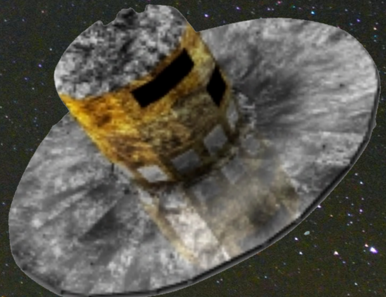
The Milky Way as a Galaxy

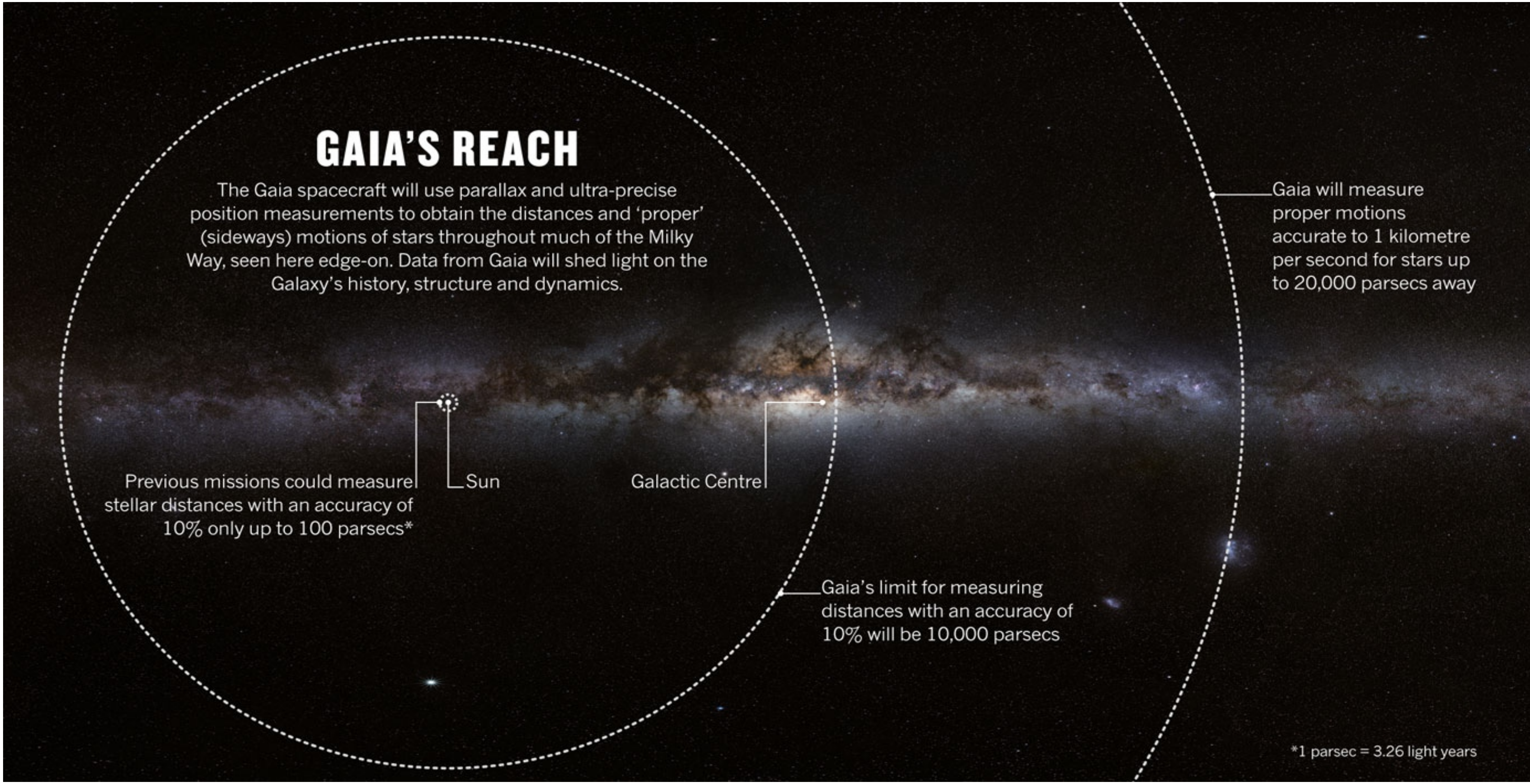
Amina Helmi



university of groningen
kapteyn astronomical institute


VS06 • gaia - December, 19th 2013

The Gaia revolution

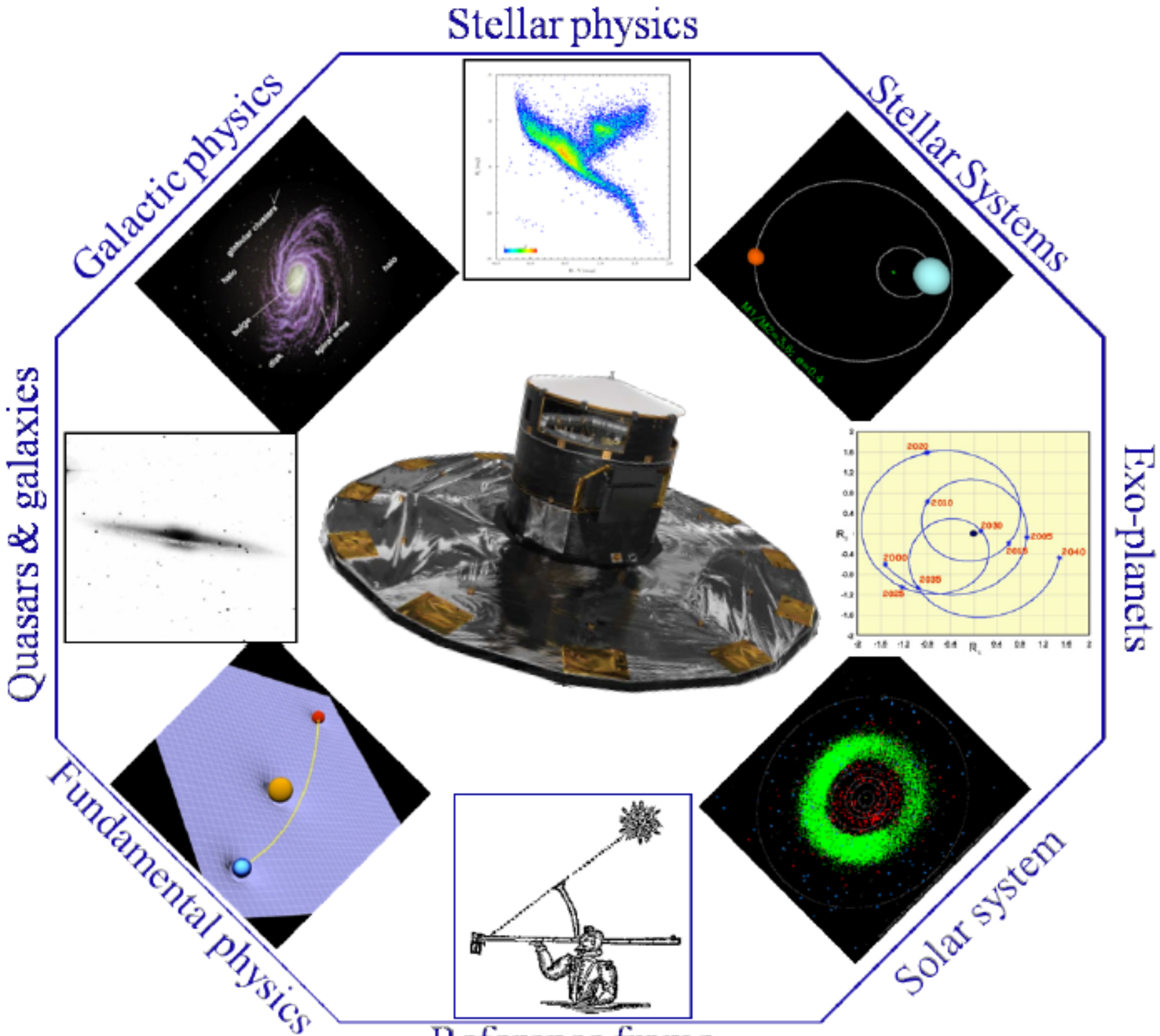


Unparalleled dataset with motions and positions for 10^9 stars across the Milky Way

10^4 times more stars with full phase-space information; 10^6 volume increase; 100x more accurate

Completely new view of the Galaxy!

Science topics

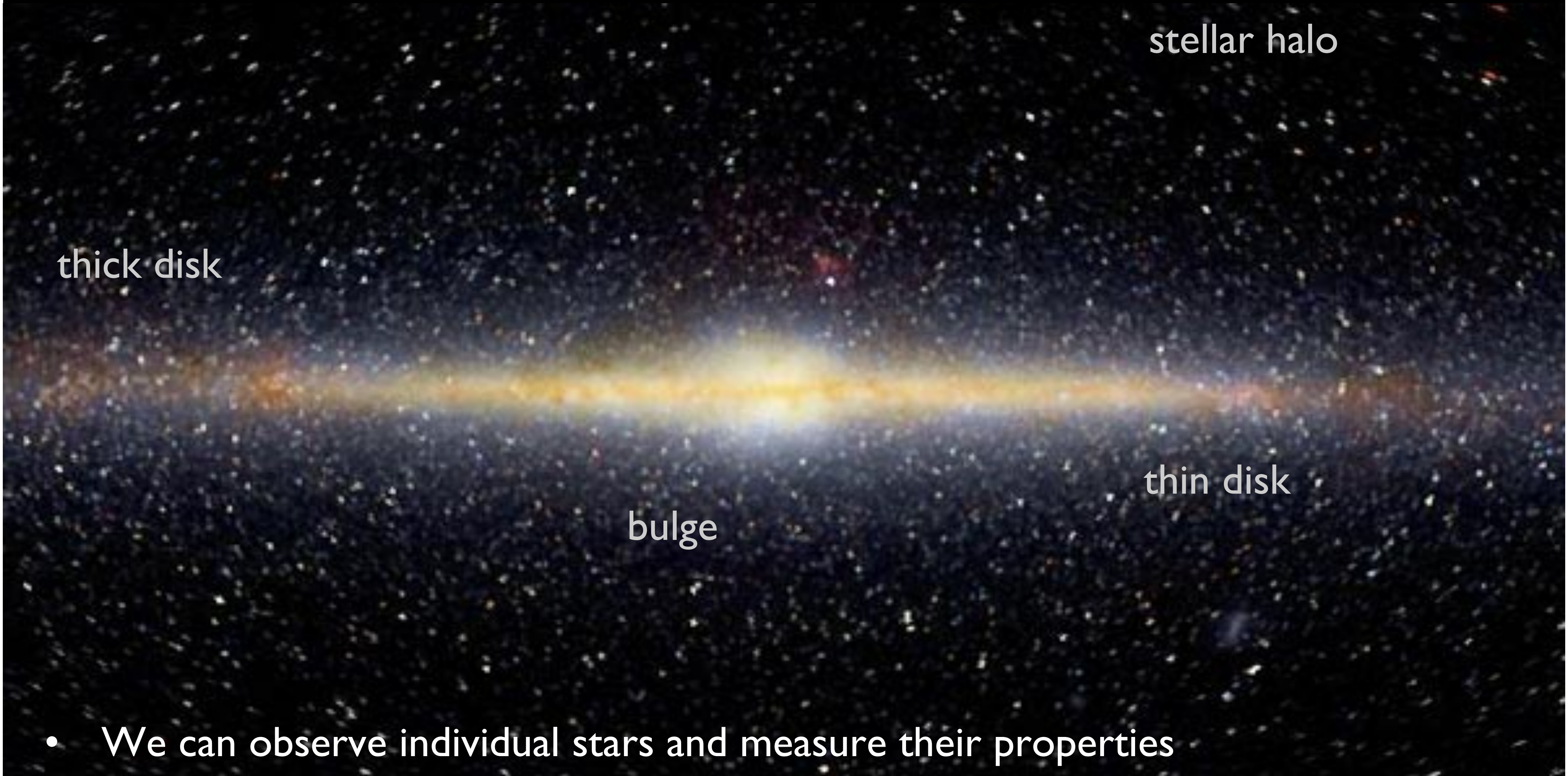


Courtesy A. Brown

The Milky Way

What is the origin/formation epoch/mechanism and relation between the various components?

