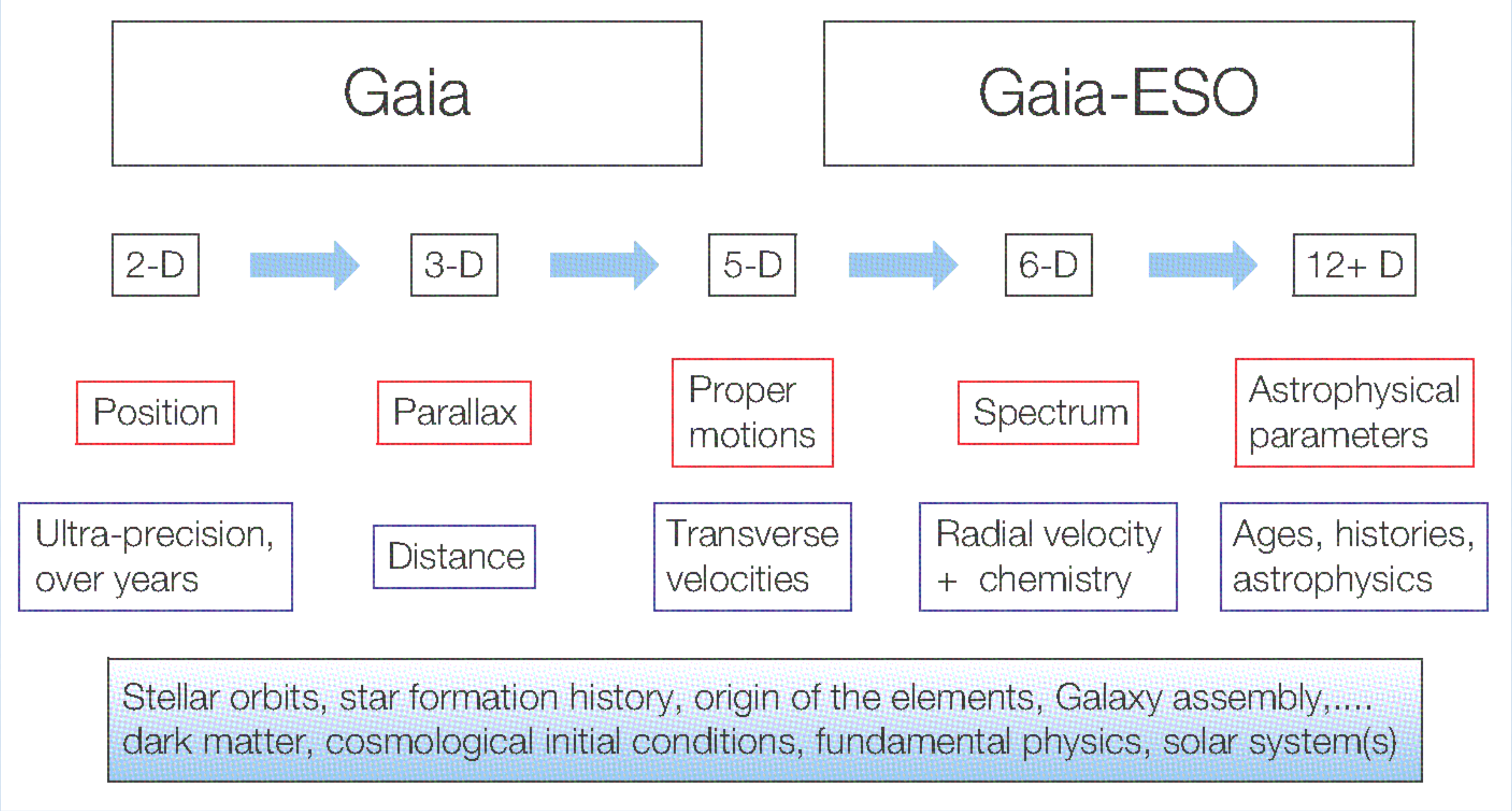
Galactic Surveys in the Gaia Era

Rosemary Wyse

JOHNS HOPKINS
UNIVERSITY

IAU Symposium 330, Nice, 24th April 2017



Gaia

Gaia-ESO

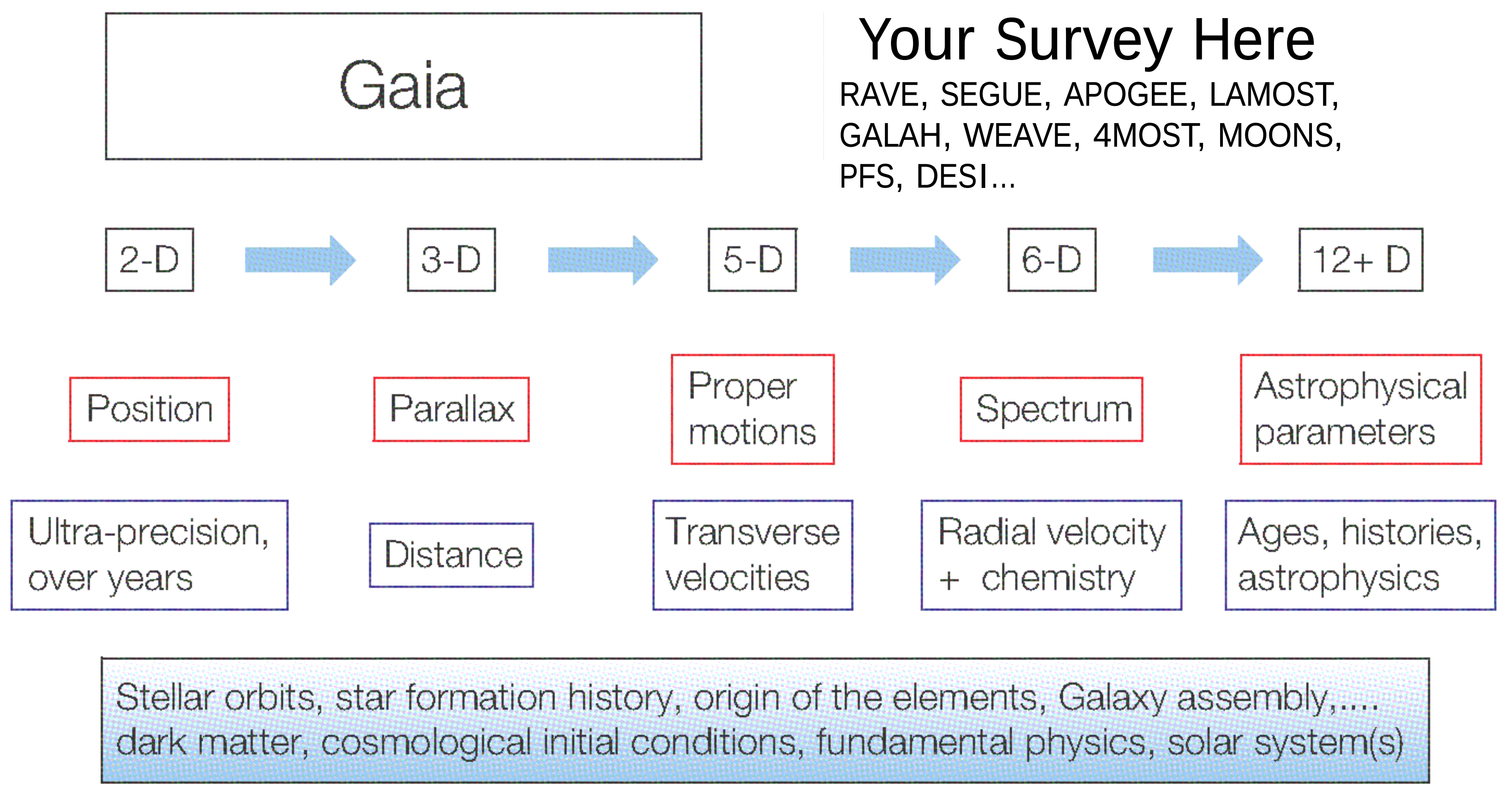
2-D → 3-D → 5-D → 6-D → 12+ D

2-D	3-D	5-D	6-D	12+ D
Position	Parallax	Proper motions	Spectrum	Astrophysical parameters
Ultra-precision, over years	Distance	Transverse velocities	Radial velocity + chemistry	Ages, histories, astrophysics

Stellar orbits, star formation history, origin of the elements, Galaxy assembly,.... dark matter, cosmological initial conditions, fundamental physics, solar system(s)

Gilmore et al 2012

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



Gaia

Your Survey Here

RAVE, SEGUE, APOGEE, LAMOST, GALAH, WEAVE, 4MOST, MOONS, PFS, DESI…

2-D → 3-D → 5-D → 6-D → 12+ D

Position | Parallax | Proper motions | Spectrum | Astrophysical parameters

Ultra-precision, over years | Distance | Transverse velocities | Radial velocity + chemistry | Ages, histories, astrophysics

Stellar orbits, star formation history, origin of the elements, Galaxy assembly,…. dark matter, cosmological initial conditions, fundamental physics, solar system(s)

Plus deep multi-band imaging surveys

Gilmore et al 2012

The Fossil Record: Galactic Archaeology

- Studying low-mass old stars ➔ near-field cosmology
  - 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 – modulo torques - kinematic and chemical phase space structure
  - Multivariate stellar distribution functions of different components overlap: need large samples with well-understood selection functions
- Complementary approach to direct study of galaxies at high redshift ➔ snapshots of different galaxies at different times vs evolution of one

