The Milky Way: Old and New Puzzles

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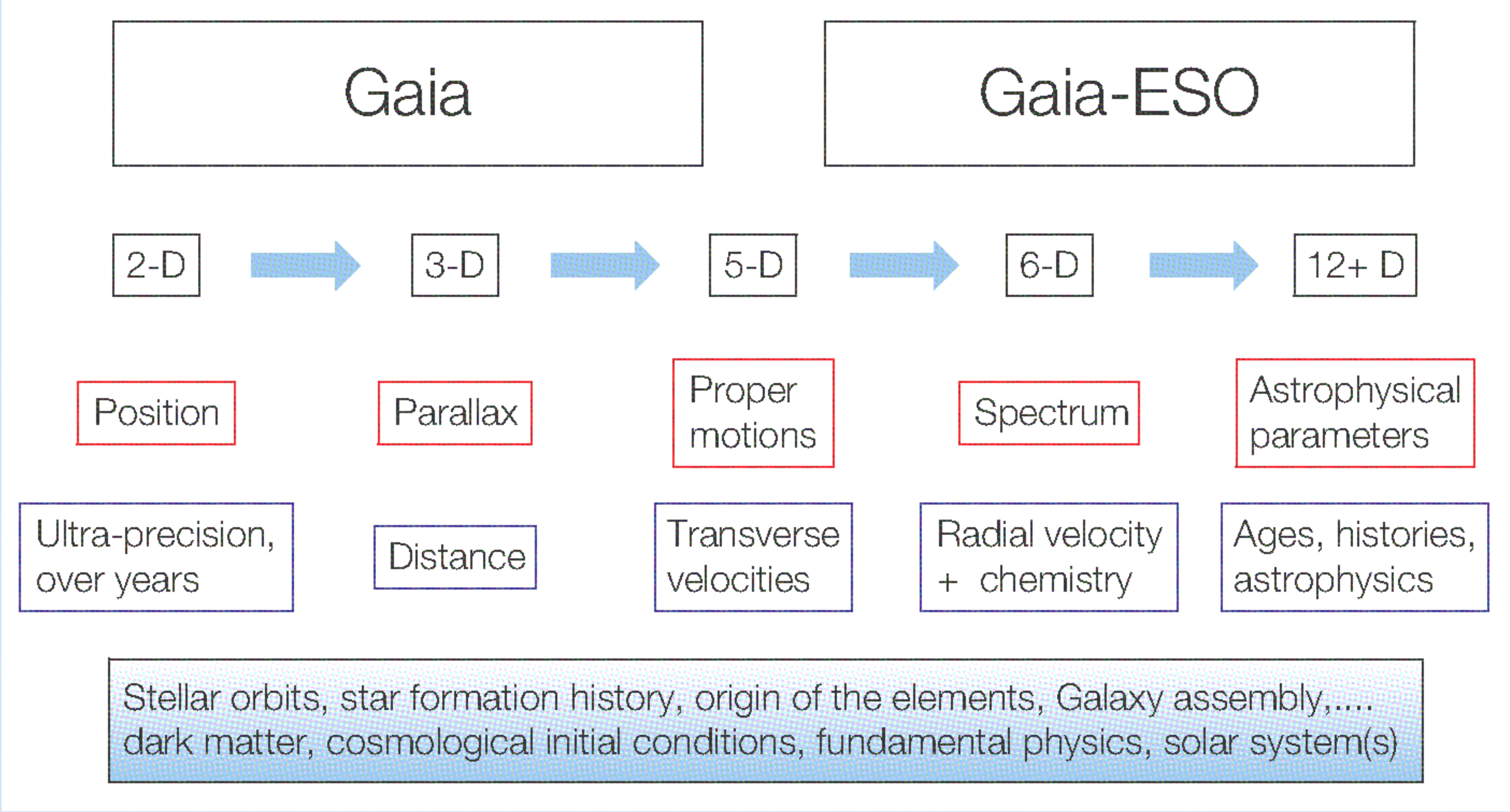
The Fossil Record: Galactic Archaeology

- Studying low-mass old stars nearby allows us to do cosmology locally
  - There are copious numbers of stars nearby that have ages $\gtrsim$ 10 Gyr : formed at redshifts > 2
    - thin disc, thick disc, bulge, halo, satellite galaxies
  - Retain memory of initial/early conditions: elemental abundances, orbital angular momentum/integrals - kinematic and chemical phase space structure
- Break degeneracy of integrated light
  - Can derive metallicity independent of age
  - Stellar Initial Mass Function – count stars at low-mass end; elemental record at high-mass end

The Fossil Record: Galactic Archaeology

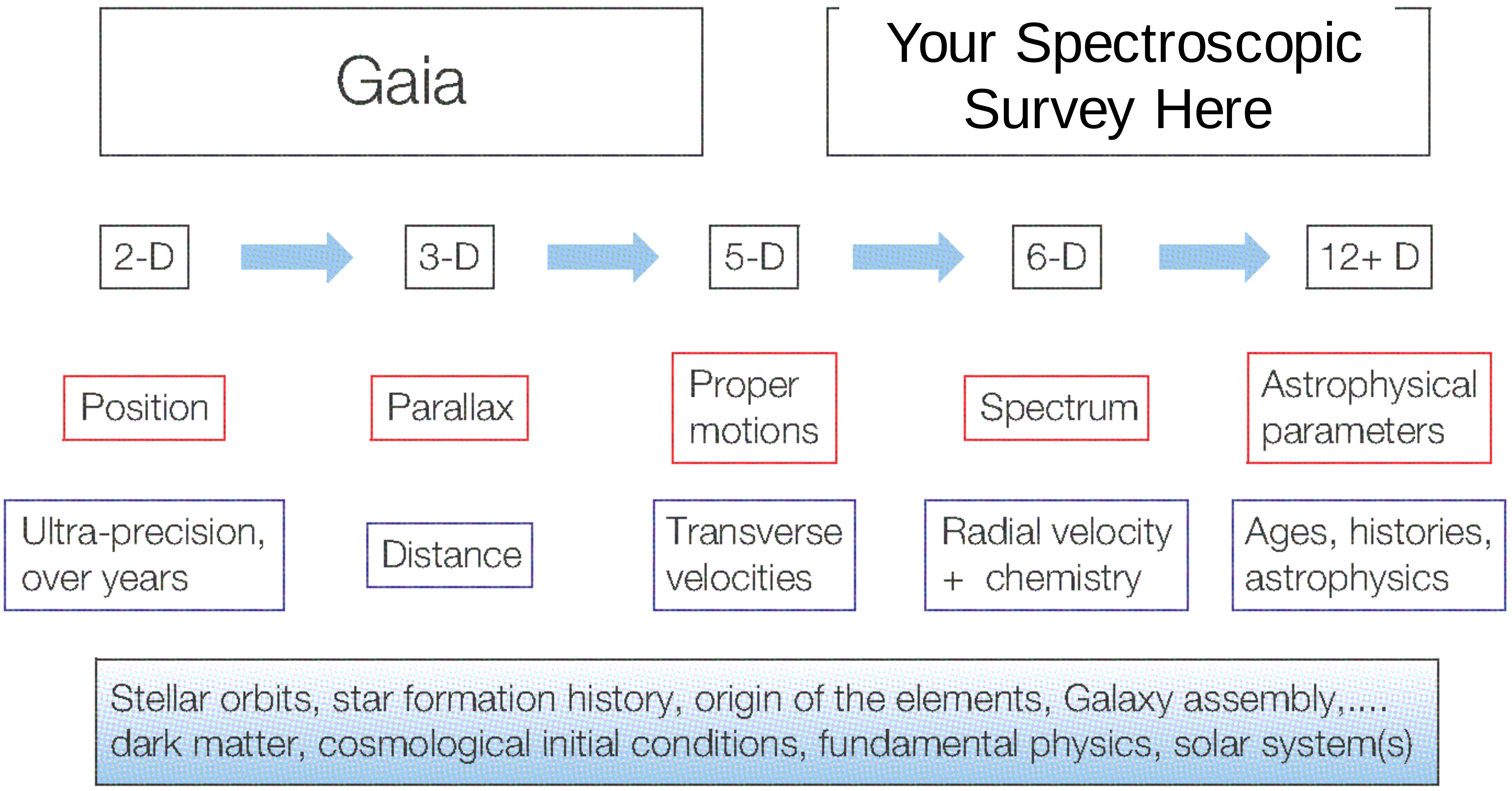
- Complementary approach to direct study of galaxies at high redshift
  - Snapshots of different galaxies at different epochs vs evolution of one (final) system
  - Milky Way is typical disk galaxy, its evolution should trace dominant physical processes
    - Addition of M31, M33 – compare and contrast but more limited data (Subaru Prime Focus Spectrograph survey of M31 in near future)
- Simulations now of Milky Way analogues in cosmological context
  - Milky Way Galaxy should not be too unusual in theory

Overview, with focus on disks and halo



Gilmore et al inc RW 2012

Several massive spectroscopic surveys each with own ‘niche’ in terms of spectral resolution, sample selection function etc



Plus deep multi-band imaging surveys, Kepler asteroseismic data

Gilmore et al inc RW 2012

What can we learn from (old) disk stars?

- Thin stellar disks are fragile and can be disturbed by external influences such as companion galaxies and mergers, in addition to internal perturbations such as spiral arms, bars and GMCs
  - Stellar systems are collisionless - cannot ‘cool’ once heated, unlike gas
  - Vertical structure: heating/merging/dissipational settling/SFR
  - Radial structure: inside-out growth, imprints of angular momentum distribution/re-arrangement

➔ Thin disk/thick disk: earliest phases of disk, heating/merger history, gas accretion to (re-)form thin disk

➔ Bending/breathing modes in thin disk: internal and external forcing of substructure

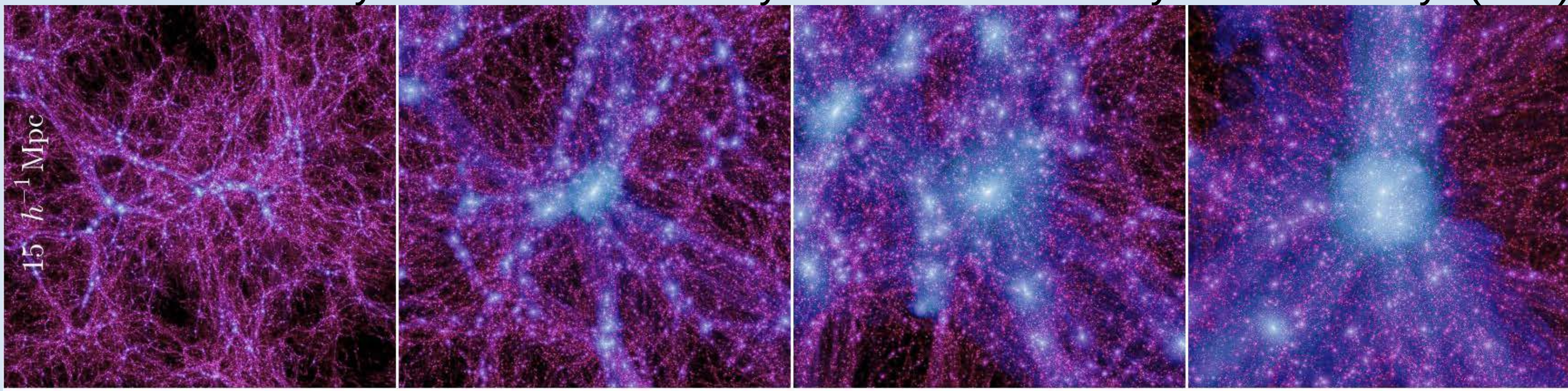
➔ Stellar Radial Migration within thin disk: size evolution, onset of star formation in outer regions

What can we learn from halo stars?

- Field stars: Low density ➔ formed in disrupted systems
  - Star clusters – no dark matter
  - Dwarf galaxies – dark matter, self-enrichment
    - What fraction from which source, and when?
  - Highest velocity stars – escape velocity, SMBH
- Tidal streams
  - Cluster disruption history
  - Accretion history
  - Overall dark halo potential
  - Dark substructure from gaps
- Surviving dwarf galaxies
  - Dark matter density profile (nature of dark matter)
    - Core/cusp: determination of star formation history critical

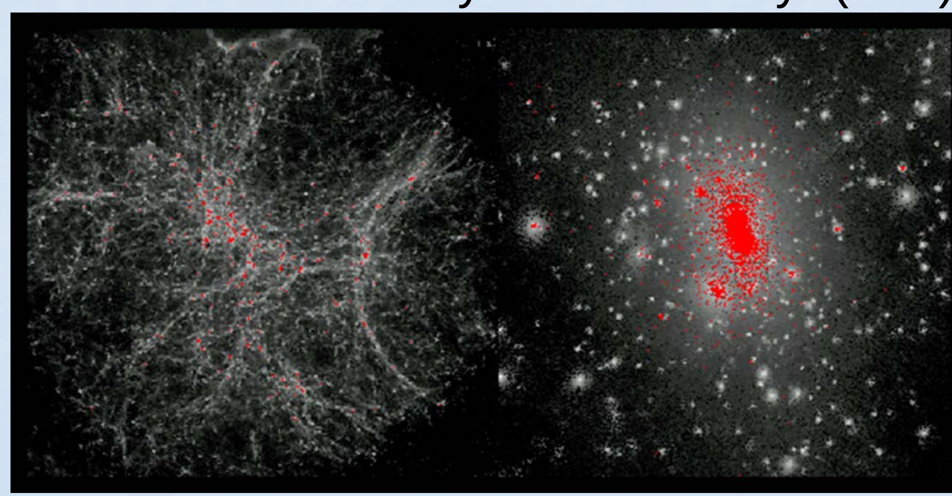
Cold Dark Matter predicts small galaxies form first, merging to form successively larger systems

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



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

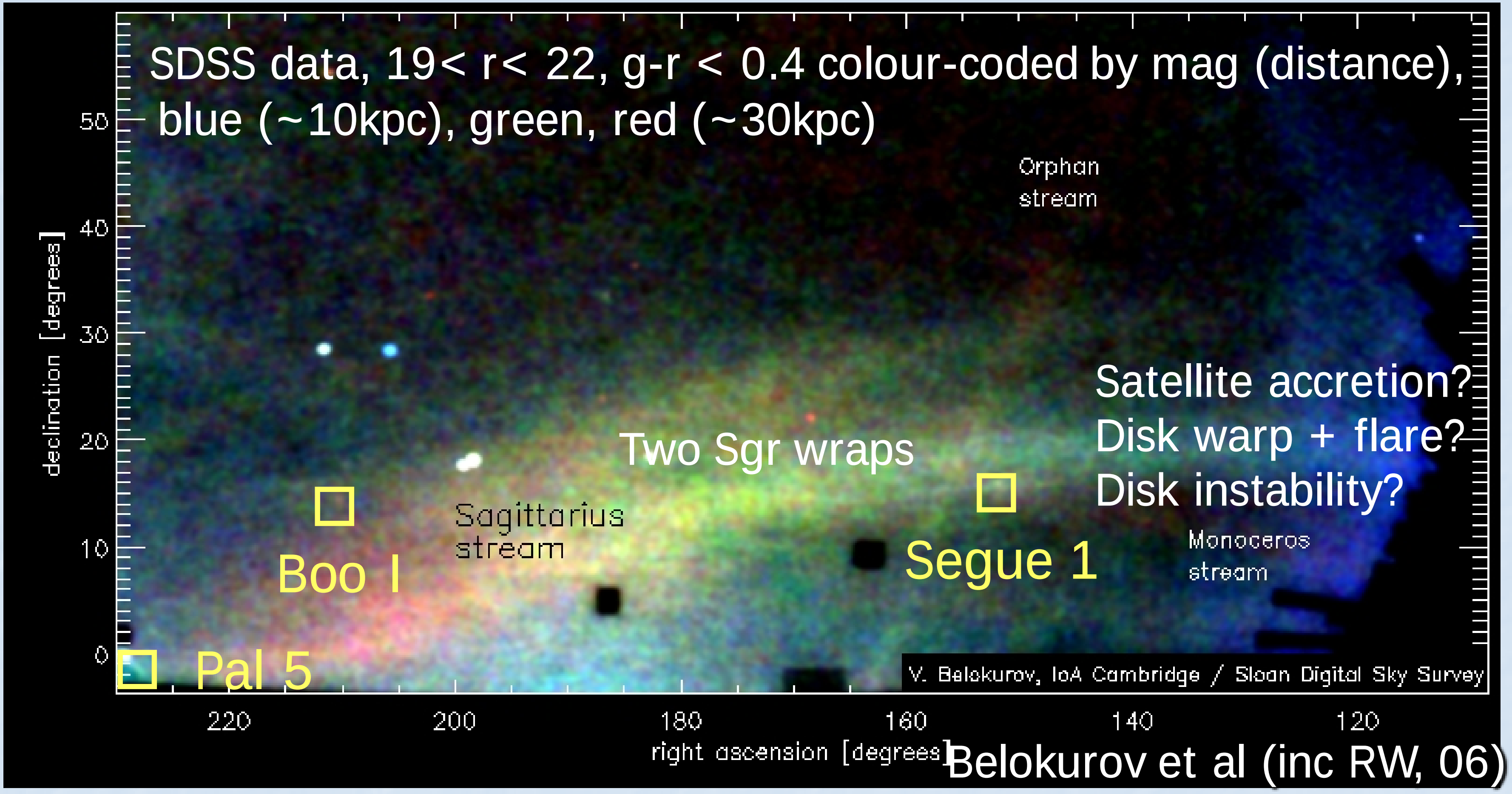
0.5Gyr 13.7 Gyr (now)



