Science with synthetic stellar surveys

Robyn Sanderson
Caltech -> UPenn/CCA

Synthetic survey of a cosmo-hydro simulation
(Sanderson et al 2018)

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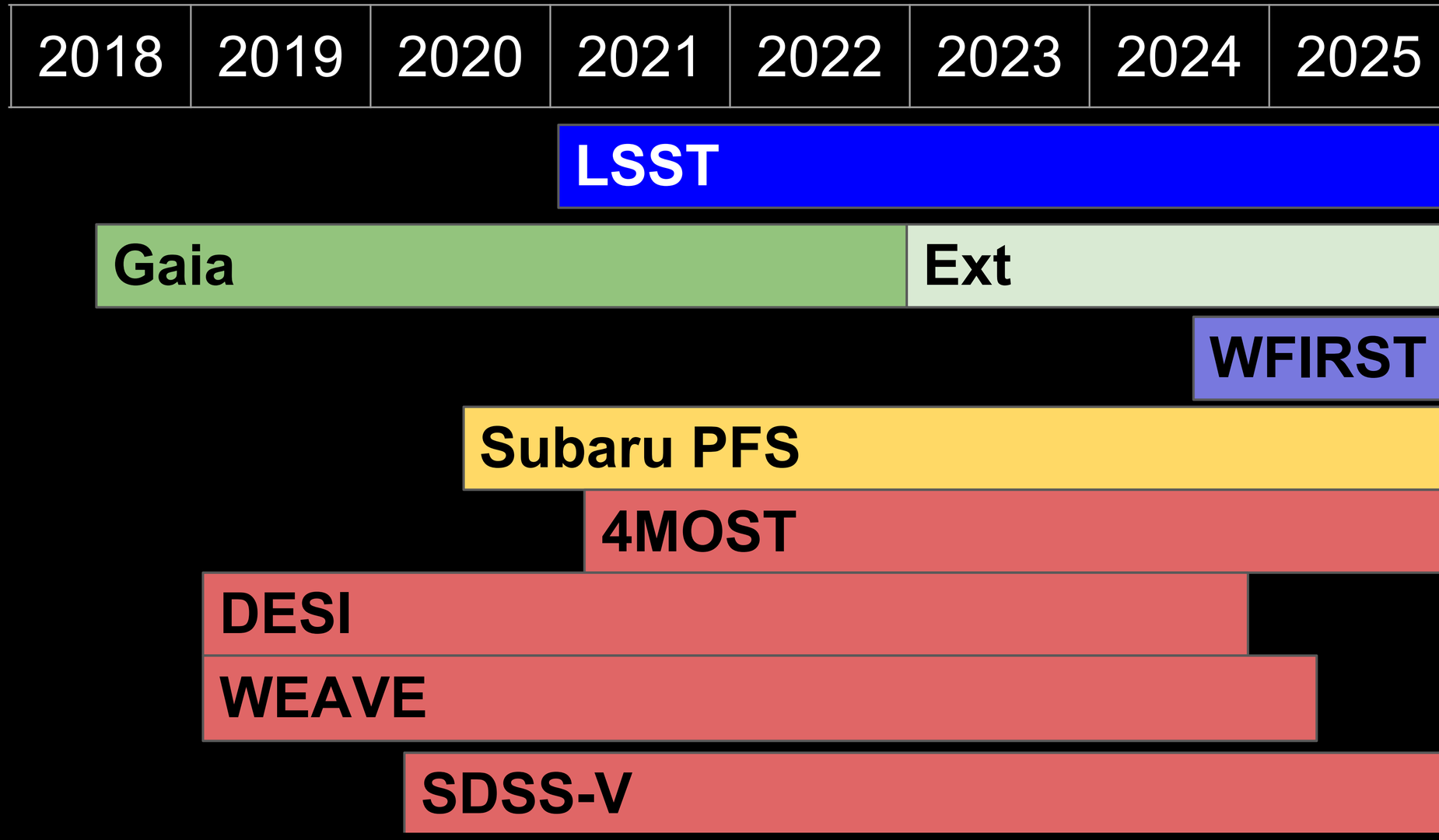
Milky Way
(image credit:ESO)

The next decade will see a Galactic renaissance[1]

