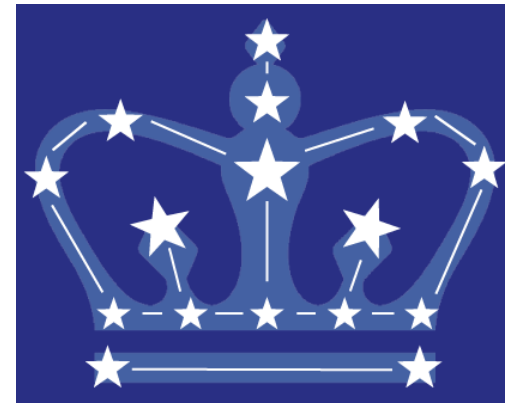


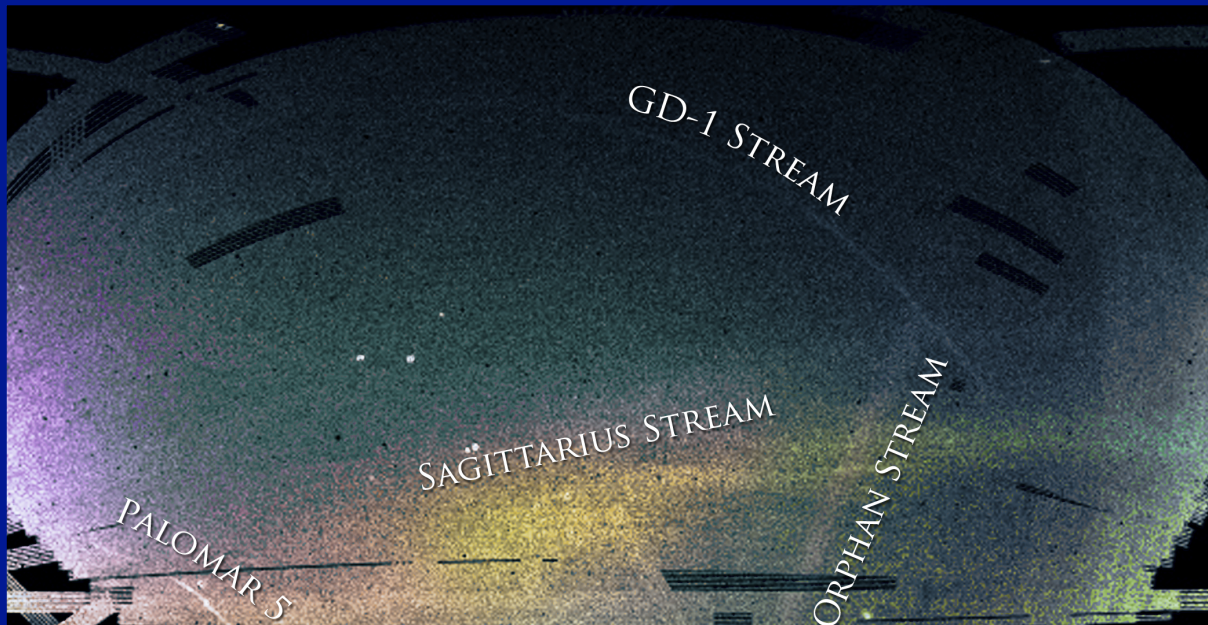
The Dark and Stellar Halo:

Formation; History; Structure

Kathryn V Johnston



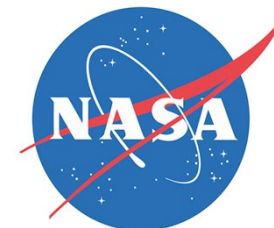
Columbia University



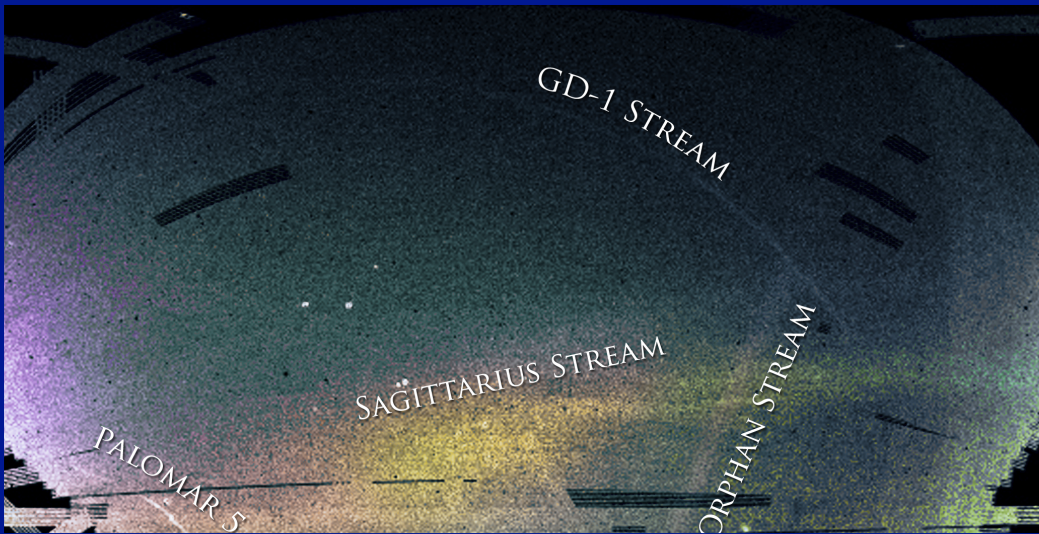
*The Milky Way
stellar halo from
SDSS data
visualized by
Bonaca,
Giguere, Geha*



Supported by the
National Science Foundation and NASA



*The Milky Way stellar halo
from SDSS data
visualized by Bonaca,
Giguere, Geha*



➔ 3-D structure of a dark matter halo

Johnston, Zhao, Spergel Hernquist (1999), Ibata et al (2001) Koposov et al (2009), Vergase & Ibata (2010), Price-Whelan & Johnston (2013), Sanders & Binney (2014), Bovy (2014), Kuepper et al (2015), Bovy (2016)

➔ finding dark matter substructures

Ibata et al (2002), Johnston, Spergel & Haydn (2002), Yoon, Johnston & Hogg (2001), Carlberg (2012), Bovy (2016), Erkal, Koposov & Belokurov (2016)

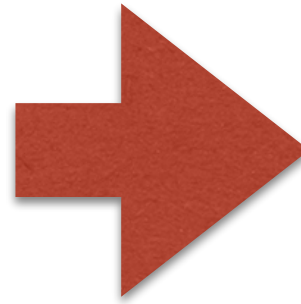
➔ accreted populations: surviving, dead and dying

Bullock & Johnston (2005), Molotov et al (2009), Cooper et al (2010), Font et al 2011), Tissera et al (2013), Pillepich et al (2015), Lee et al (2013)

Formation? History? Structure?

**kicking
the disk
to make
the halo**

physical
manifestations
of
chaos and regularity



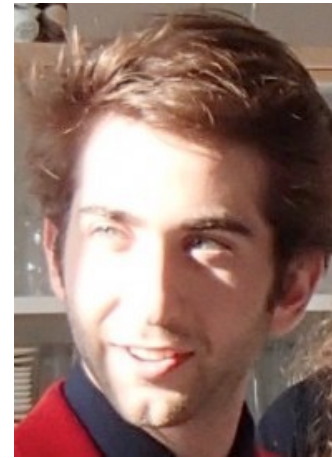
structure
of our
**dark
matter
halo**



Adrian
Price-Whelan



Sarah Pearson



Chervin Laporte



David Hendel



Andreas Kuepper

The Columbia
StreamTeam
(past and present)



Robyn Sanderson



Duane Lee



Sanjib Sharma



Allyson Sheffield



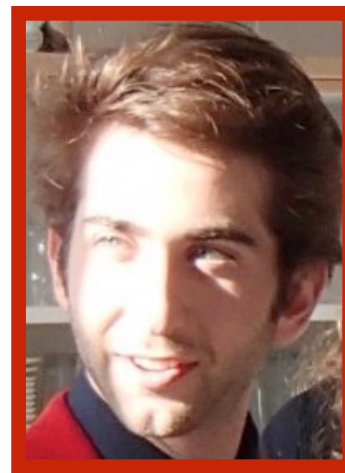
Maureen Teyssi r



Adrian
Price-Whelan



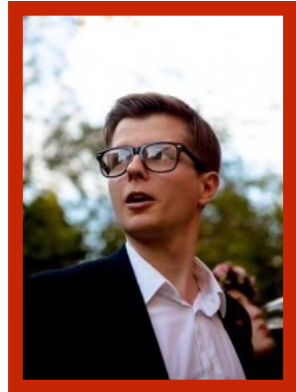
Sarah Pearson



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Allyson Sheffield



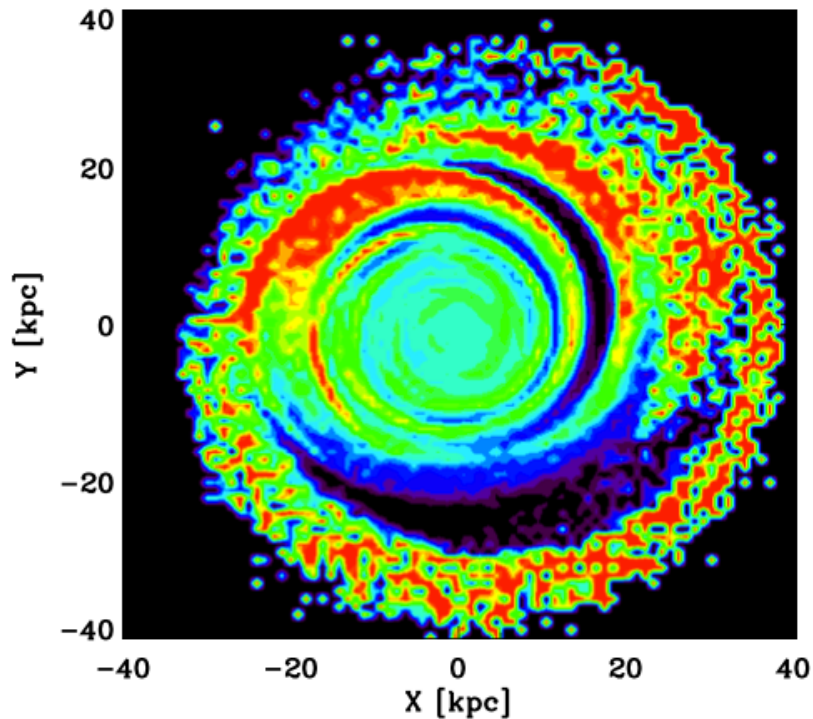
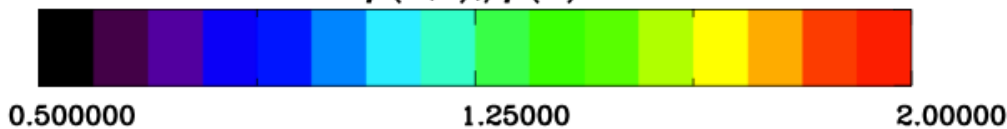
Maureen Teyssièr⁵