Overview of current understanding, for context; focus on discs

The Fossil Record: Galactic Archaeology

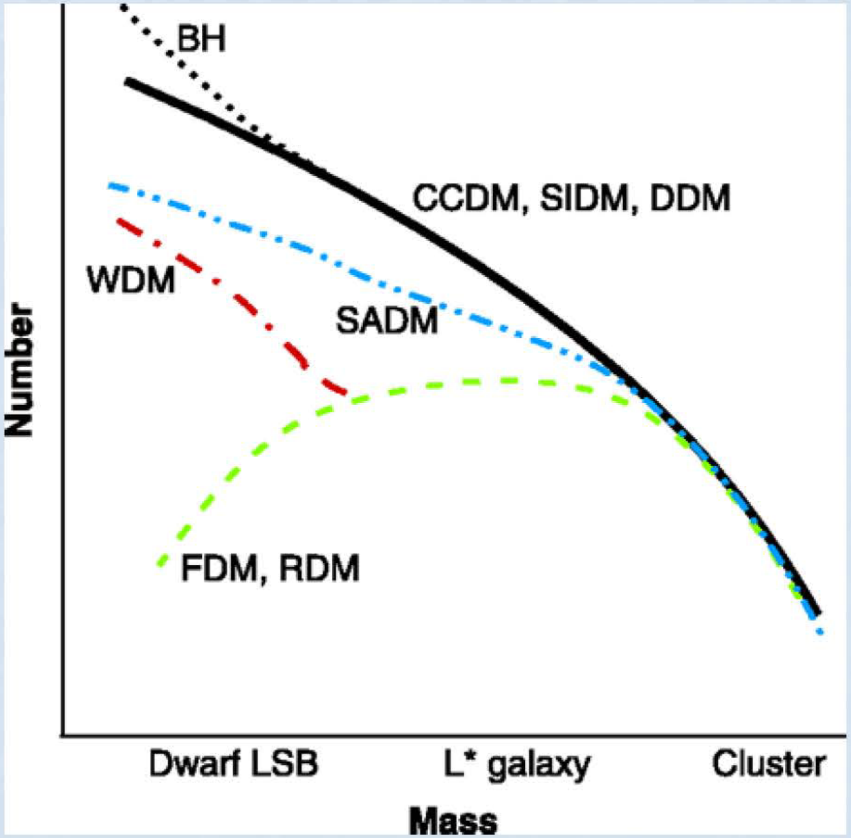
- Studying low-mass old stars ➔ near-field cosmology
  - There are copious numbers of stars nearby that have ages $\gtrsim$10 Gyr : formed at redshifts > 2 - thin disc, thick disc, bulge, halo, satellite galaxies
  - Retain memory of initial/early conditions: elemental abundances, orbital angular momentum/integrals – modulo torques - kinematic and chemical phase space structure
  - Multivariate stellar distribution functions of different components overlap: need large samples with well-understood selection functions
- Complementary approach to direct study of galaxies at high redshift ➔ snapshots of different galaxies at different times vs evolution of one

Also Allende Prieto talk

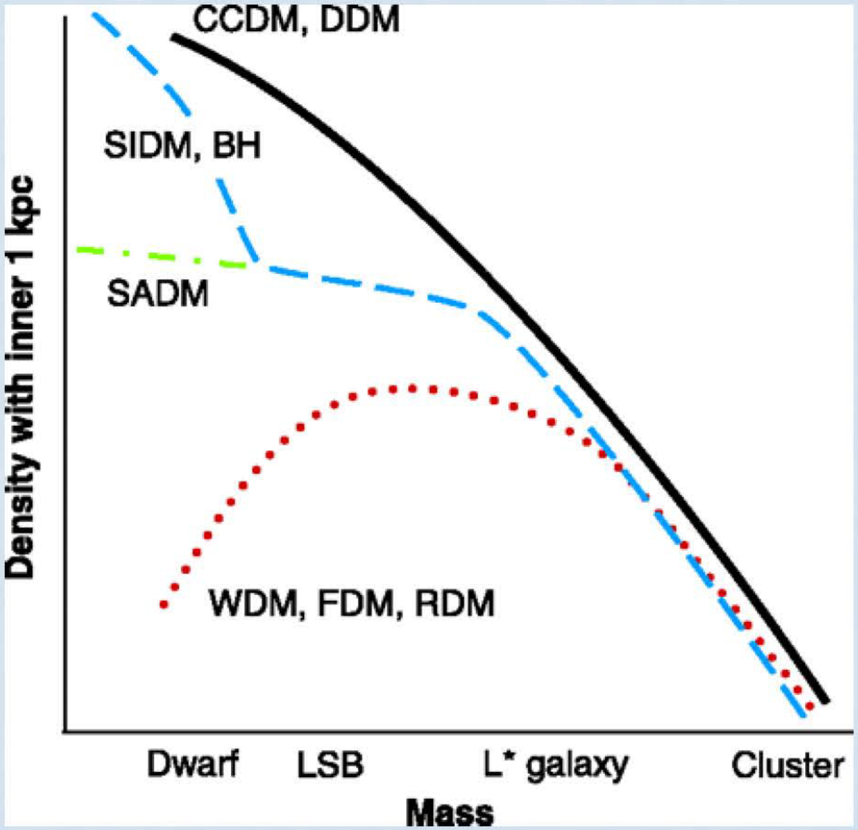
Overview of current understanding, for context; focus on discs

Small Scales Reveal Nature of Dark Matter

Ostriker & Steinhardt 2003



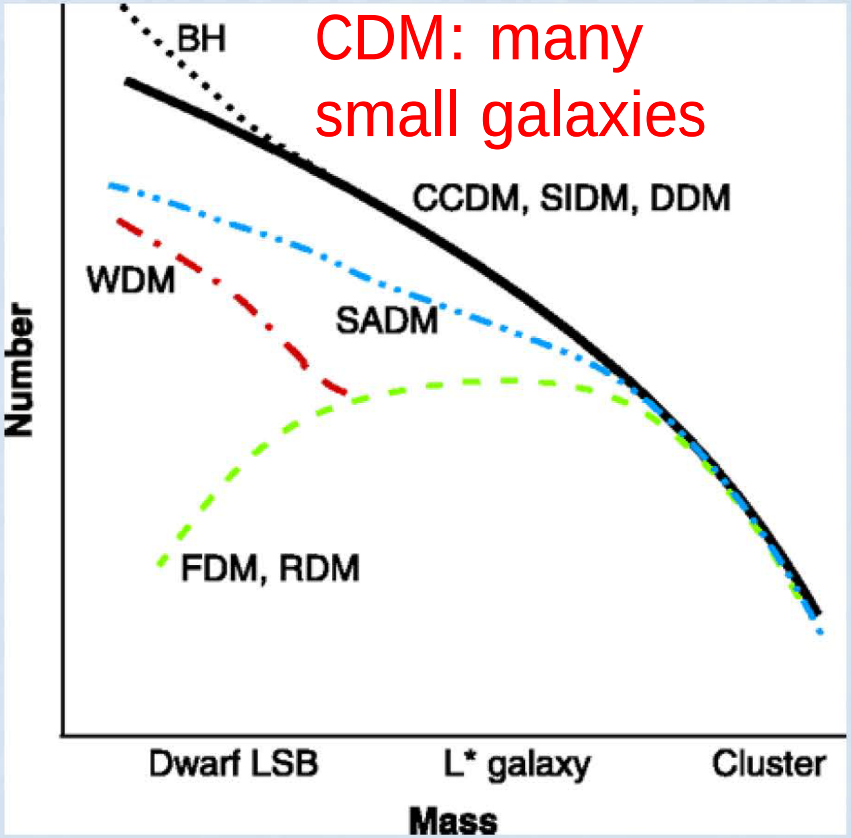
Galaxy mass function depends on DM type



Inner DM mass density depends on the type(s) of DM

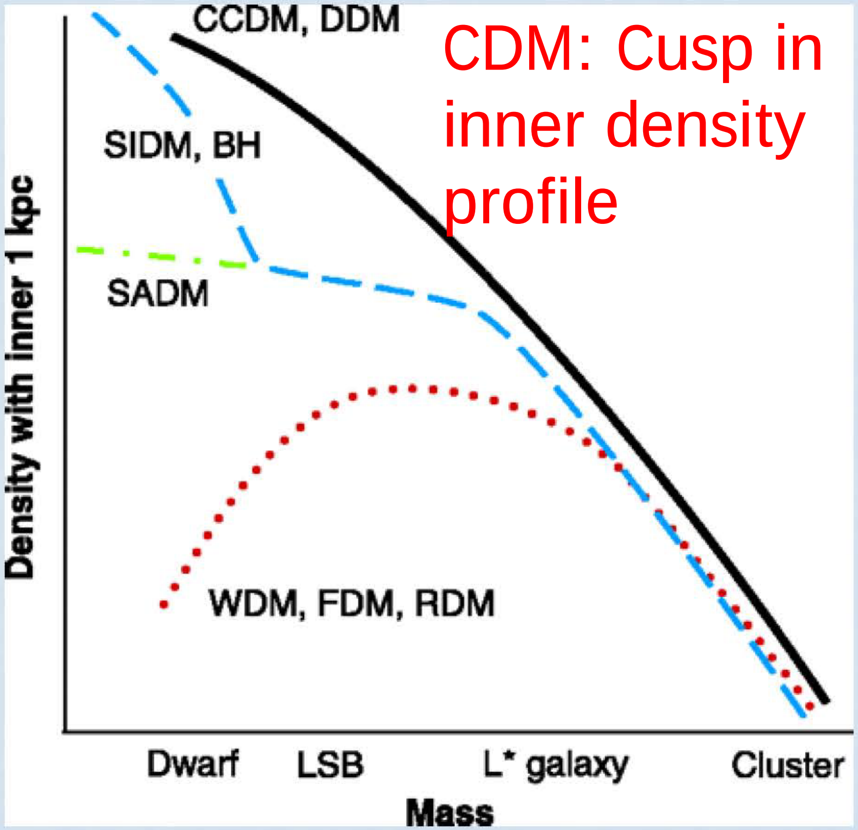
Small Scales Reveal Nature of Dark Matter

Ostriker & Steinhardt 2003



CDM: many small galaxies

Galaxy mass function depends on DM type



CDM: Cusp in inner density profile

Inner DM mass density depends on the type(s) of DM

What can we learn from (old) disk stars?

- Retain memory of initial/early conditions: elemental abundances, orbital angular momentum/integrals – modulo torques - kinematic and chemical phase space structure
- 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 history, timescales, gas accretion to (re-)form thin disk

➔ Bending 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 (old) disk stars?