Boylan-Kolchin et al 09
Moore et al 1999

- Where and when satellite deposits stars depends on when accreted, orbit, (relative) density (contrast with background halo) and mass (dynamical friction)
    - Dense, massive satellites contribute to central regions
- The stellar population in debris set by star formation history and chemical enrichment
    - Mass-metallicity relation in dSph; elemental abundance pattern
- Lower mass contribute to outer halo on longer timescales
- Effects on stellar and gaseous disk: Heating/thickening, modify angular momentum distribution, stimulate bending/oscillation modes

Wide-Field Star Counts: Field of Streams (and dots)

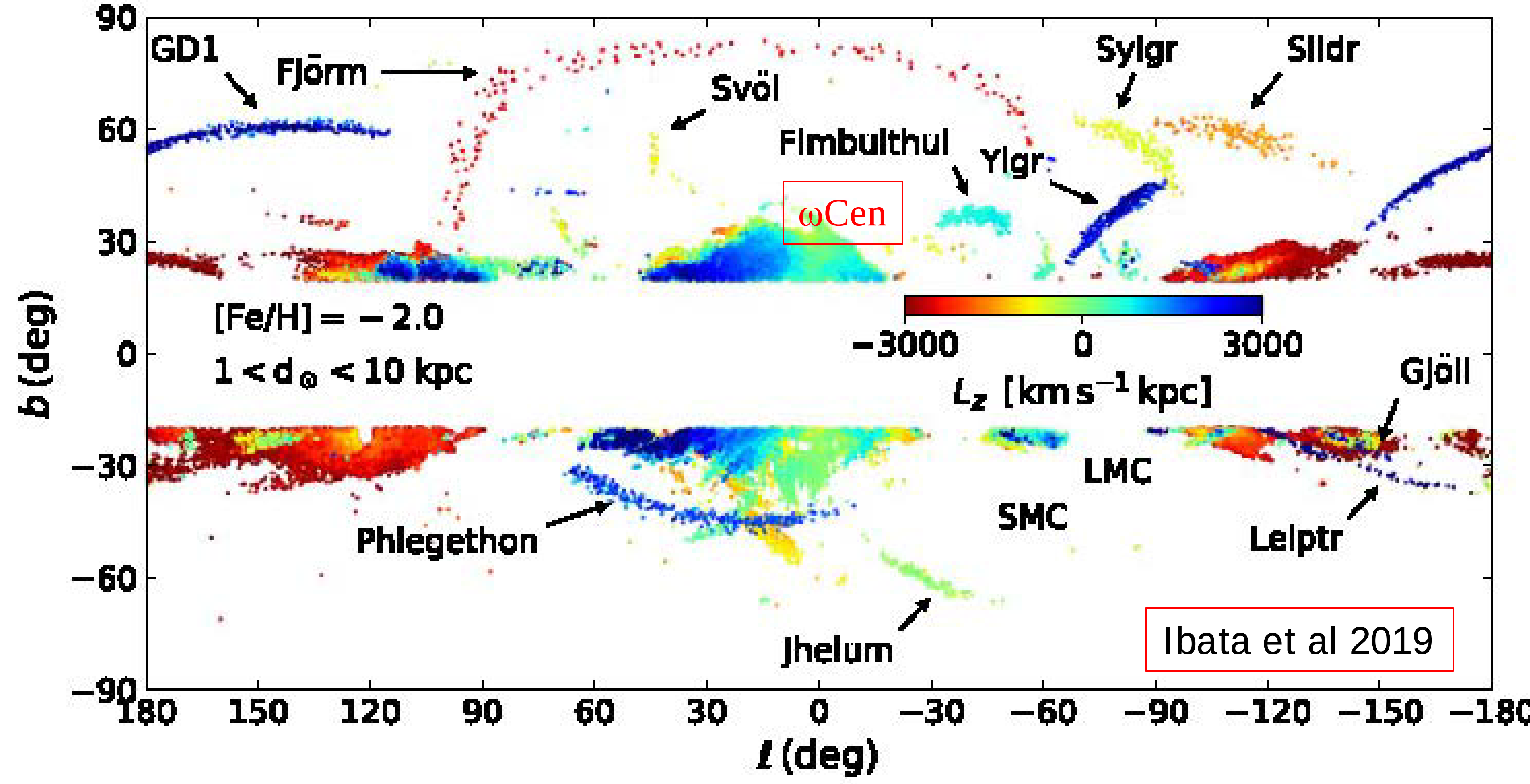


Belokurov et al (inc RW, 06)

- Outer stellar halo overdensities dominated by Sgr dSph debris - smooth mass ~ 4 x 10^8 $M_\odot$ (1-40kpc, Bell et al 2008) plus ~ $10^8 M_\odot$ in Sgr (Niederste-Ostholt et al 2010)
- How much structure is internal to the disk(s)?

A lot! – outer regions

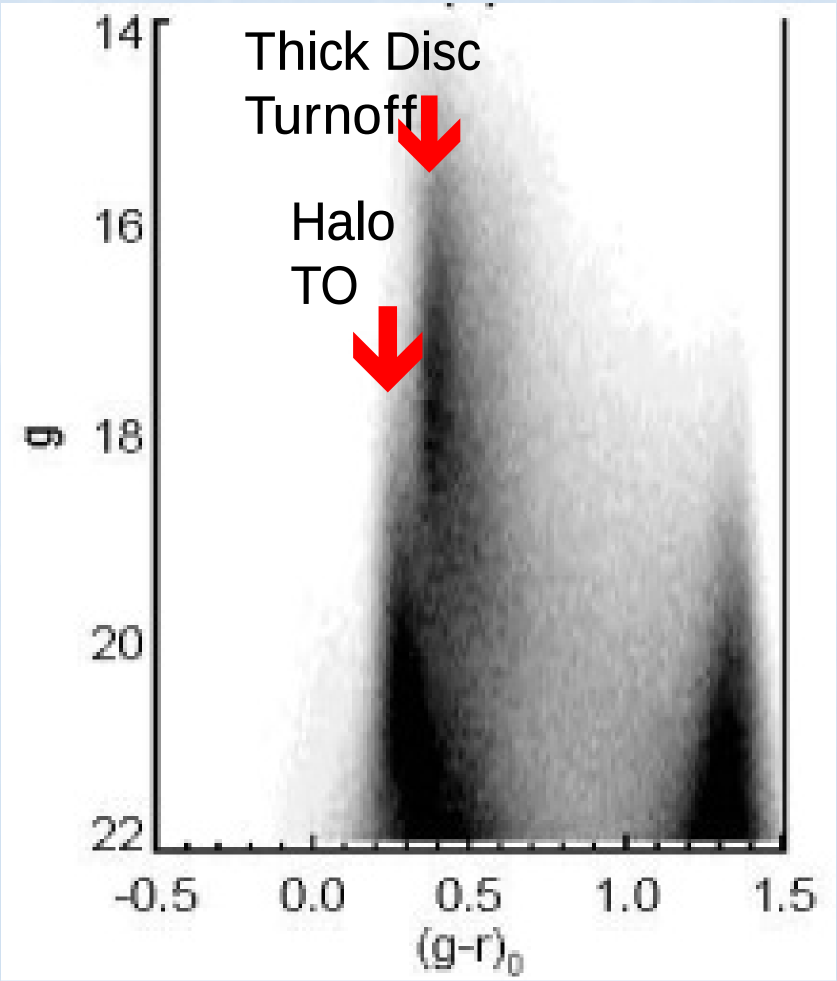
Field of Streams in the Gaia Era



STREAMFINDER: Input Gaia proper motions, photometry, adopt model SSP, then “for each star we calculate many thousands of orbits and calculate the stream likelihood by summing over all stars in the survey”; the process is repeated until every star in the survey has been examined in this way. Angular momentum is a derived output.

Wide Field Star Counts (pre Gaia): Smooth components above the plane have old ages

- Star counts at intermediate latitudes show two well-defined main-sequence turn-offs, $(g-r)_0 \sim 0.25$ and $(g-r)_0 \sim 0.4$
- Old, metal-poor populations, halo (bluer, more metal-poor) and thick disk (redder, more metal-rich)



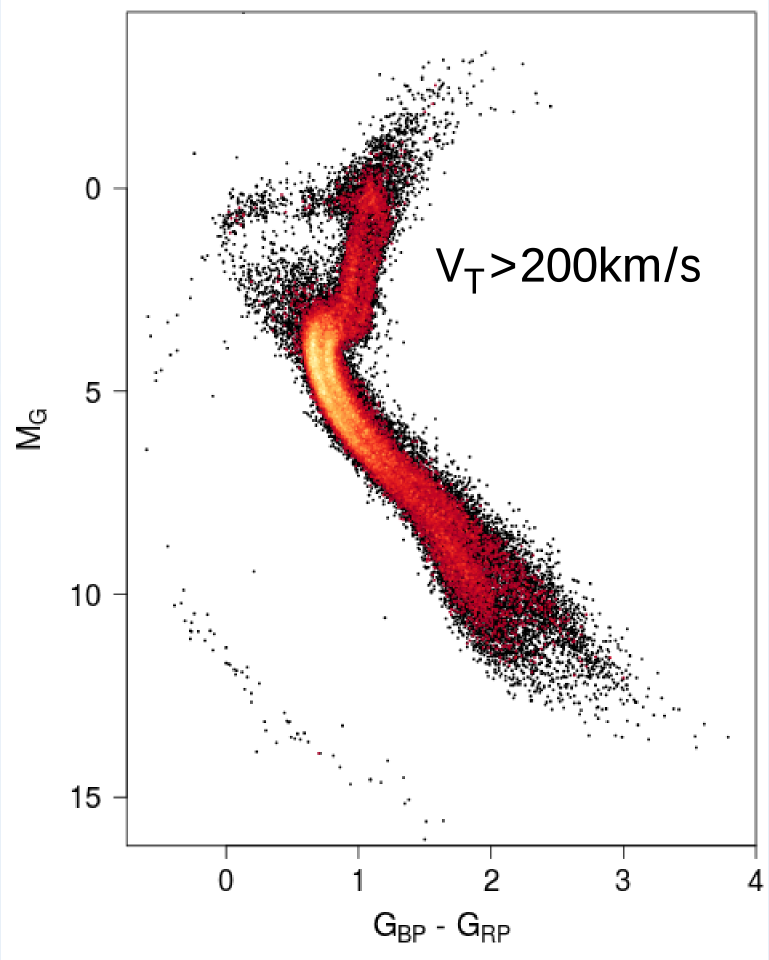
Mean age ~ 10-12Gyr,
[Fe/H] ~ -1.5 halo, -0.5 thick disk

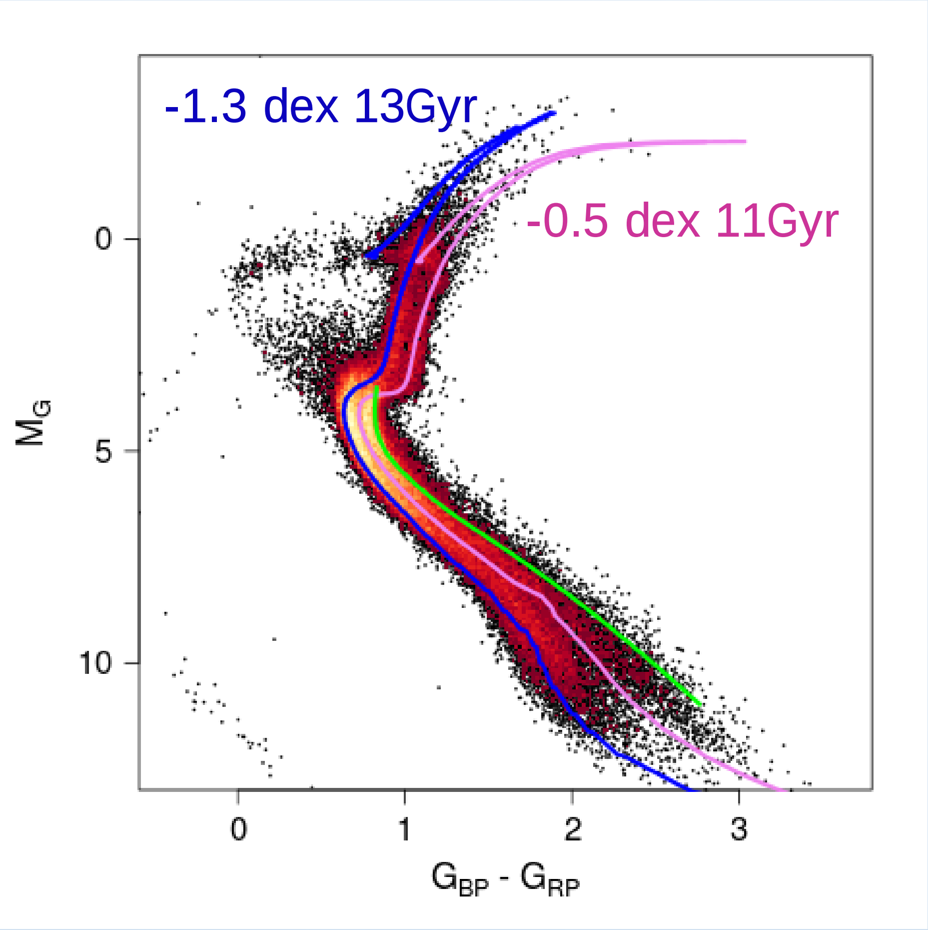
SDSS star counts, equatorial stripe, 32 x 2 degree fields, |b| ~ 45^o +/- 15^o , l ~ 270^o +/- 30^o

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

The Gaia Era

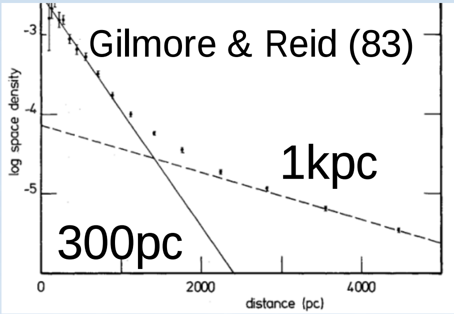
- Double old main sequence turn-off seen in exquisite detail in high transverse-velocity stars (Babusiaux et al 2018) – stellar halo and thick disk (?)