The Milky Way is a Rosetta stone



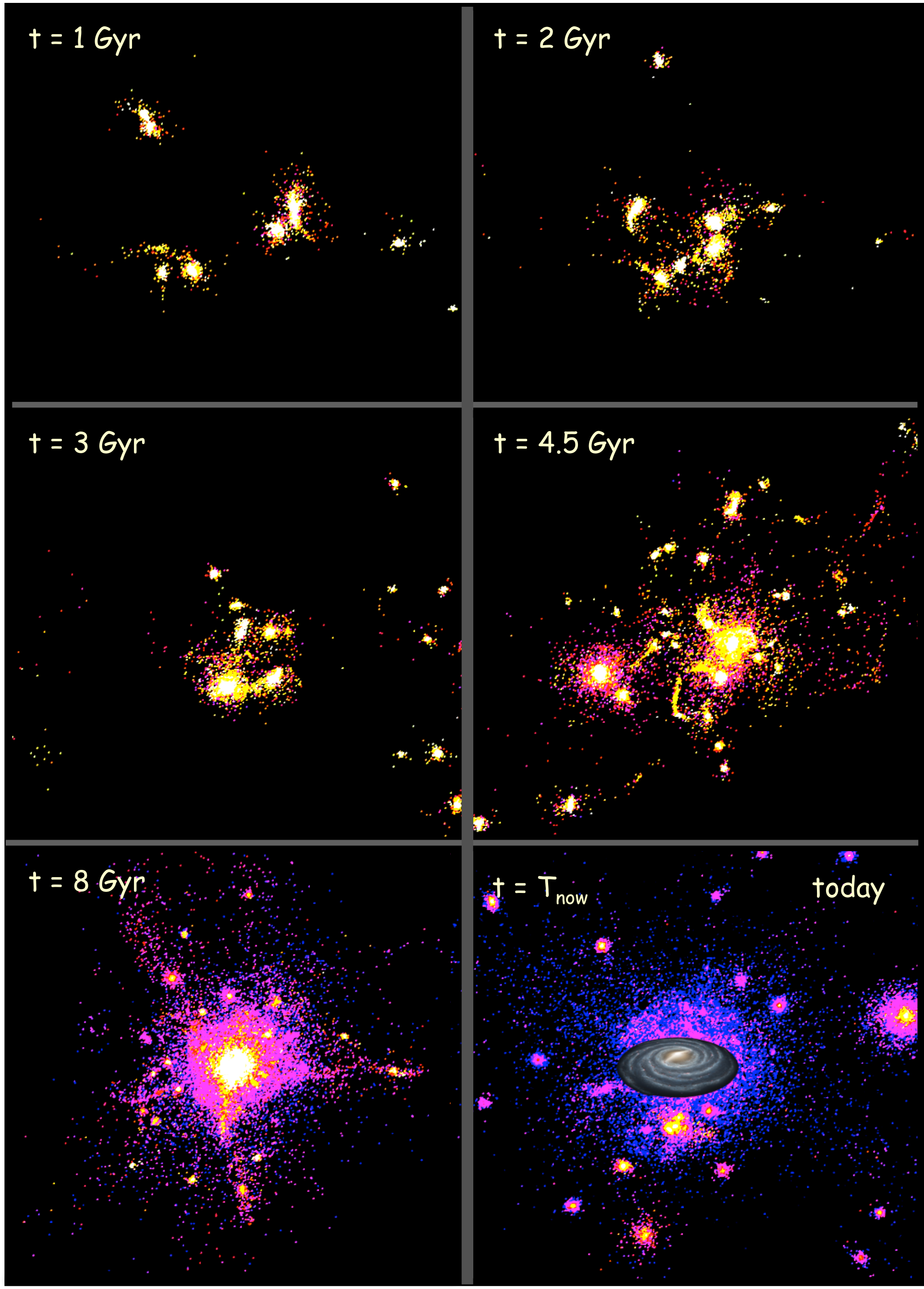
- We can observe individual stars and measure their properties
- Distributed in various Galactic components, each with specific characteristics
  - Different clues to history; for example, halo stars are as nearly as old as the Universe

Galactic Archaeology

- Key ingredient of galaxy formation: mergers

  - Were mergers important for Milky Way?
  - How often and when did they happen?
  - What were the building blocks?

- Stars are "fossils"
  - Motions, ages, chemical composition trace origin
  - Substructures pinpoint to debris from accretion events
  - Probe force field ➔ mass (gravity)



snapshots: J. Gardner

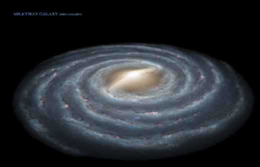
Testing the cold dark matter paradigm

Is this “picture” correct?

- Are galaxies like the Milky Way embedded in dark matter halos like those predicted by the cosmological model?

Testing the cold dark matter paradigm

Is this “picture” correct?



- Are galaxies like the Milky Way embedded in dark matter halos like those predicted by the cosmological model?

Testing the cold dark matter paradigm

Is this "picture" correct?

- Are galaxies like the Milky Way embedded in dark matter halos like those predicted by the cosmological model?
- How much dark matter is there?
  - how is it distributed?
  - what is the dark matter?
- Is Gravity correct?

Studies of the Milky Way: Detailed view of physical processes in galaxy evolution

Star-formation

initial mass function, star clusters and cluster mass function, star formation profile along Galactic plane, link to dynamics/structure and environment, cold flows/gas accretion/ IGM

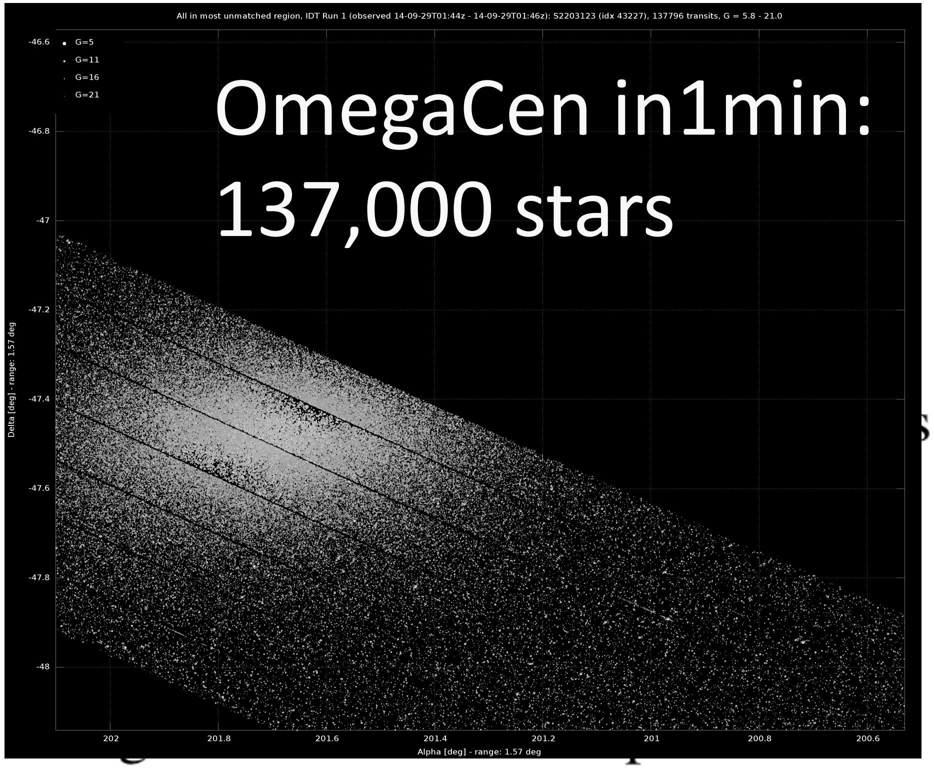
Dynamics

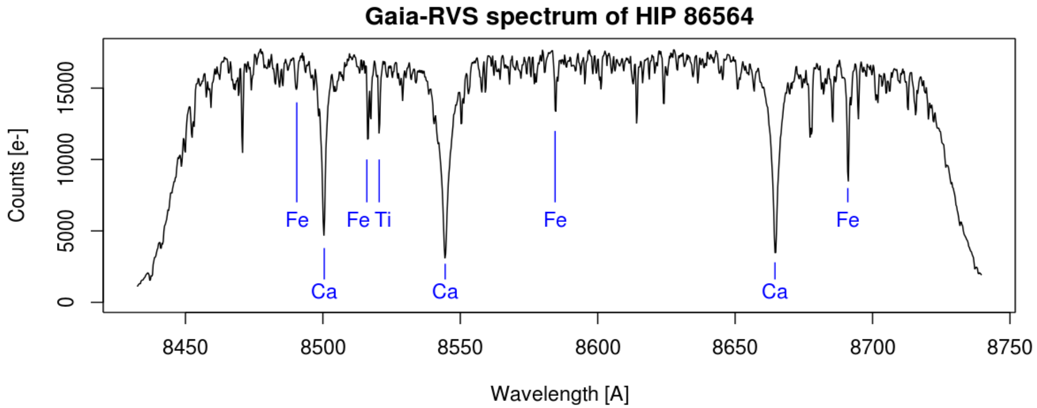
Central few parsecs (near SMBH), bar/bulge and impact on other components, dark matter and rotation curve, spiral structure, tidal shredding, warping

