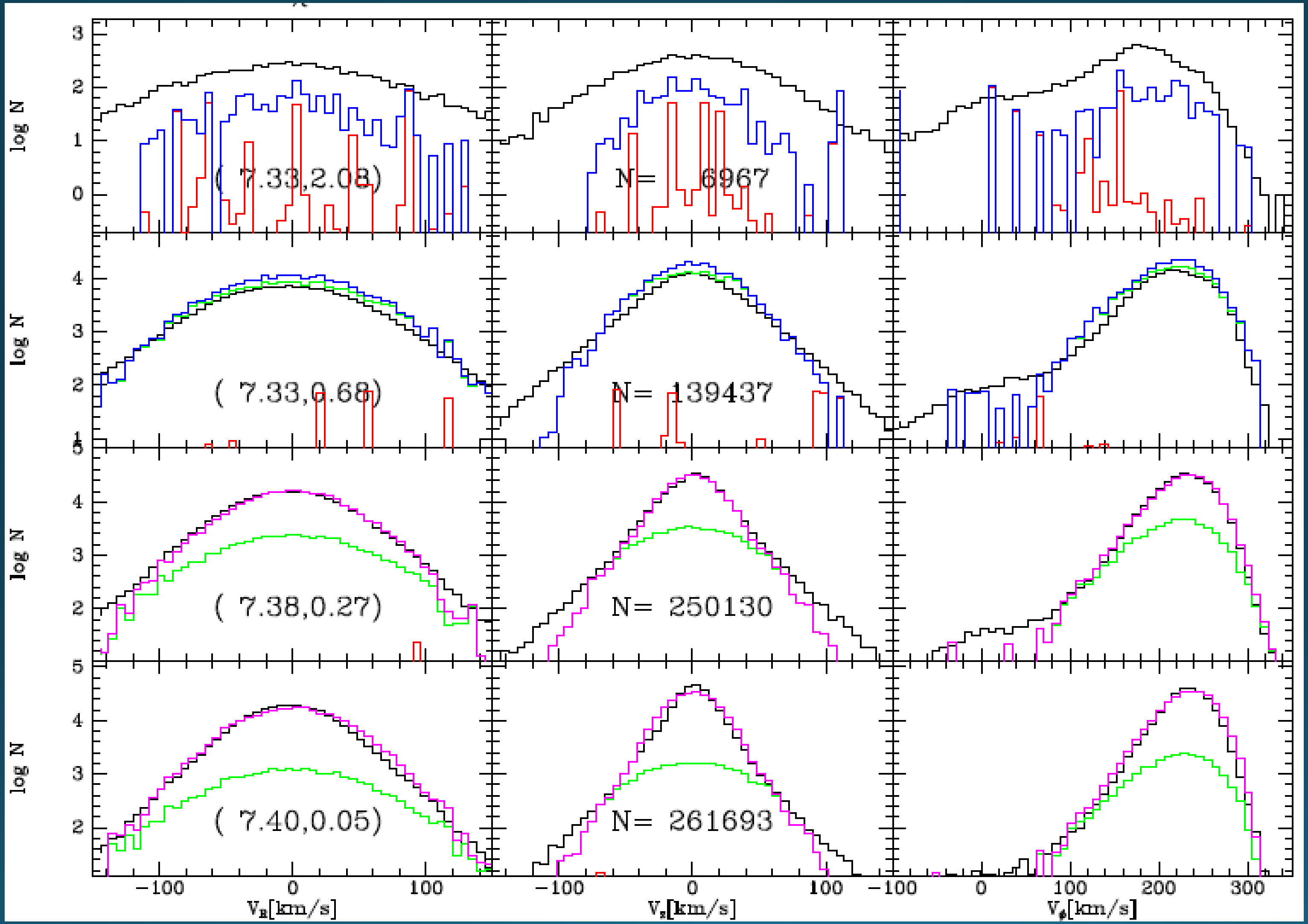
- Our Galaxy is a giant machine, typical of 10s of billions of others in the observable Universe
- Important roles are played by stars, interstellar gas and dark-matter particles
- It is held together by the jointly generated gravitational field
- Stars dominate the field near the centre, but dark matter dominates in most of the volume
- 95% of the mass in contributed by dark matter
- We broadly understand how the Galaxy formed:
  - Most of the stars form a disc – which has thin & thick components
  - The thick disc was formed very early on & the thin disc has accumulated gradually
  - Elements >Li are continuously added to the ISM: first C,Mg then Fe
  - The orbits of stars evolve (a) suddenly during mergers, and (b) gradually as a result of scattering by spiral arms & gas clouds
  - We can exploit these facts to reconstruct the assembly history
- In April 2018 there was a qualitative change in our bank of data
- We have developed new techniques and with them aim to construct a living Standard Galaxy Model

How will we do this?