Kicking the Disk

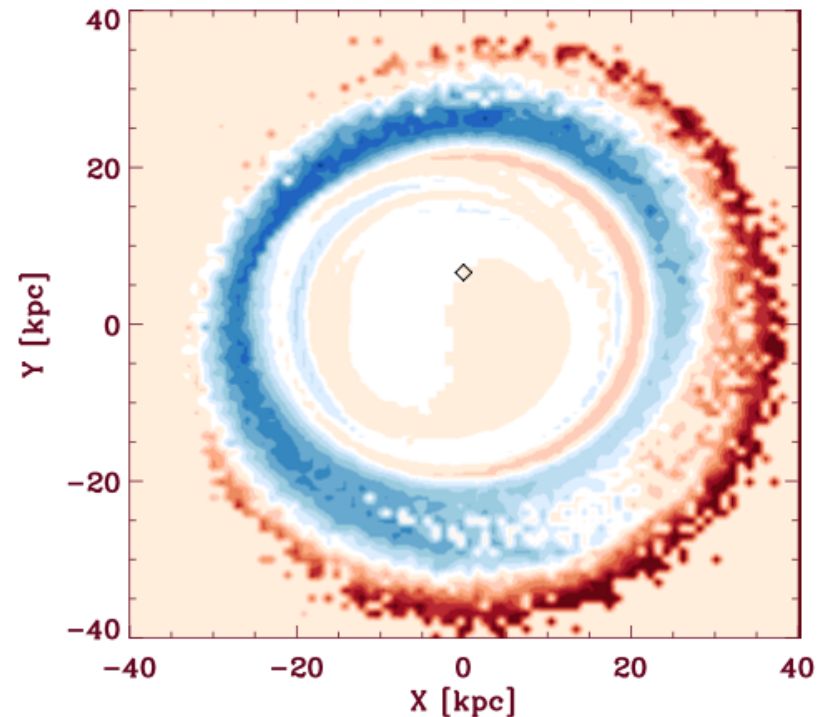
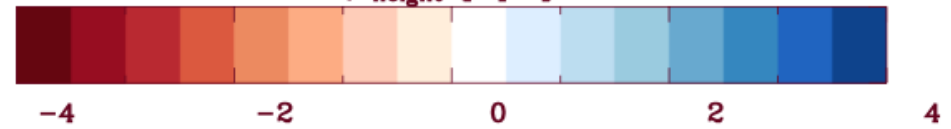
Models of satellite/disk interactions

Laporte, Gomez, Besla, Johnston & Garavito-Camarago, 2016

$\rho(R,\theta)/\rho(R)$



μ_{height} [kpc]

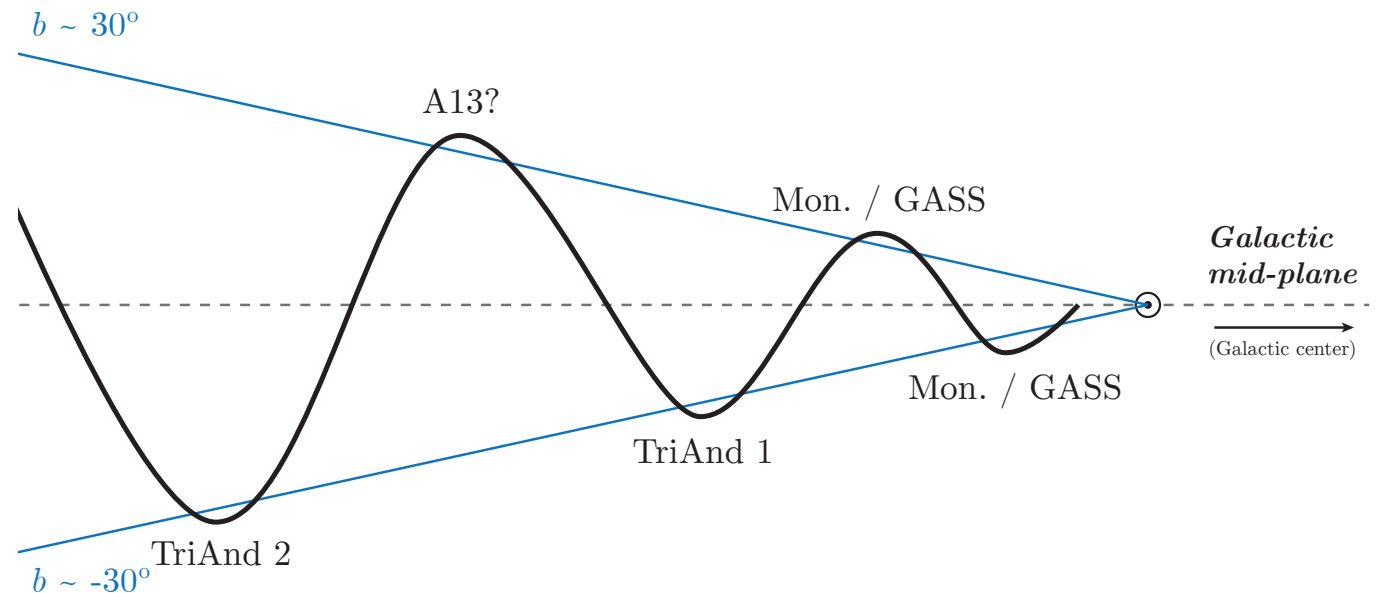


??? the MW disk response ???

Unified model:

Xu et al (2015)

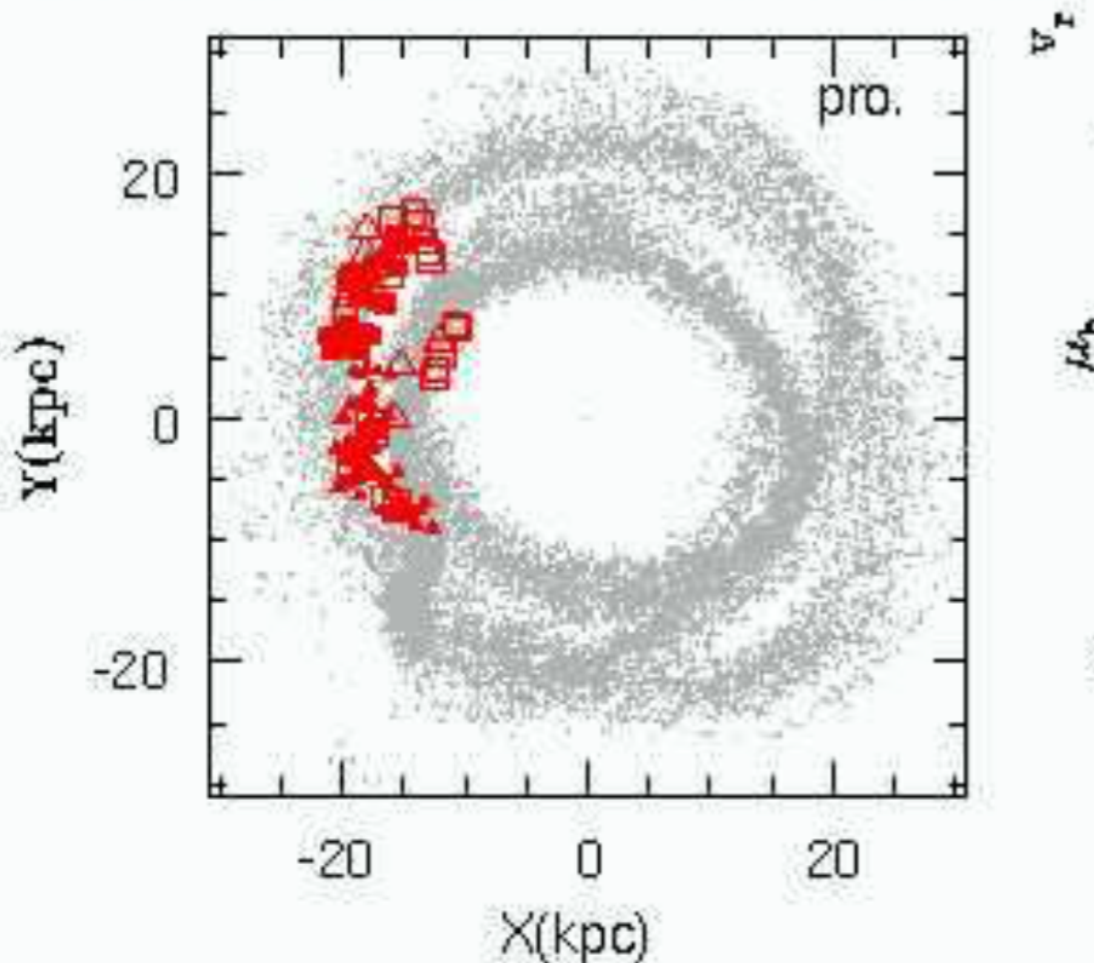
Price-Whelan,
Johnston, Sheffield,
Laporte and Sesar
(2015)