- Retain memory of initial/early conditions: elemental abundances, orbital angular momentum/integrals – modulo torques - kinematic and chemical phase space structure
- 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

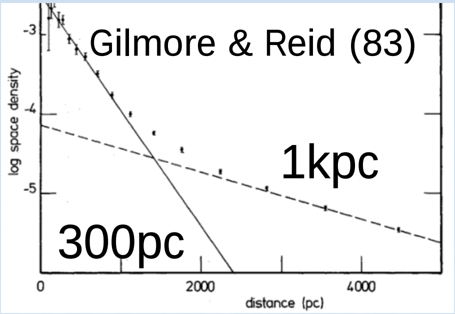
➔ Thin disk/thick disk: earliest phases of disk, heating history, timescales, gas accretion to (re-)form thin disk

➔ Bending 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

Local Milky Way Thick Disk

geometric definition, 1980s/90s



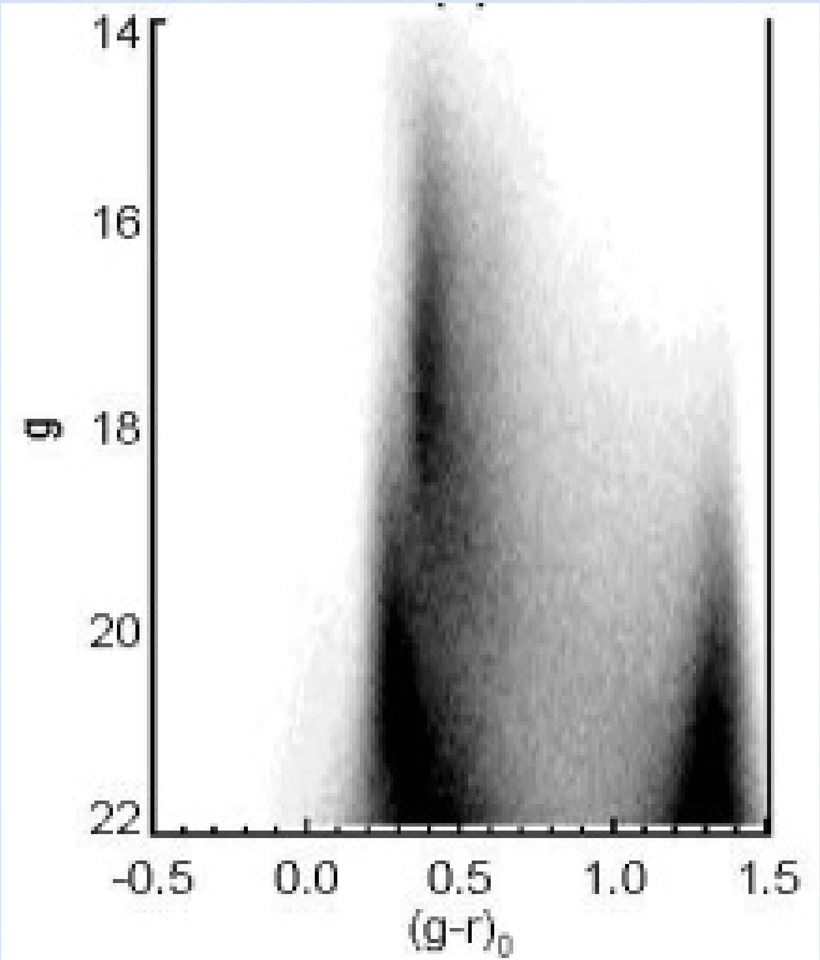
Gilmore & Reid (83)

- 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?
- Mean metallicity ~ -0.5 dex
- Elemental abundances ‘alpha-enhanced’ ([α /Fe] > 0)
- Most thick disk stars are old, ~ 10-12 Gyr → redshift > 2
  - strong constraint on merger history, disk heating (and radial mixing)
- Derived mass > 20% (50%?) of thin disk mass i.e. > 10^{10} $M_\odot$

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

Wide Field Star Counts: Old Ages

- Thick disc has well-defined main-sequence turn-off, $(g-r)_0 \sim 0.4$ no significant population bluer: dominant population is old, age ~ 10Gyr, metallicity ~ 1/3 solar



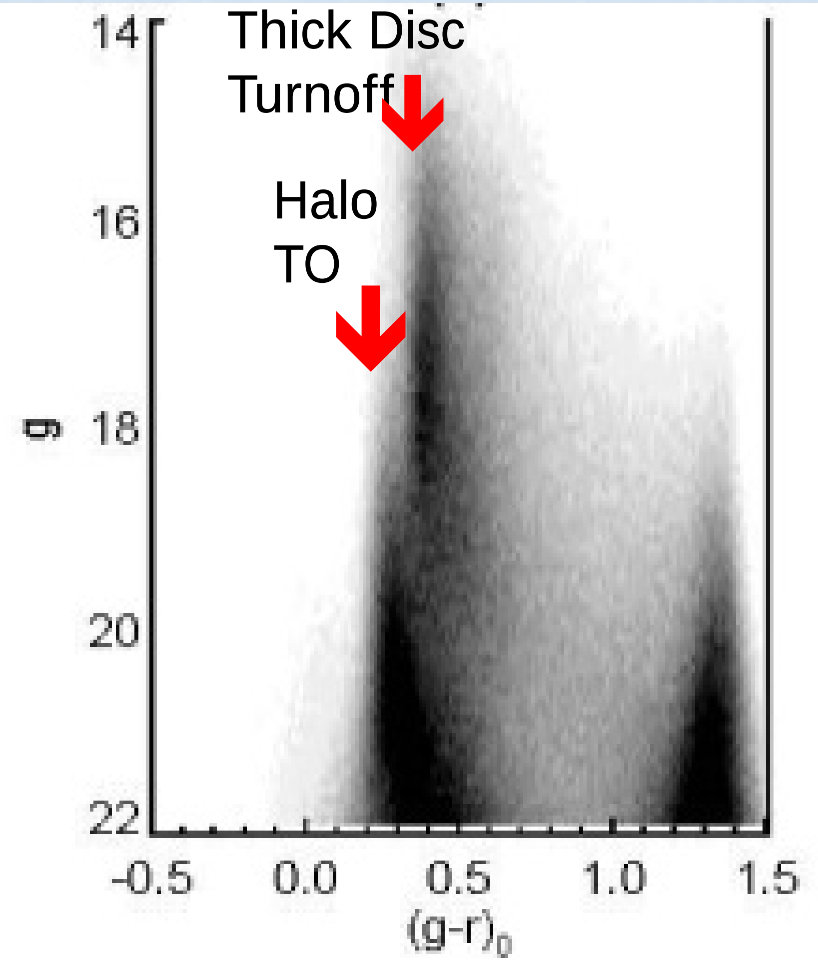
- Thick discs in external galaxies also consistent with old age, distinct from thin discs, and more metal-poor (e.g. Yoachim & Dalcanton 2008)

SDSS star counts, equatorial stripe, 32 x 2 degree fields, $|b| \sim 45^o \pm 15^o$, $\ell \sim 270^o \pm 30^o$

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

Wide Field Star Counts: Old Ages

- Thick disc has well-defined main-sequence turn-off, $(g-r)_0$ ~ 0.4 no significant population bluer: dominant population is old, age ~ 10Gyr, metallicity ~ 1/3 solar



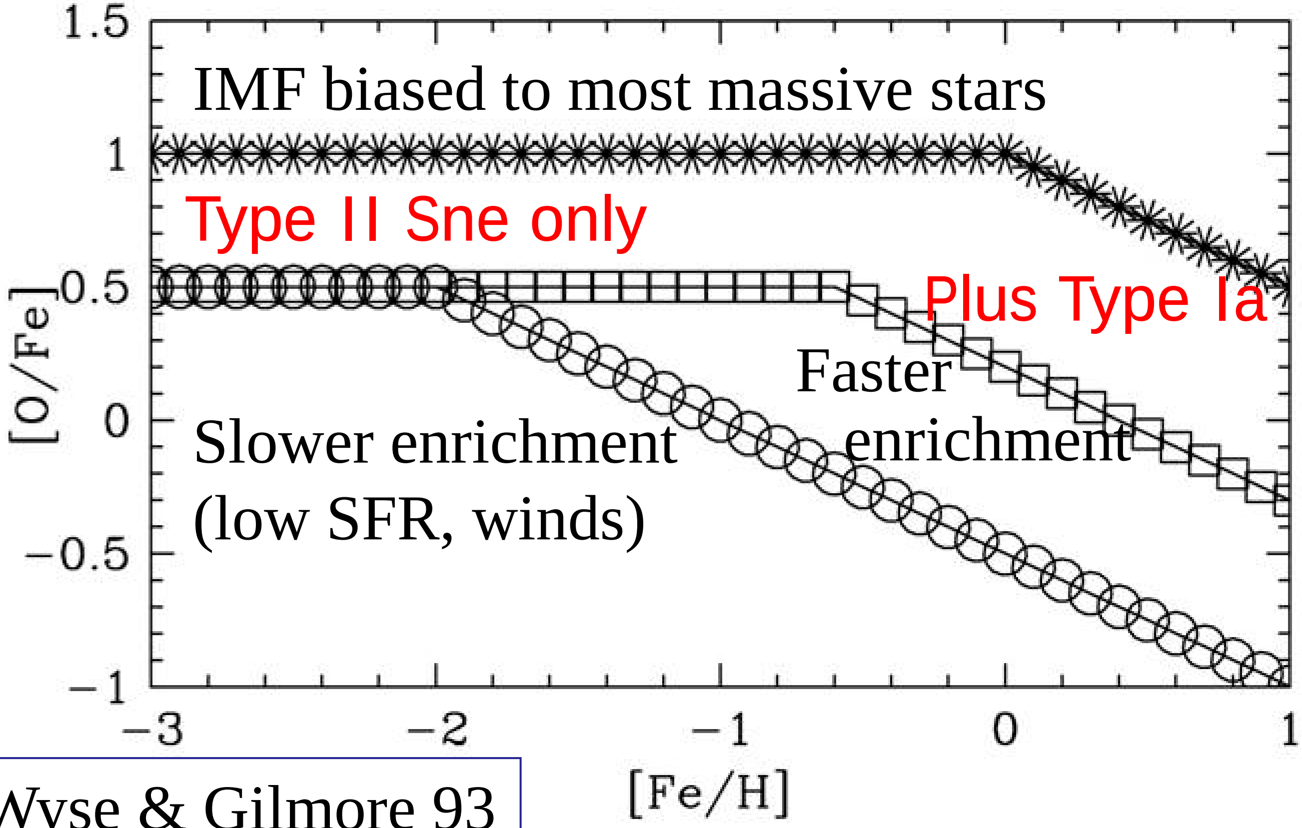
- Thick discs in external galaxies also consistent with old age, distinct from thin discs, and more metal-poor (e.g. Yoachim & Dalcanton 2008)