Local Milky Way Thick Disk

geometric definition, 1980s/90s

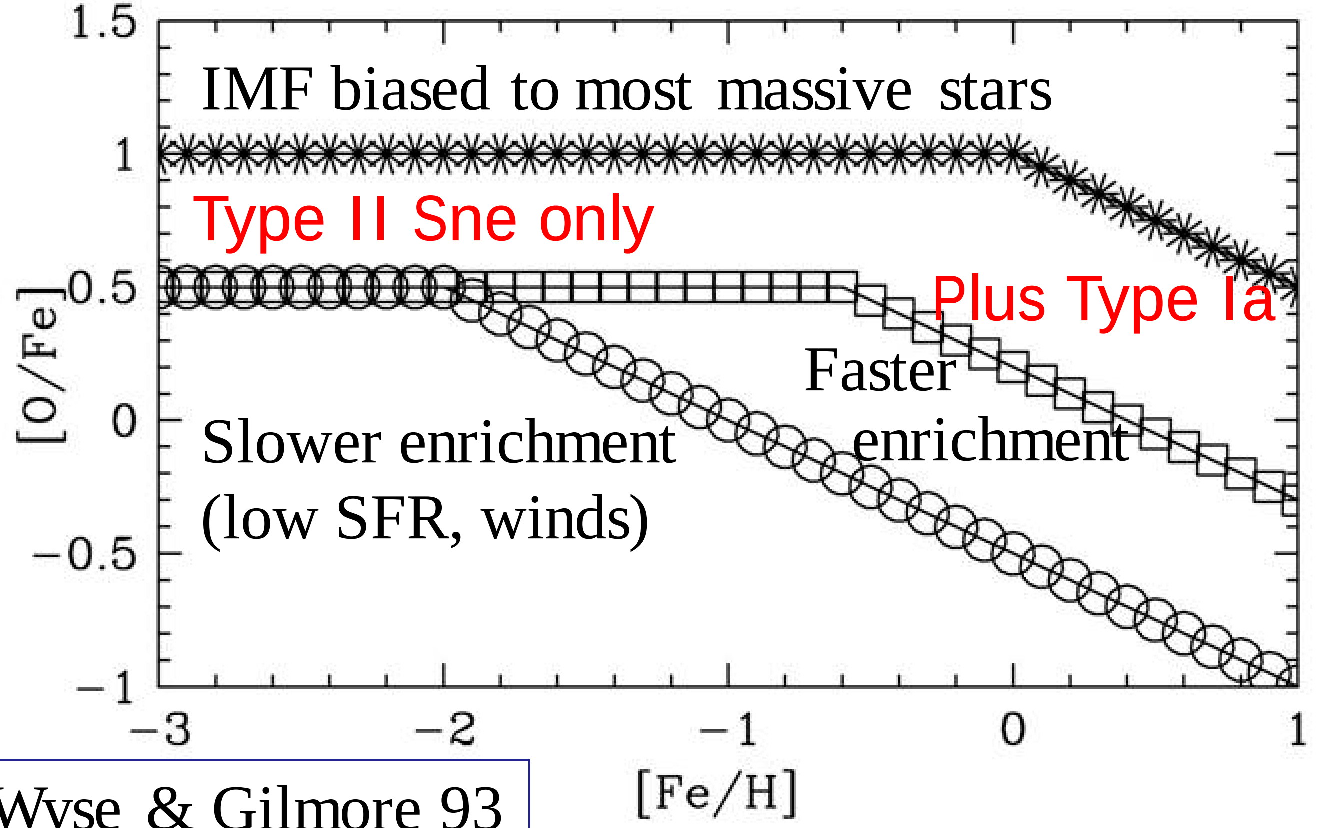


- Star counts at SGP fit by two exponentials
- Kinematics intermediate between thin disk and halo
  - mean rotation velocity lags thin disk by ~ 50km/s, vertical velocity dispersion ~ 40km/s ➔ thick, with scale height of ~1kpc
    - too hot to result from internal disk heating e.g. spiral, GMCs
    - discontinuous trend with thin disk ➔ Exceptional event? Merger? Rapid cooling from thick phase to thin?
- Mean metallicity [Fe/H] ~ -0.5 dex
- Elemental abundances 'alpha-enhanced' ([α/Fe] > 0)
- Most thick disk stars are old, ~ 10-12 Gyr → formation redshift > 2
  - strong constraint on merger history, disk heating (and radial mixing)
- Derived mass > 20% (50%?) of thin disk mass i.e. > 10^{10} $M_\odot$

Burkert, Carney, Edvardsson, Freeman, Fuhrmann, Gilmore, Morrison, Majewski, Norris, Reid, Sandage, Truran, Wyse….

Elemental Abundances - star formation and enrichment histories: chemically distinct thin and thick disks

Alpha element (core-collapse SNe) and iron (Type Ia SNe)



Wyse & Gilmore 93

Self-enriching star-forming region, non-bursty star formation.
Model assumes massive-star IMF average yields

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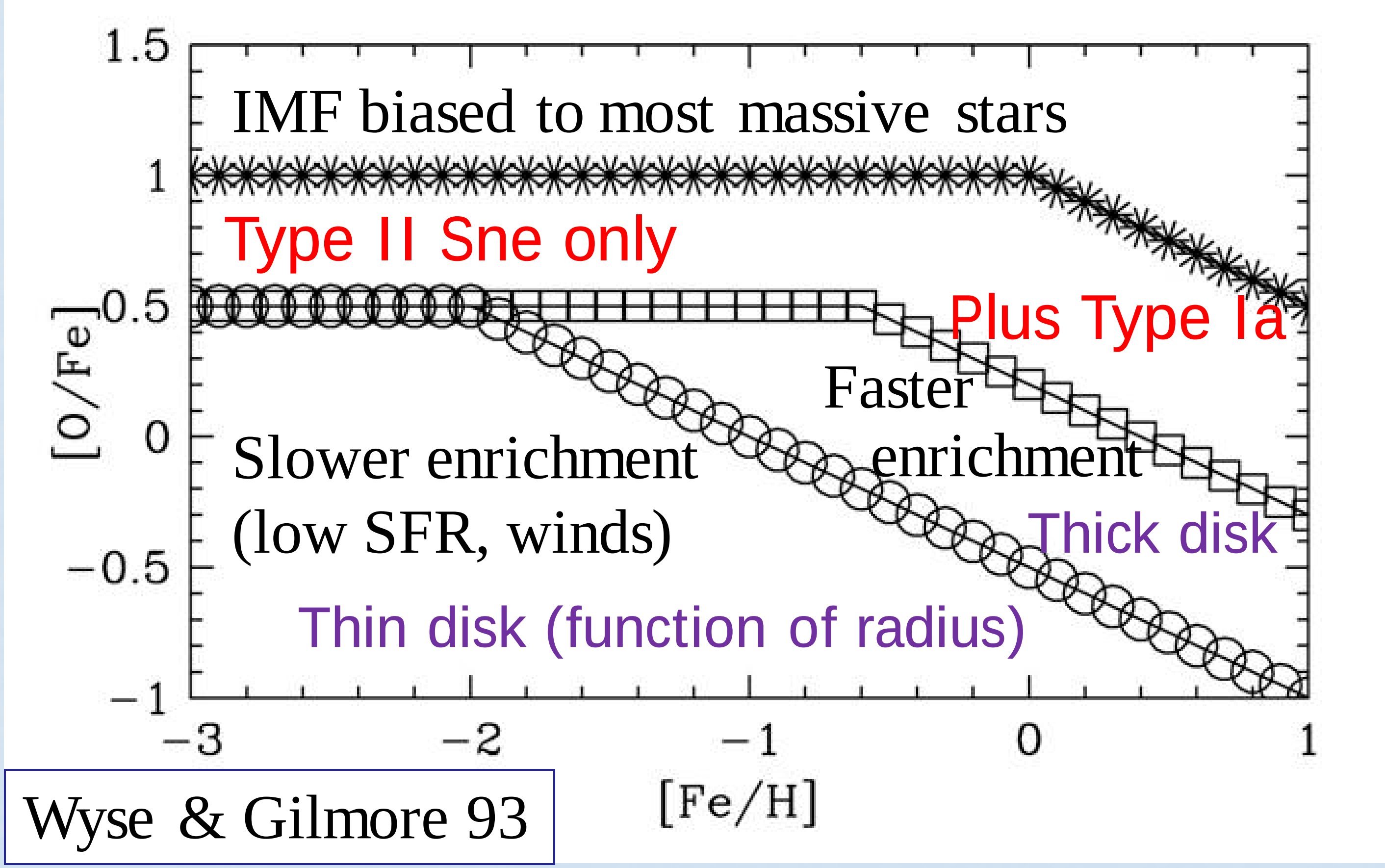

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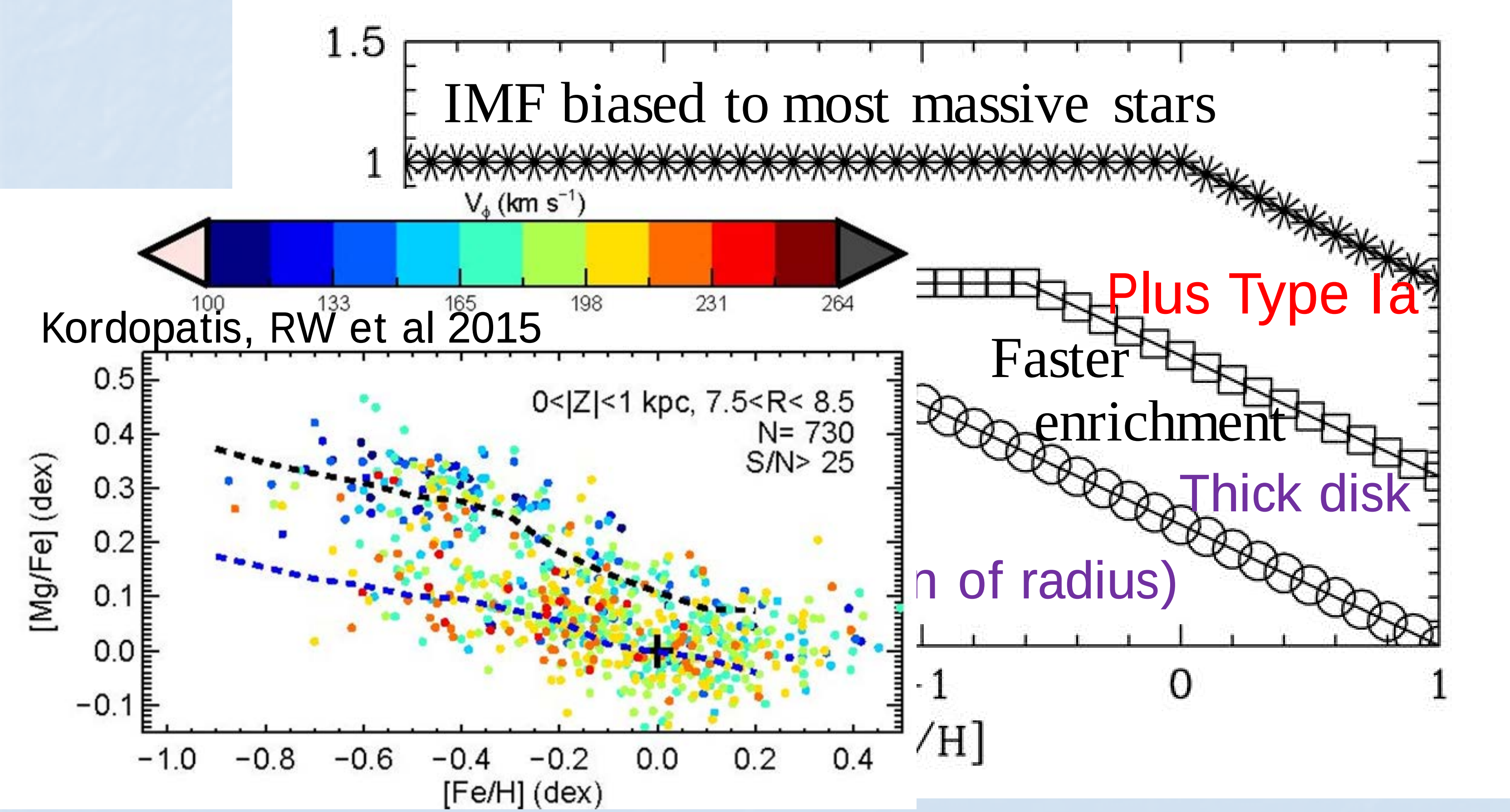

Kordopatis, RW et al 2015

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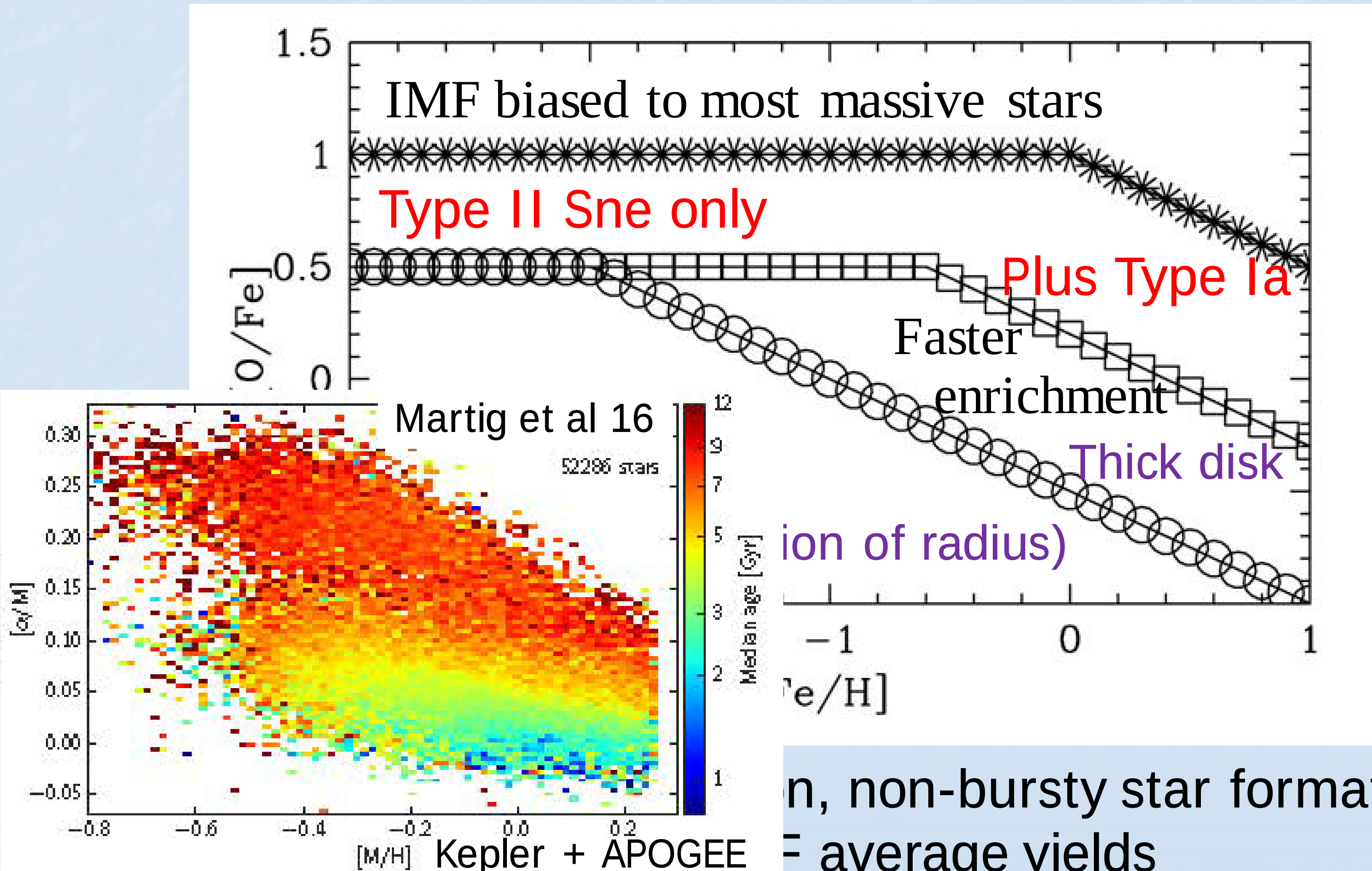


n, non-bursty star formation.