- *GASS/the Monoceros Ring*: SDSS: Newberg et al, 2002, Ibata et al 2003; 2MASS: Rocha-Pinto et al. 2003
- *The Triangulum-Andromeda Clouds and A13*: 2MASS: Rocha-Pinto et al, 2004; Martin et al 2007; 2MASS: Sharma, Johnston et al, 2010
- *Asymmetries in local v_z distribution* : SDSS/SEGUE: Widrow et al, 2012; RAVE: Williams et al, 2013

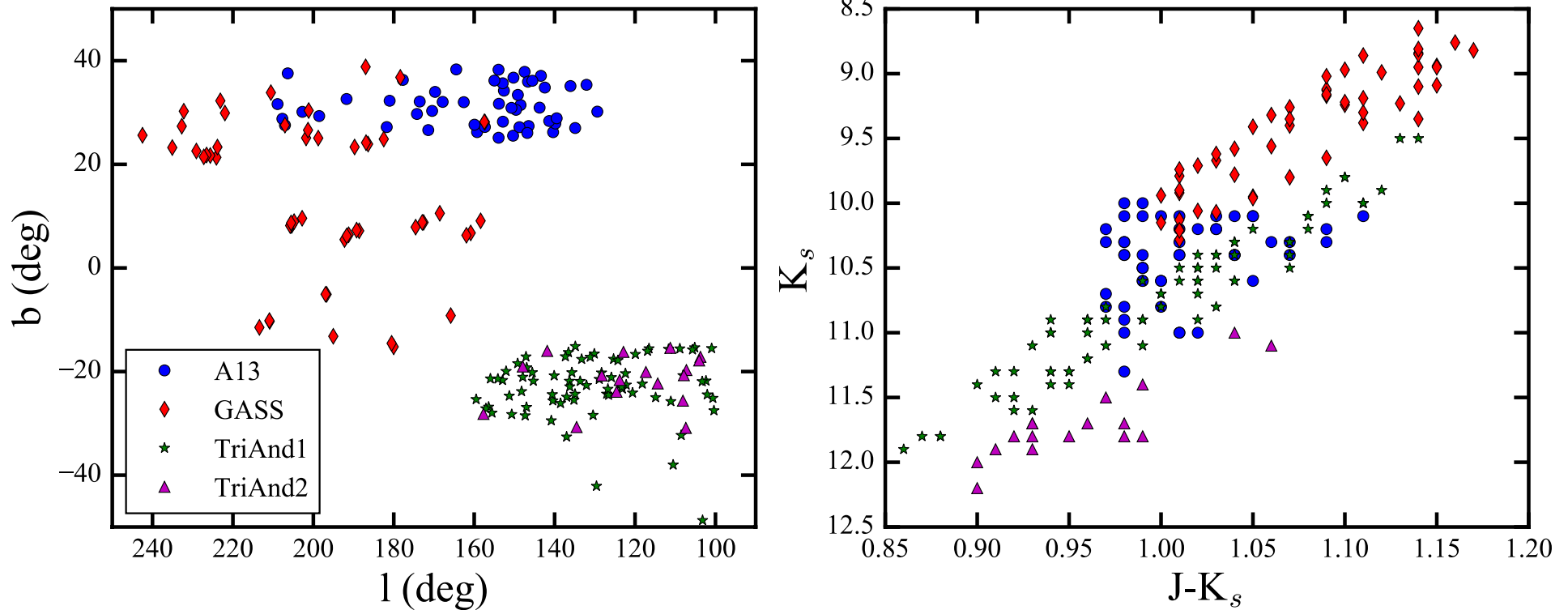
??? or satellite debris ???

□ Newberg et al. (2003) ■ Rocha-Pinto et al.
△ Ibata et al. (2003) ▲ Crane et al (2003)



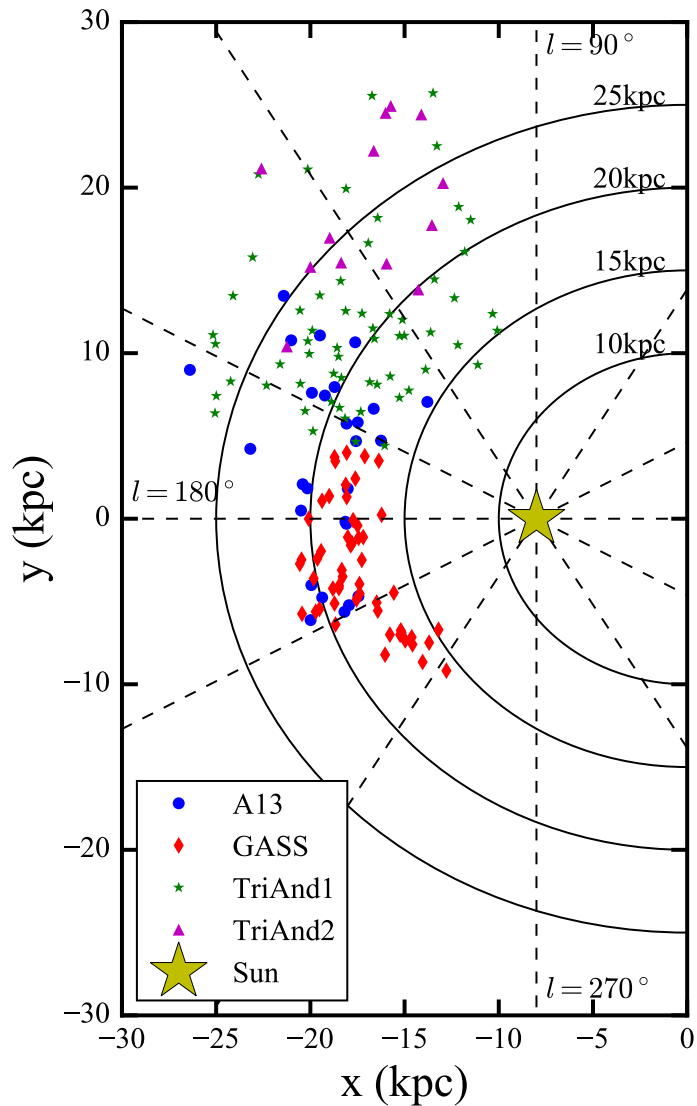
Penarrubia et al (2005)
Chou et al (2010, 2011)
Sheffield, Johnston et al (2013)

GASS/Mon+TriAnd+A13 - space



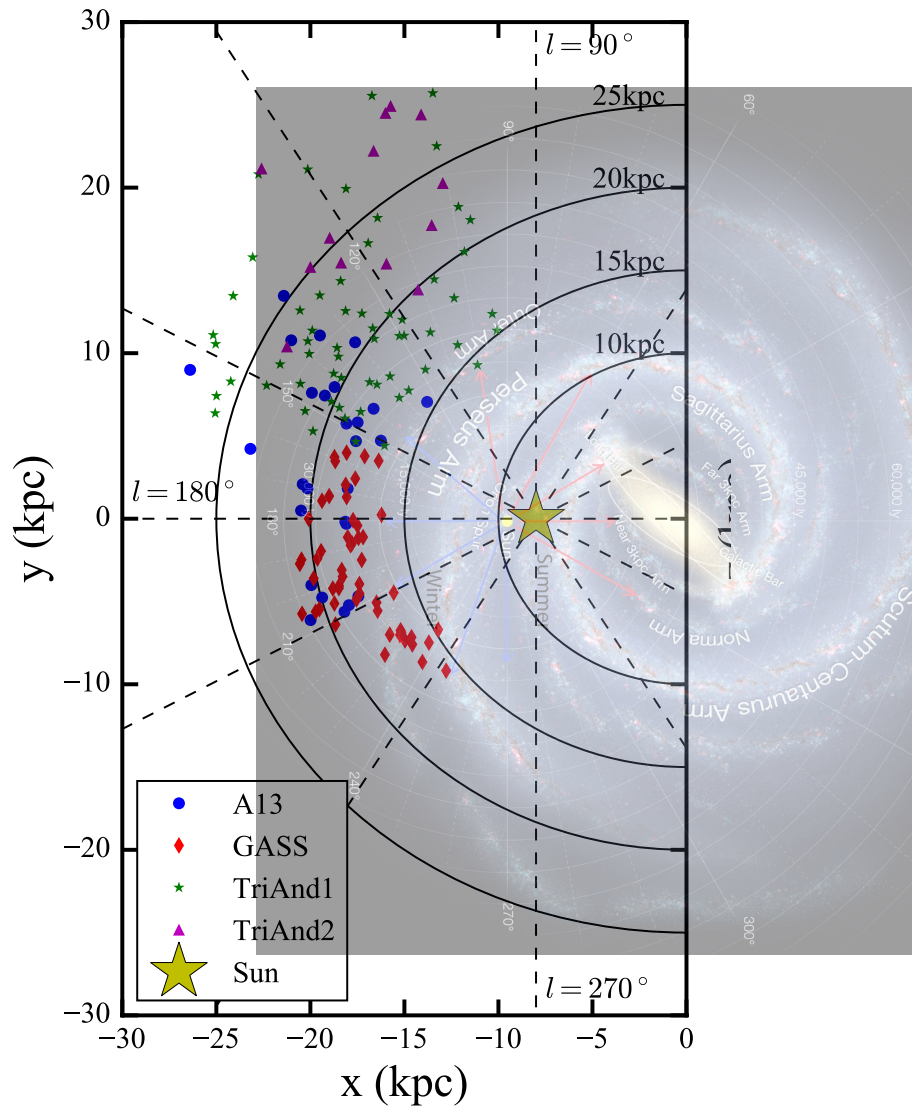
M-giants from 2MASS selected for follow-up spectra - Crane et al (2003), Sheffield, Johnston et al (2013), Li et al (2016)