[1]E. Kirby, 2017



Astrometric + spectroscopic

Photometric + astrometric

Spectroscopic: <4-m class

Spectroscopic: >4-m class

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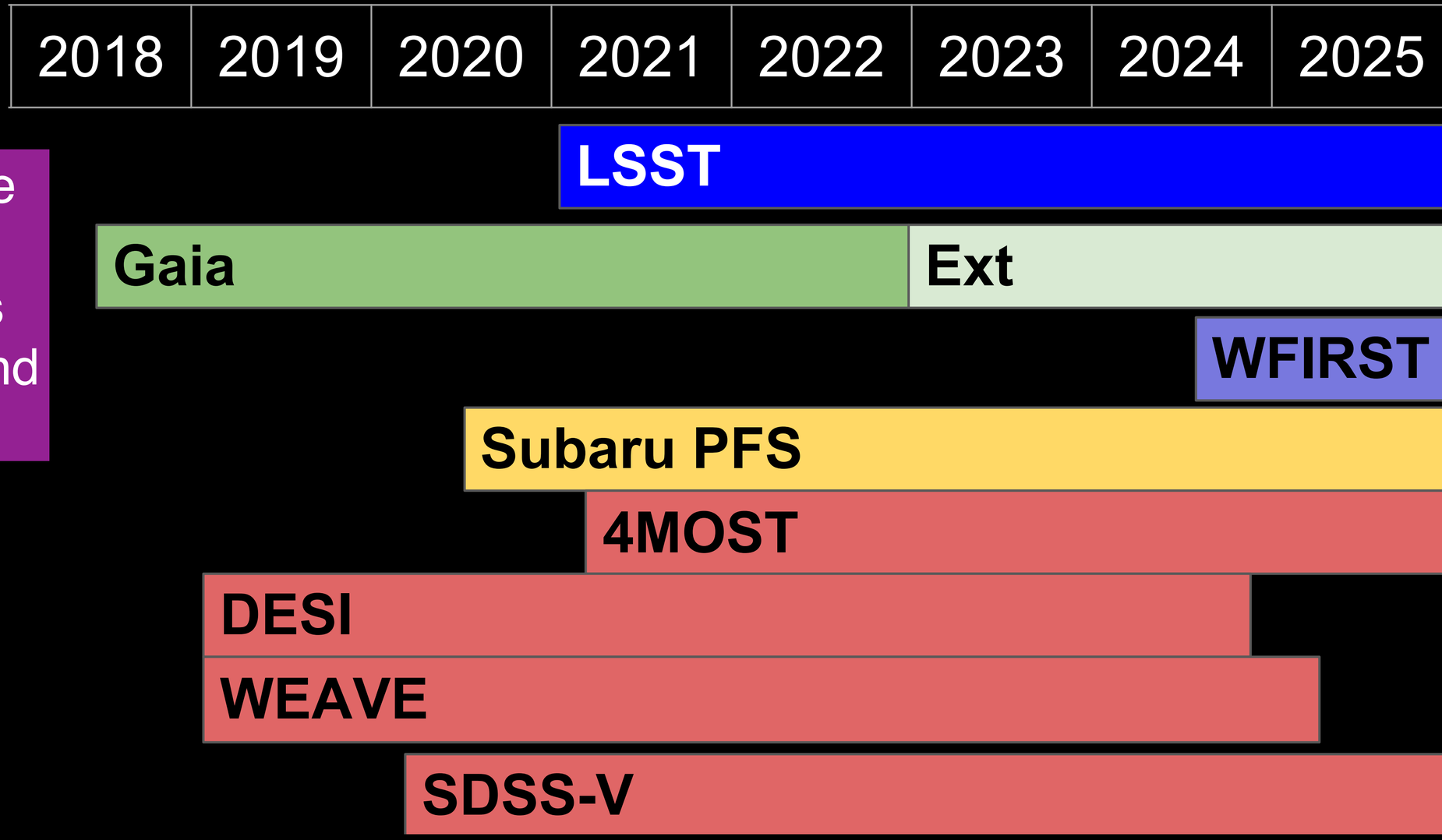

By 2028, we will have 6+D information for stars to the MW's virial radius and beyond (~300 kpc)…