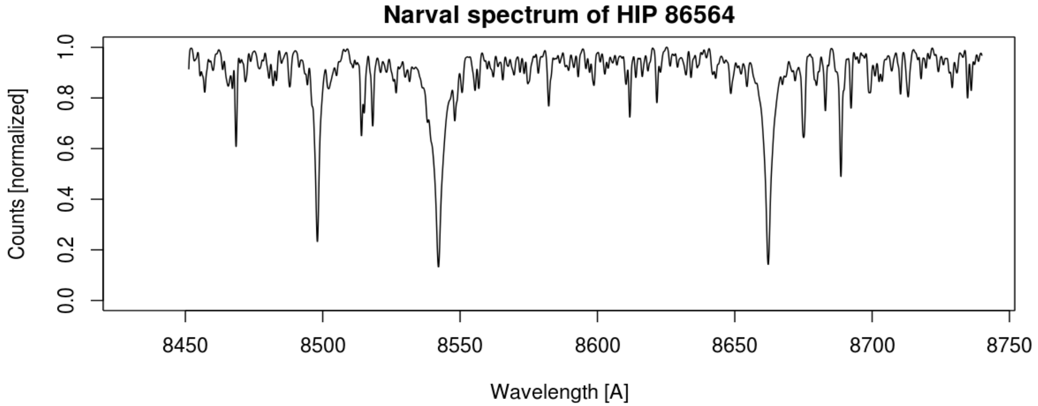
Chemical enrichment

Stellar yields, primordial nucleosynthesis, role of massive stars, binaries, first stars, link to ISM, environment, formation timescales

Gaia







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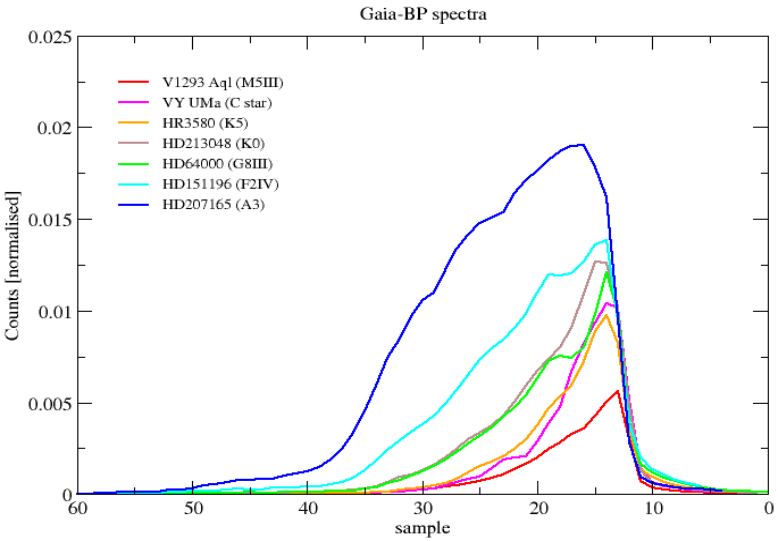
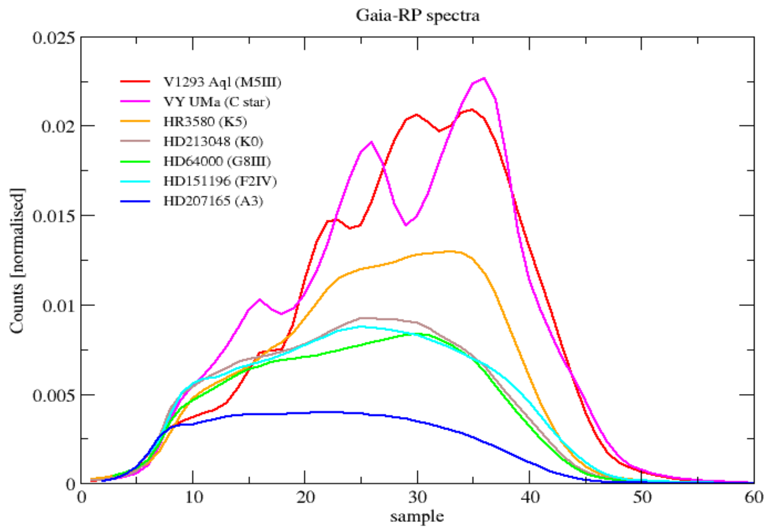
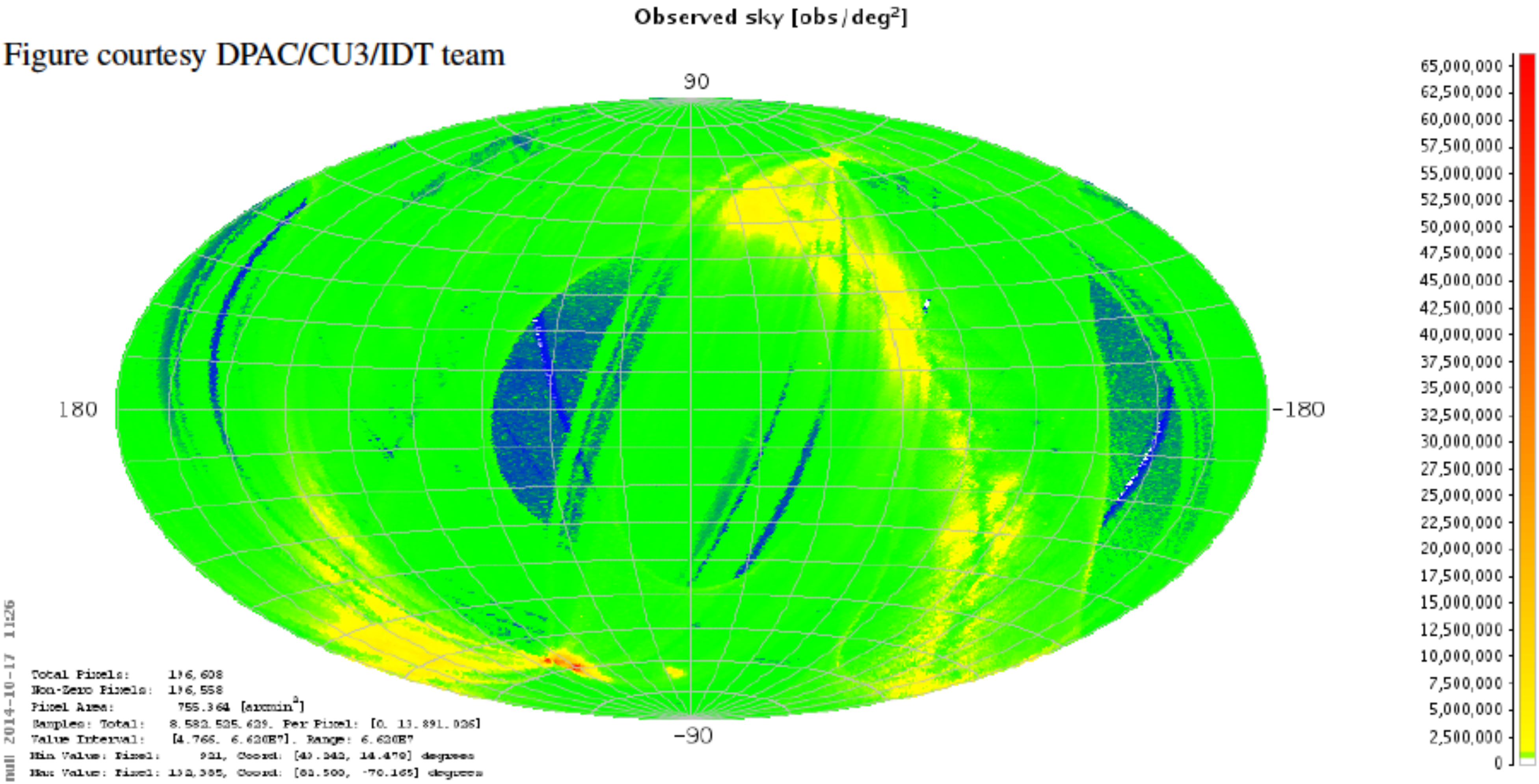




Data collection stats

Number of astrometric observations per square degree up to Oct 17

Figure courtesy DPAC/CU3/IDT team



Whole sky seen by Gaia! — Up to 65 million per square degree

As of End Jan 2015: 16 billion astrometric/photometric transits, 1.6 billion spectroscopic

Courtesy A. Brown

Scientific performance predictions

Performance predictions for G2V star			
V magnitude	Astrometry (parallax)	Photometry (BP/RP integrated)	Spectroscopy (radial velocity)
3 to 12	5–14 μas	4 mmag	
3 to 12.3			1 km s^{-1}
15	24 μas	4 mmag	
15.2			15 km s^{-1}
20	540 μas	60 (RP) – 80 (BP) mmag	

Calculations by: Airbus DS, D. Katz, C. Jordi, L. Lindegren, J. de Bruijne

- Full 6D phase-space information only available for a subset
  -> Incomplete dynamical map of the Galaxy

- Gross abundances (Fe/H], [alpha/fe] only for a subset of brightest stars
  -> MDF only known within few kpc from the Sun, in sections of the bulge or in dwarf galaxies

- Detailed elemental abundances missing
  -> crucial for chemical history, star formation and assembly history

- *Ground-based synergetic follow-up/supplementary surveys are a must*

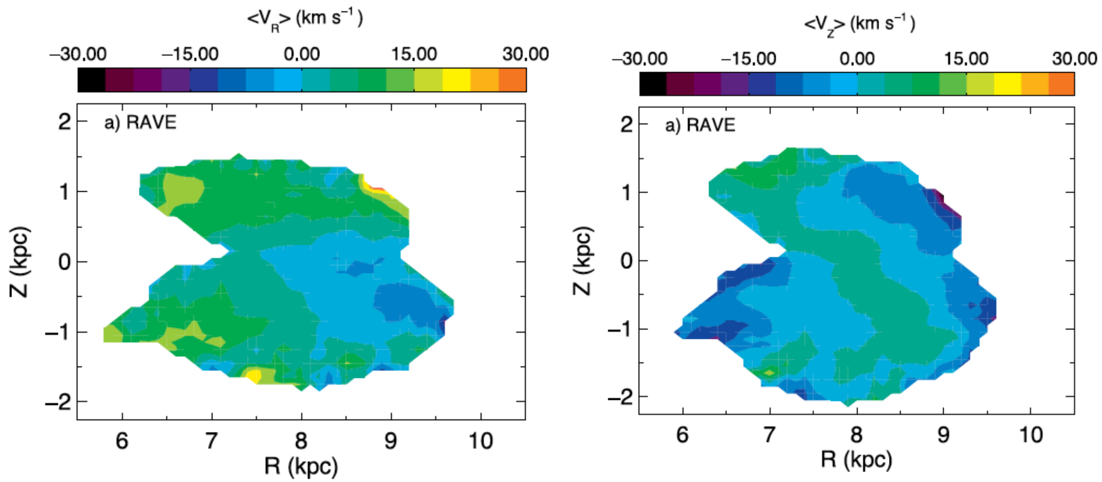
What do we know now about the Milky Way?