GASS/Mon+TriAnd+A13 - space



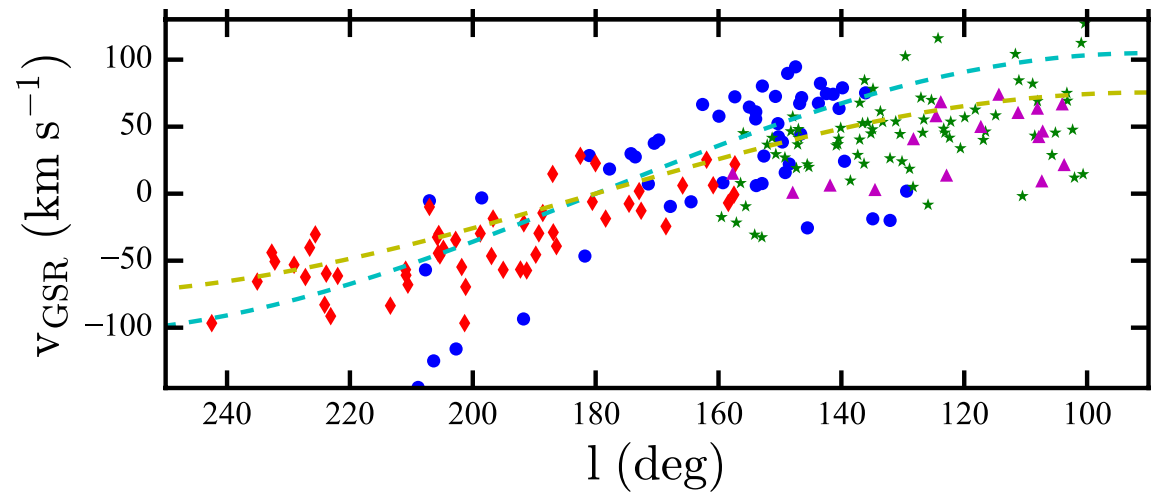
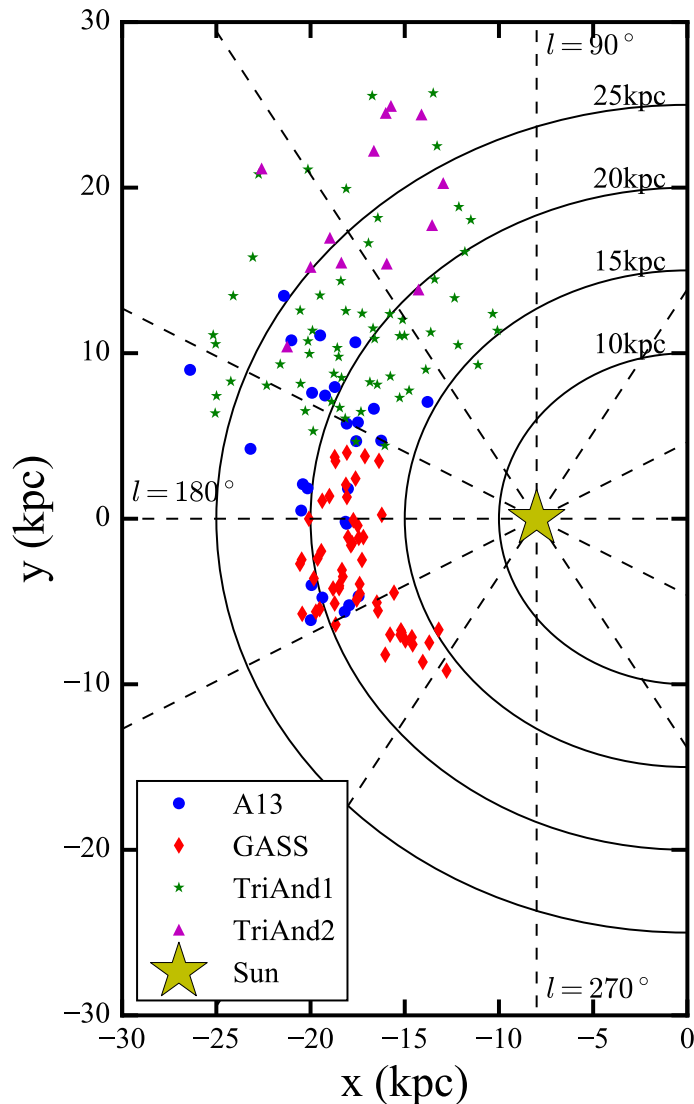
Projection in disk plane

GASS/Mon+TriAnd+A13 - space



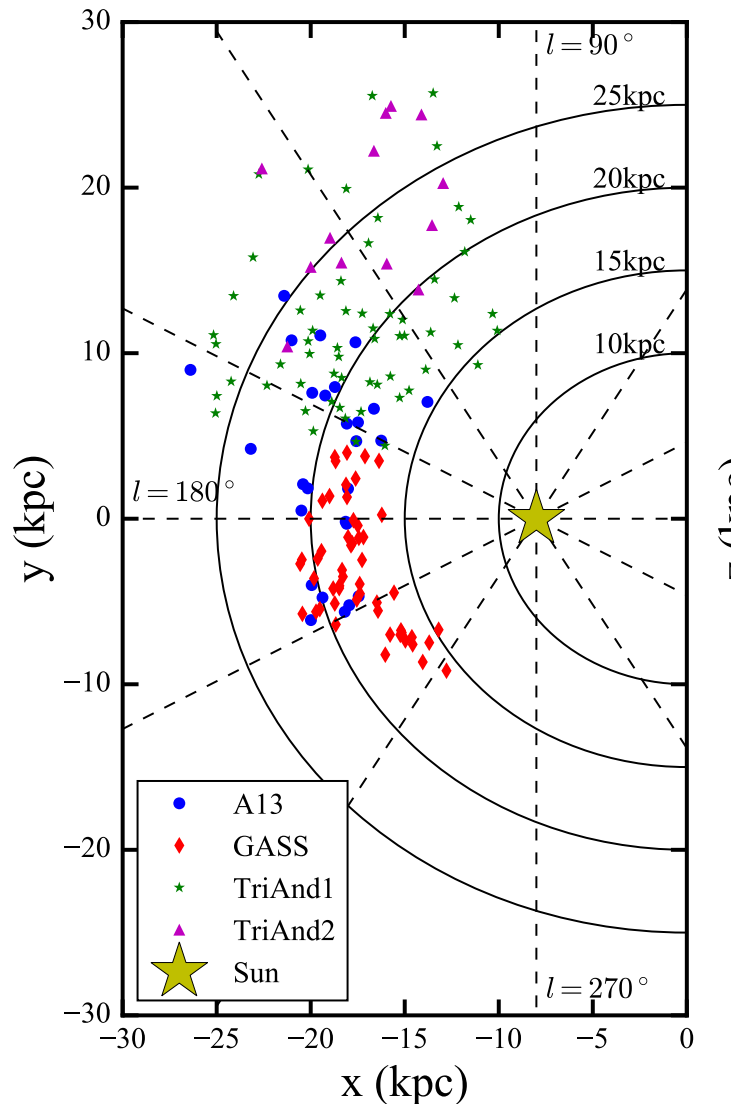
Projection in disk plane:
note the scale!

GASS/Mon+TriAnd+A13 - velocities

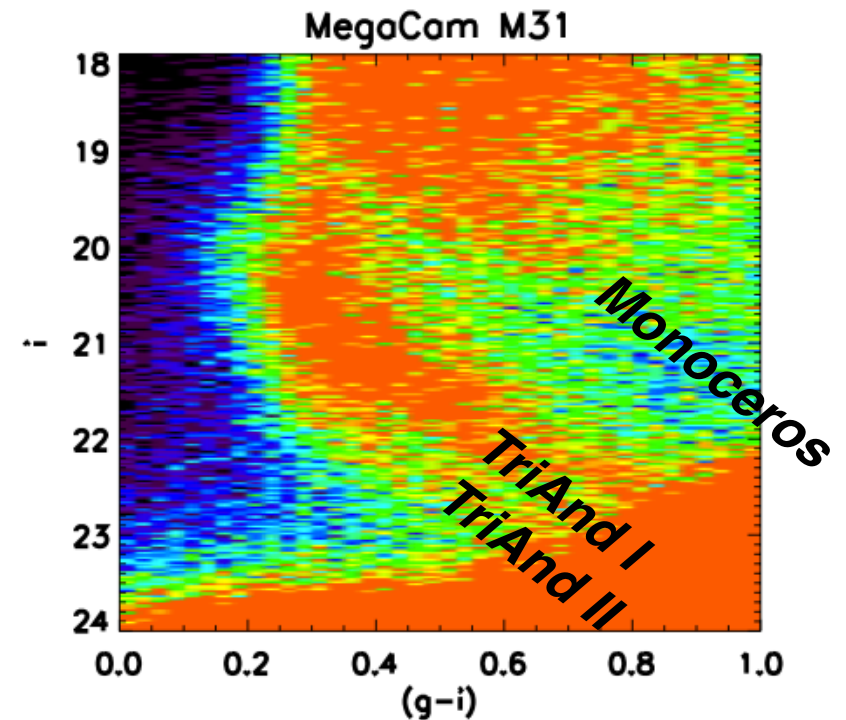


- similar (small) dispersion
=> disk or dwarf
- continuous sequence \sim
Galactic rotation => disk