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 & RW 1987

Elemental Abundances: star formation history and enrichment history

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

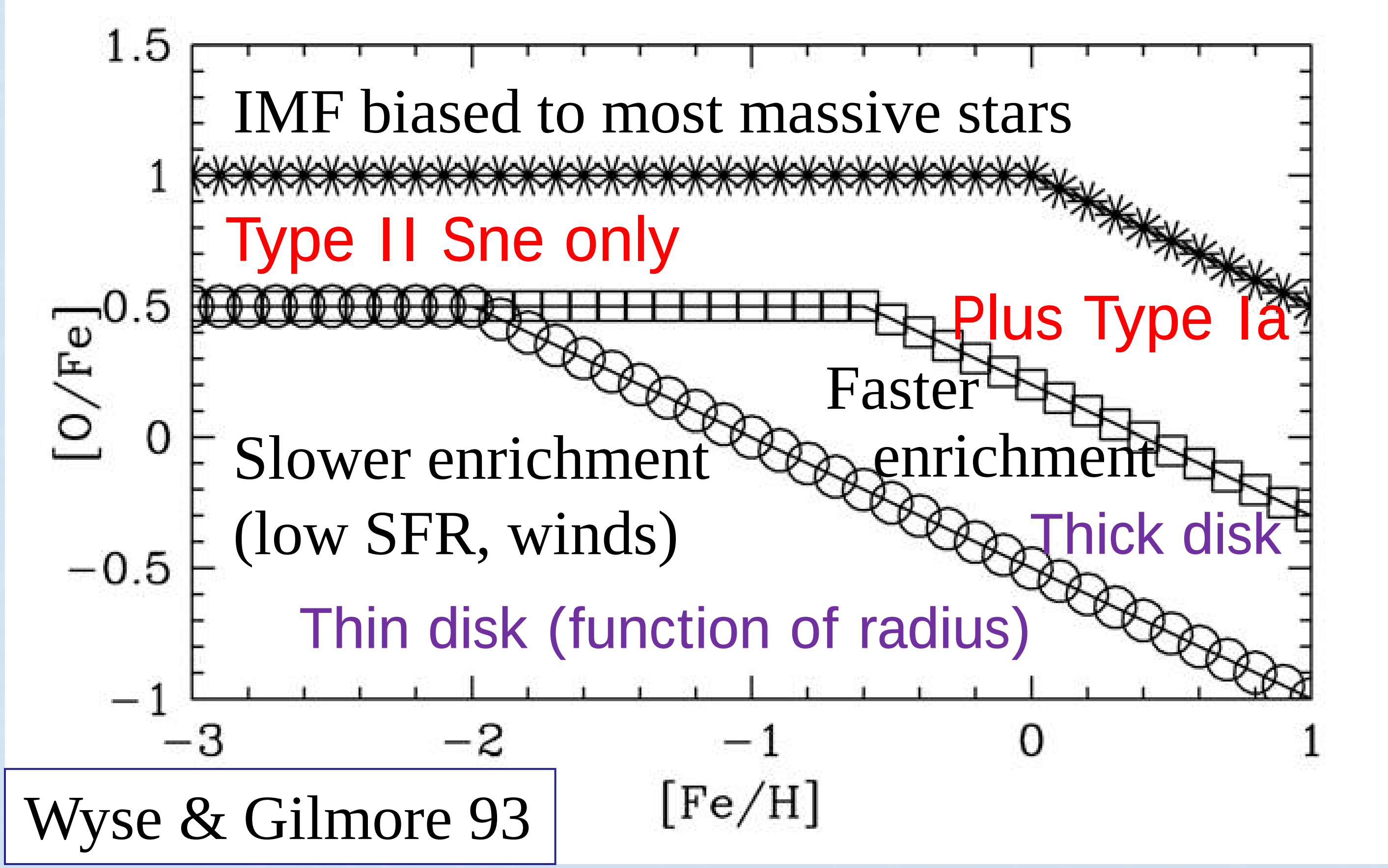


Wyse & Gilmore 93

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

Elemental Abundances: star formation history and enrichment history

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

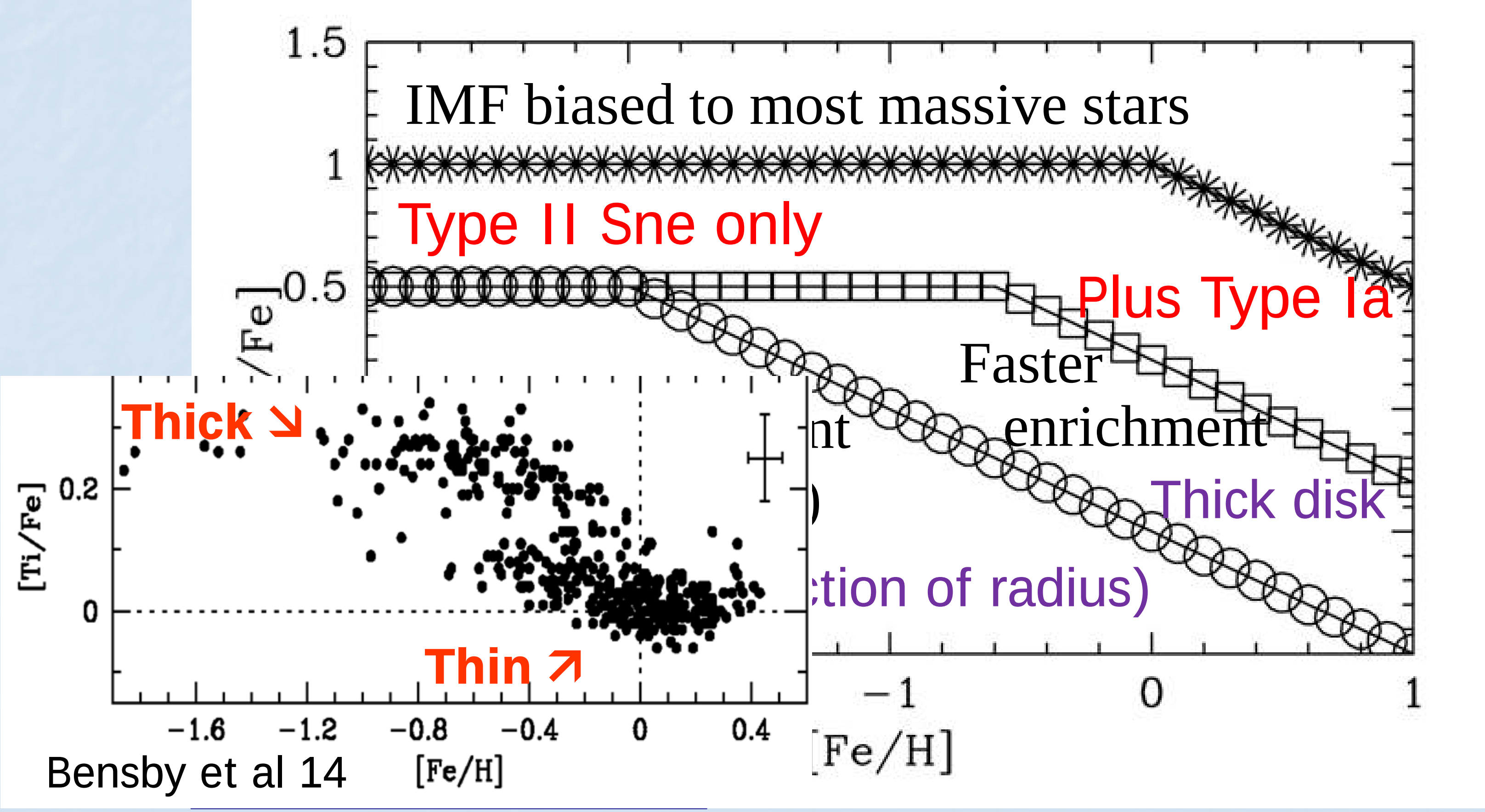


Wyse & Gilmore 93

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

Elemental Abundances: star formation history and enrichment history

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

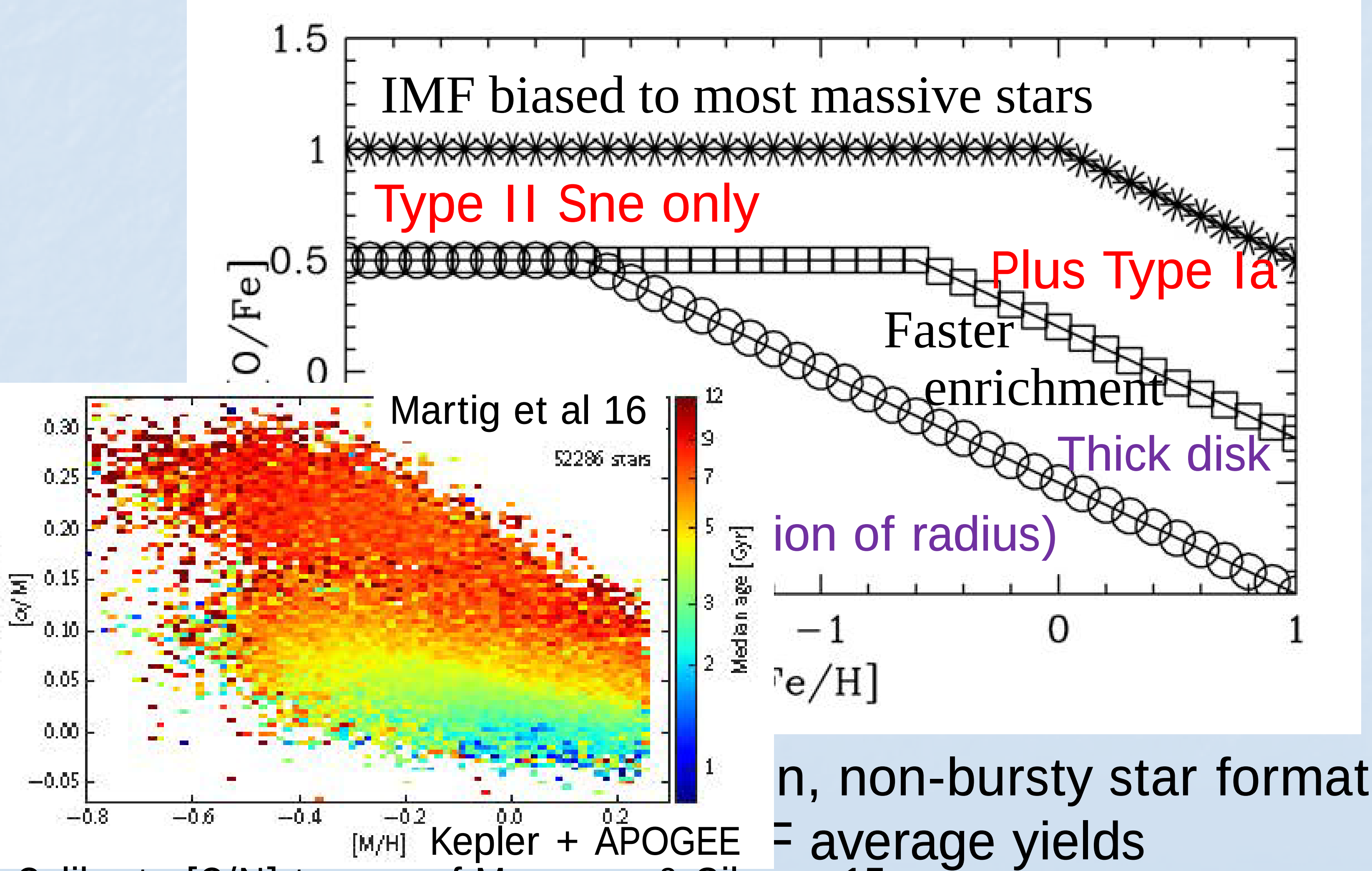


Bensby et al 14

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

Elemental Abundances: star formation history and enrichment history

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



IMF biased to most massive stars

Type II Sne only

Plus Type Ia

Faster enrichment

Thick disk

ion of radius)