Some recent highlights

and some interesting questions

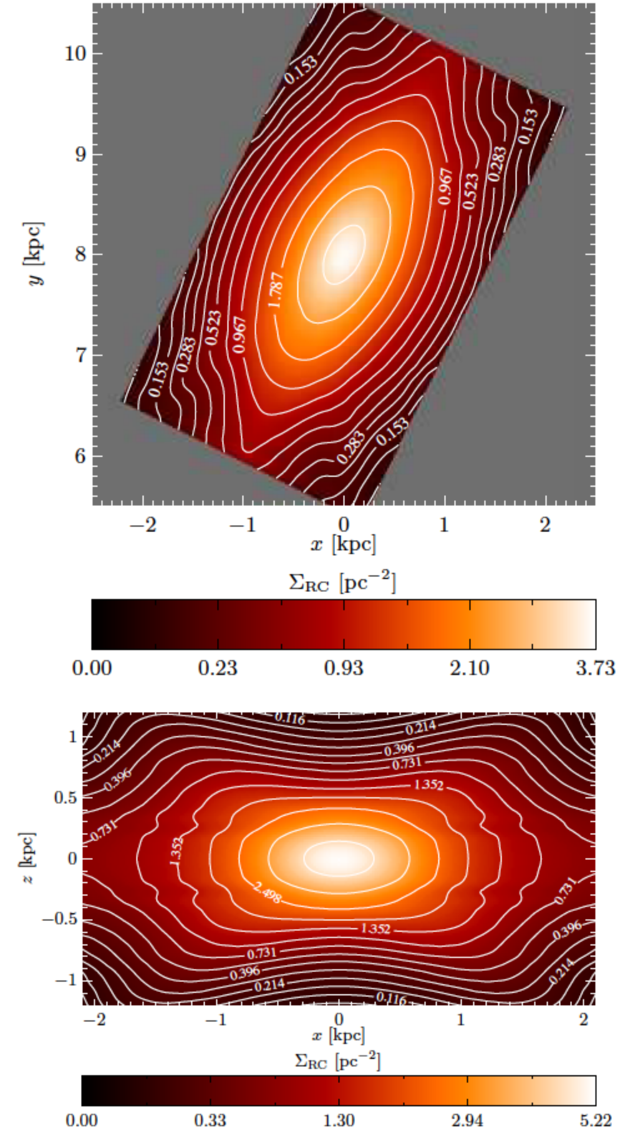
The Milky Way bar and spiral arms

- Peanut-shaped bar/bulge from VVV, also explains kinematics in inner regions (Martinez-Valpuesta & Gerhard 2011; Ness et al. 2013)
  - Is there also a long bar? (Lopez-Corredoira et al. 2005)
  - How fast does bar rotate?
- Bar and spiral arms influence dynamics of disk stars
  - Streaming (non-circular) motions and the wobbly Galaxy from RAVE



Williams et al (2013)

VVV red clump

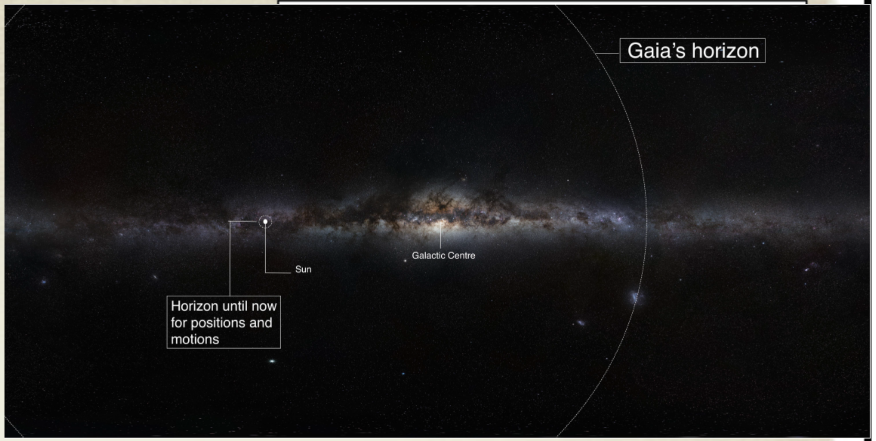


Gerhard & Wegg (2014)

•Generally important: physics of disks, build up of disks, bars and bulges, throughout cosmic time

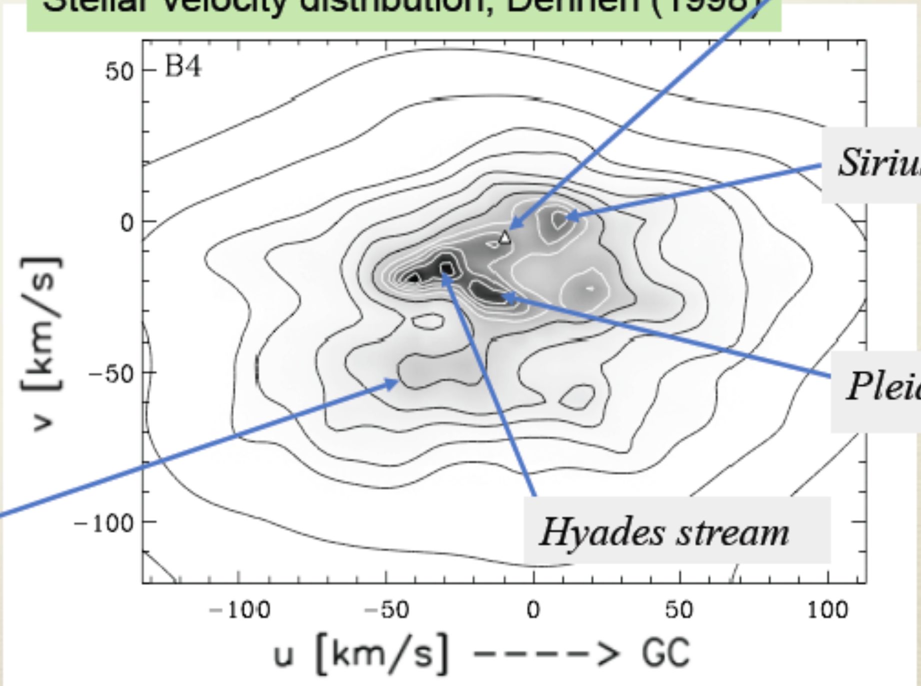
MOONS combined w/VISTA and Gaia: the abundances/MDF obscured view

Hipparcos stellar velocity distribution



- Lots of structure in the u-v plane.
- The most prominent low-velocity moving groups in the solar neighborhood favor a dynamical origin (Famaey et al. 2008, Bovy & Hogg 2009).
- Created near resonances with bar or spiral structure

Stellar velocity distribution, Dehnen (1998)



High-resolution (1 – 5 km/s) velocity maps of disk (beyond Sun) constrain both bar angular velocity and orientation

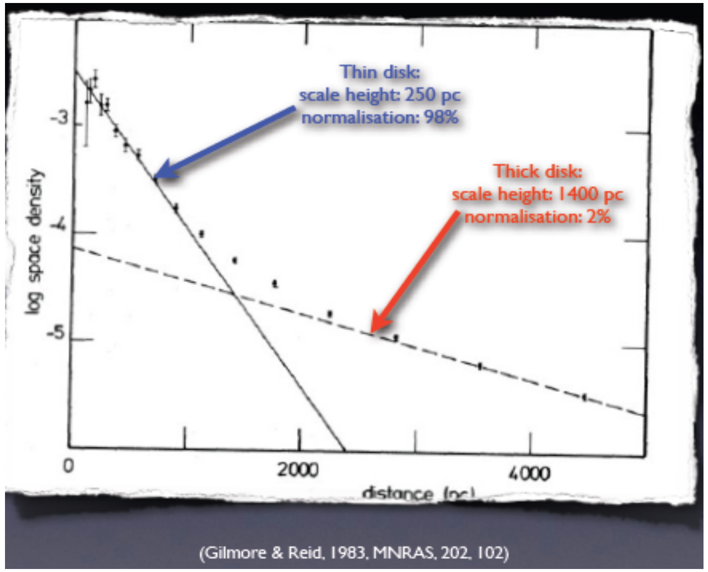
With detailed abundances how star formation proceeded in disk

➔ 4most complementing Gaia

Courtesy of I. Minchev

The thick disk

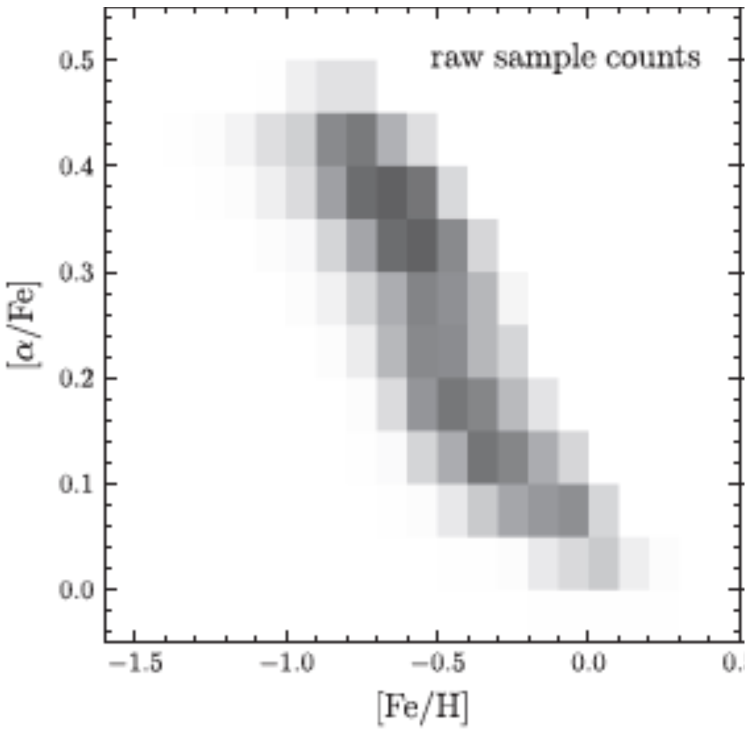
- Older, more metal-poor stars -> more pristine
  - link to high-z disks, clumpy-disks (Elmegreen++2009, Förster-Schreiber et al 2011)
- Existence as separate physically distinct from thin disk highly-debated
  - role of radial migration (Schonrich & Binney 2009; Bovy, Rix & Hogg 2012)
- Accurate detailed abundances: critical