F average yields

Calibrate [C/N] to age; cf Masseron & Gilmore 15

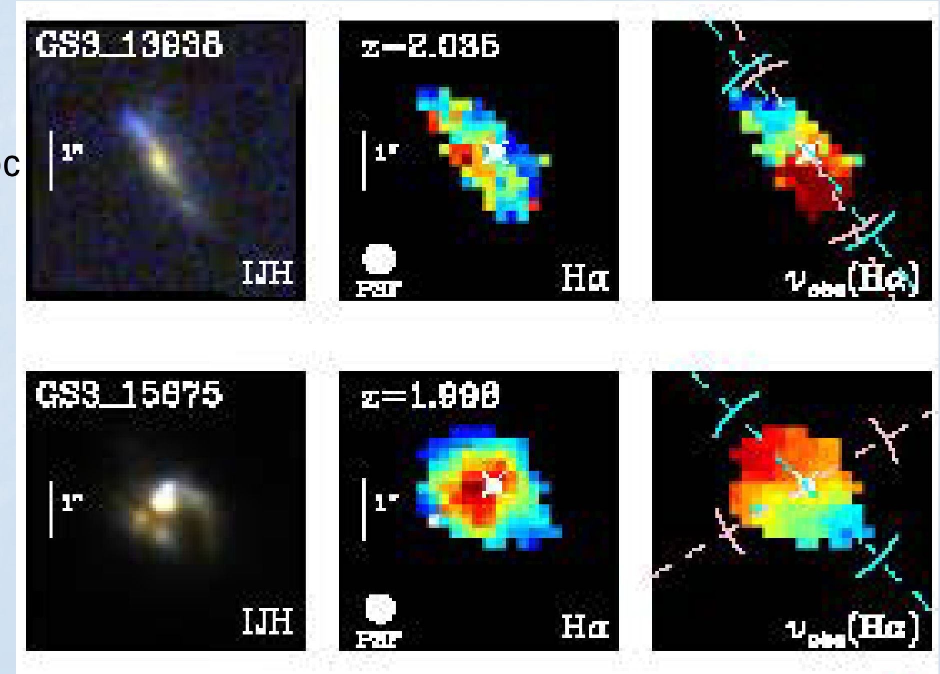
Thick Disk probes Earliest Phase of Disk

- Thick disk stars are old, most formed at lookback time of >10Gyr or redshift > 2: epoch of peak cosmic star formation
- High velocity dispersion, short timescale of star formation implies (likely) formed prior to equilibrium/virialization of halo ➔ while active assembly/mergers (cf Jones & Wyse 1983, Gilmore 1984; Brook et al 2002, Bird et al 2013; Wetzel et al 2016; Ma et al 2017)
- Mass ($M_\star > 10^{10}\ M_\odot$) and inferred SFR (several $M_\odot$/yr) similar to star-forming disks at z ~ 2, where observe organized rotation in clumpy, turbulent ionized gas disks, rotation velocities ~ 100-200 km/s, internal velocity dispersion large, ~ 50-100 km/s ➔ thick clumpy **ionized gas** disk – how does it evolve? ➔ settling into equilibrium? Need more data for neutral gas at z ~ 2
- Use thick and thin stellar disks in local universe as guide

The Redshift ~2 Universe: Old Disks in Formation

- Peak of cosmic star formation (Madau & Dickinson 2014)
- Direct study of (massive, $M_\star > 10^{10}\ M_\odot$) star-forming galaxies at redshifts ~ 2 shows organized rotation in clumpy, turbulent ionized gas disks
- v_{rot}/σ decreases to lower redshift ➔ settling to thin disc?
- Gravitational driving of turbulence (Krumholz et al 2018) through mergers?
- Caution: Neutral gas (ALMA) in starburst galaxy at z~ 2.6 shows cooler kinematics, more like local disks (Lelli et al 2018) and dust morphology indicates spiral arms, bar at z>2 (Hodge et al 2019)

8kpc

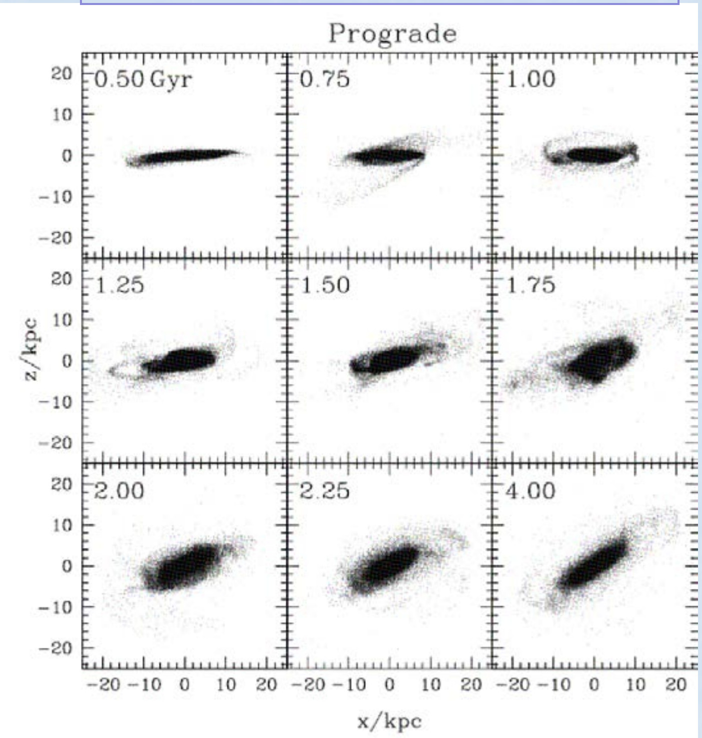


Wisnioski et al 2015

Thick Discs through Minor Mergers

Villalobos & Helmi 2008

cf Gilmore & Wyse 1985



Disc after collisionless merger with 1:5 mass-ratio satellite

- Initially thin stellar disc, orbital energy absorbed into internal degrees of freedom of the disc, increasing vertical velocity dispersion and scale-height

$$\Delta\sigma^2 \sim v_{orbit}^2 \, (M_{sat}/M_{gal})^{(1\text{-}2)}$$

(cf Ostriker 1990; Hopkins et al 2008)

- Thick disc will be compressed and heated by (slow) accretion of gas and re-formation of thin disc
- Orbital angular momentum ➔ tilt
- Satellite debris ➔ where is it now in galaxy?

- Including gas causes less heating/thickening (radiate energy)
- More mergers cause more heating ➔Hierarchical clustering of ΛCDM generically leads to thick discs, with range of stellar ages

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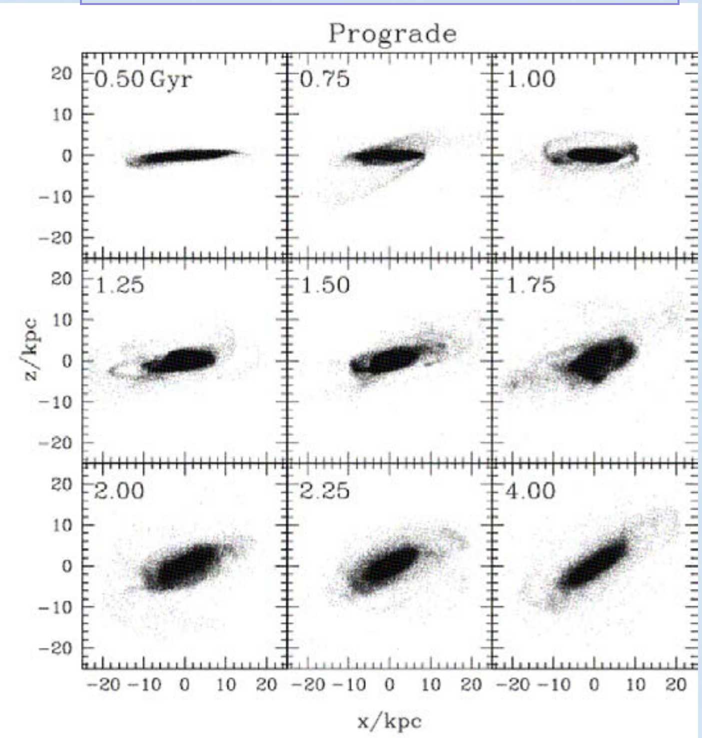

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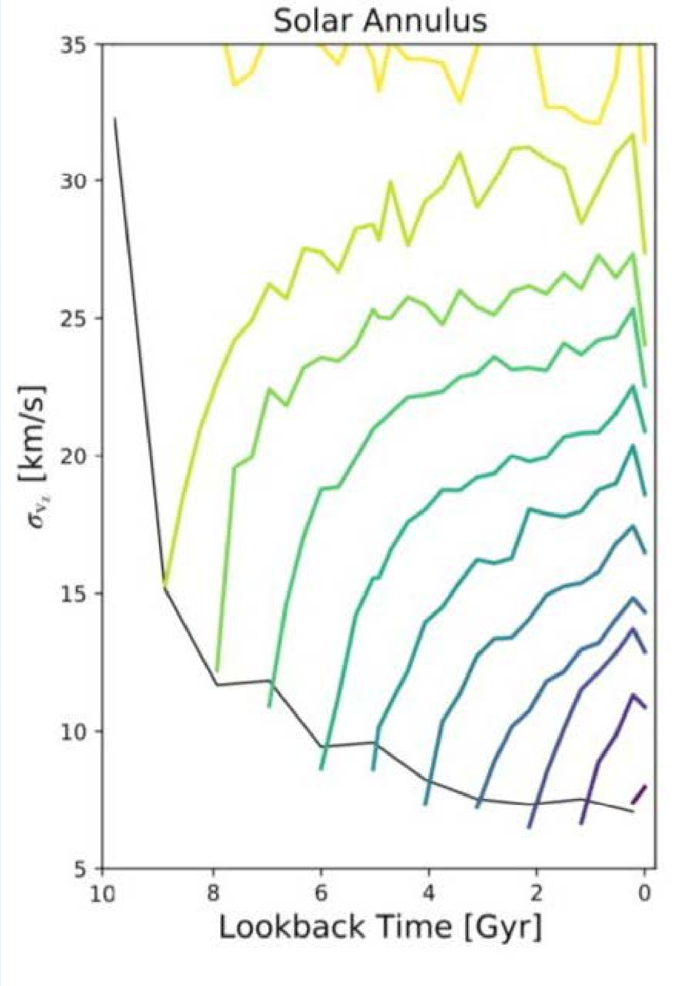
Old Age of Thick Disk Stars Limits Recent Mergers

- Mergers heat the thin disk and input stars formed up to that epoch into the thick disk (and perhaps halo)
- There are stars of wide range of ages in the thin disk, reflecting continuous star formation since early times
- Dominant old age of thick disk stars implies no significant (1:5) merger since redshift for look-back time equal that (old) age
  ➔Quiescent merger history since redshift $\gtrsim$ 2 (Wyse 2001)
  - Relatively quiet merger history consistent with inferred assembly history from globular cluster population (Mackey & Gilmore 2004; Kruijssen et al 2018), structure of stellar halo (Lancaster et al 2019)
- Minor mergers/interactions ongoing with the Sagittarius dwarf affect outer thin disk (flare, warp, corrugations, phase spiral?..)

Accurate and precise (old) stellar ages are crucial in evaluation of last significant mergers, as are detailed predictions from galaxy formation models to make comparisons

Upside Down Disk Formation?

- Most galaxy formation simulations that succeed in forming a thin disk at z=0 form it `upside down' (cf Bird et al 2013, 2019; Grand et al 2016, 2017)

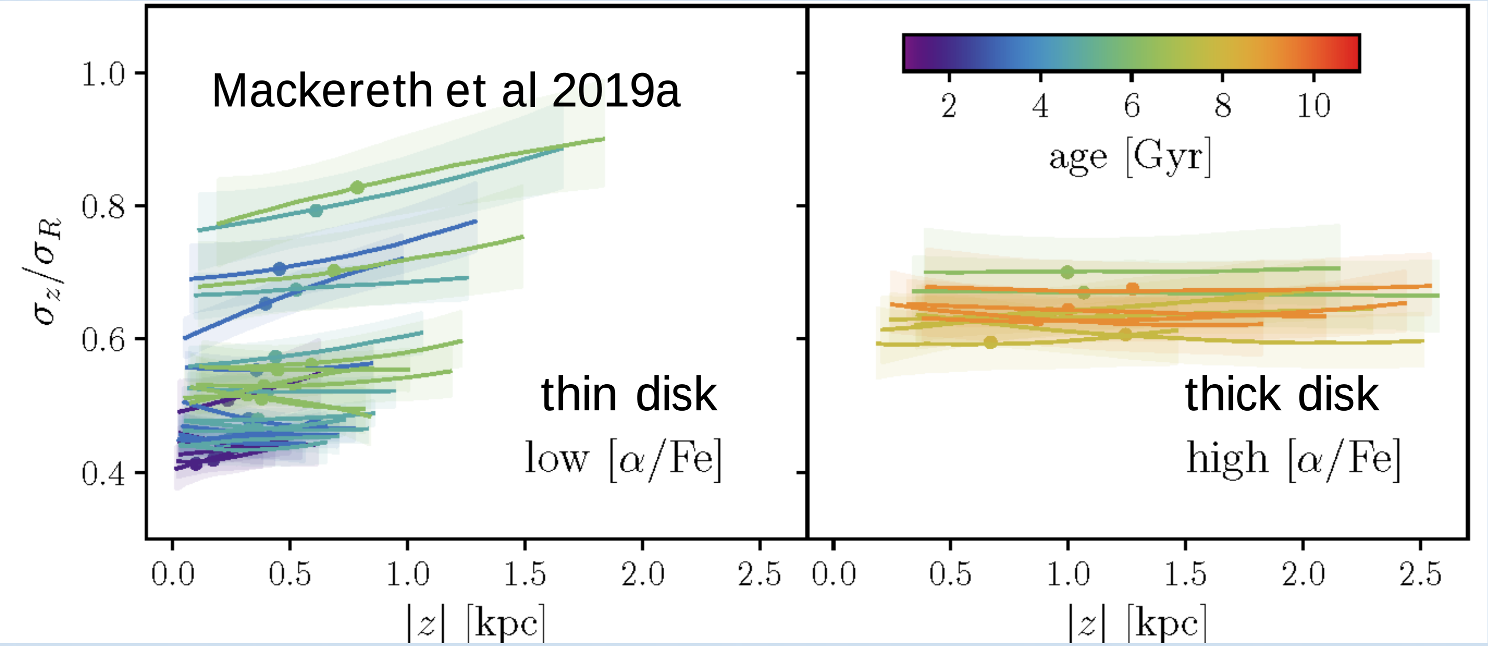


- Initial thick, turbulent gas phase followed by steady cooling and settling to cooler thinner disk, as star formation proceeds
- Age-velocity dispersion relation for thin disk stars reflects initial conditions at stellar birth, i.e. cooling plus later secular heating

Bird et al, in prep

Upside Down Disk Formation?