GASS/Mon+TriAnd+A13 - space



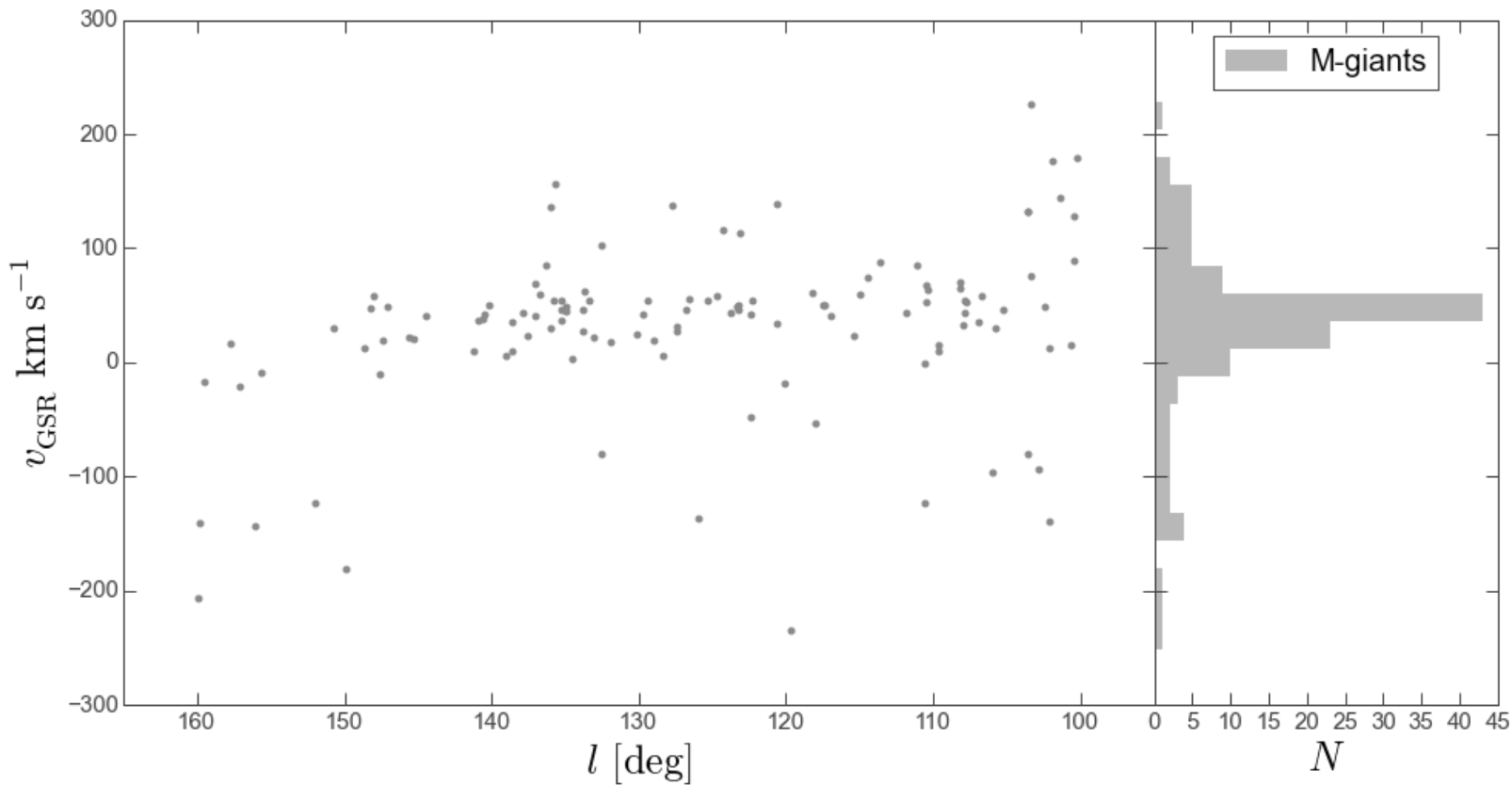
... but are these really “rings”?



Martin et al (2007)

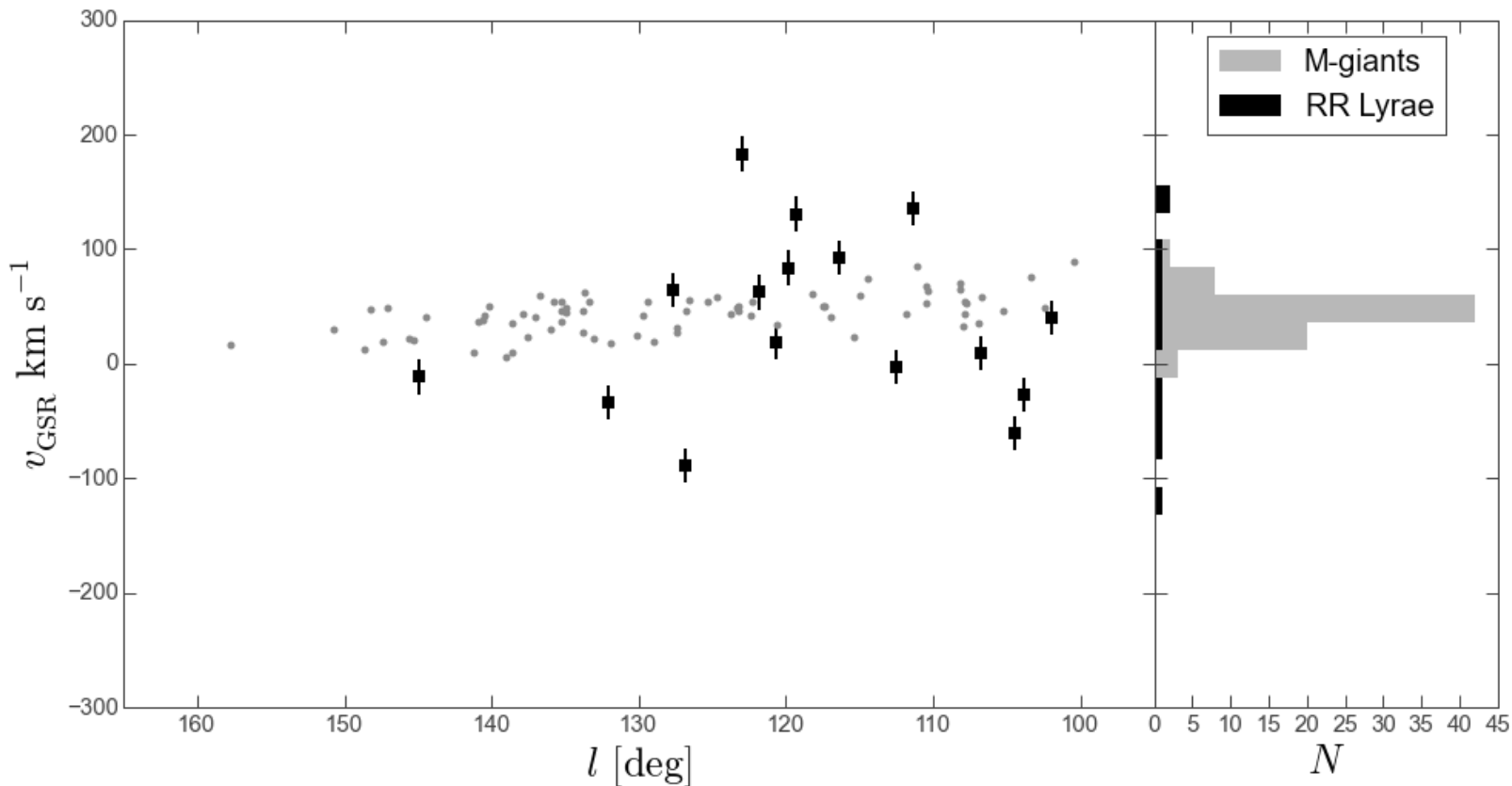
GASS/Mon+TriAnd+A13 - space

Mapping TriAnd I/II in RR Lyrae?????



GASS/Mon+TriAnd+A13 - space

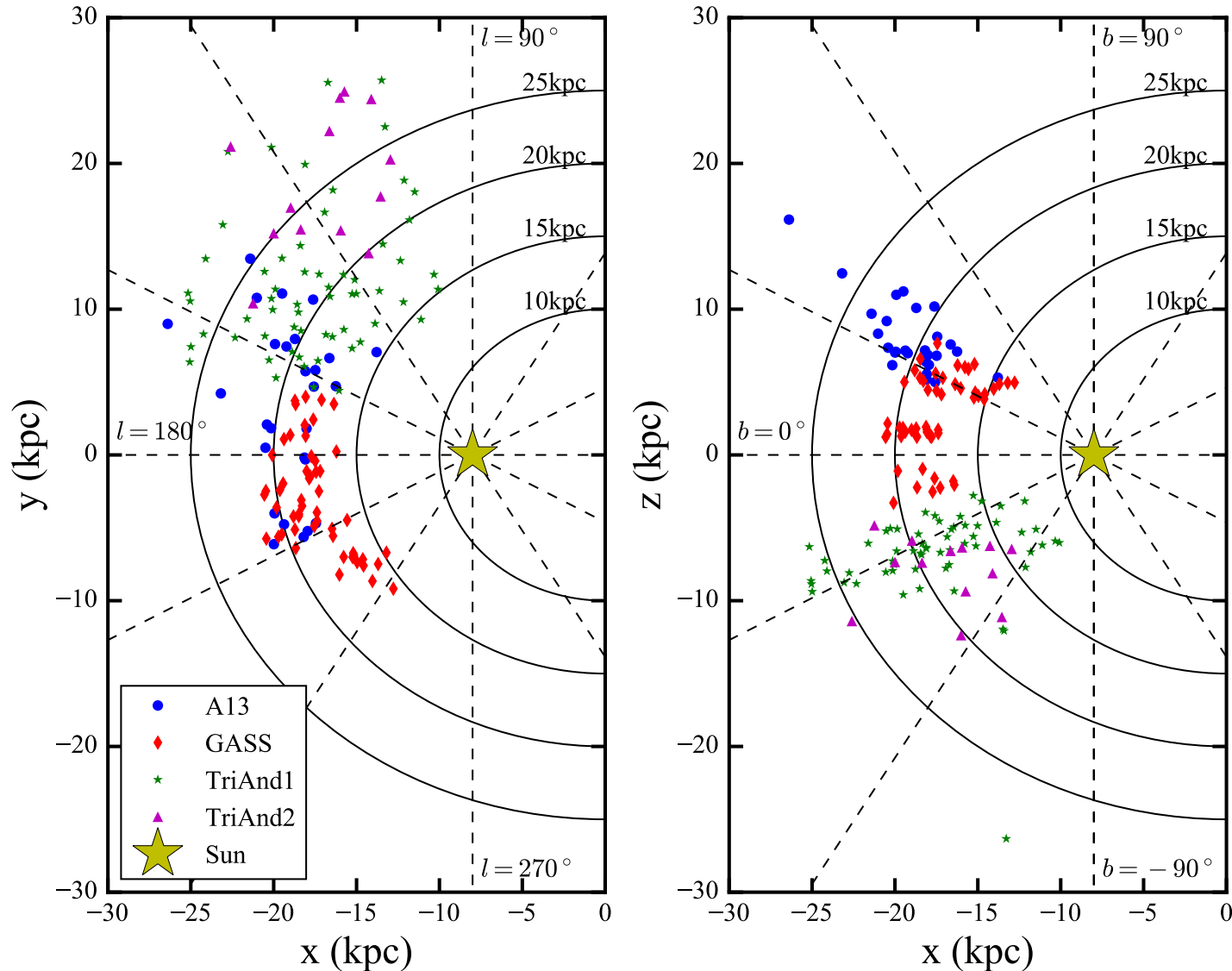
Mapping TriAnd I/II in RR Lyrae??????