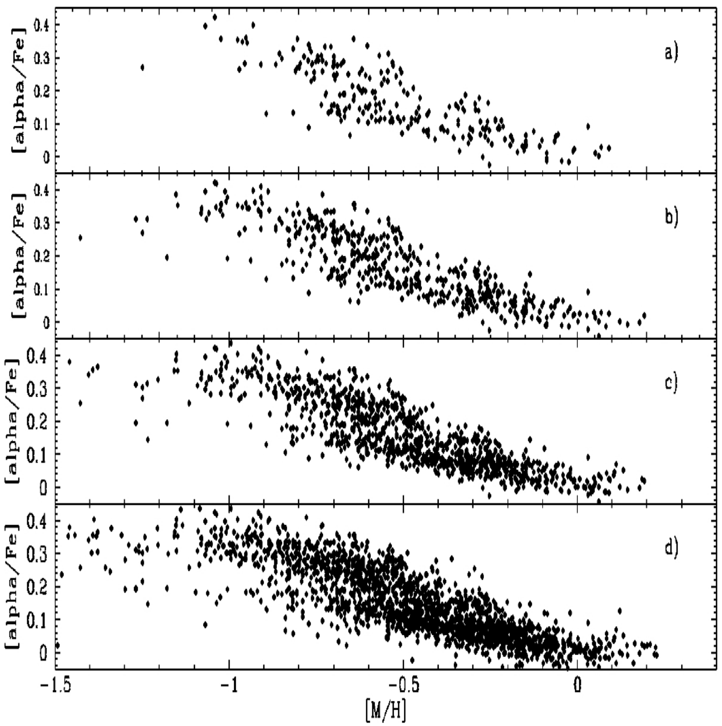


(Gilmore & Reid, 1983, MNRAS, 202, 102)

SDSS/SEGUE vs Gaia-ESO survey

Bovy et al. 2012

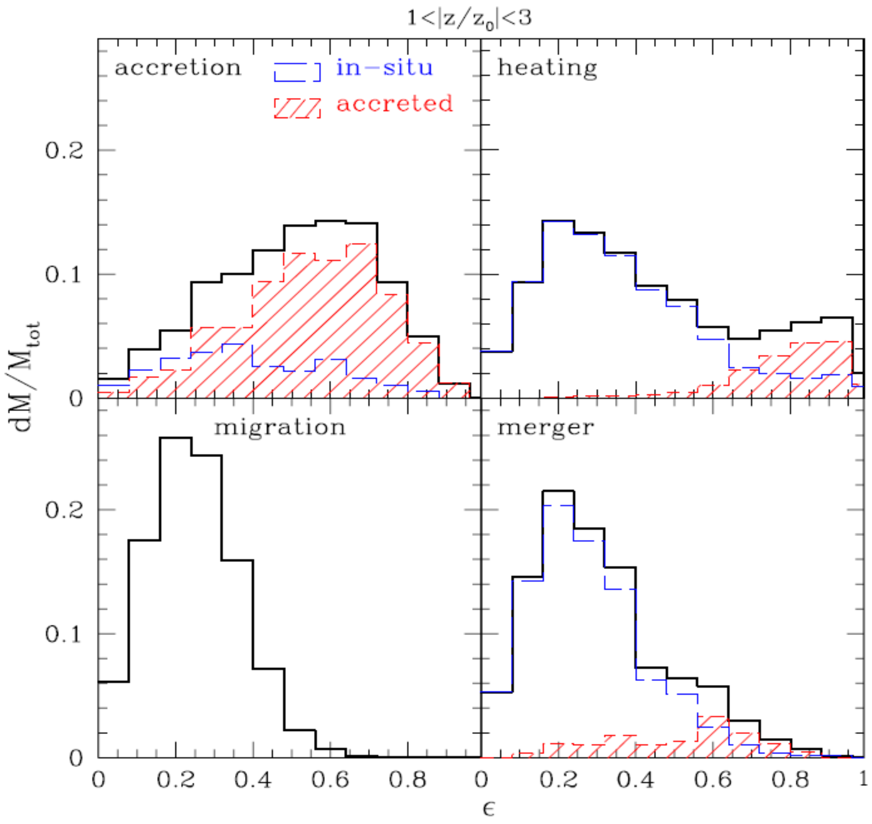


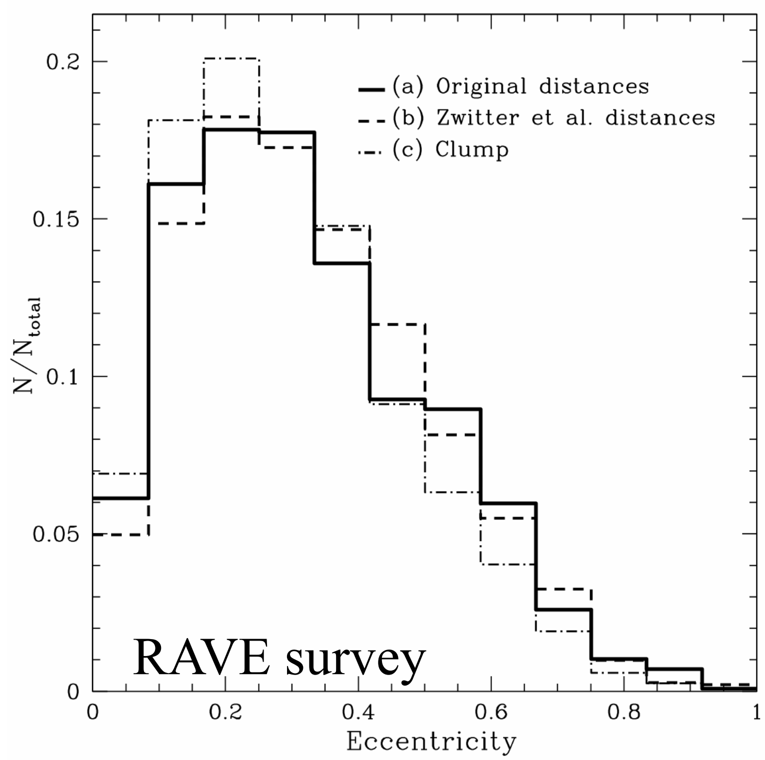


Recio-Blanco et al. 2014

Orbital eccentricity: indicator of formation paths

Sales et al. 2009





Wilson et al. (2010)

- Prominent peak at low eccentricity rules out accretion model
  - Most thick disk stars formed in-situ

- Shape near the Sun appears most consistent w/merger model
  - Need to probe beyond Sun's vicinity (different mechanisms dominate at different radii)