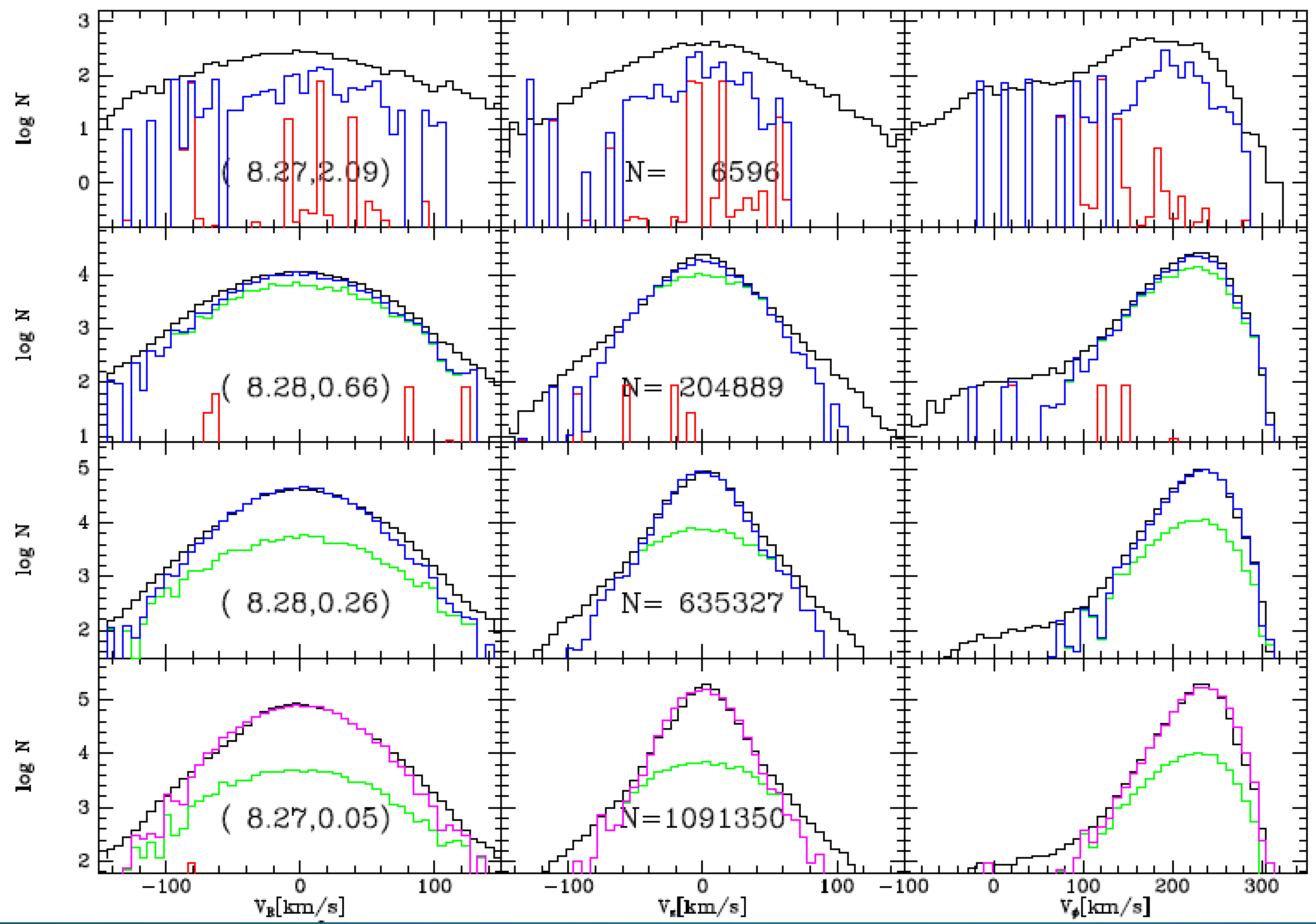
- By associating orbits with points in 3d `action space'
  - Usual coordinates (J_r, J_ϕ, J_z)
- Orbits in volume element d^3J are assigned a number of stars / DM particles of each age, mass, chemical composition by a DF f(J)
- The mass of particles of a given type is $\mathrm{M} = (2\pi)^3 \int d^3 J \; f(J)$
- Any non-negative function f(J) defines a component!
- Once all DFs chosen, we solve for the jointly generated gravitational field
- Then we can compute any observable with arbitrary precision
- The DFs are adjusted until their predictions fit data
- The code library AGAMA provides software for doing this