- Combination of Gaia DR2 and APOGEE allows detailed study of age-velocity dispersion relation(s) – look at different components of velocity
  - Thick disk and thin disk in same radial range of disk had `entirely different heating histories' (Mackereth et al 2019a)
  - Thin disk stars formed with cold kinematics, typical of ISM (Ting & Rix 2018)
  - Outer thin disk had extra heating, external perturbation likely

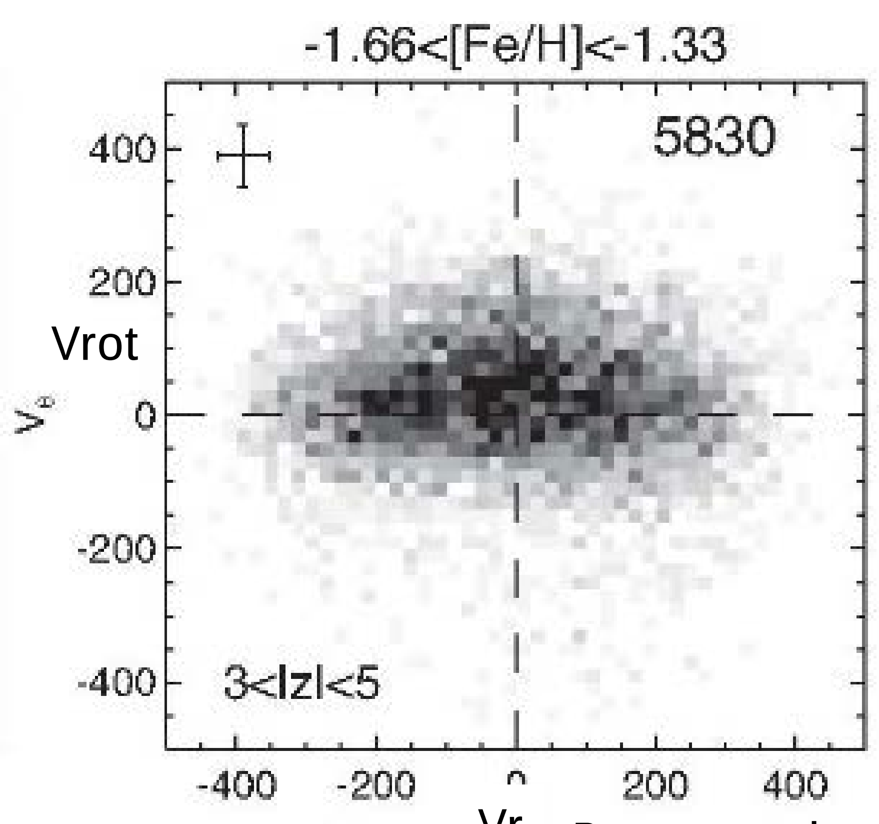


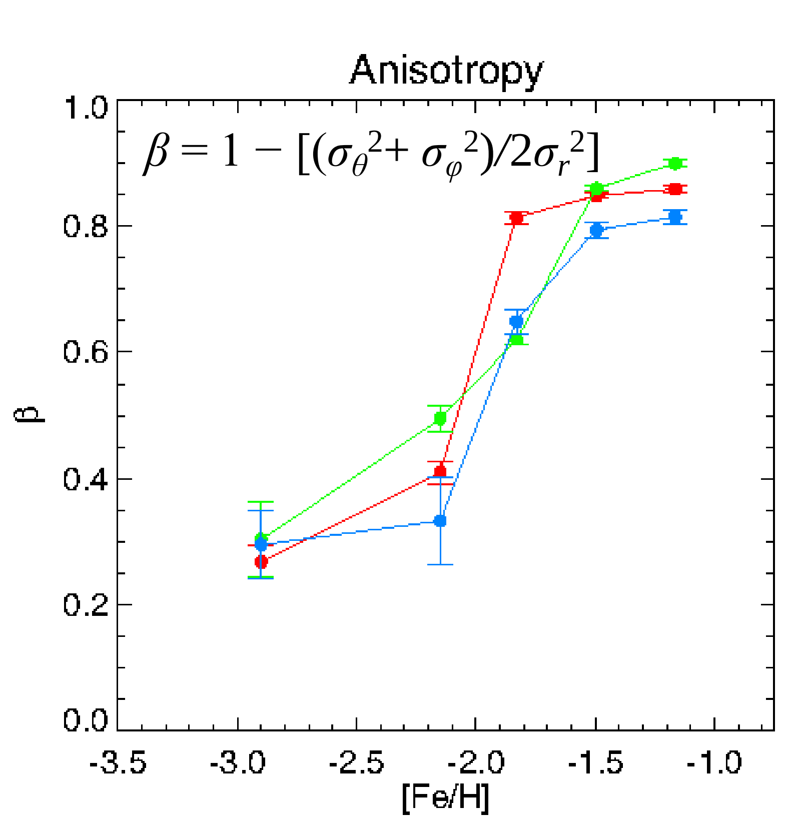
Satellite Debris from Last Significant Merger

- Stars at a few kpc from the midplane found to show hotter kinematics than standard thick disk, thought to show cylindrical rotation, in particular significantly lower rotational velocity component, still prograde (Gilmore, RW & Norris 2002; Wyse et al 2006)
  - Satellite debris proposed as explanation
- Satellites on prograde orbits couple better to a pre-existing thin disk, may be favoured (Quinn & Goodman 1986)
- Or is this simply a manifestation of kinematic and metallicity gradients within thick disk (Spagna et al 2010; Kordopatis et al 2011; Re Fiorentin, Lattanzi & Spagna 2018) ?

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 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

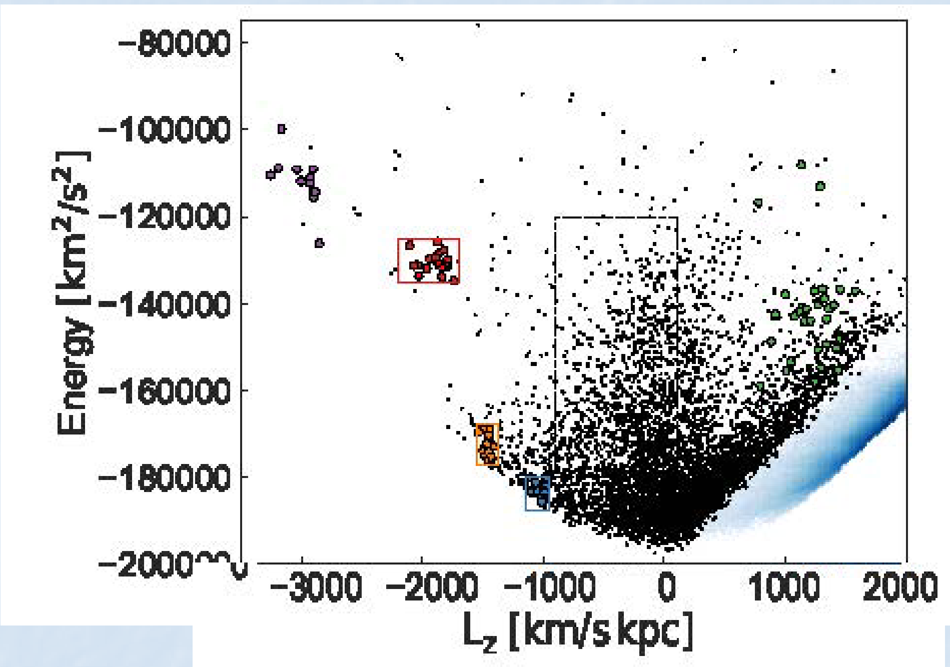




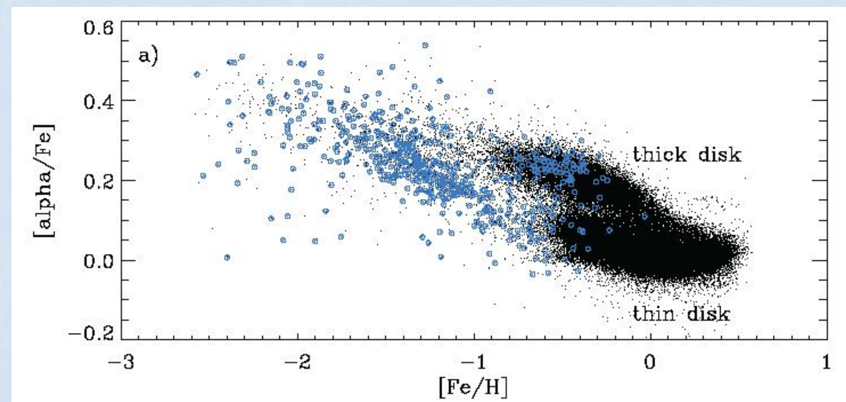
Proper motions from SDSS-Gaia DR1

The Gaia Era

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



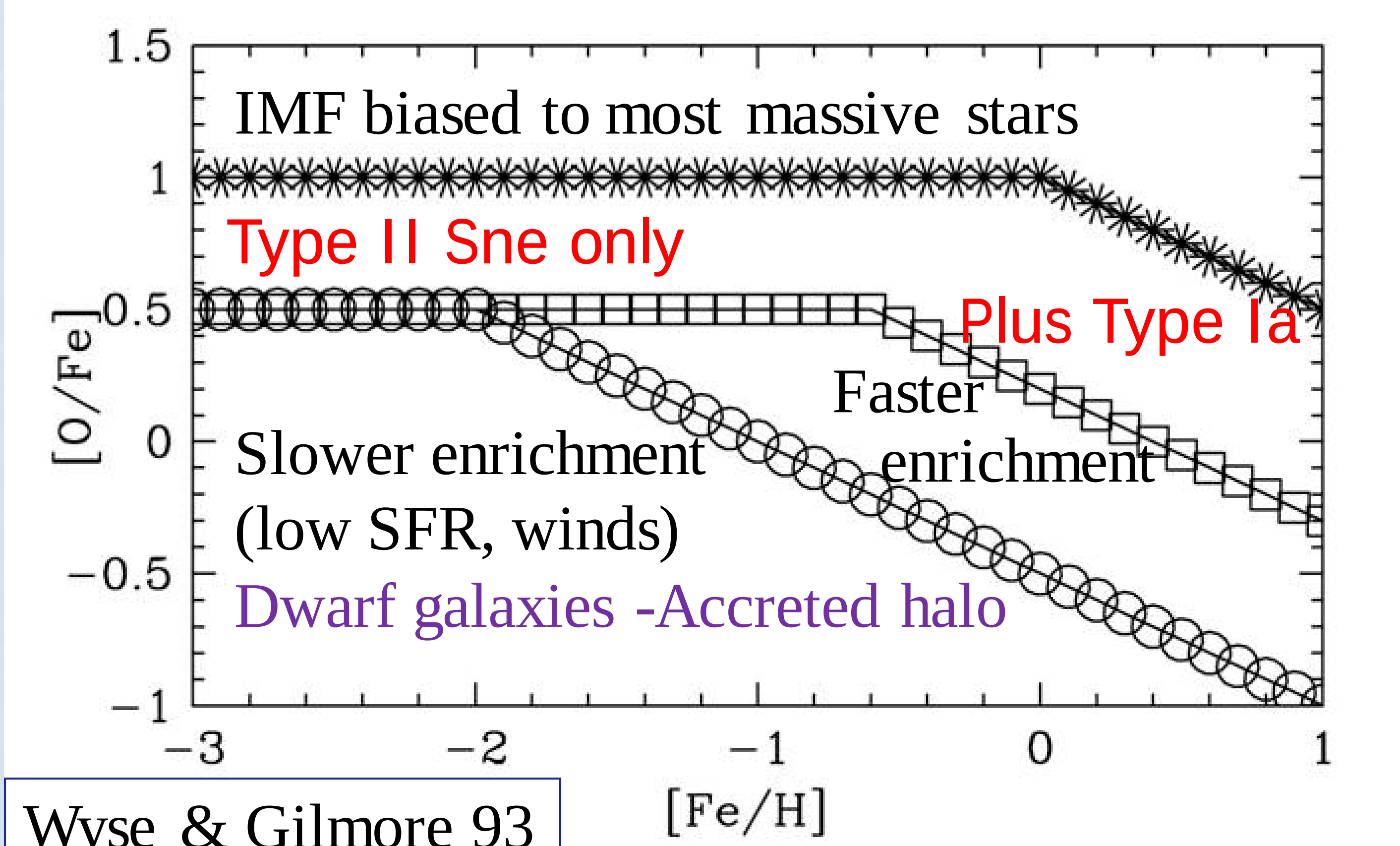
- Cross-correlate with APOGEE elemental abundances – low-alpha sequence `accreted' (Helmi et al 2018)



- 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)

Elemental Abundances: star formation history and enrichment history – distinct thin and thick disks

Alpha element (core-collapse SNe) and iron (Type Ia SNe)

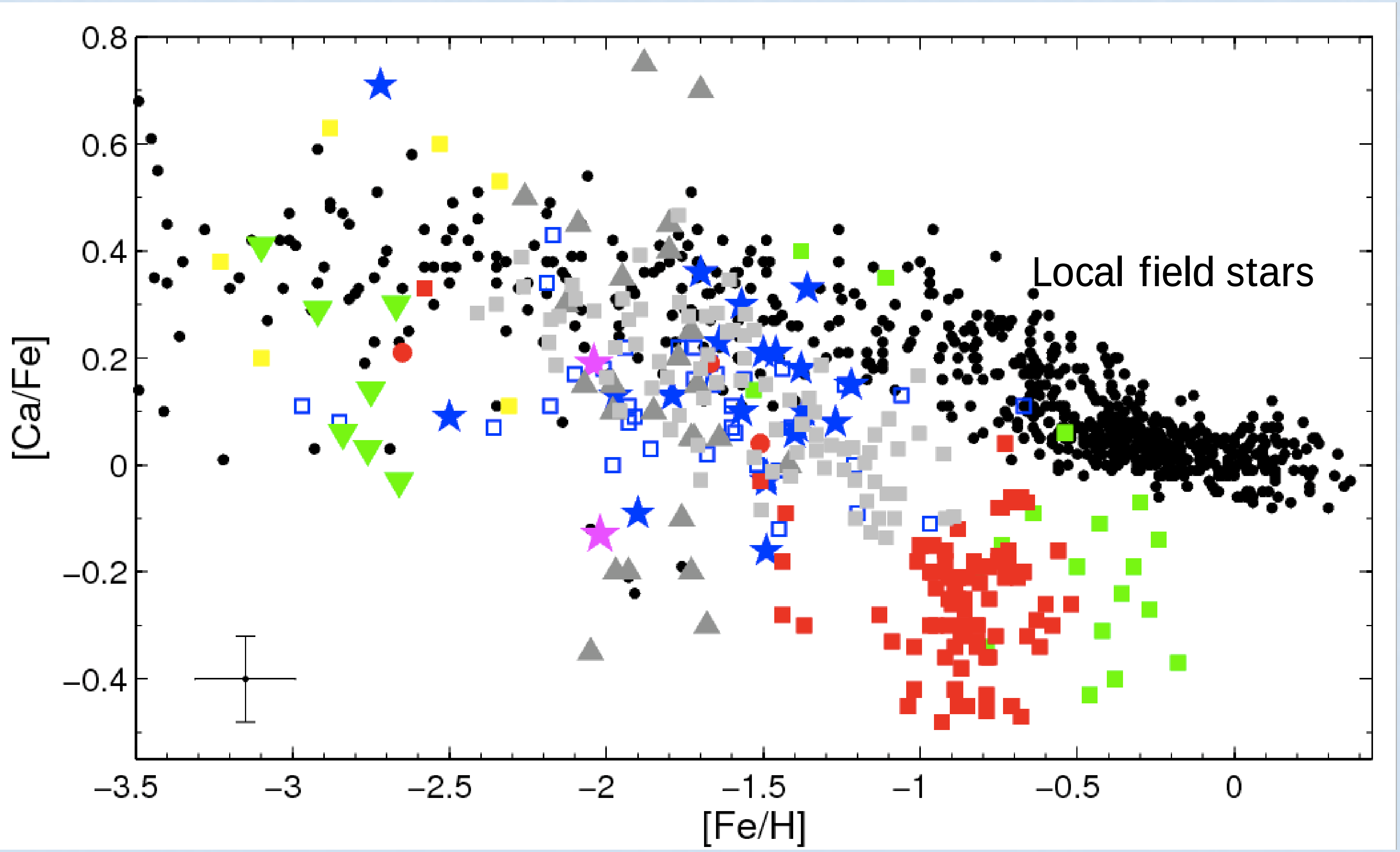


Wyse & Gilmore 93

Self-enriching star-forming region, non-bursty star formation. Model assumes massive-star IMF average yields

dSphs and local Milky Way abundances

(from A. Koch, 2009)