4most + Gaia: large samples across whole disk

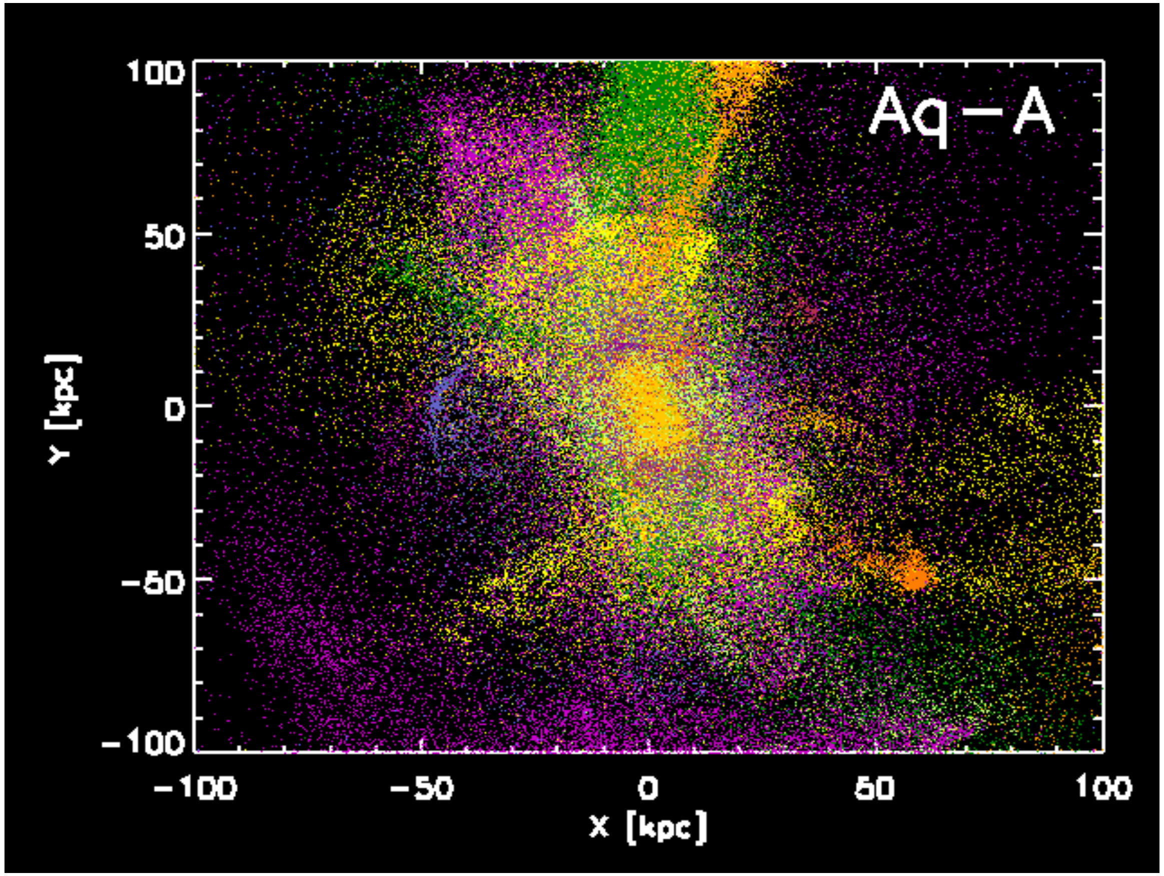
The stellar halo

- Most metal-poor and ancient stars
  - window into the early Universe

- Orbiting outskirts of galaxies: good mass probes

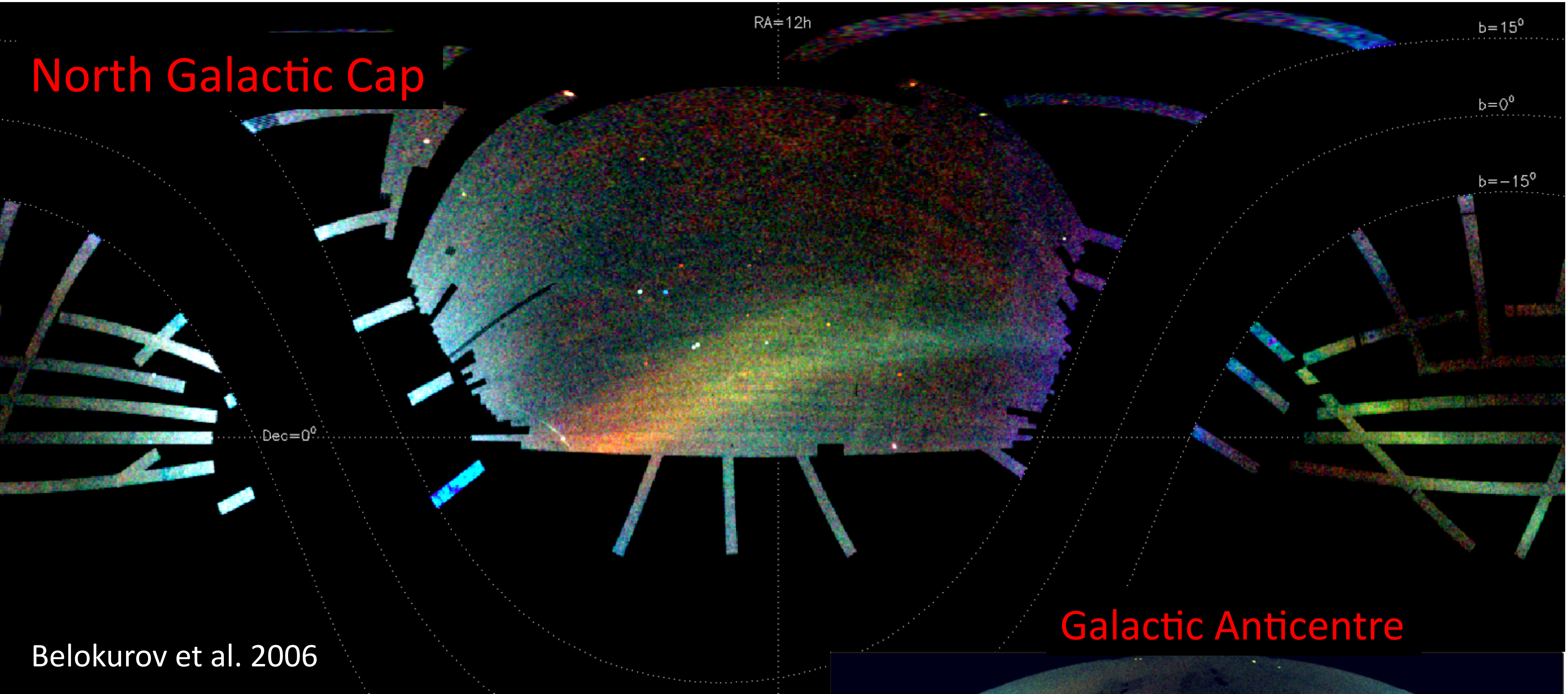
- Can form from the superposition of disrupted satellites

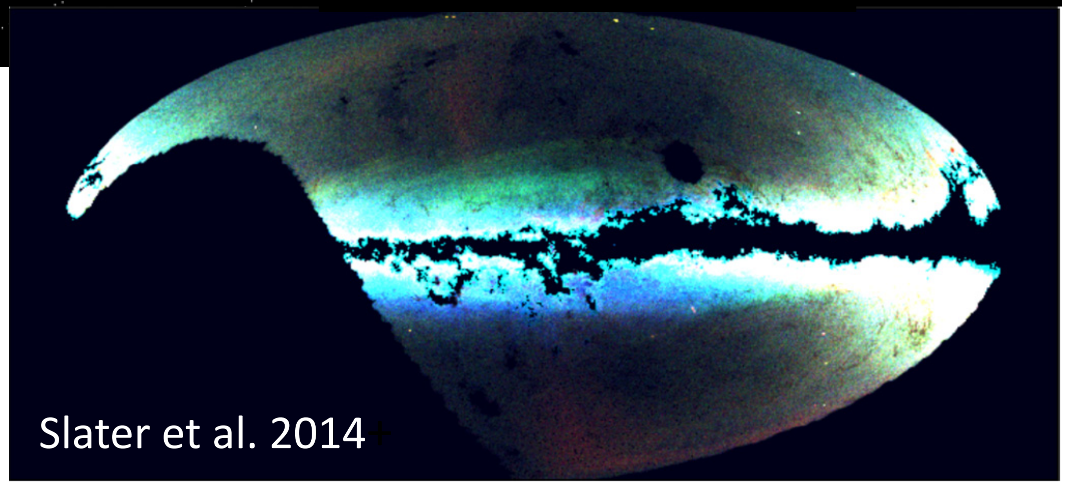
- Some fraction (?) likely formed in-situ
  - In gas rich mergers
  - Scattered off from disks during mergers



Helmi et al. (2011)

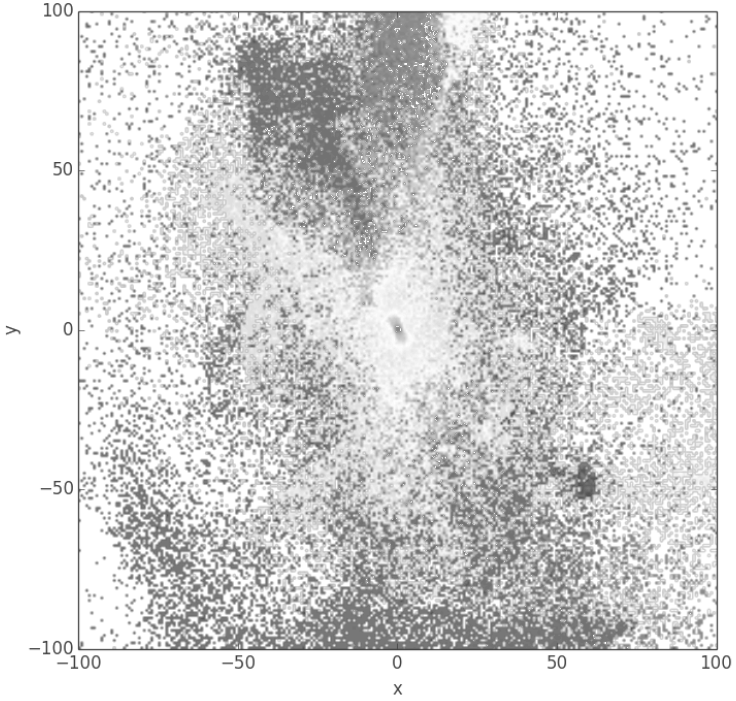
The Galactic halo from SDSS/PanStarrs





Outer halo:
- Clear evidence of substructure
- Limited to high-surface brightness features (progenitors/time of events)

Kinematics for large numbers of halo stars: crucial



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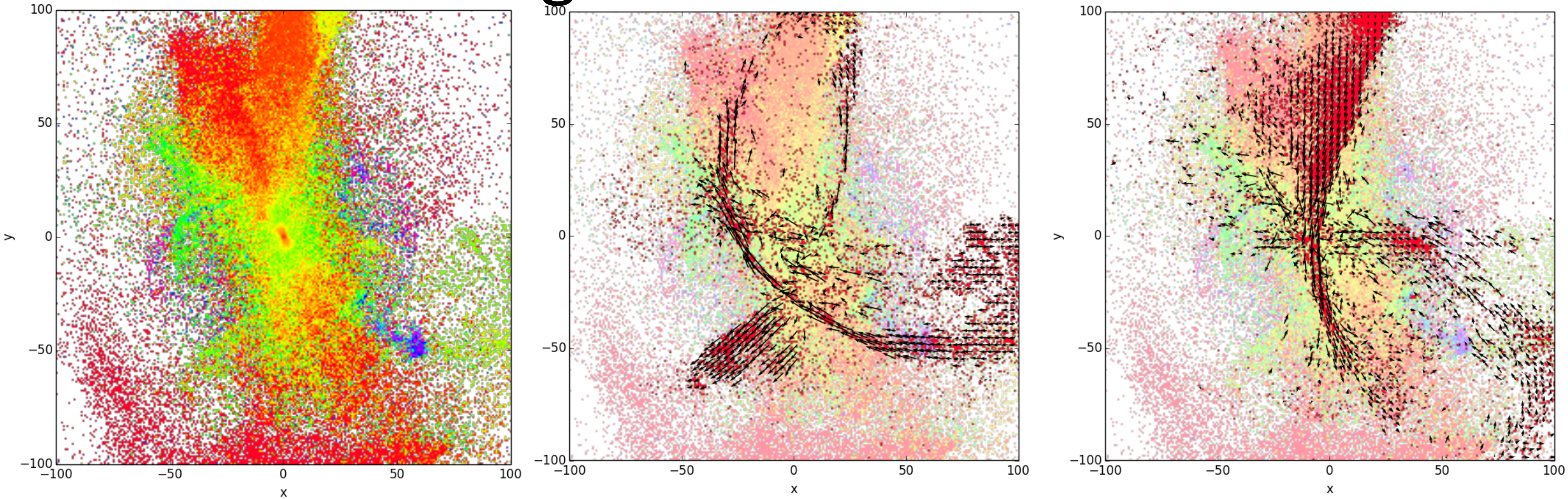
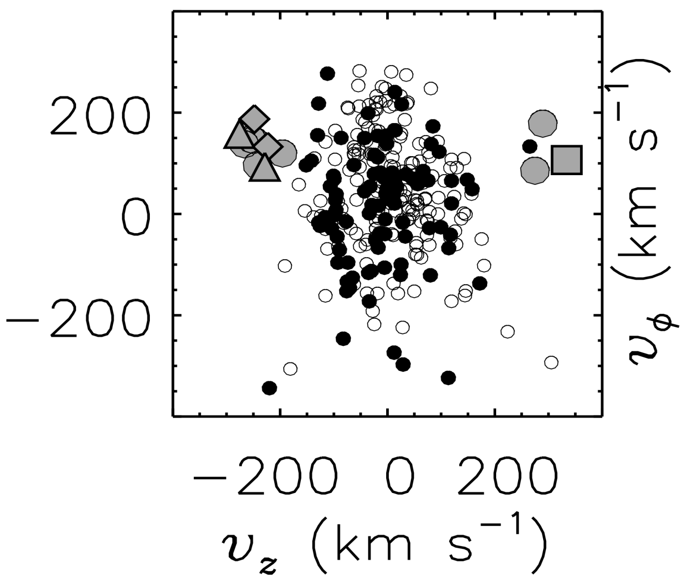


Velocity space near the Sun

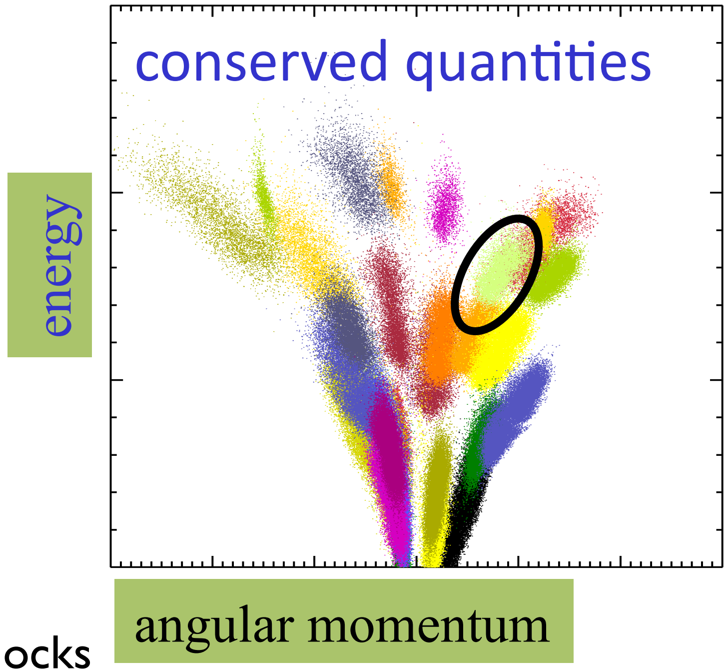
Helmi et al. 1999



100s more predicted and possibly hiding…

How to find these? Gaia!