No RR Lyrae => **DISK** population

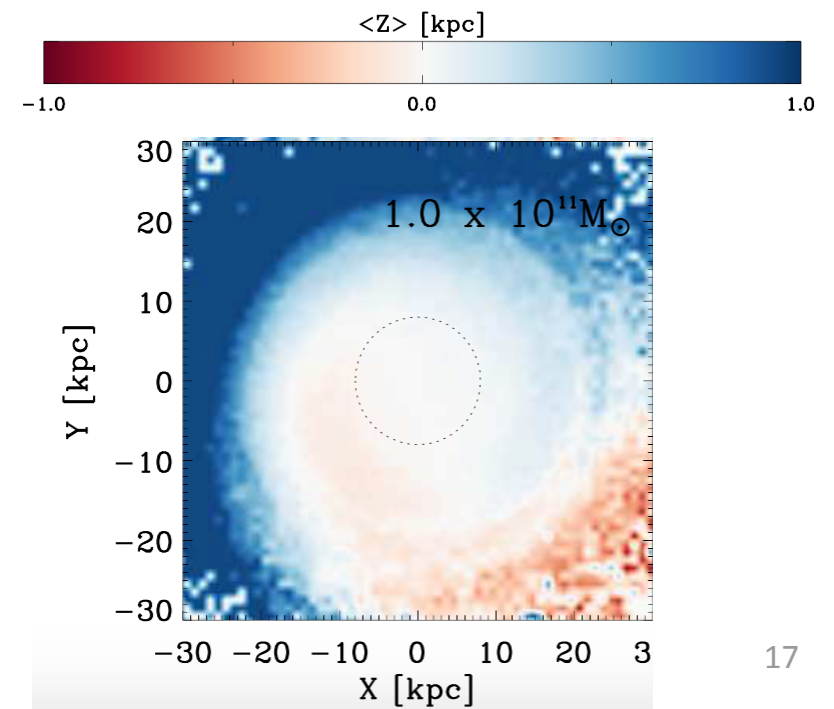
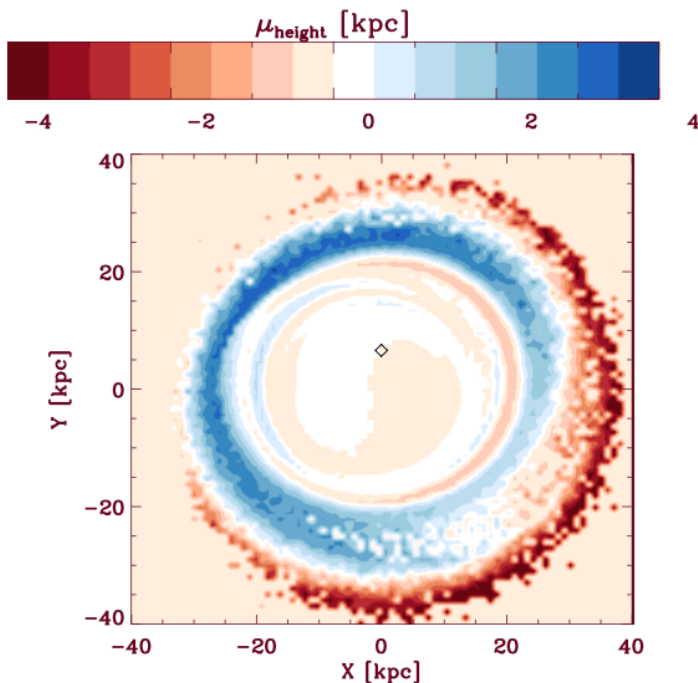
Price-Whelan, Johnston, Sheffield, Laporte & Sesar (2015)

Kicking the Disk to make the Halo



Galactoseismology

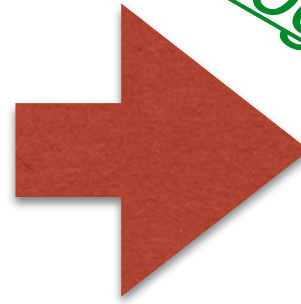
- response of disk depends on
 - mass, orbit and orbital phase of perturber
 - mass distribution in MW
- e.g. Sgr vs LMC



Formation? History? Structure?

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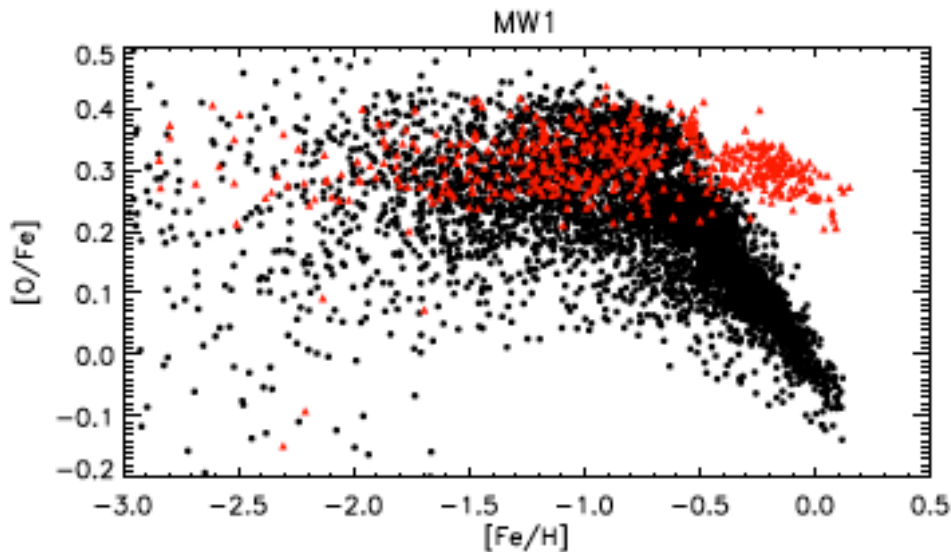
Galactoseismology



physical
manifestations
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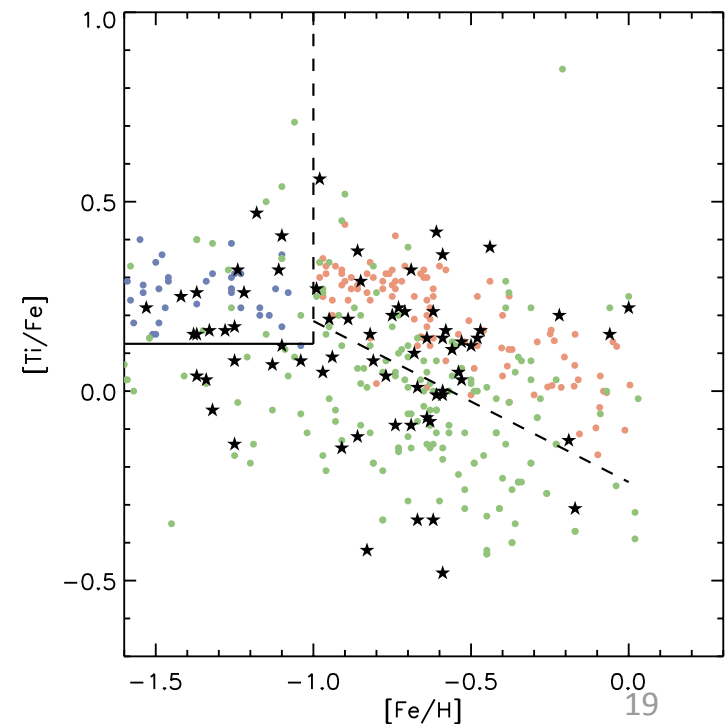
structure
of our
**dark
matter
halo**