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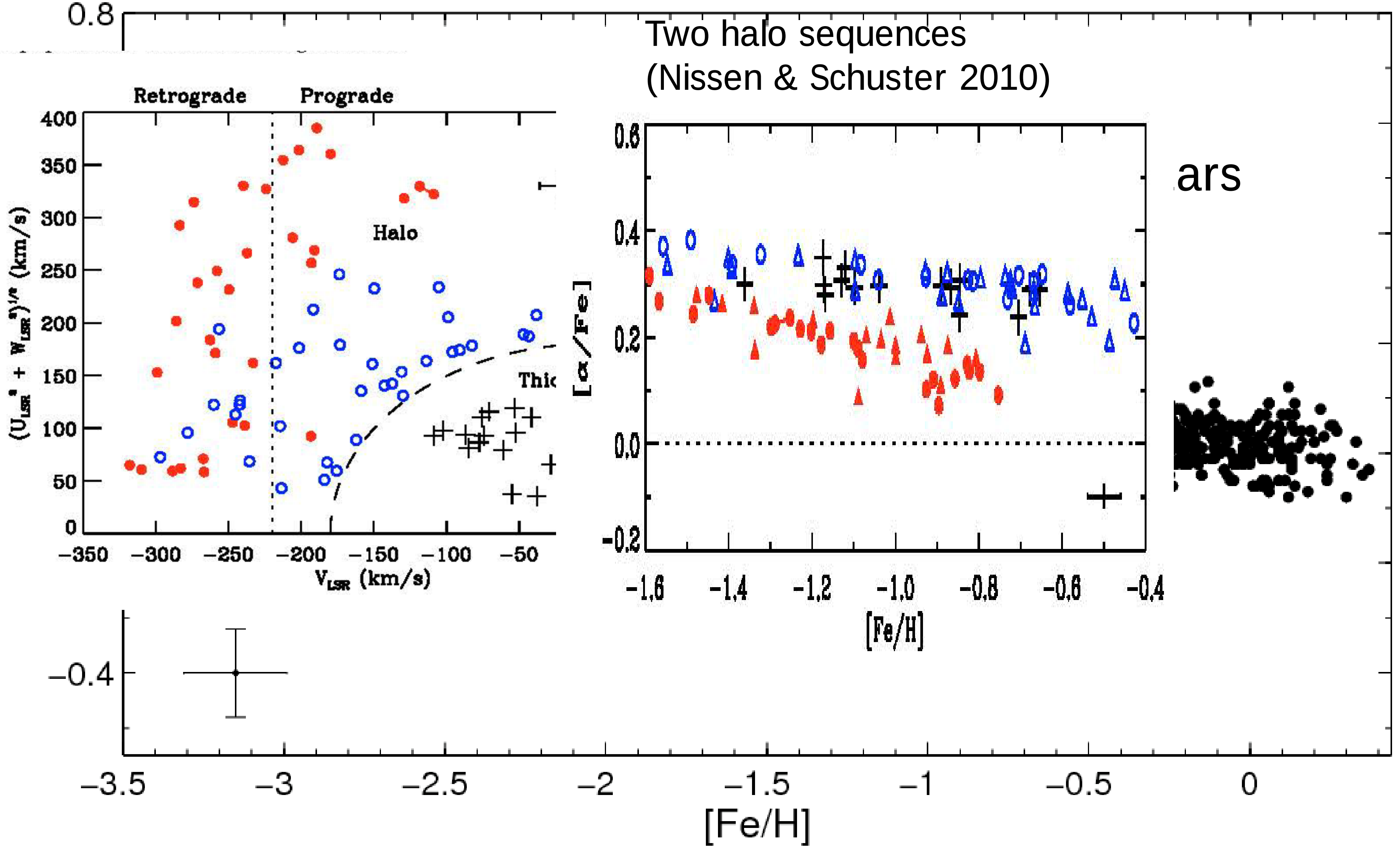
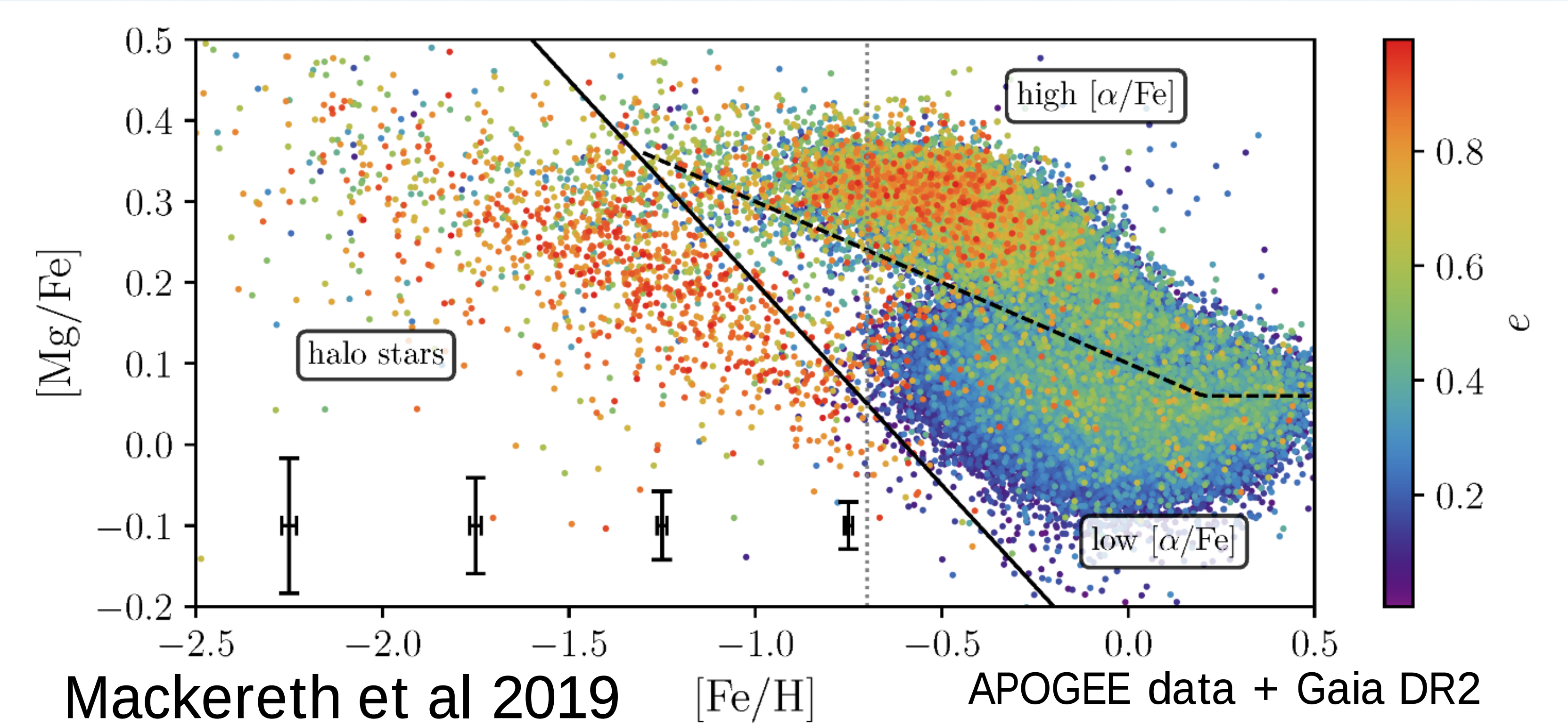


The Era of Gaia + Surveys with High Resolution Multi-object Spectrographs

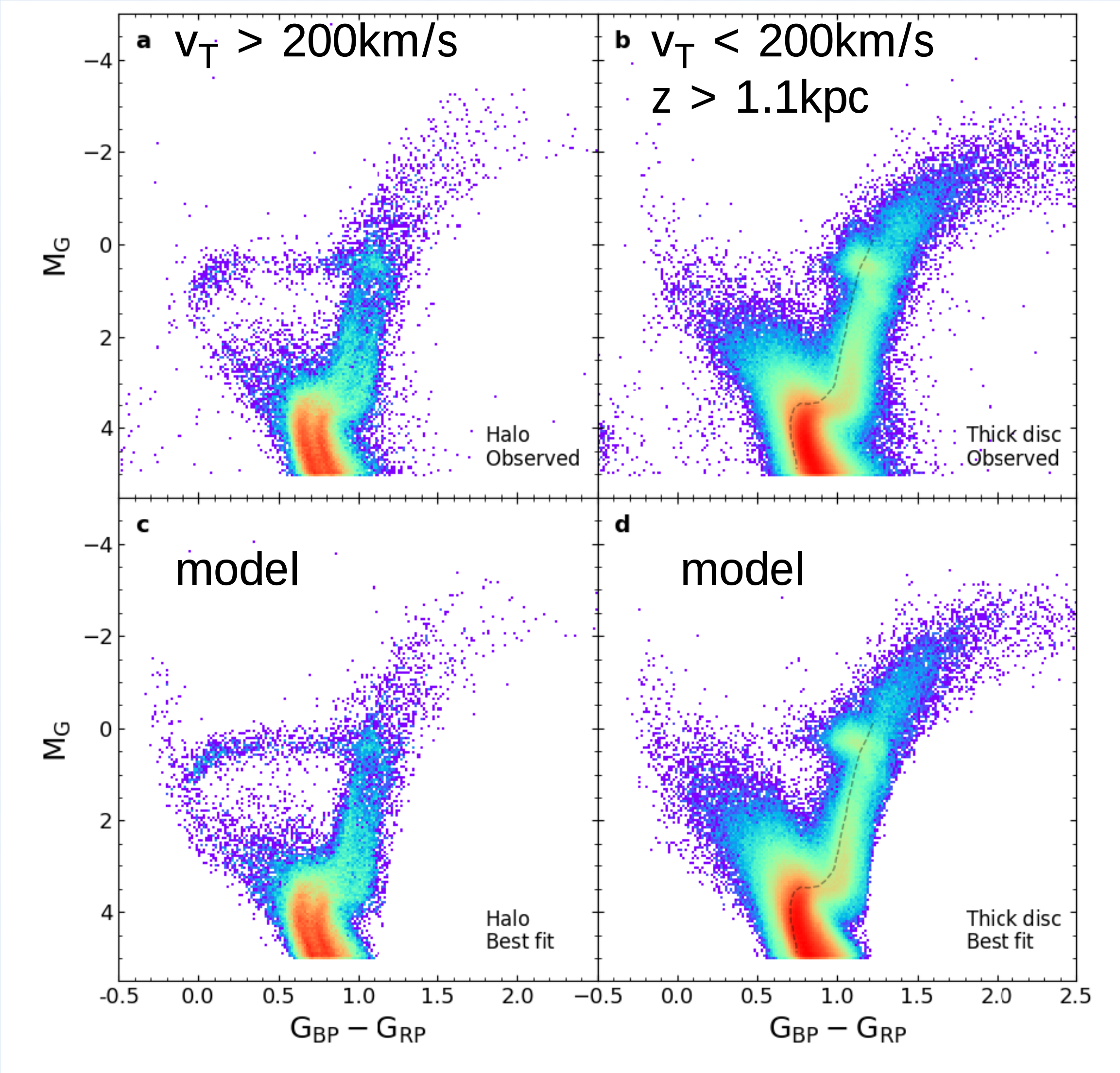


Mackereth et al 2019

APOGEE data + Gaia DR2

- High orbital eccentricity halo stars have low values of [α/Fe], form accreted component, most of stellar halo
- Comparison to EAGLE suite of cosmological simulations → merger 8-9 Gyr ago

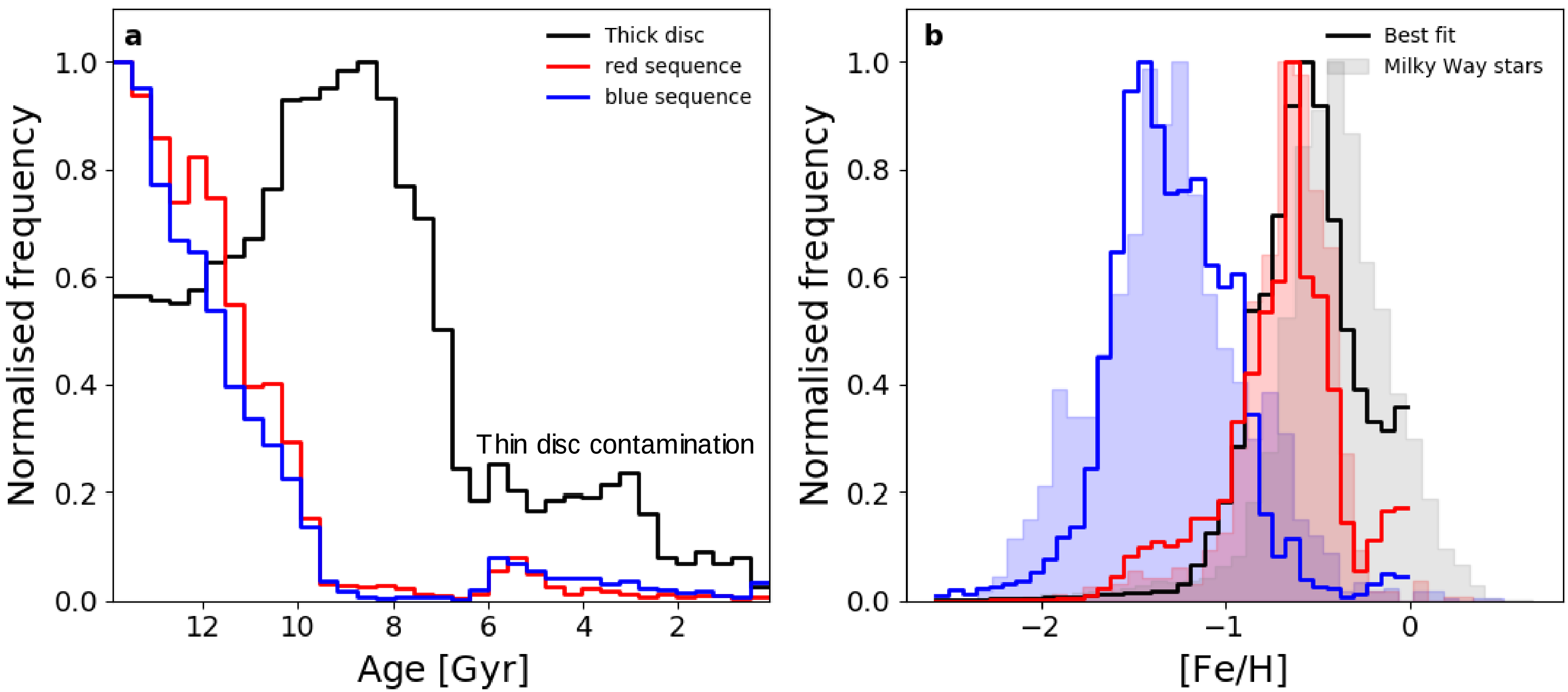
- Further slice Gaia CMD (within 2kpc) in kinematics/position to isolate thick disk from halo and derive SFH and metallicity distributions:



Gallart et al 2019

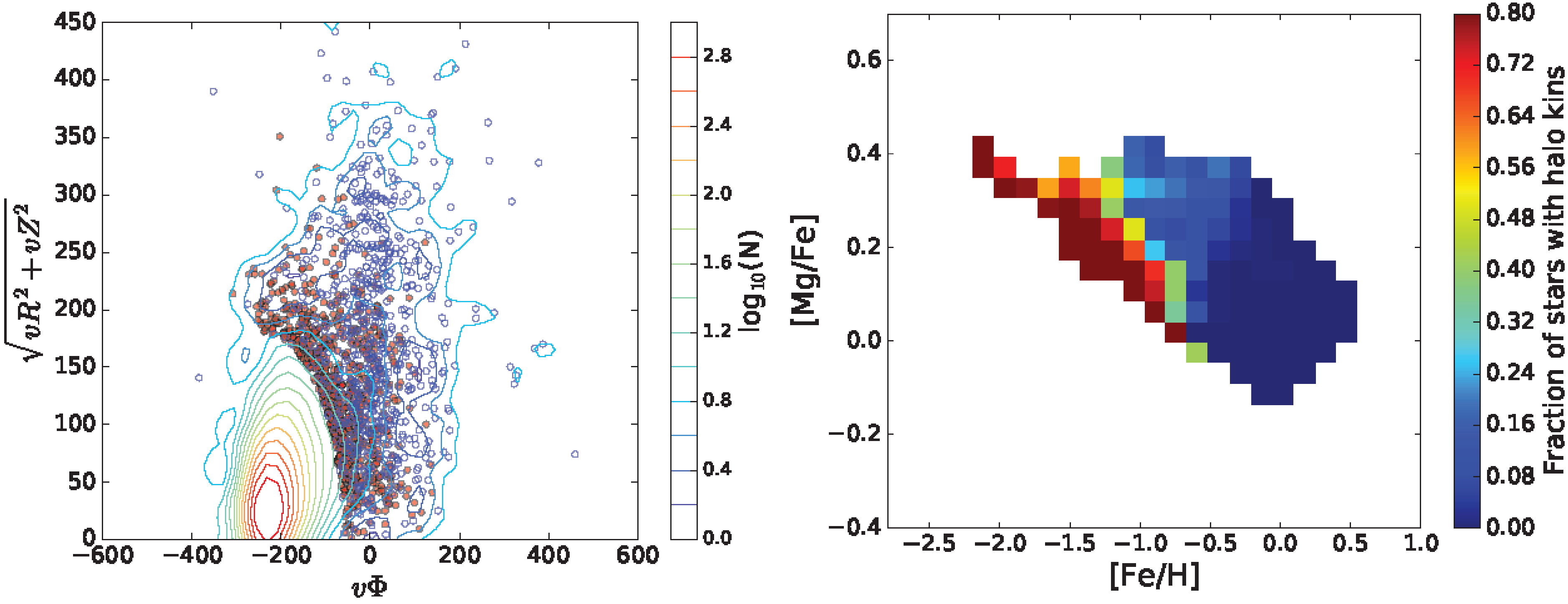
Thick disk main sequence has very similar location to red halo

Gallart et al 2019



- Dual stellar halo – accreted (blue) and formed in situ (red) - plus thick disk, slightly younger
  - Or is the red halo the hotter kinematic tail of the thick disk? (cf di Matteo et al 2019)
- Thick disk created during/by merger a long time ago, ~10Gyr, blue halo is the debris of the massive satellite

Di Matteo et al 2019 APOGEE + Gaia DR2



- The entire stellar halo is accreted – that merger heated the preexisting thin disk into `in situ' halo plus thick disk - `in situ halo' kinematic tail of thick disk
- Last significant merger happened ~10 Gyr ago (age of thick disk/high-alpha component)

Sausage or Enceladus or ??

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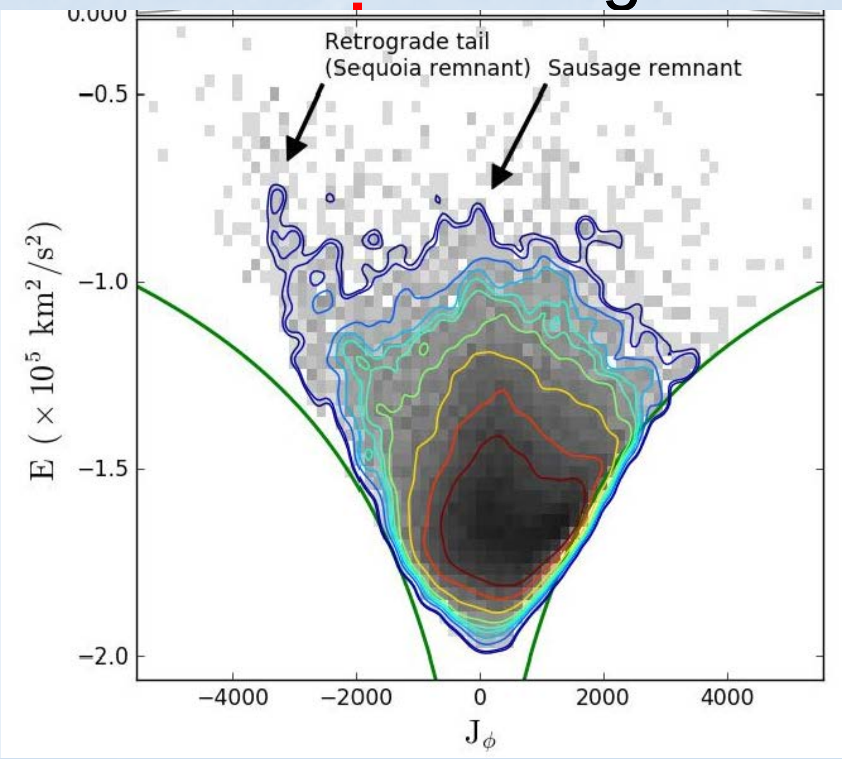
- Enter the Sequoia

Sausage or Enceladus or ??

- Enter the Sequoia (Barba et al 2018)
  - Large, luminous globular cluster on retrograde orbit
  - Plausibly associated with other retrograde substructure, including ωCen, long suspected of being the nucleus of stripped dwarf galaxy (Bekki & Freeman 2003)
- Enceladus $\stackrel{?}{=}$ Sausage + Sequoia (Myeong et al 2019)



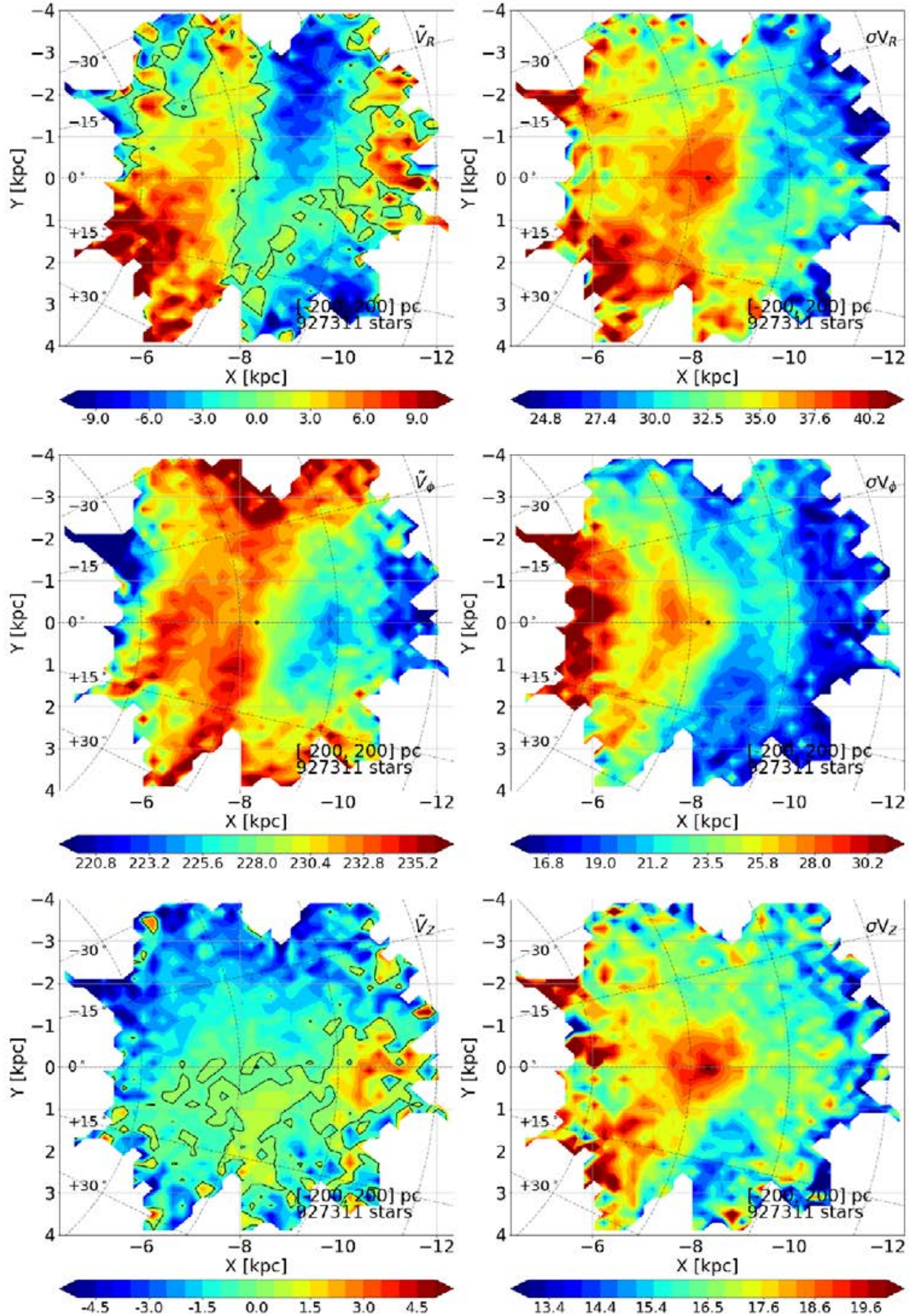
- Sequoia galaxy (~ $10^{10} M_\odot$) less massive than Sausage galaxy (~ $10^{11} M_\odot$)
- (Slight) difference in elemental abundance patterns (cf Mackereth et al 2019; Matsuno et al 2019)

The Disk in DisEquilibrium

- Gaia has revealed a wealth of structure in the velocity field of disk stars
  - Much more detailed than earlier datasets (Hipparcos, RAVE, SDSS..)
- A wealth of possible mechanisms has been proposed, both internal - bar buckling, bar resonances (OLR, CR), spiral arms – and external – primarily Sgr
- The field of Galactoseismology very active (cf Widrow et al 2012)
- Significant `stellar halo' substructure may rather be part of the **disk** response to gravitational perturbations, particularly in the outer parts where restoring forces weaker

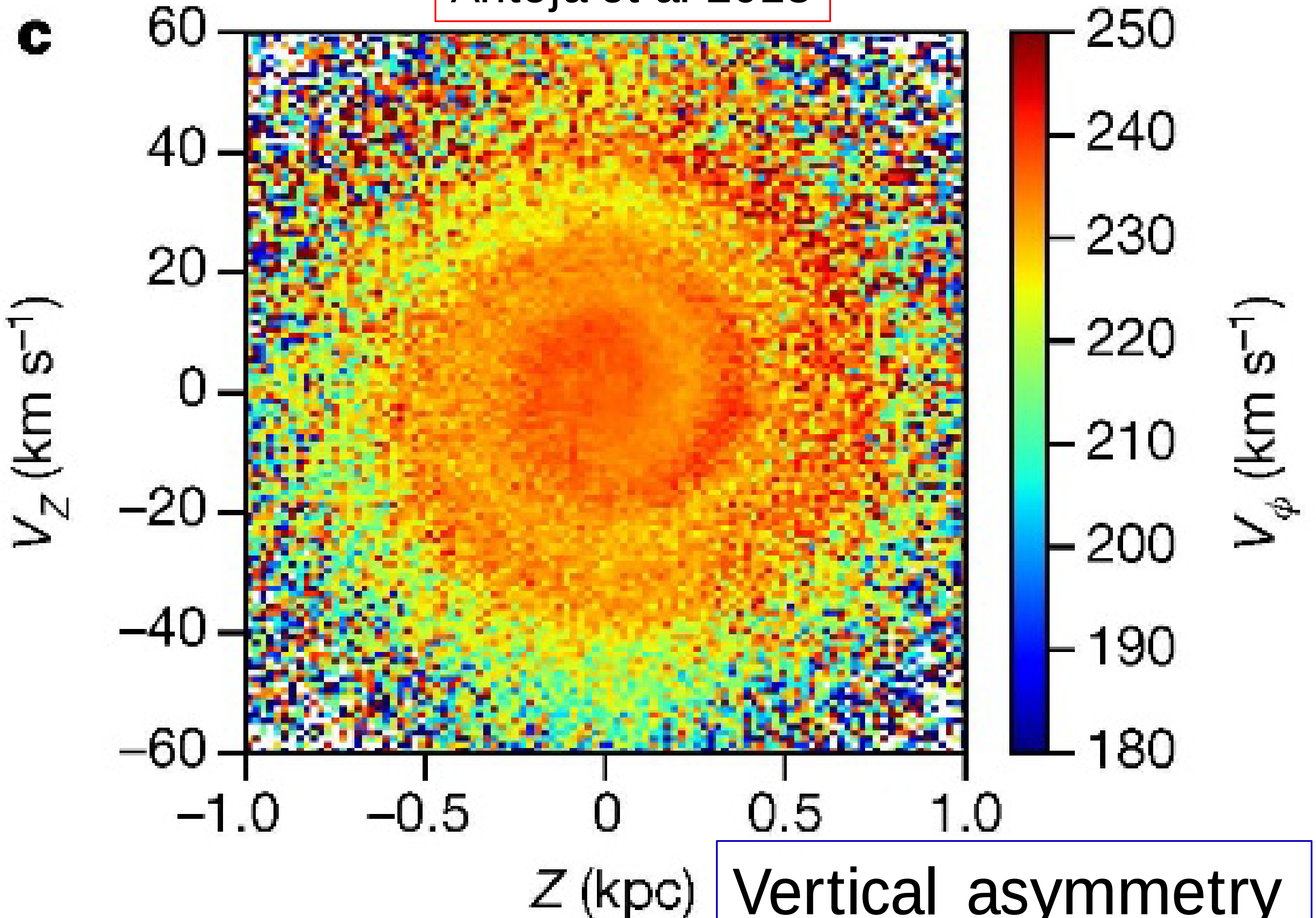
Gaia DR2

Katz et al 2018



The Gaia Phase Space Spiral (or snail shell)