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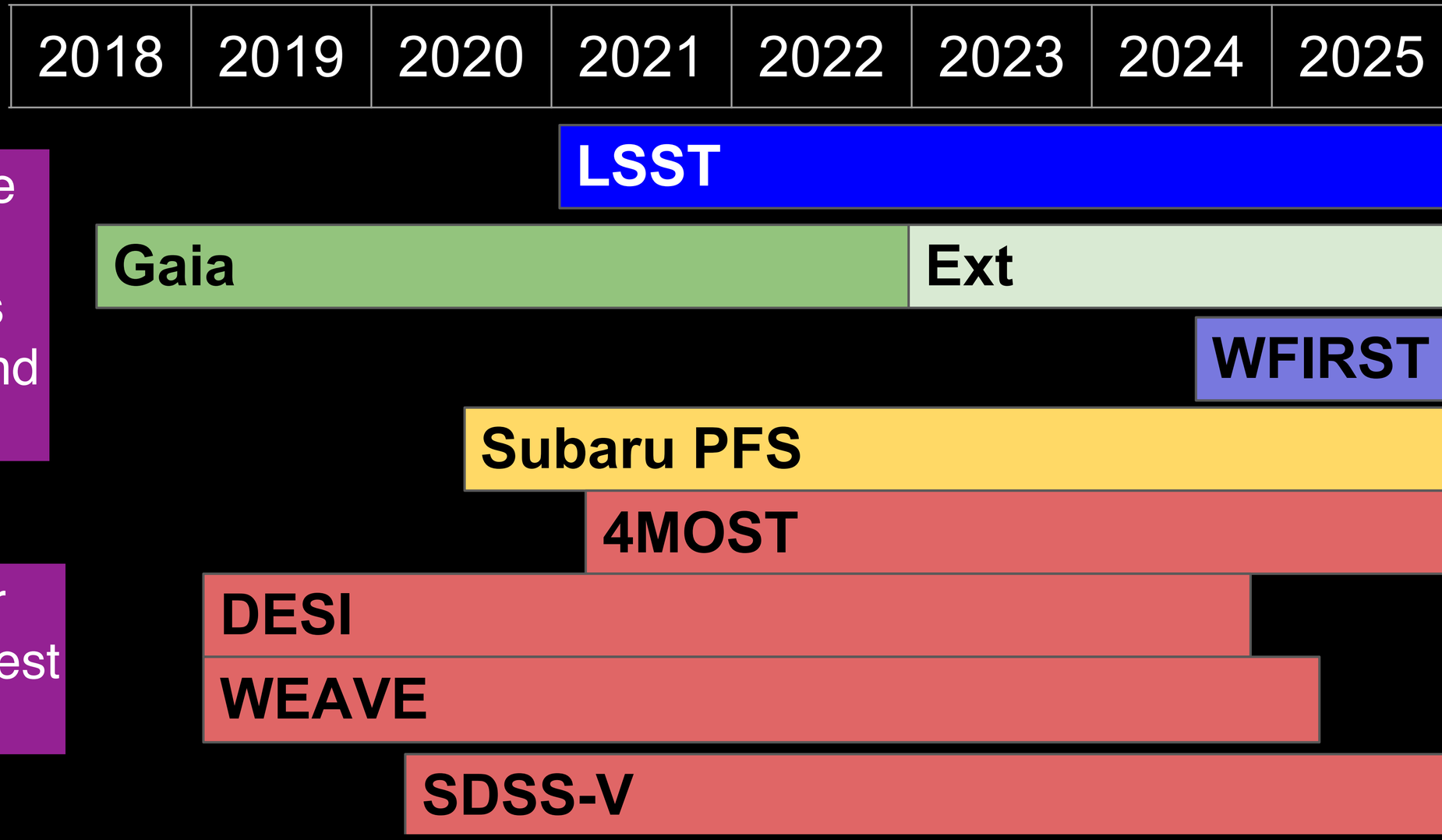

By 2028, we will have 6+D information for stars to the MW's virial radius and beyond (~300 kpc)…