Martig et al 16

Kepler + APOGEE

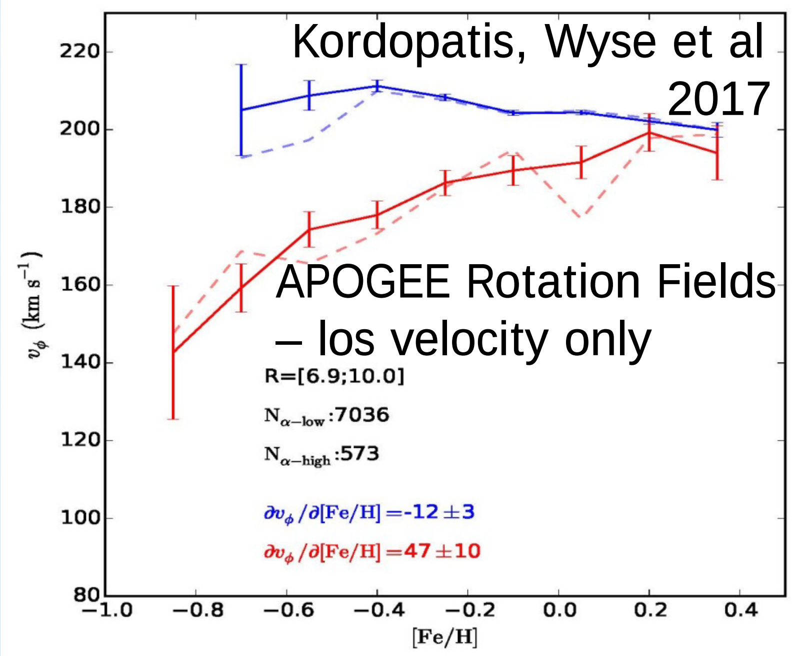
n, non-bursty star formation.

average yields

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

Chemically Defined Thick and Thin Disks

- Disk stars separated by elemental abundance patterns, obtained from high resolution spectra ➔ two sequences with distinct star-formation and enrichment histories
- Mean properties of chemically defined `high-alpha’ and ‘low-alpha’ disks compare well with those of geometrically defined disks
- **‘High-alpha’ sequence is old, has ‘hot’ kinematics: thick disk**
- **‘Low-alpha’ sequence is young to old, has ‘cold’ kinematics: thin disk**

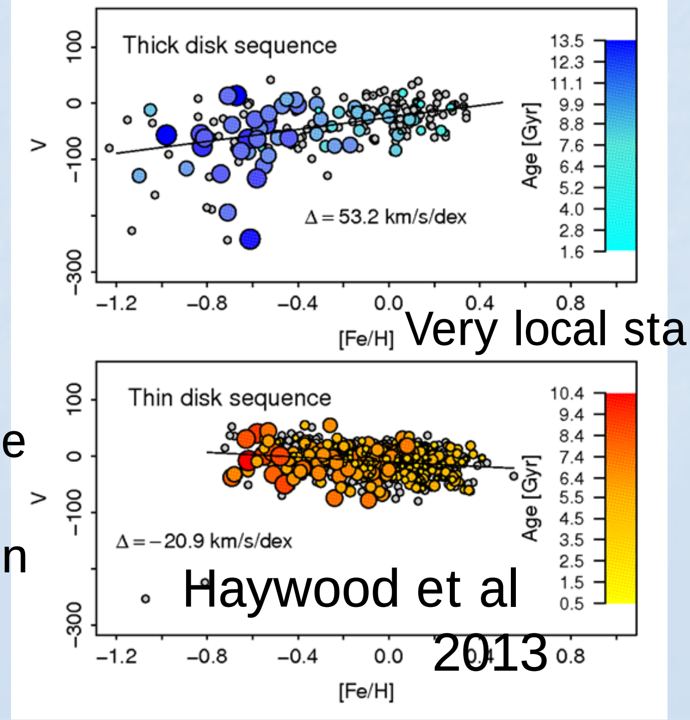


Kordopatis, Wyse et al 2017

APOGEE Rotation Fields – los velocity only

Merge at metal-rich ends, ambiguity

Very local sample has complex selection function (planets)

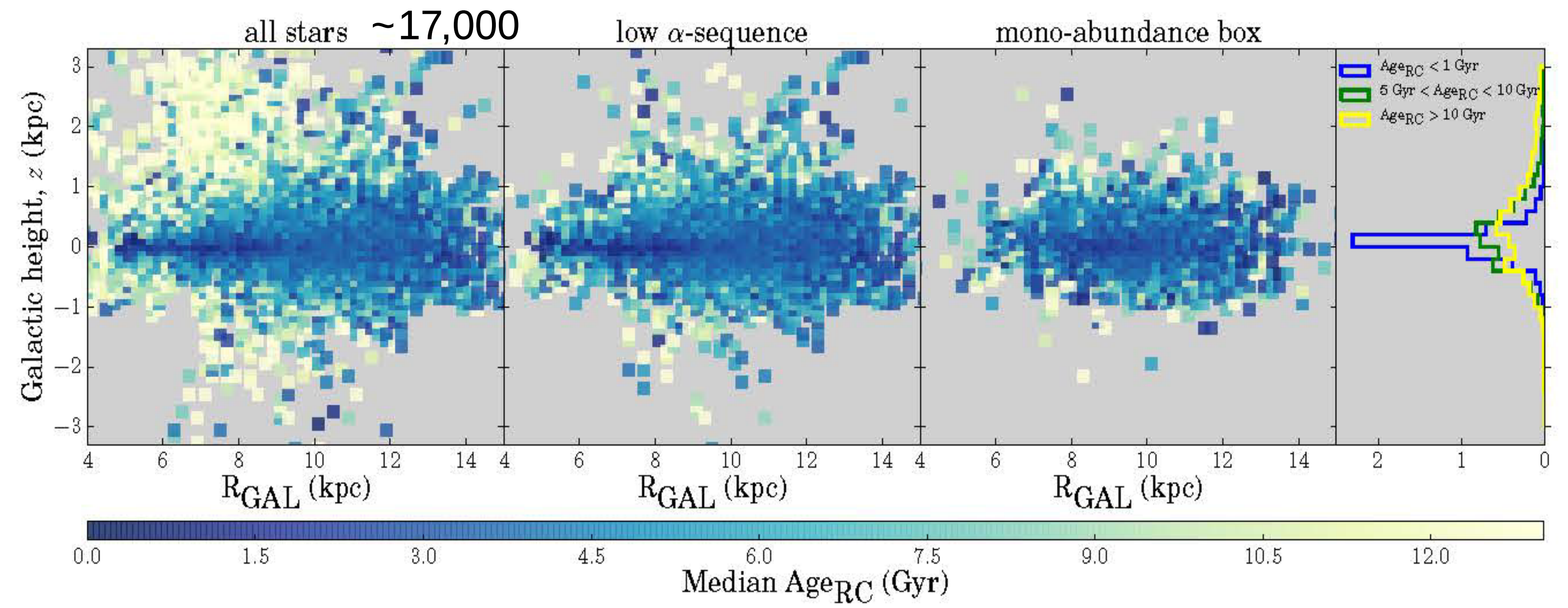


Very local stars

Haywood et al 2013

Ness et al 16

APOGEE data



- Upper sequence in elemental abundance plane (high-alpha) has spatial distribution of thick disk and is old, 10-12Gyr
- Lower sequence (low-alpha) in thin disk, contains stars of all ages, from very young, < 1Gyr, to old, 10-12Gyr
- Younger stars at higher heights in outer disk ➔ thin disk flaring
- Mono-abundance population (bin in [α /Fe], [Fe/H]) has a range of ages

Thick Disk probes Earliest Phase of Disk

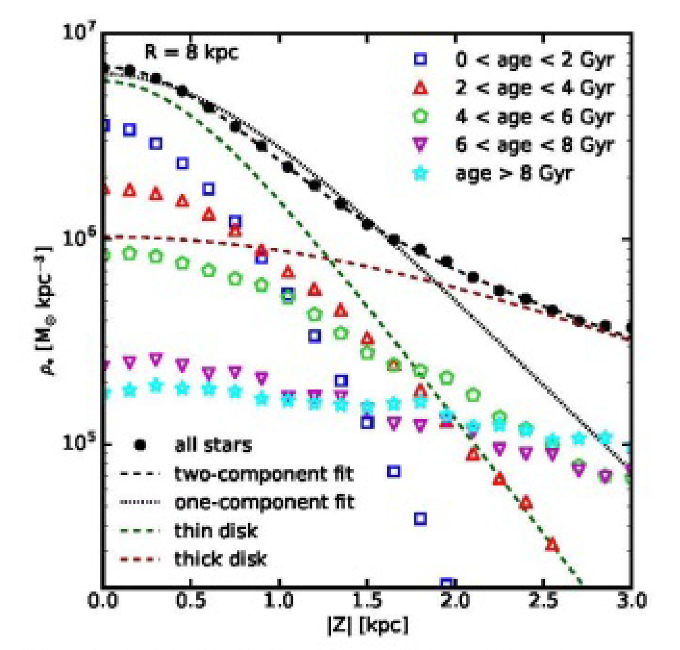
- Thick disk stars are old, formed at lookback time of ~10-12Gyr or redshift > 2: epoch of peak cosmic star formation
- High velocity dispersion, short timescale of star formation implies (likely) formed prior to equilibrium/virialization of halo ➔ while active assembly/mergers, turbulent gas (cf Jones & Wyse 1983, Gilmore 1984; Brook et al 2002, Wetzel et al 2016)
- 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 **gas** disk – how does it evolve? ➔ settling into equilibrium?
- Use thick and thin stellar disks in local universe as guide