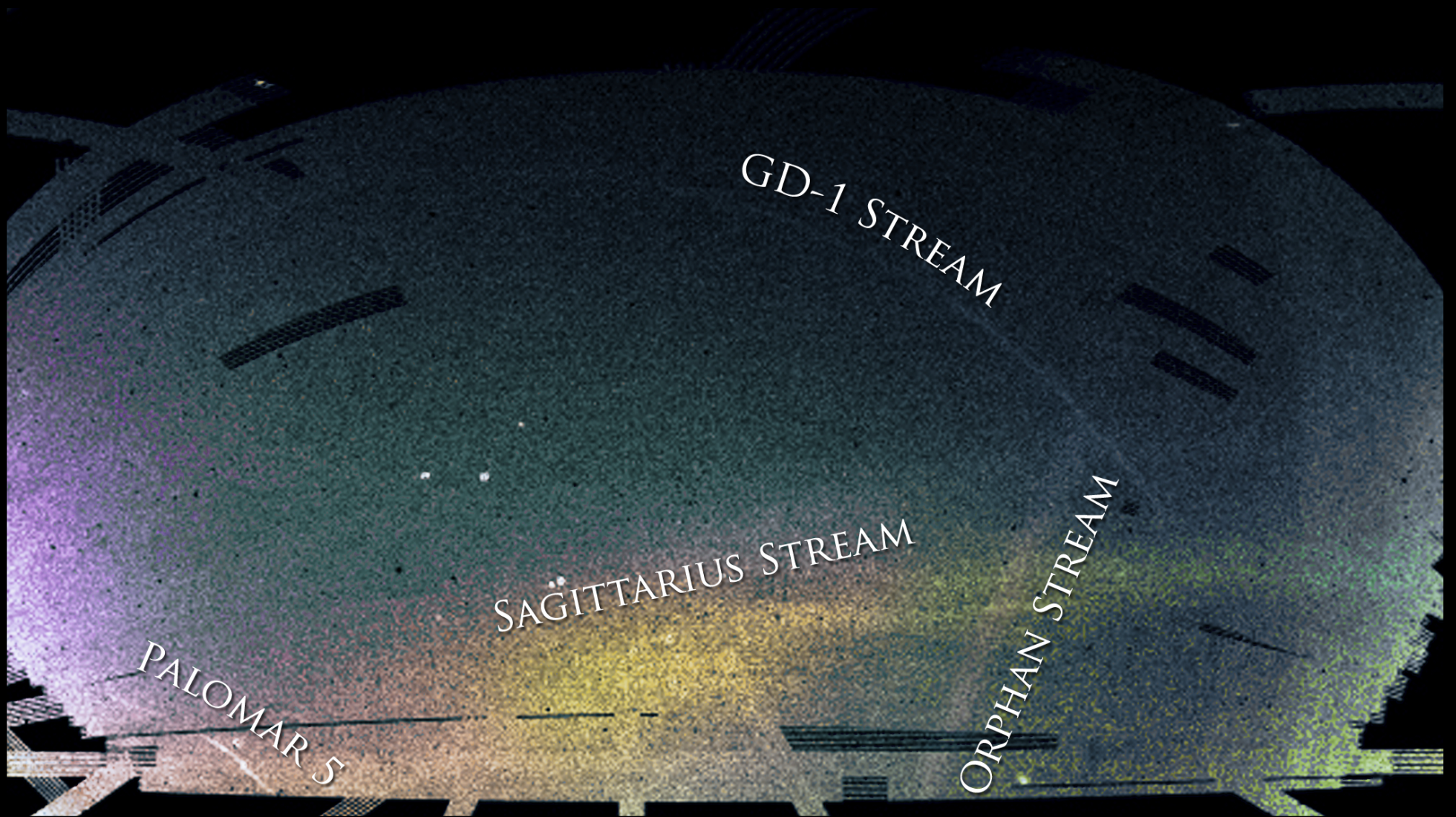
?? Finding **Disk** stars in the **Halo** ??



- simulations from Zolotov et al 2010: **accreted** vs **kicked-out-from-disk**

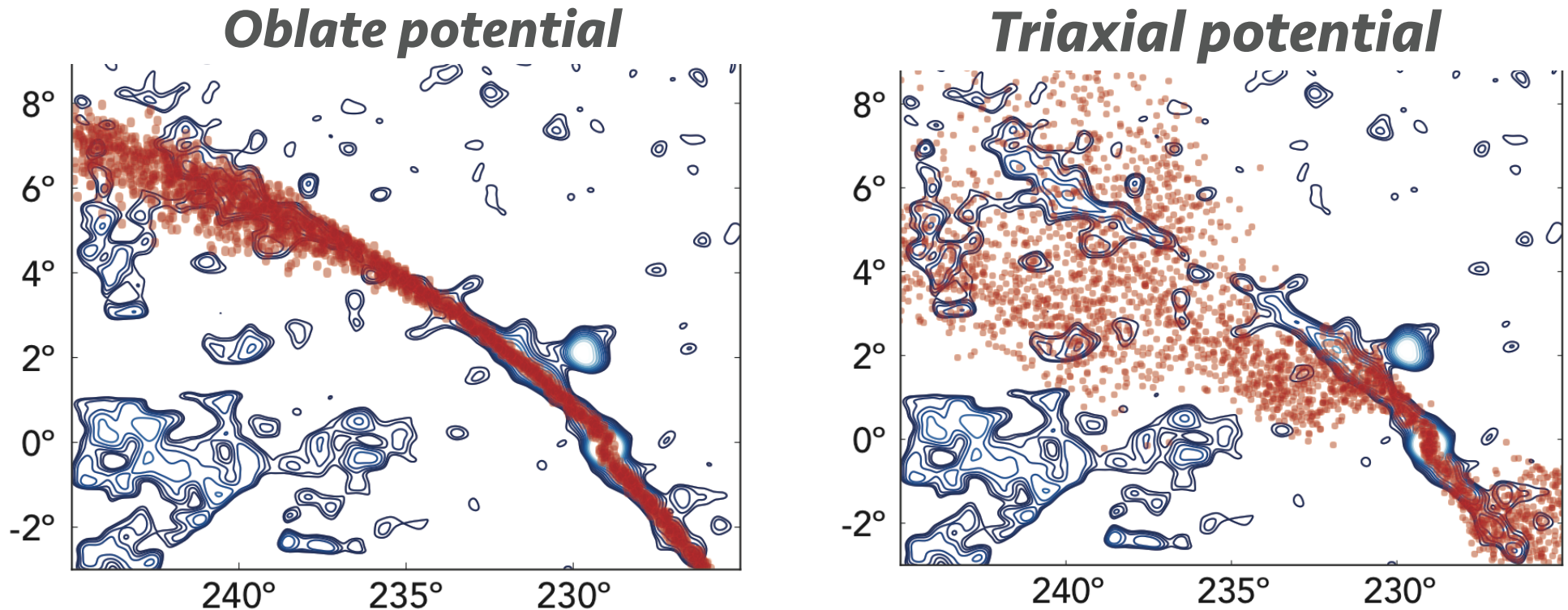
- “high-velocity” M-giants observed by Sheffield, Johnston et al (2012): some have disk-like abundances





*The Milky Way stellar halo from SDSS data
visualized by Bonaca, Giguere, Geha*

Manifestations of Chaos and Regularity



Pearson, Kuepper, Johnston & Price-Whelan (2015)

Disruption of globular on Pal-5 orbit in Law & Majewski (2010) potential => stream "fanning". ?Why?

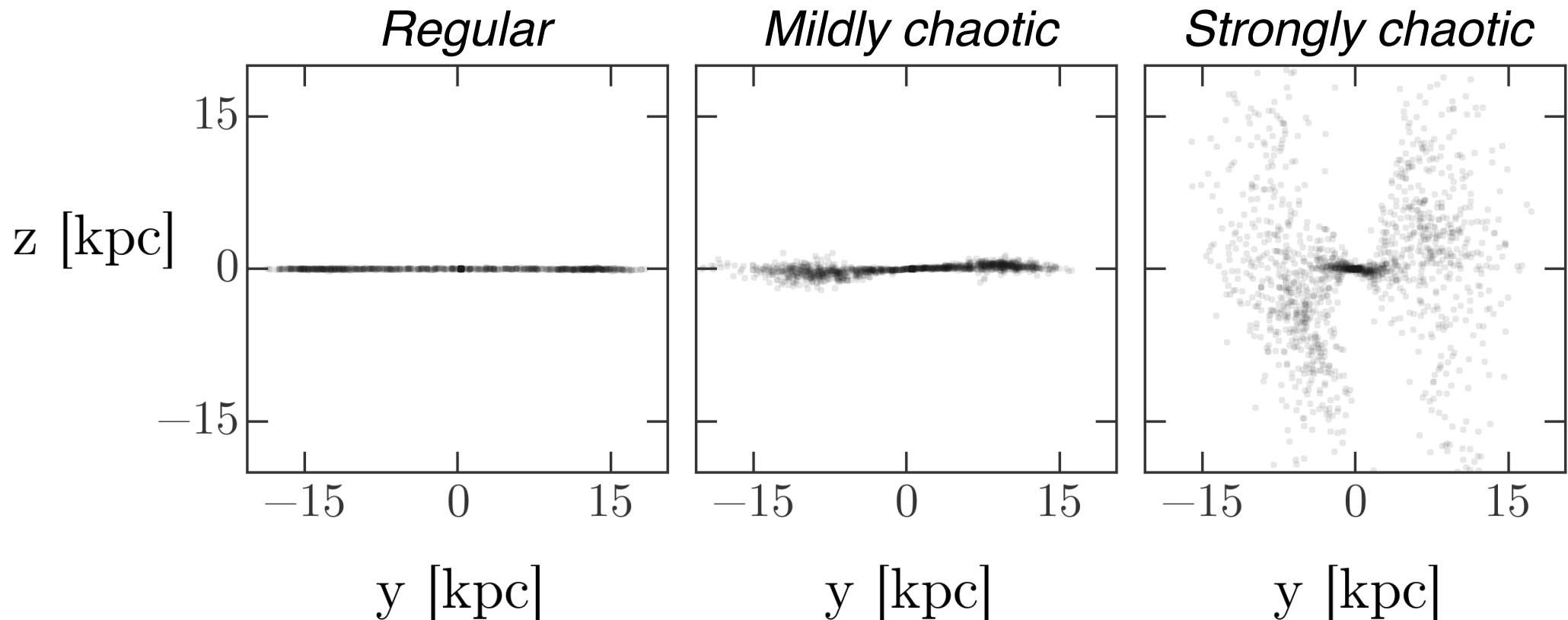
Characterizing Chaos

- Lyapunov time \sim *exponential growth in phase-space distance between two points*
- Frequency drift \sim *time for frequencies to drift by factor unity*

Both ~ 100 Gyrs for Pal 5 model exhibiting stream “fanning” \Rightarrow only mildly chaotic

Manifestations of Chaos and Regularity

- Price-Whelan, Johnston, Valluri, Pearson, Kuepper & Hogg (2015): Disruption along orbits in triaxial NFW