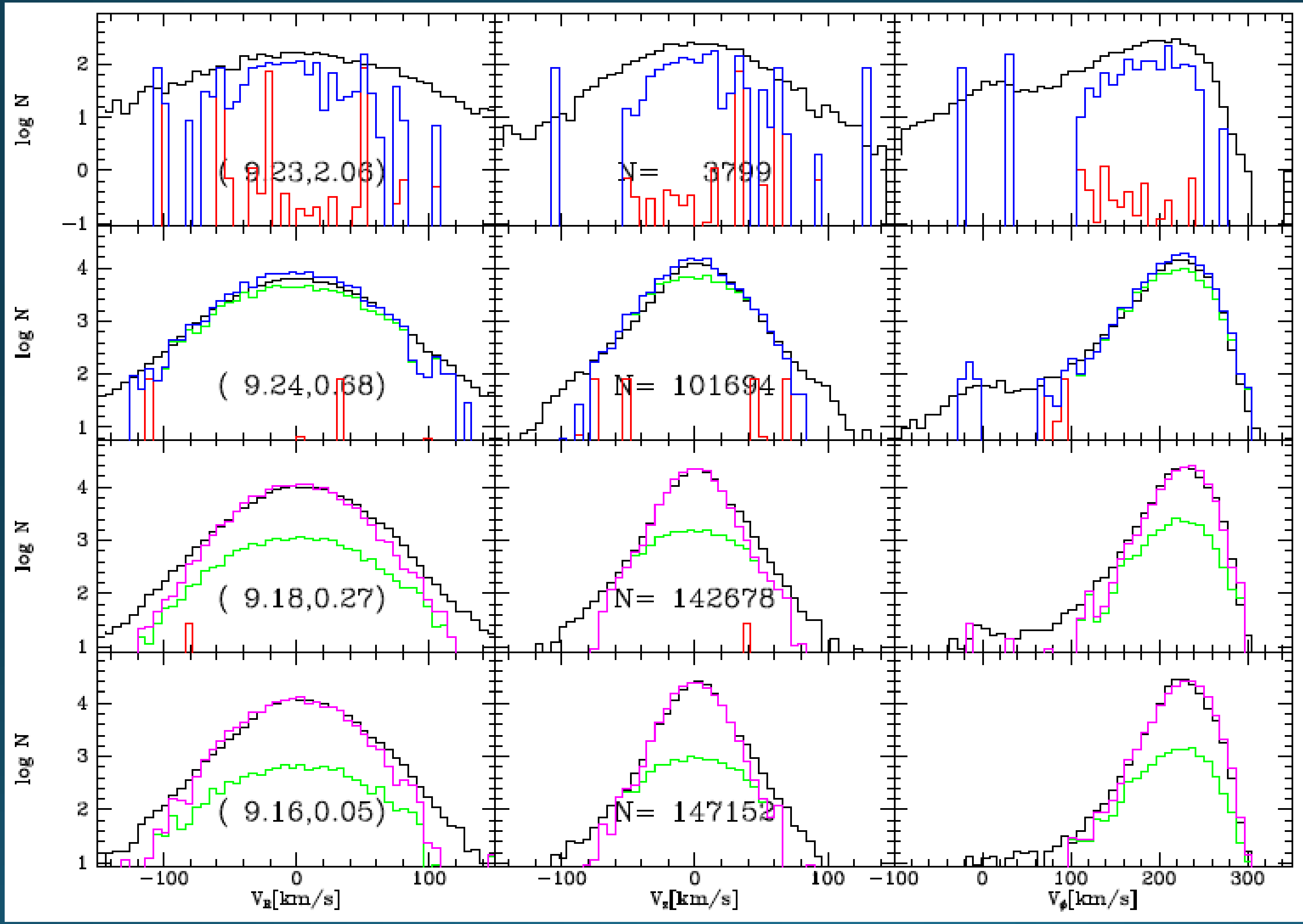


log N
(6.49,1.97)
N= 2588
(6.25,0.68)
N= 104308
(6.32,0.27)
N= 117292
(6.37,0.05)
N= 76826
V_R[km/s]
V_z[km/s]
V_φ[km/s]



log N
(7.33,2.08)
N= 6967
(7.33,0.68)
N= 139437
(7.38,0.27)
N= 250130
(7.40,0.05)
N= 261693
V_R[km/s]
V_z[km/s]
V_φ[km/s]


(8.27,2.09)
N= 6596
(8.28,0.66)
N= 204889
(8.28,0.26)
N= 635327
(8.27,0.05)
N=1091350
log N
V_R[km/s]
V_z[km/s]
V_ϕ[km/s]


(9.23,2.06)
N= 3799
(9.24,0.68)
N= 101694
(9.18,0.27)
N= 142678
(9.16,0.05)
N= 147152
log N
V_R[km/s]
V_z[km/s]
V_ϕ[km/s]