Old Age of Thick Disk Stars Limits Merger History

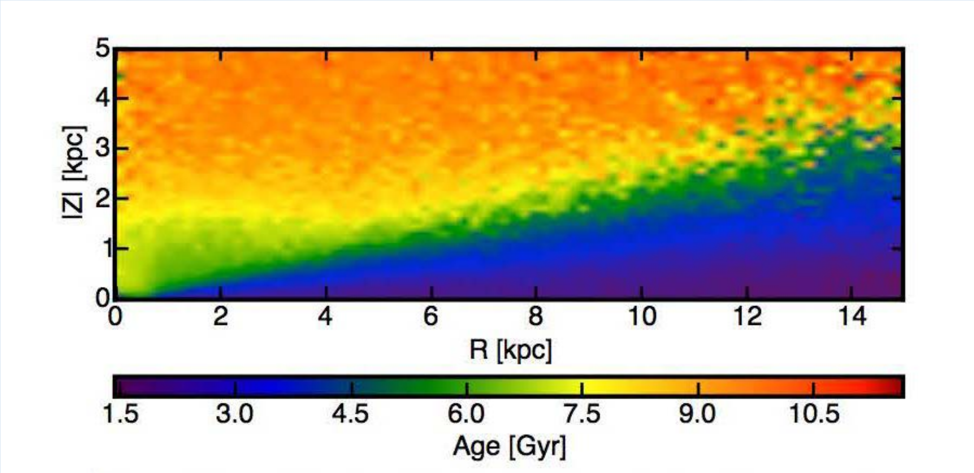
- Mergers heat the thin disk and input stars formed up to that epoch into the thick disk (and perhaps halo)
- There are stars of all ages in the thin disk, reflecting continuous star formation since early times
- Dominant old age of thick disk stars implies no significant merger since redshift at which look-back time equals age of thick disk stars
  - ➔Quiescent merger history since redshift $\gtrsim 2$ (Wyse 2001)
  - Quiet merger history consistent with no significant dark or stellar accreted disk (e.g. Ruchti et al 2015) and with inferred mild rotation and steep density profile of stellar halo (Deason et al 2017, 2014)
- Minor mergers/interactions e.g. Sagittarius dwarf affect outer thin disk (flare, warp..)

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

Thick and thin disks in typical ΛCDM Milky Way analogue disk galaxy

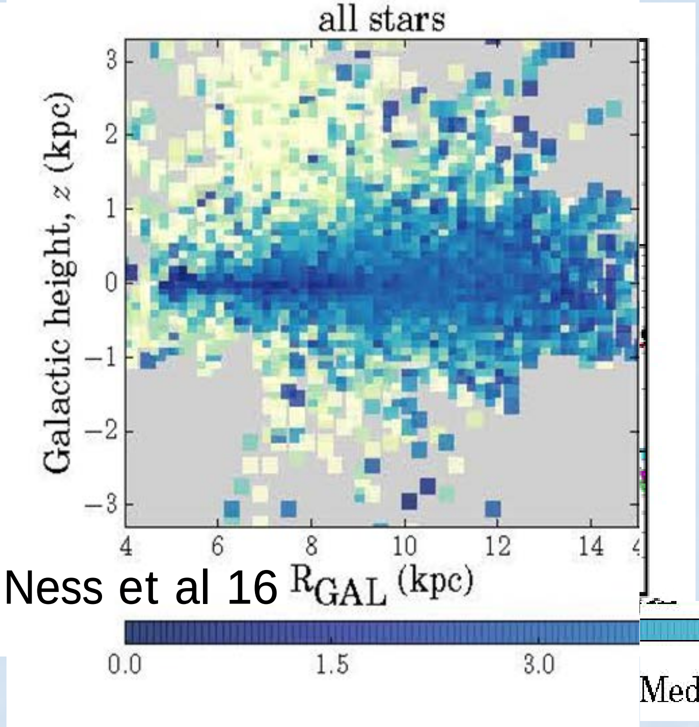


Ma et al 2017



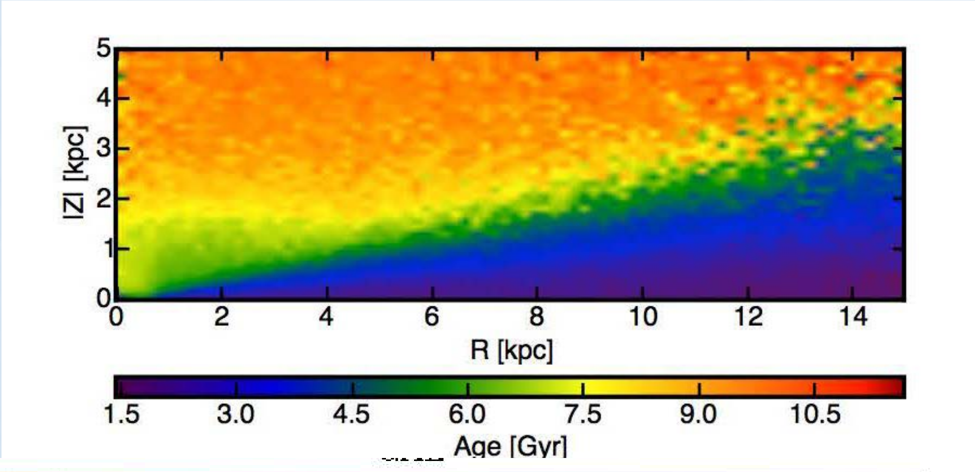
- Last significant merger at z ~ 0.7, lookback time 6 Gyr ➔ thick disk at solar circle equivalent contains stars of ages down to < 6Gyr
- Milky Way thick disk significantly older, 10-12Gyr ➔ last merger at higher redshift, $z \gtrsim 2$, significantly more quiescent merger history than typical in ΛCDM

Thick and thin disks in typical ΛCDM Milky Way analogue disk galaxy



Ness et al 16

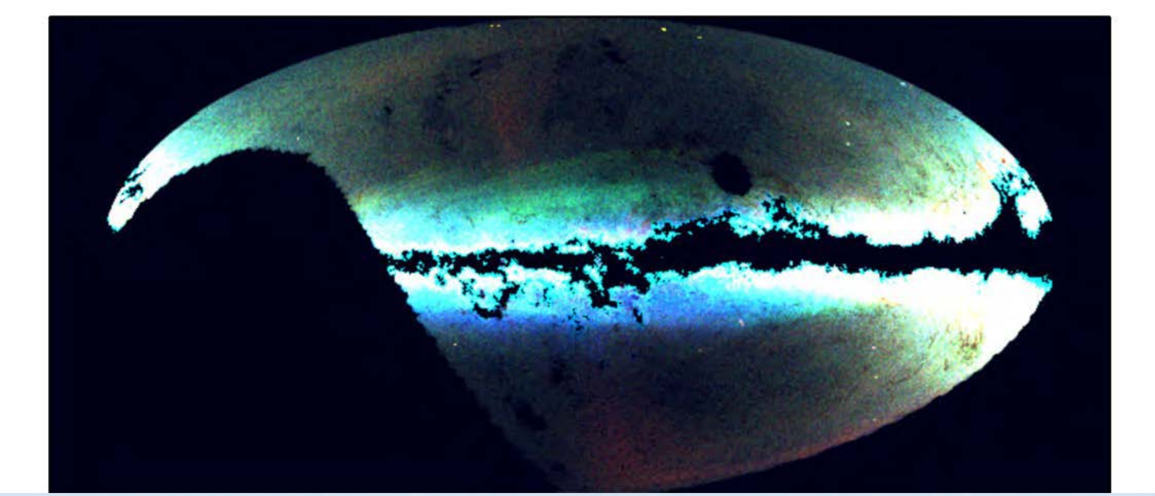
Ma et al 2017

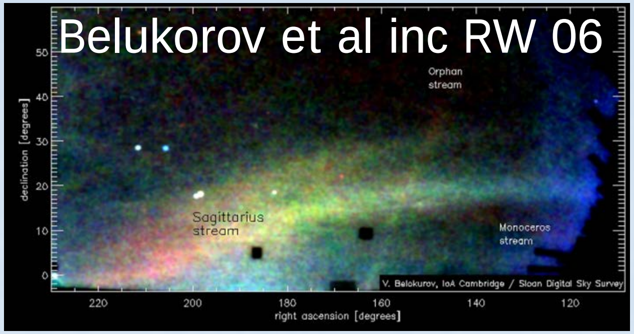


- Last significant merger at z ~ 0.7, lookback time 6 Gyr ➔ thick disk at solar circle equivalent contains stars of ages down to < 6Gyr
- Milky Way thick disk significantly older, 10-12Gyr ➔ last merger at higher redshift, $z \gtrsim 2$, significantly more quiescent merger history than typical in ΛCDM
- Note younger stars in outer disk at large heights, as observed: flaring due to lower restoring force from disk self-gravity, plus...