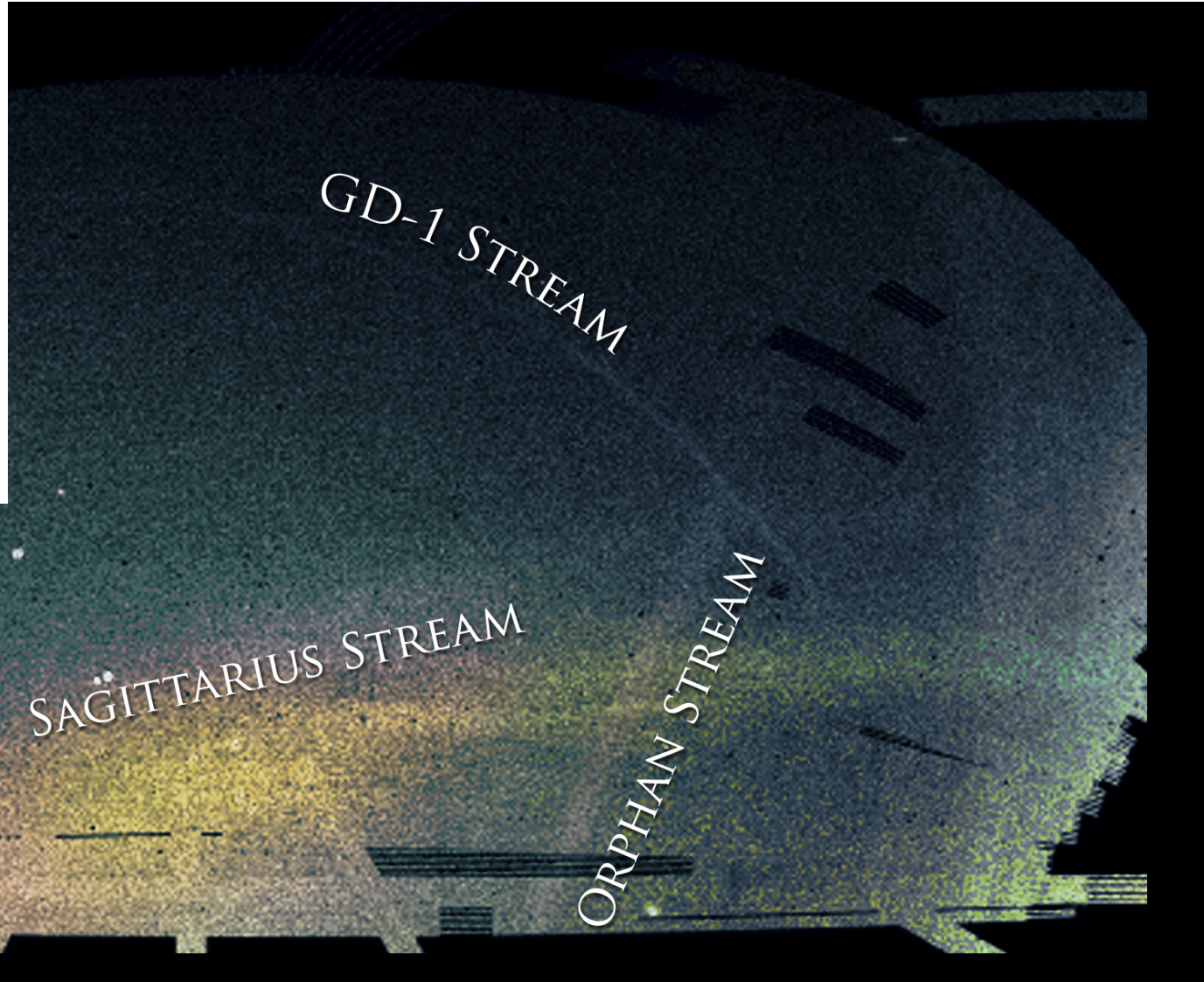
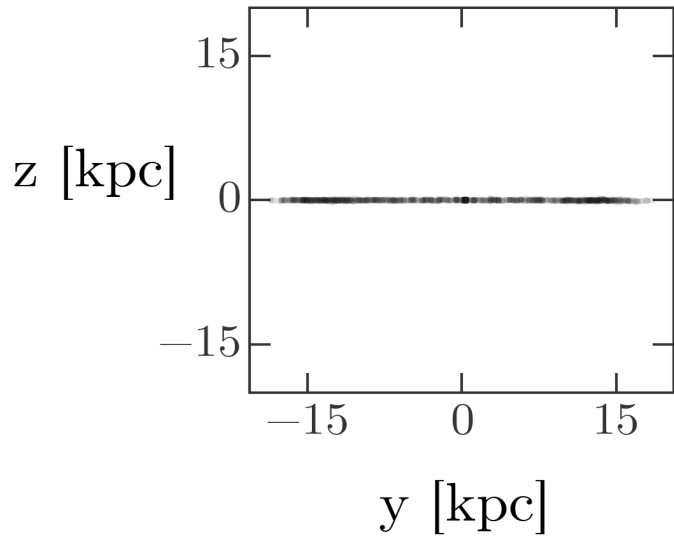


Manifestations of Chaos and Regularity

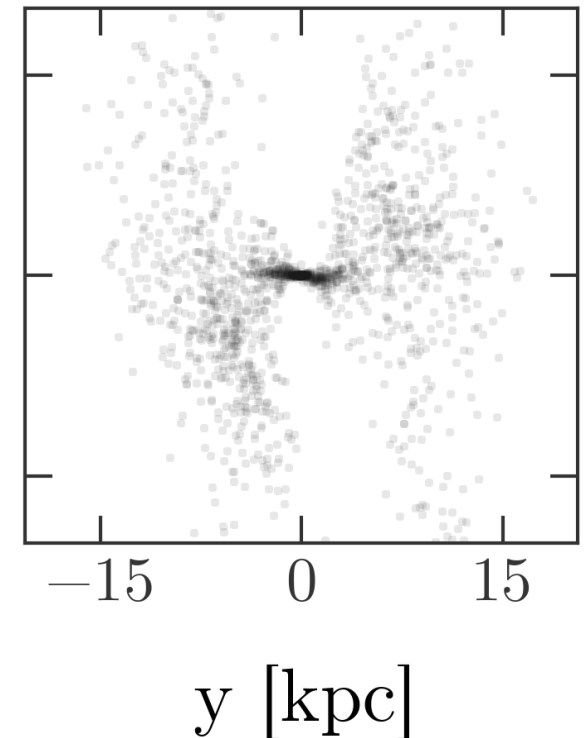
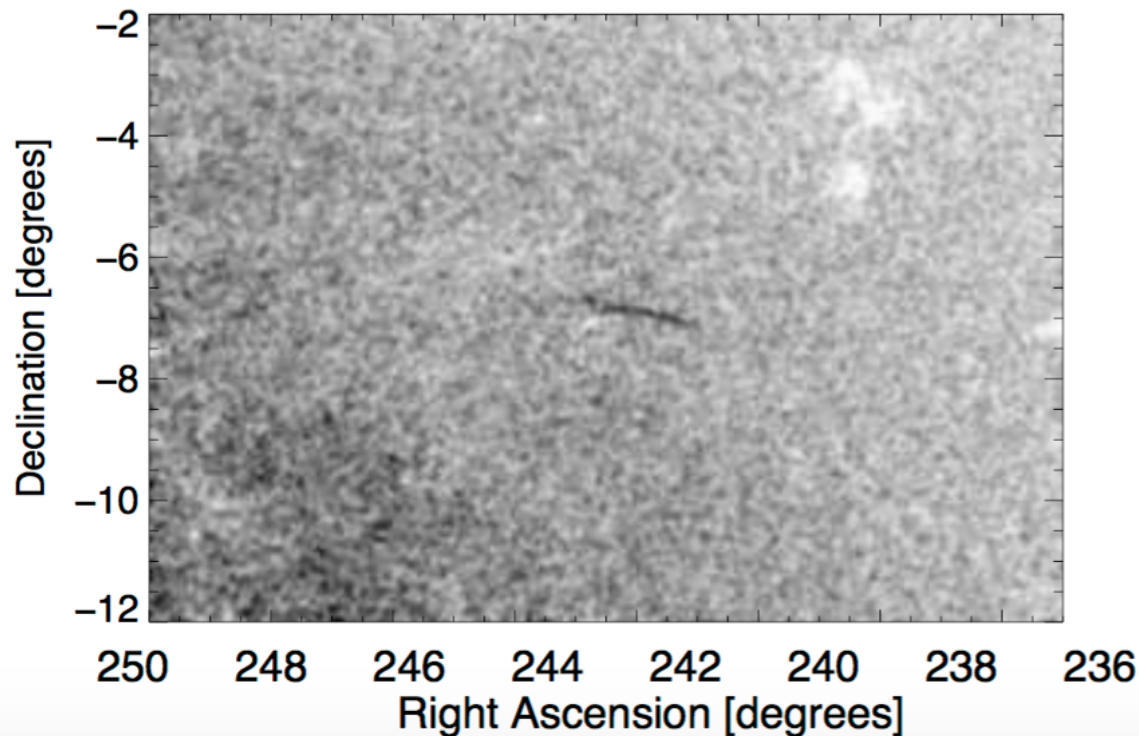
Why fanning on even mildly chaotic orbits?

- ??? Small (1%) spreads in frequencies intrinsically in globular cluster debris ????
- Large excursions in frequencies along chaotic orbits even with low mean-drift rate

Regular orbits = Pal 5, GD1, Orphan



Chaotic orbits = Ophiuchus

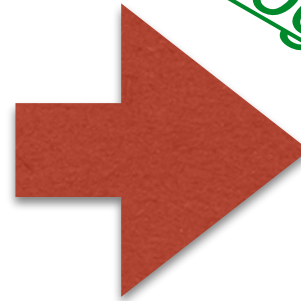


- Bernard et al (2014)
- Sesar et al (2015), Sesar, Price-Whelan et al (2016), Price-Whelan, Sesar, Johnston & Rix (2016)
- see also Hattori, Eerkal & Sanders (2016)

Formation? History? Structure?

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Galactoseismology



structure
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streams
or not?