- Clustering in conserved quantities
- Follow-up:
    - SFH and chemical evolution of building blocks



Helmi & de Zeeuw 2000

Halo metallicity distribution function

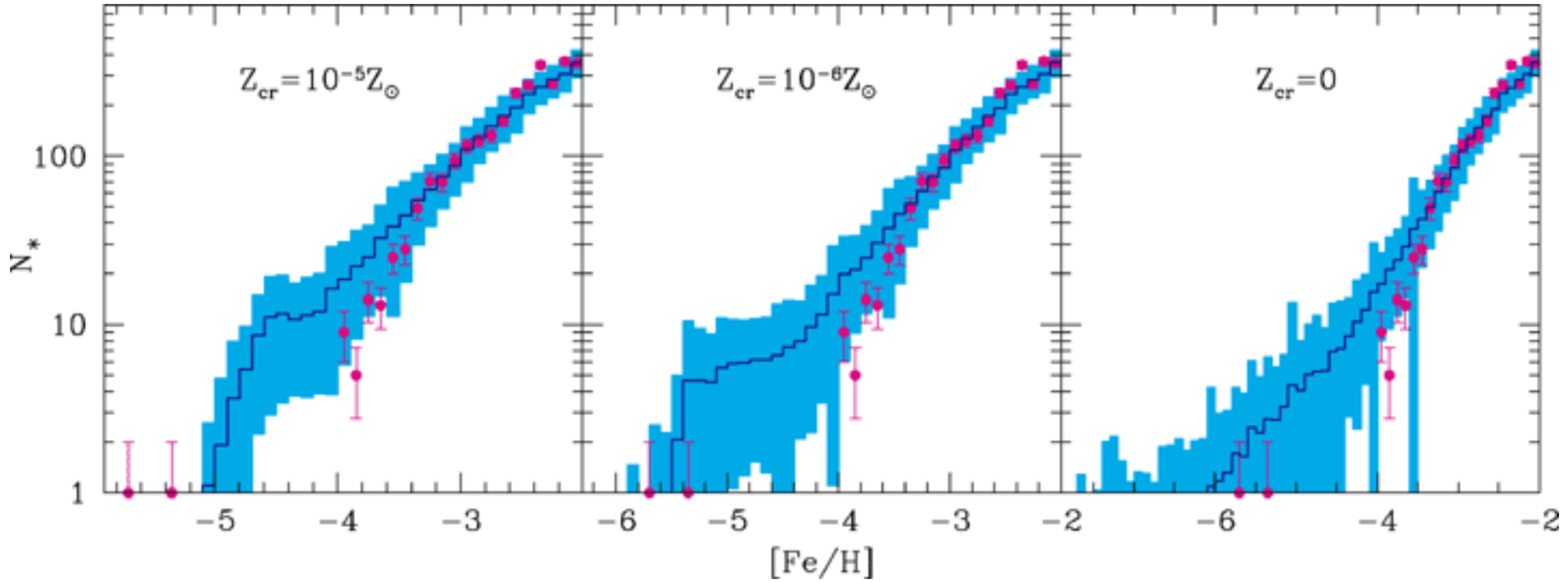
-Very small number of extremely metal-poor stars known to date

-Direct counts provide constraints on the IMF at high-redshift

e.g. there may be a critical Z below which only very massive stars form

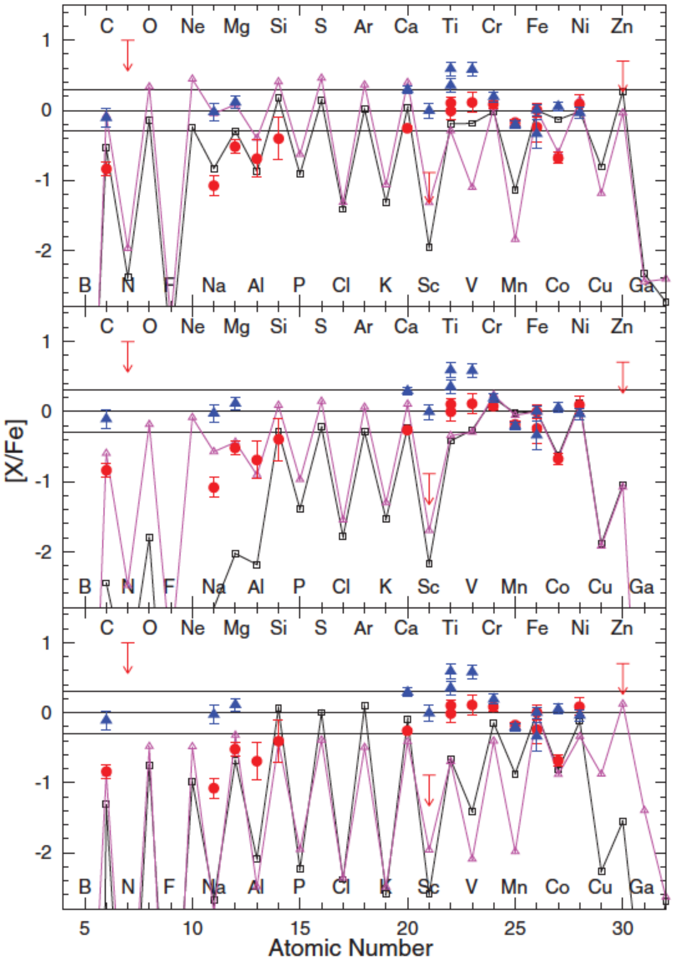
-Currently limited by small number statistics

Salvadori et al. 2007

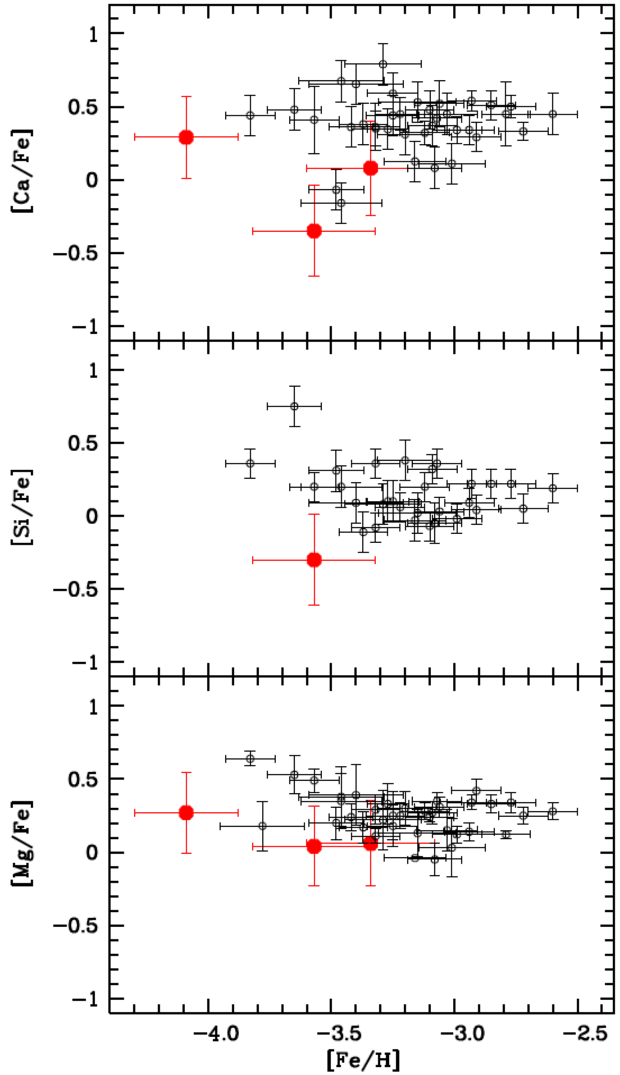


Spectroscopic survey of 10^5 halo stars at intermediate resolution to identify candidates for follow up
-> Wide-field, deep & 100 multiplex

Chemistry of metal-poor components



Aoki et al. 2014



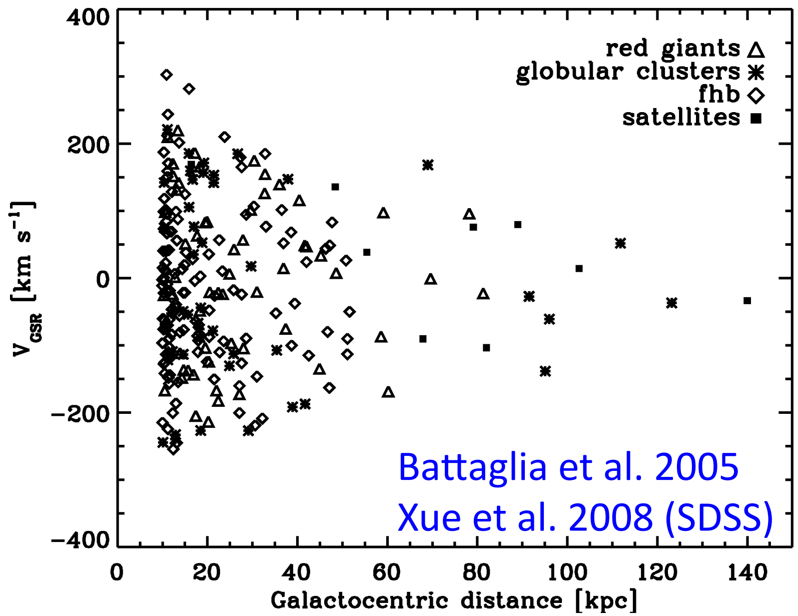
Caffau et al. 2013

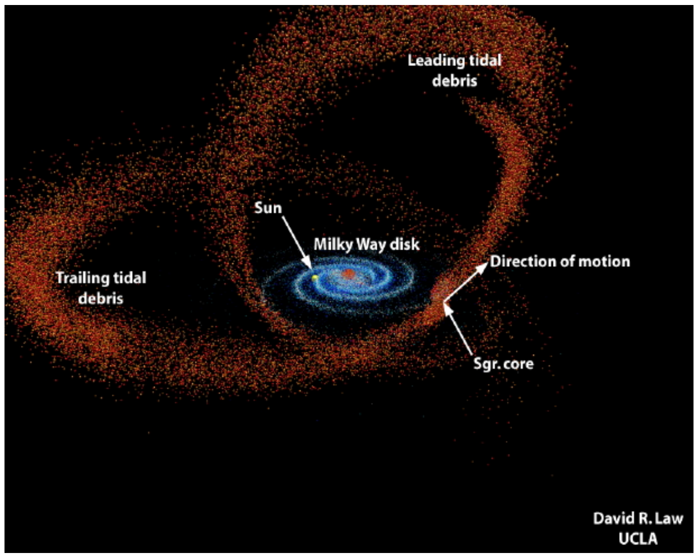
Knowledge of very metal-poor stars detailed abundance patterns -> high-res slit spectroscopy (follow-up from Gaia, 4most, Skymapper, ...) > also for distant stars (8m + E-ELT)