Outer Disk with Pan-STARRS

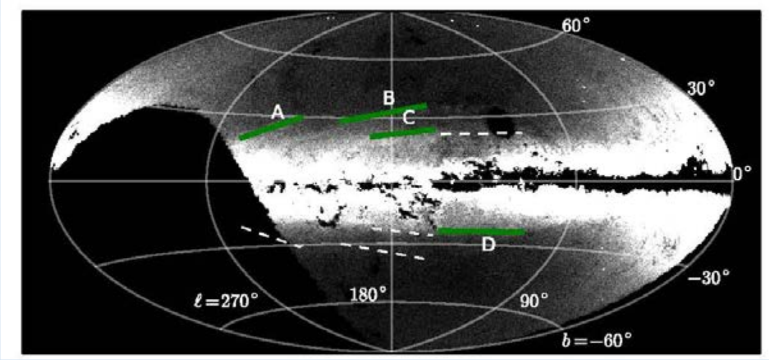
Low-latitude ‘field of streams’



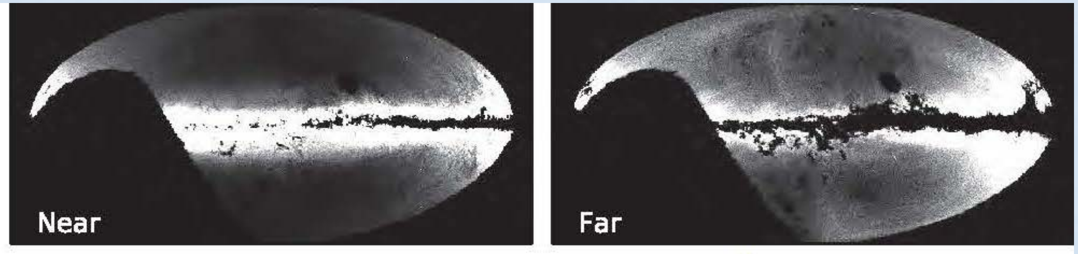

Belukorov et al inc RW 06

Slater et al (inc RW) 14

Complex structure!



7.5-11 kpc ‘Monoceros Ring’
Complex Structure
Sharp Features



5-6.5 kpc

14.5-17.5 kpc
Sgr Stream

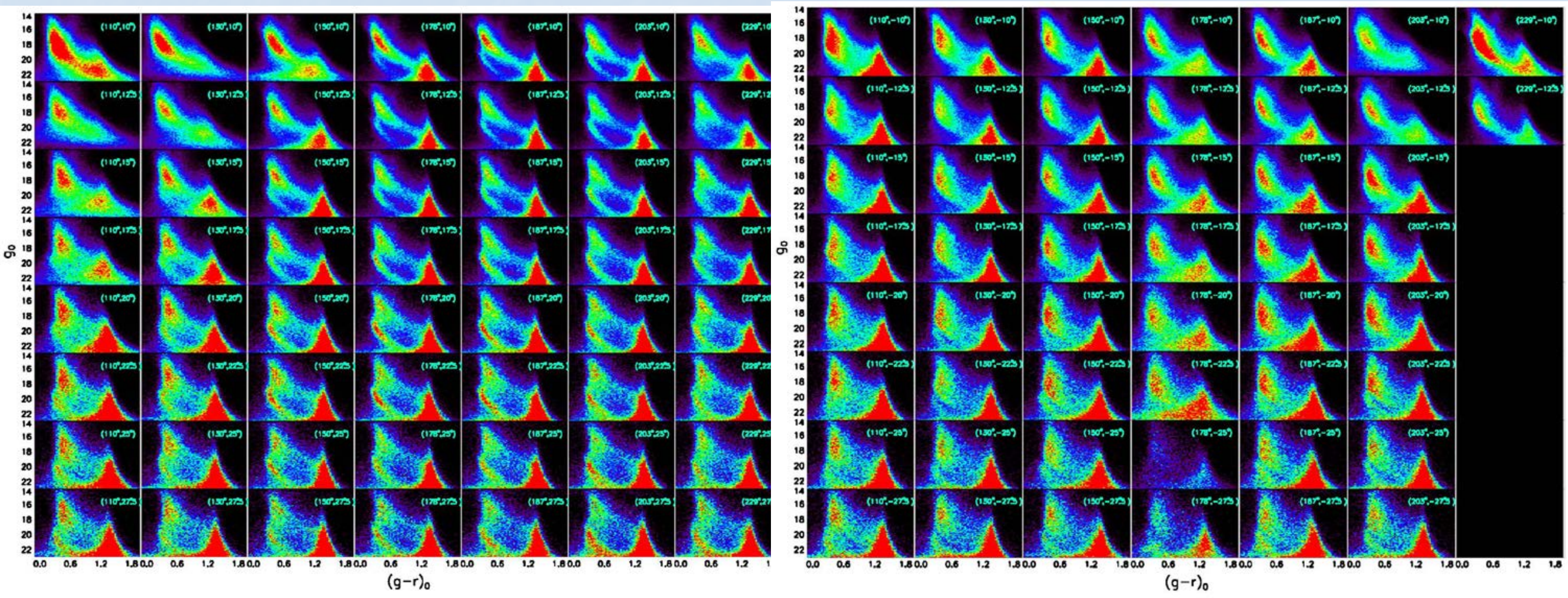
MSTO stars, $0.2 < (g-r)_0 < 0.3$

See also Bernard et al 2016, PS1 halo substructure

Outer Disk with SDSS

Hess Diagrams $(g\text{–}r)_0$ vs g_0

Xu, Newberg et al 2015



North (left) and South (right) of the Galactic Plane

- Main point: systematic differences between north and south

2.5° x 2.5° bins in (*ℓ*,*b*), Col: constant *ℓ*; Row: constant *b*

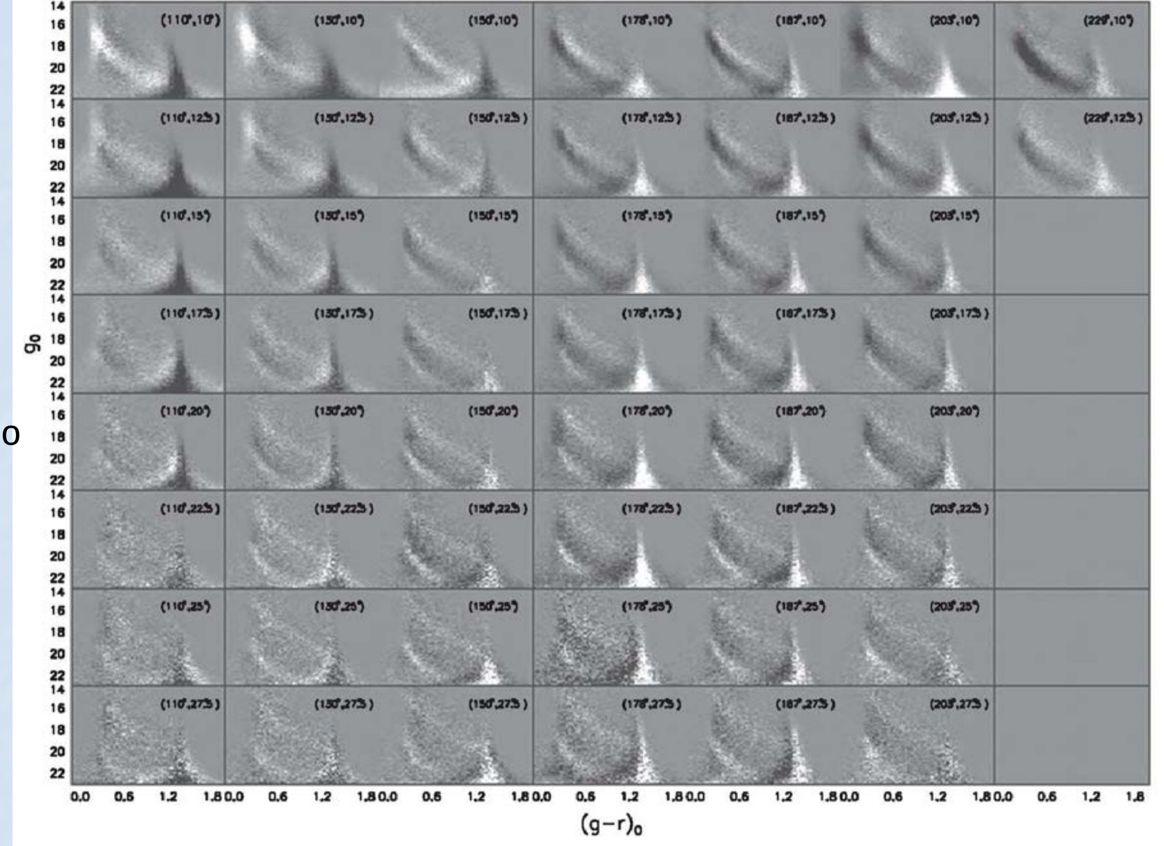
Anti-centre fields: 110° < *ℓ* < 229°, 10° < |*b*| < 30°

Residuals from North – South of the Galactic Plane

Xu, Newberg et al 2015

$\ell = 178^{o}$

$|b| = 20^{o}$



Anti-centre fields

2.5^{o} x 2.5^{o} bins in $(\ell, |b|)$

Col: fixed ℓ

Row: fixed $|b|$

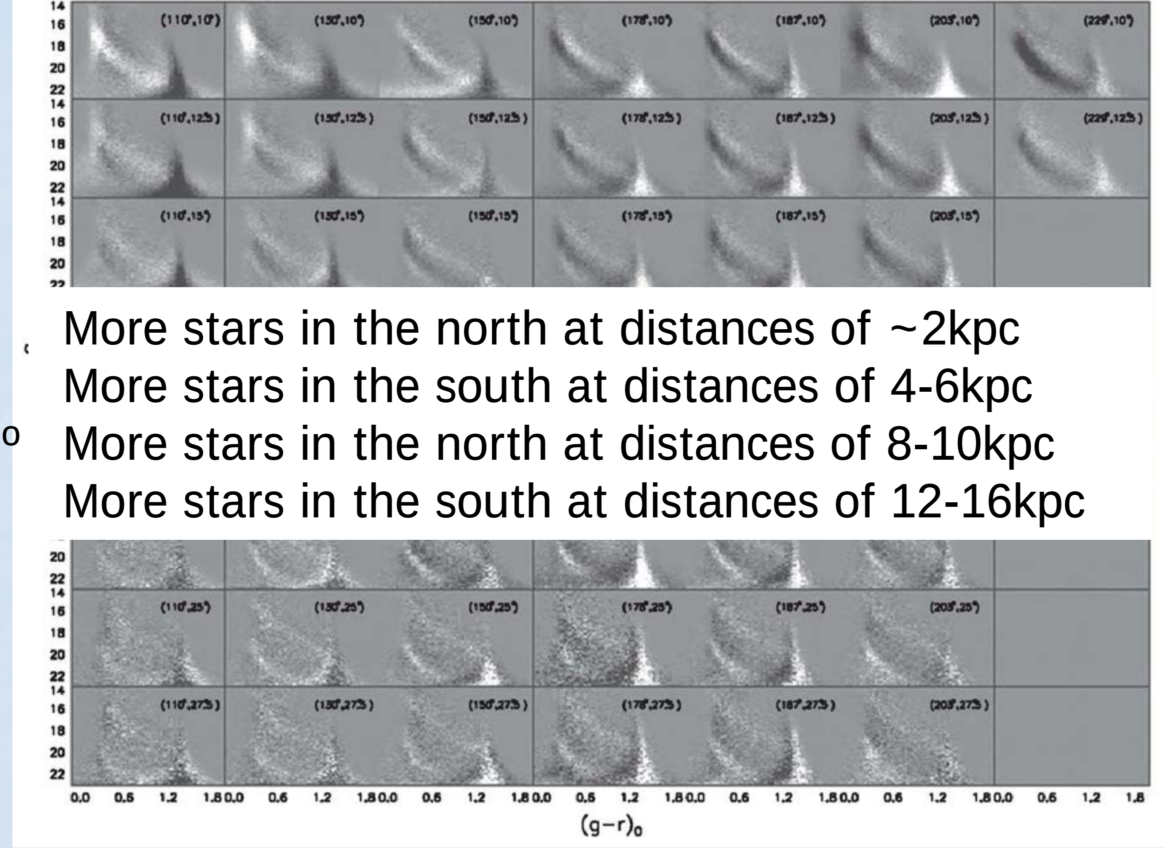
➔Main sequence stars show alternating white/black stripes as a function of apparent magnitude (distance), factor of $\lesssim 2$ variations : Rings? Coherent vertical oscillations in disk?

