The Dark and Stellar Halo: Formation; History; Structure
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The Milky Way stellar halo from SDSS data visualized by Bonaca, Giguere, Geha

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3-D structure of a dark matter halo

finding dark matter substructures

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
The Columbia StreamTeam
(past and present)
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Adrian Price-Whelan
Sarah Pearson
Chervin Laporte
David Hendel
Andreas Kuepper
Sanjib Sharma
Allyson Sheffield
Robyn Sanderson
Duane Lee
Maureen Teyssier
Kicking the Disk ......

Models of satellite/disk interactions
Laporte, Gomez, Besla, Johnston & Garavito-Camarago, 2016
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

??? or satellite debris ???

Penarrubia et al. (2005)
Chou et al. (2010, 2011)
Sheffield, Johnston et al. (2013)
GASS/Mon+TriAnd+A13 - space

Projection in disk plane
GASS/Mon+TriAnd+A13 - space

Projection in disk plane: note the scale!
• similar (small) dispersion => disk or dwarf
• continuous sequence ~ 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?????
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No RR Lyrae => **DISK** population

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
kicking the disk to make the halo

physical manifestations of chaos and regularity

Galactoseismology

structure of our dark matter halo
Finding **Disk** stars in the **Halo**

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

- Simulations from Zolotov et al 2010: **accreted** vs **kicked-out-from-disk**
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Manifestations of Chaos and Regularity

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 $\sim 100$ Gyrs for Pal 5 model exhibiting stream “fanning” => only mildly chaotic
Manifestations of Chaos and Regularity

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)
- see also Hattori, Eerkal & Sanders (2016)
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streams or not?