Antoja et al 2018

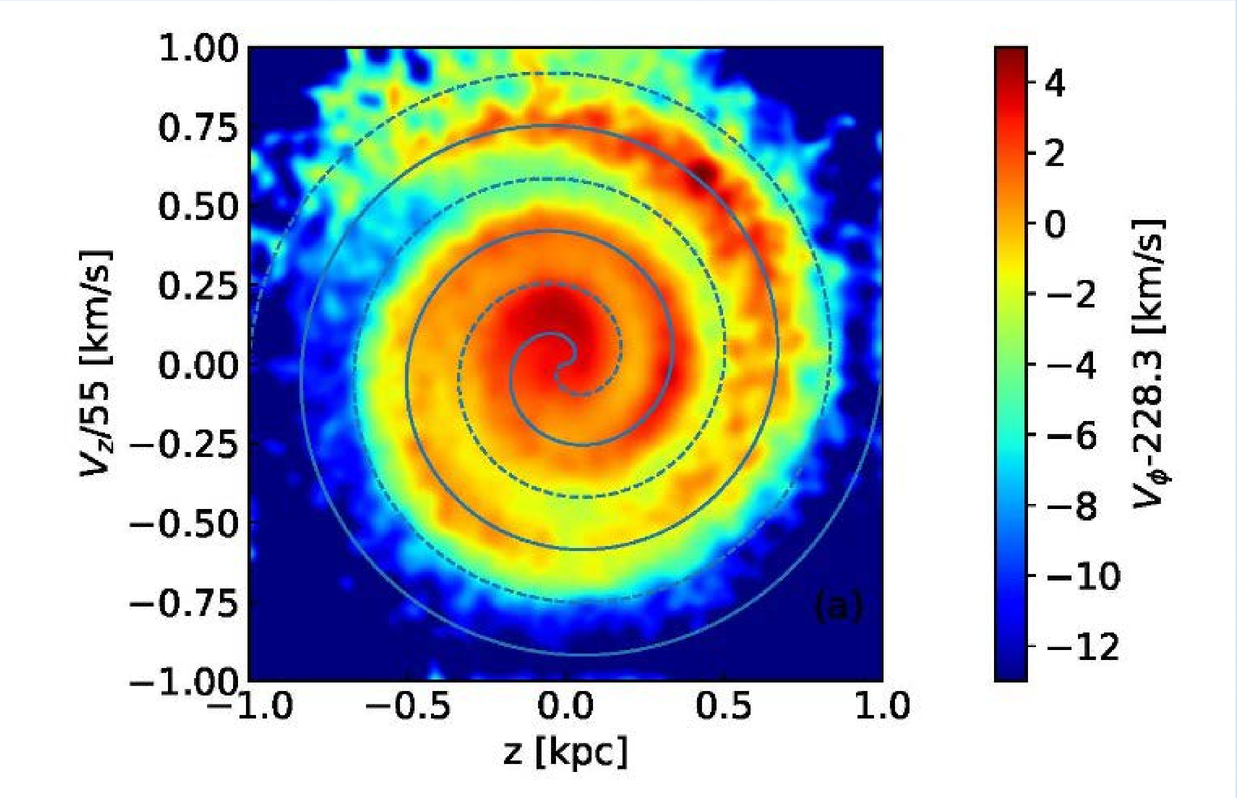


Vertical asymmetry

A Dynamically Young and Perturbed Milky Way Disc

The Galah Spiral

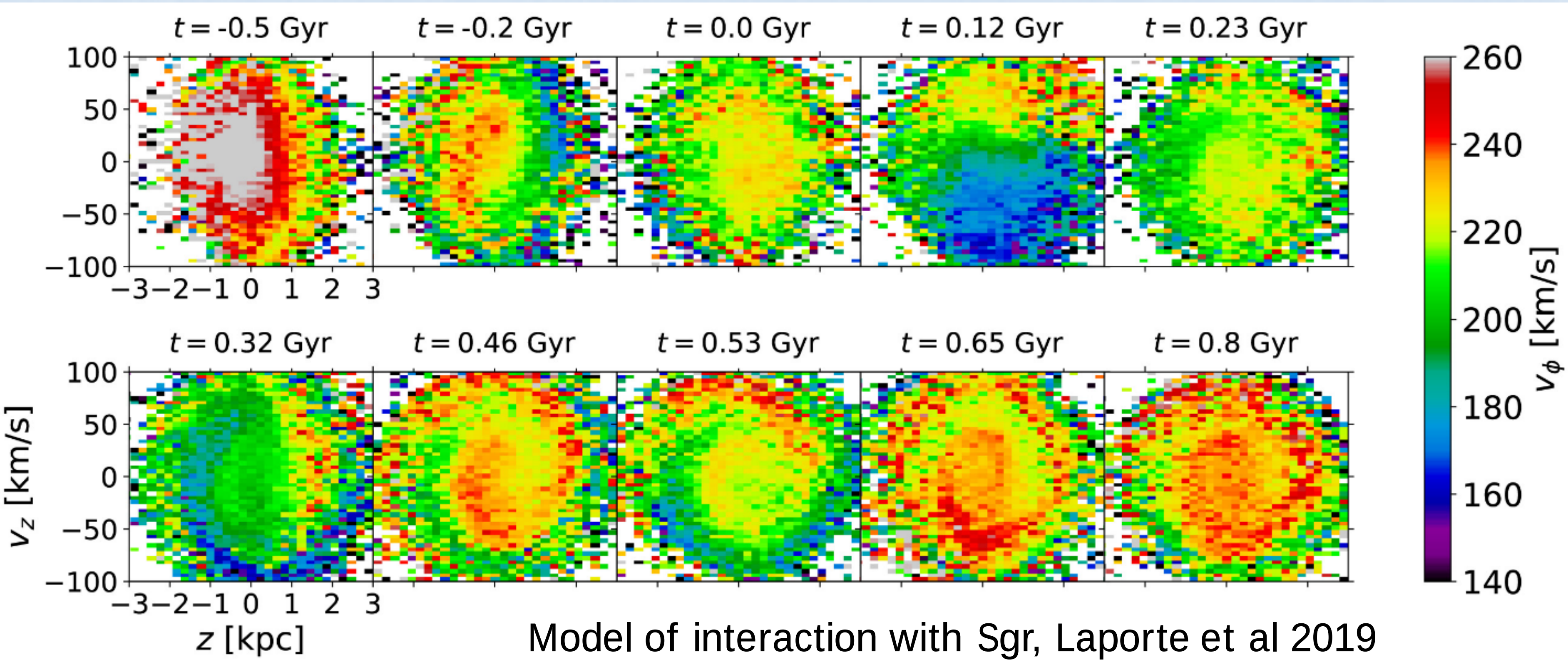
Bland-Hawthorn et al (inc RW) 2019



Stars within 1kpc of the solar radius and 15^o in azimuthal angle

Stronger spiral in low-alpha disk – younger, cooler kinematics

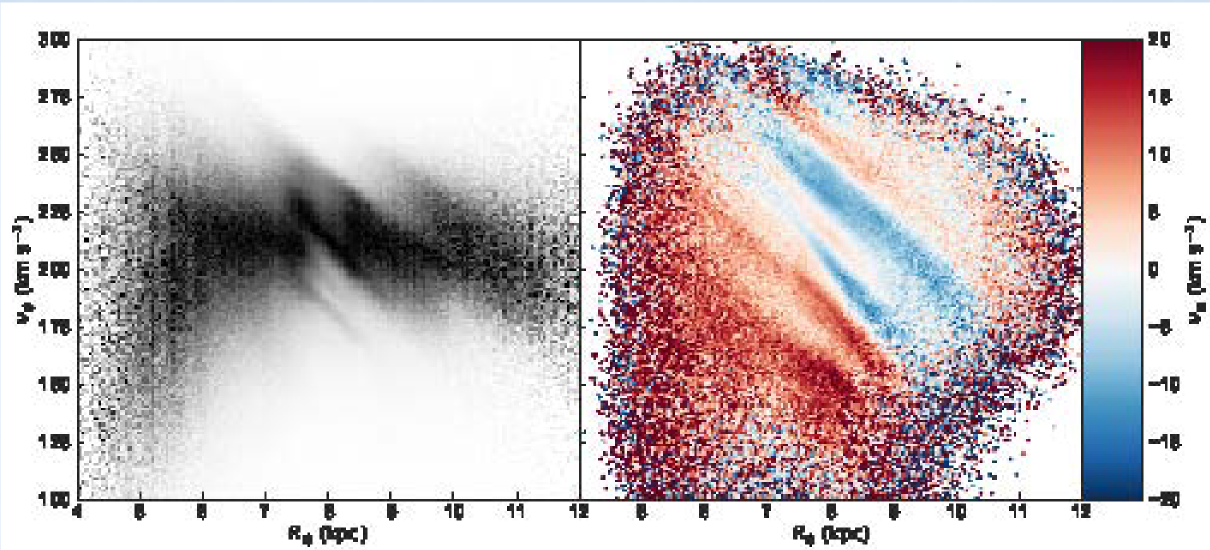
- Vertical phase mixing after a perturbation (Binney & Schonrich '18)
  - the frequency at which stars oscillate vertically depends on angular momentum Lz in addition to the amplitude of vertical oscillations
  - Phase space spirals in $<v_R>$ and $<v_\phi>$ should form whenever a massive substructure, such as the Sgr dwarf galaxy, passes through the plane
  - Primary driver is the component of the tidal force that lies in the plane
  - Role of self-gravity?



Model of interaction with Sgr, Laporte et al 2019

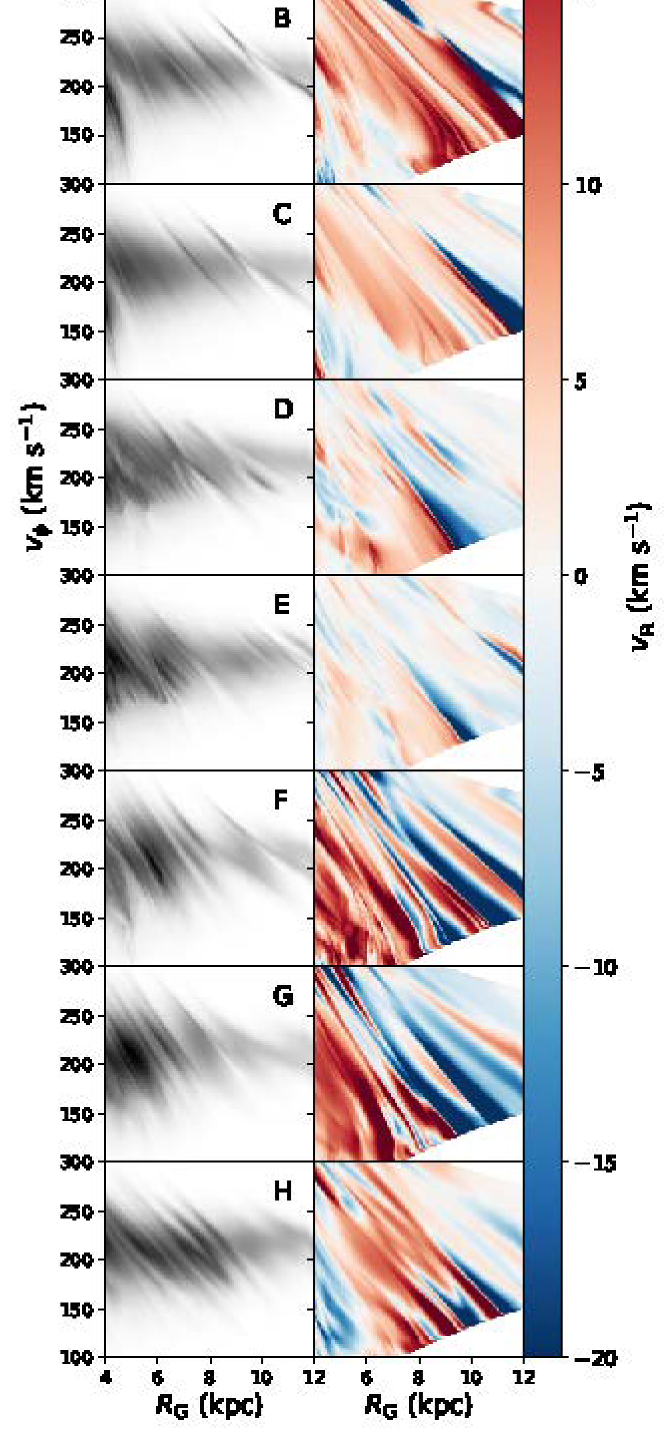
Hunt et al 2019

Radial structure



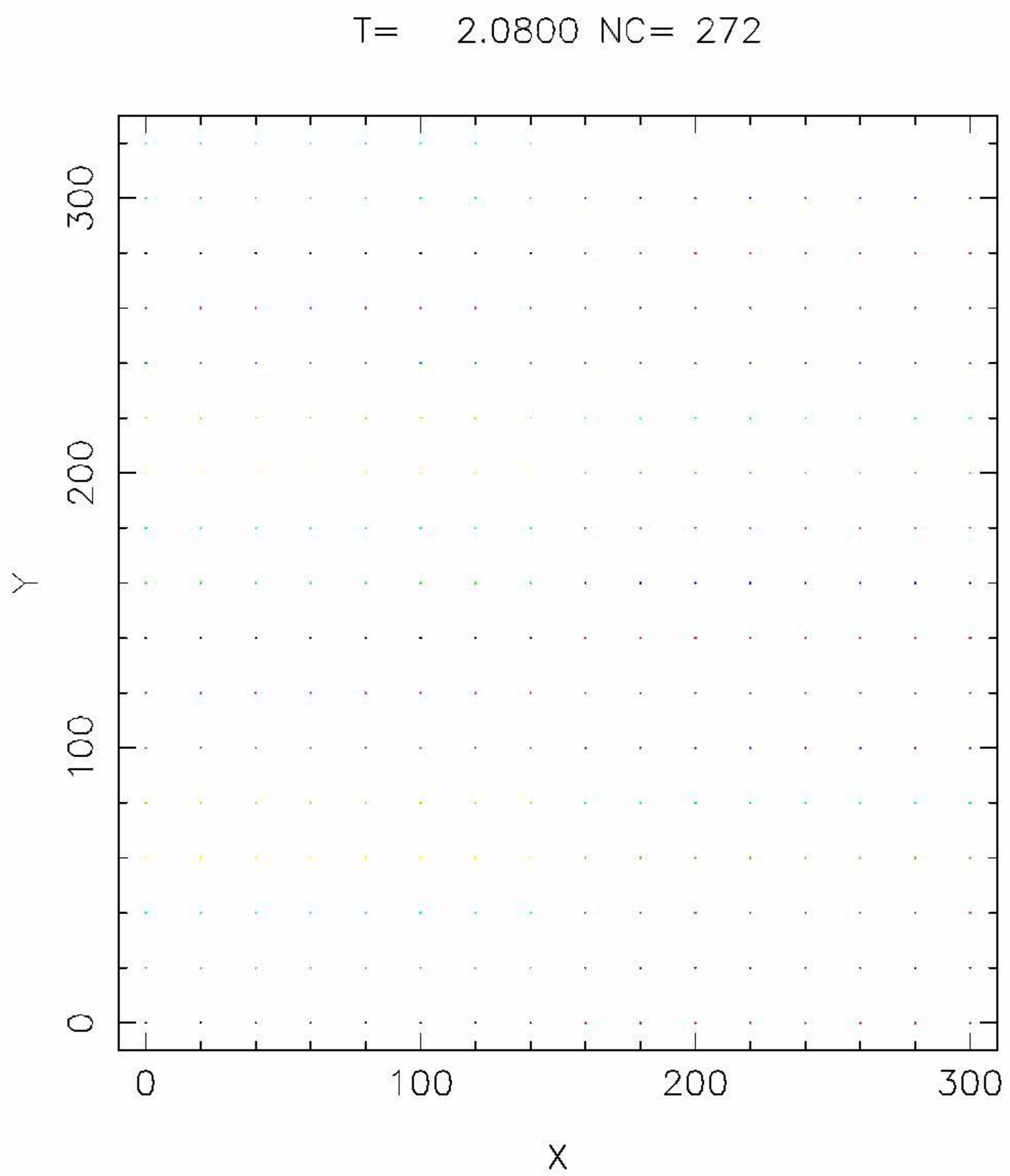
Gaia DR2

Various models of bar plus spiral patterns



The Halo in DisEquilibrium

- Inherent in hierarchical merging
- LMC having significant perturbative effect now on both stellar and dark halo (e.g. Belokurov et al 2019) – and on the Orphan stream (Erkal et al 2018)
- Cold tidal streams from disrupting globular clusters not simple to analyse in terms of constraining dark substructure (Carlberg 2019)
  - Seed subhaloes in Via Lactae II at high redshift with systems of globular clusters and follow evolution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Concluding Remarks

- The combination of Gaia data with spectroscopic data is proving immensely powerful
- The more we discover, the less we understand
- More and better data are coming - need to develop models to match