➔Need good distances (cf. Schönrich and Aumer 2017)

Residuals from North – South of the Galactic Plane

Xu, Newberg et al 2015

$\ell = 178^o$



More stars in the north at distances of ~2kpc
More stars in the south at distances of 4-6kpc
More stars in the north at distances of 8-10kpc
More stars in the south at distances of 12-16kpc

$|b| = 20^o$

Anti-centre fields

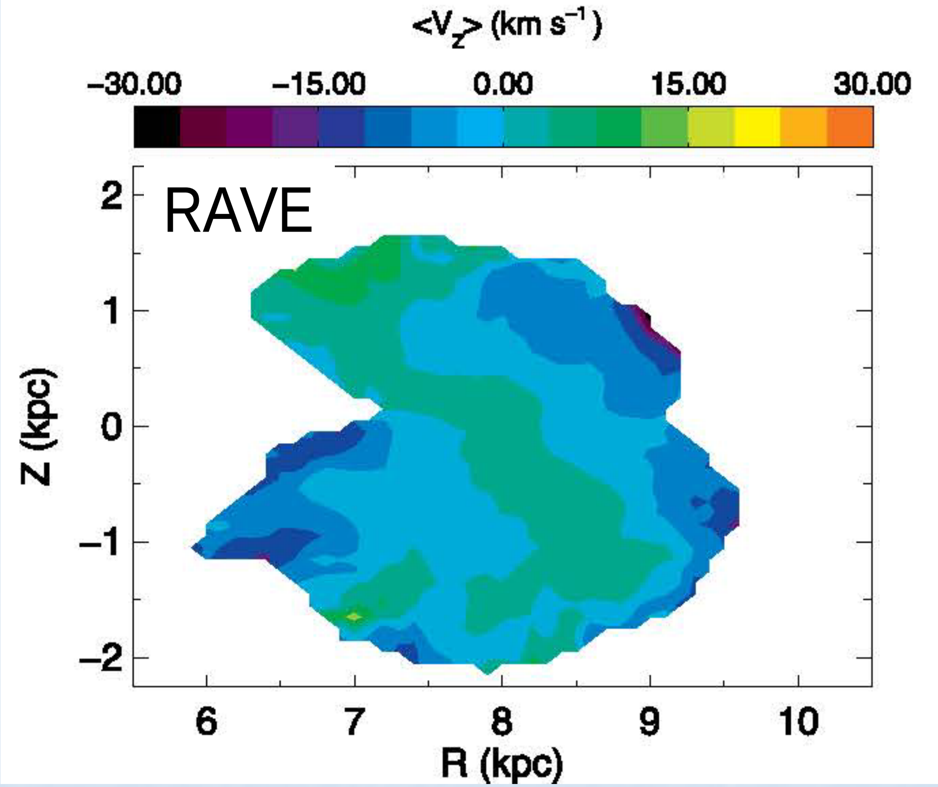
$2.5^o \times 2.5^o$ bins in $(\ell, |b|)$

Col: fixed ℓ

Row: fixed $|b|$

- ➔ main sequence stars show alternating white/black stripes as a function of apparent magnitude (distance), factor of $\lesssim 2$ variations : Rings or coherent vertical oscillations in disk
- ➔ 'Monoceros Ring' one of several oscillatory overdensities in thin disk – not debris from an accreted satellite

Oscillatory kinematics



Systematic variations – asymmetries and oscillatory patterns - in mean vertical motions seen in three large spectroscopic surveys:
SDSS/SEGUE (Widrow et al 2012),
RAVE (Williams et al, inc RW, 2013)
and LAMOST (Carlin et al 2014)

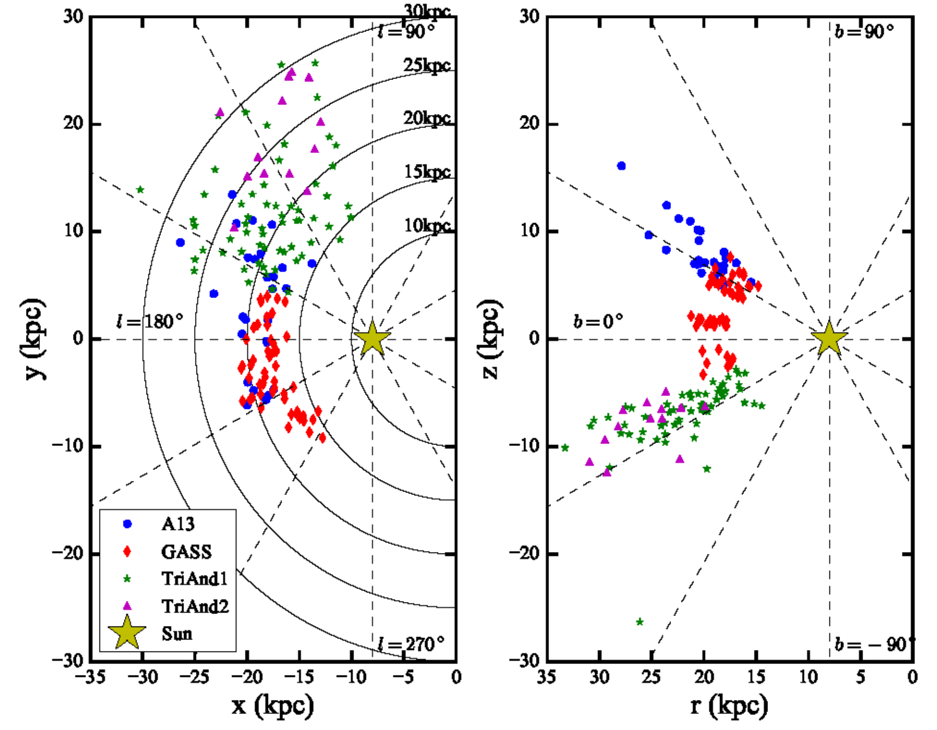
- Breathing/bending modes of perturbed thin disk (Widrow et al 2012) – stars have disk metallicities
- Due to bar/spirals (Debattista 14) and/or due to satellite (Sgr? Gomez et al 13; Widrow et al 14; D'Onghia et al 2016) - but overdensities are not necessarily tidal debris from satellites
- Perturbations can also move stars within thin disk – radial migration

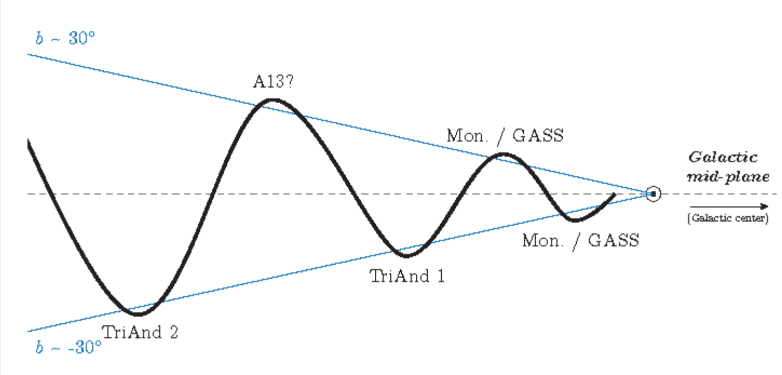
Internal, Secular Evolution to Re-arrange Disks?

- **Radial migration** (Sellwood & Binney 2002) can move stars of order the disk scale-length during lifetime of disk, without associated kinematic heating (maintaining orbital circularity): acts for stars captured at co-rotation resonance of transient spiral pattern
  - More effective for stars on closer-to-circular orbits, less so for populations of higher velocity dispersion/lower angular momentum orbits (e.g. Solway et al 2012; Vera-Circo et al 2014, Daniel & Wyse 2015, 2017)
  - Efficiency depends on parameters of spiral pattern – amplitude, duty cycle, wave number, number of arms etc
  - Brings super-solar stars to local thin disk, from inner disk (e.g. Kordopatis et al inc RW 2015) ➔ structure in low-alpha sequence?
    - Could play major role (cf Schönrich and Binney 2009) – did it?

Halo, disk...?

- Some `halo’ substructure also may be disturbed disk





Li et al 2017

- Disk stars can be scattered/heated into halo
  - High-velocity metal-rich stars (Hawkins et al inc RW 2015)
  - Mergers can build up inner halo and bulge from disk (e.g. Pillepich et al 2015) – outer halo from tidal debris

Concluding remarks

- “More data are needed”: Positions, distances, space motions, ages, chemical abundances all critical to characterise the present stellar populations of the Galaxy and to understand the roles of different physical processes in its evolution
- Need to be clear to what we refer when using terms halo/bulge/thin disk/thick disk
    - entity defined through different parameters may have different history
- Even if clear separation in the mean properties of different components, overlapping multivariate distribution functions require large samples, with well defined selection functions and well-understood uncertainties and biases
    - Uniform analysis techniques for elemental abundances (NLTE!)
- Exciting times ahead: wonderful observational data for stars plus improved simulations of galaxy formation in cosmological context(s) plus high-redshift data