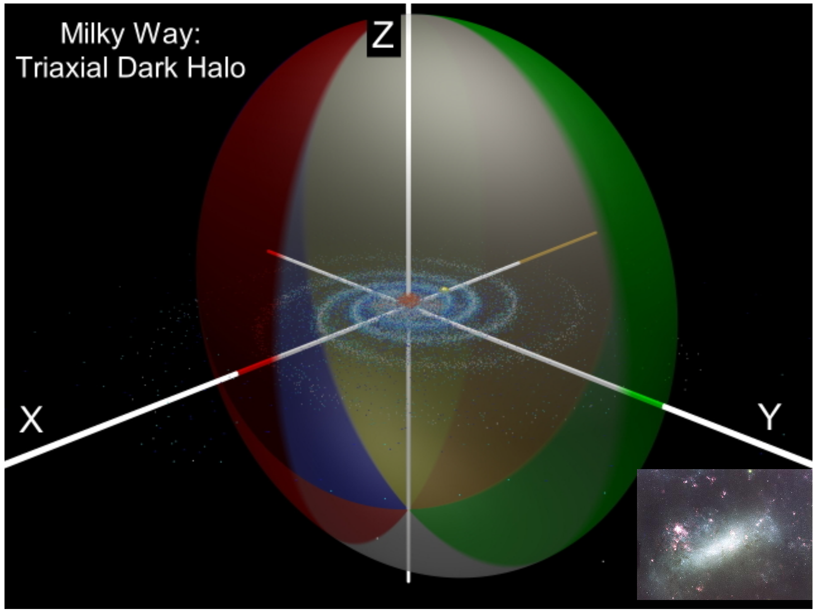
- Constraints on the IMF
- On the nature of the first stars and explosions (SN or HN)
- On the early history of the Galaxy

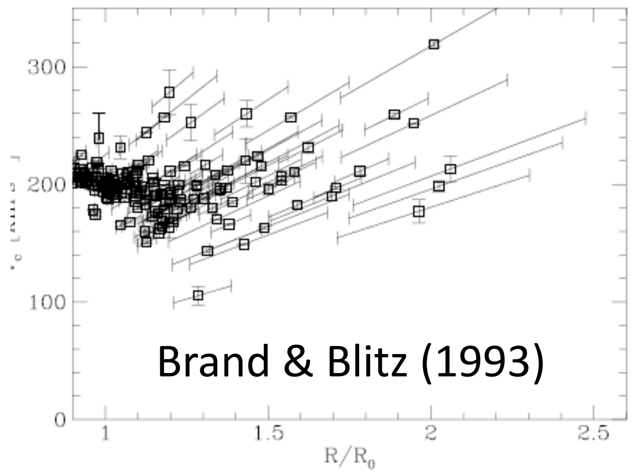
The dark halo

- Critical for what is dark matter
  - link to cosmological model ; constraint on nature of particle / Gravity
- Total mass: $7 \times 10^{11} - 1.5 \times 10^{12}\ M_{sun}$ (factor 2 uncertainty!)
- Rotation curve, density profile … poorly characterised
- Shape constraints:
  - not too flattened towards disk
  - possibly triaxial at large distances but based on just 1 stream: Sagittarius; very debated



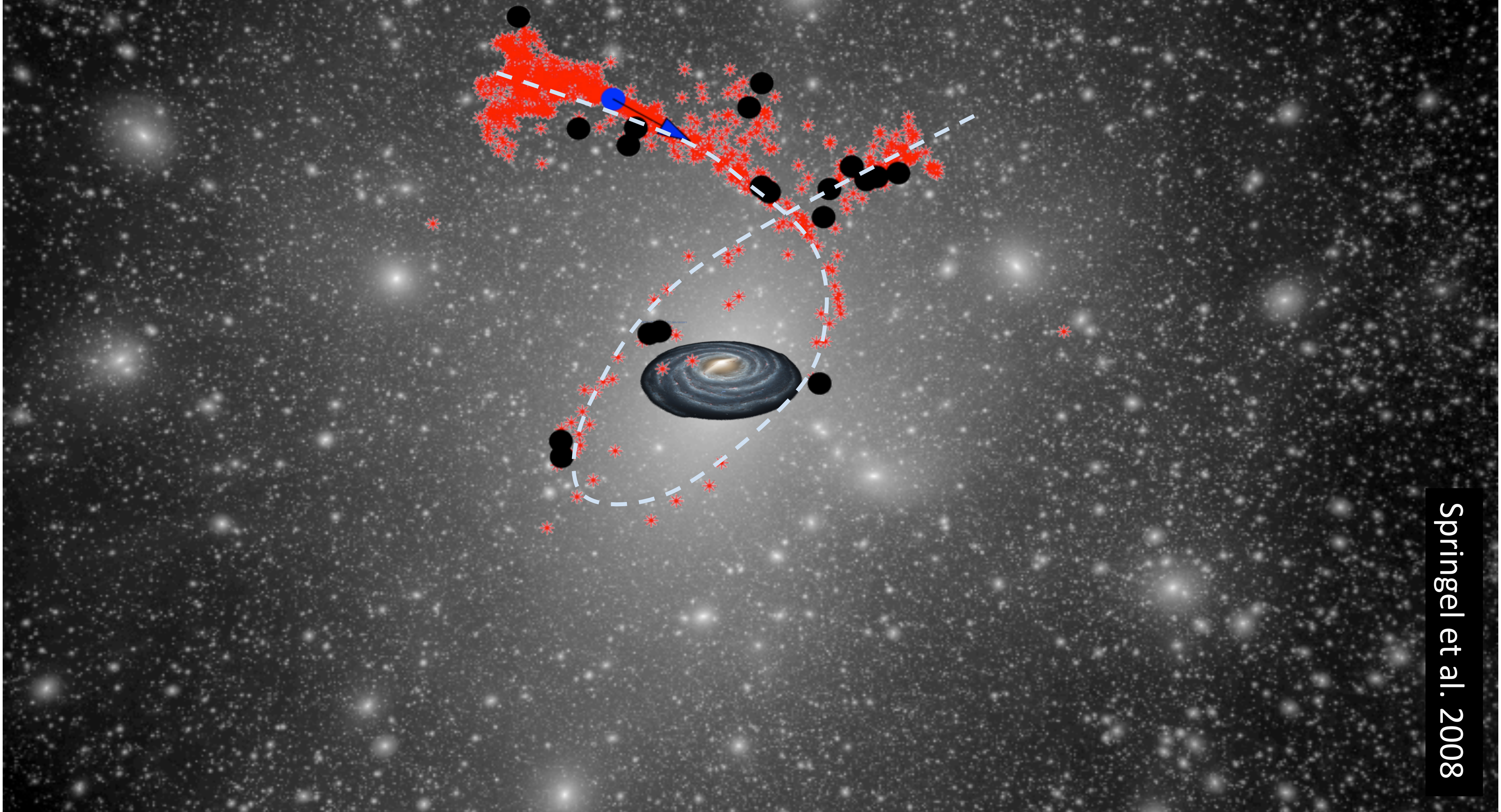






but LMC's influence might be important! (Vera-Ciro & AH, 2013)

Is this “picture” correct?



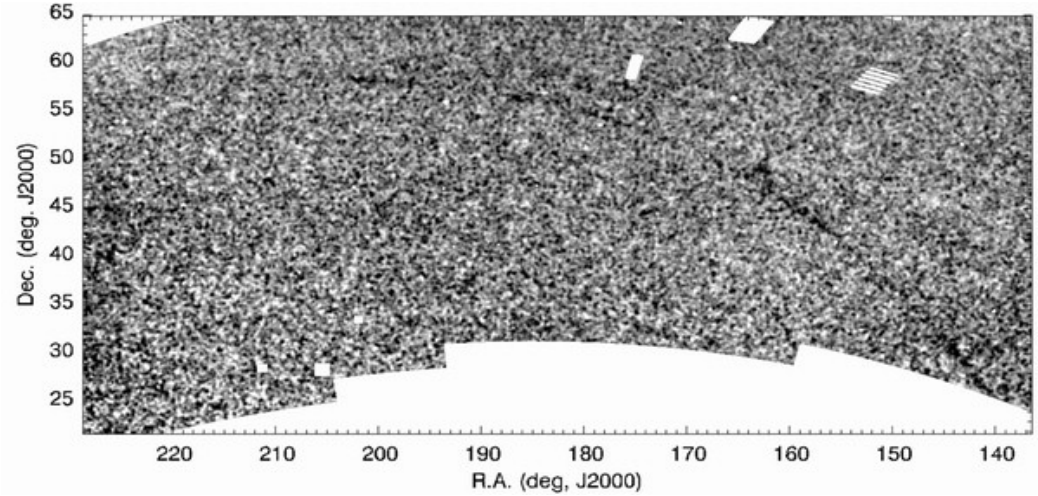
Granularity: Hundreds of thousands dark clumps if dark matter particle is cold

Narrow streams

Thin long streams better probes (more reliable tracers of underlying potential; Eyre & Binney 2009)

Internal velocity dispersions are few km/s

GD-1 stream in SDSS: dissolved cluster



Koposov et al. 2009

- Halo granularity: need very accurate radial velocities

  - Distant streams preferred (d ~ 10 – 40 kpc) to isolate other effects
    -> faint stars
  - Low surface brightness -> need to go as far down on RGB
  - Need to follow stream across large area on the sky

-> **Wide-field, accurate RV, faint magnitudes, multiplex ~ 100**

4most, MOONS, and beyond… also LSST for imaging

Some top questions for next decade

1. Which stars form and have been formed where?
2. What is the mass distribution throughout the Galaxy?
3. What is the spiral structure of our Galaxy?
4. How is mass cycled through the Galaxy?
5. How universal is the initial mass function?
6. What is the impact of metal-free stars on Galaxy evolution?
7. What is the merging history of the Galaxy?
8. Is the Galaxy consistent with ΛCDM?

from ESO/ESA Working Group on the MW

Answers to those (and many more) questions…

- Gaia will revolutionise our knowledge of the Galaxy

- Complementary ground-based instruments (MOS) are much needed in the 2020s
  - For follow-up observations of particularly interesting samples selected from Gaia observations
  - For complementary observations of selected samples of stars fainter than the limit of the spectrograph on-board Gaia

- European leadership in Galactic research as regards astrometry (Hipparcos, Gaia), spectroscopy (multi-object spectro), and photometry (VISTA+VST) + unique European expertise in modelling.

- Give European astronomers a lead in the exploitation of the Gaia catalogue.

GaiaESO 4MOST WEAVE

MOONS

Multi Object Optical and Near-infrared Spectrograph

Thank you for your attention