..and resolved stellar maps of the ~100 nearest MW-like galaxies

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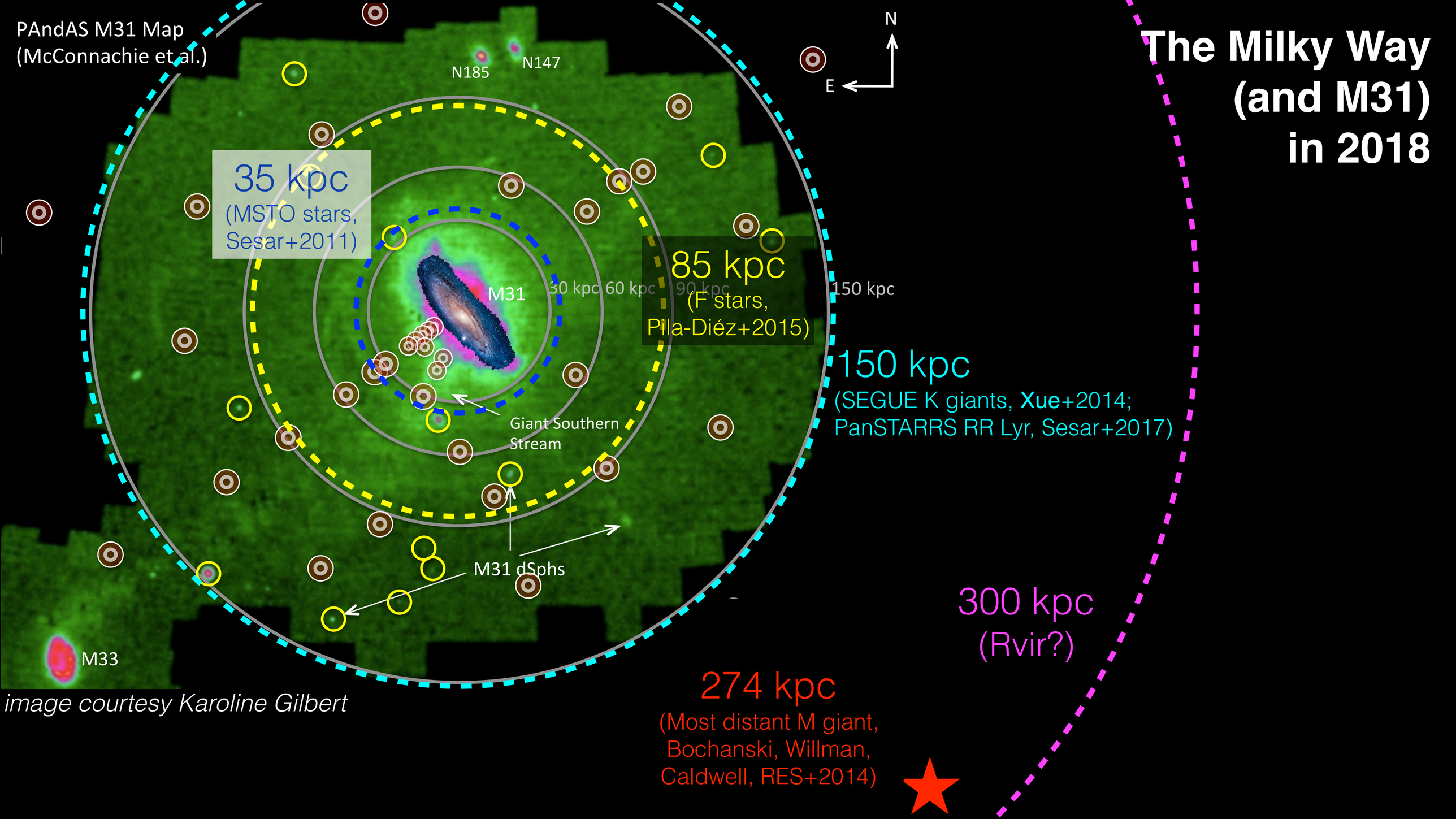
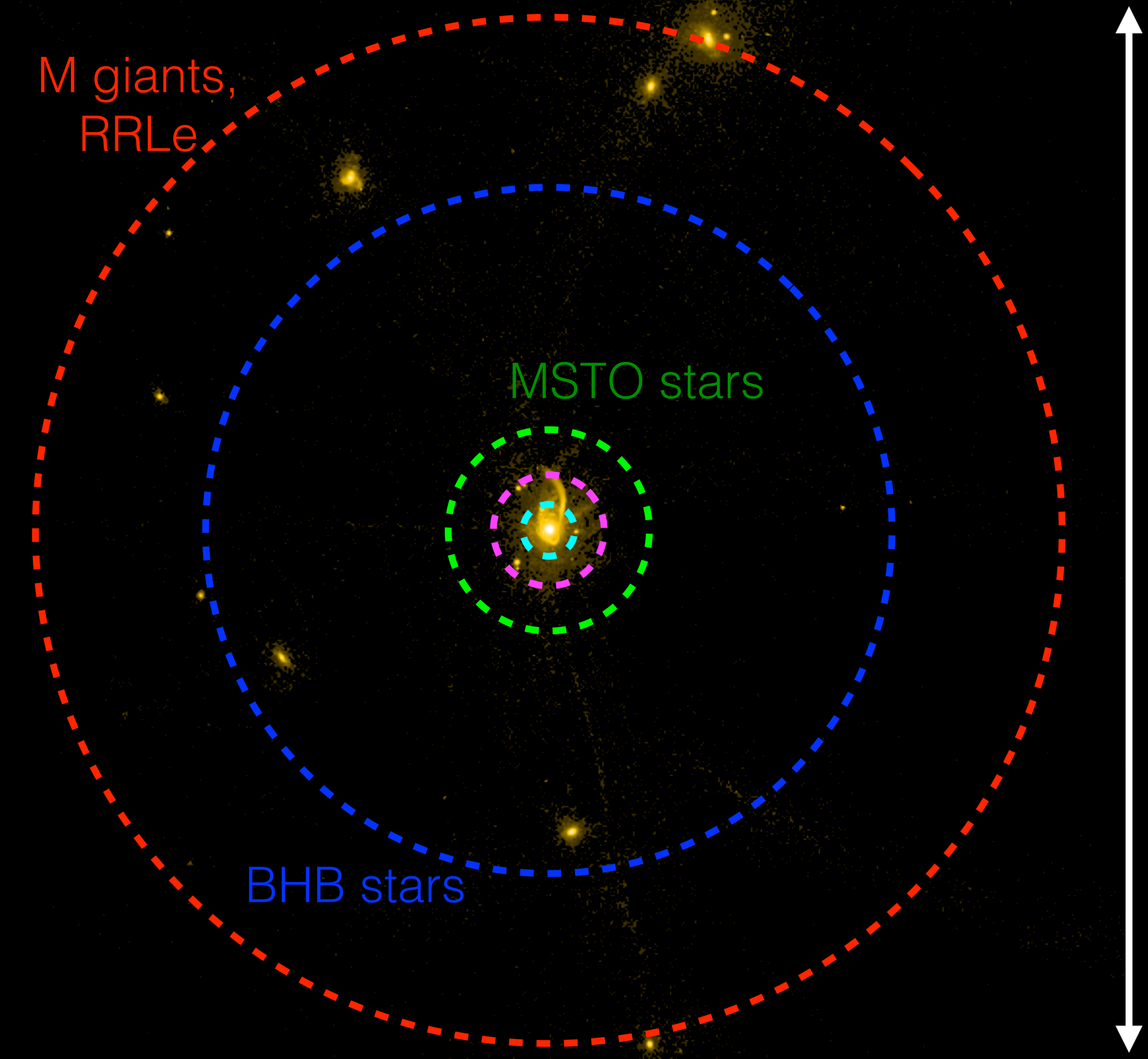

PAndAS M31 Map
(McConnachie et al.)
N185
N147
N
E
35 kpc
(MSTO stars,
Sesar+2011)
M31
30 kpc
60 kpc
90 kpc
150 kpc
85 kpc
(F stars,
Pila-Diéz+2015)
150 kpc
(SEGUE K giants, Xue+2014;
PanSTARRS RR Lyr, Sesar+2017)
Giant Southern
Stream
M31 dSphs
M33
300 kpc
(Rvir?)
274 kpc
(Most distant M giant,
Bochanski, Willman,
Caldwell, RES+2014)
The Milky Way
(and M31)
in 2018
image courtesy Karoline Gilbert



The Milky Way in 2028

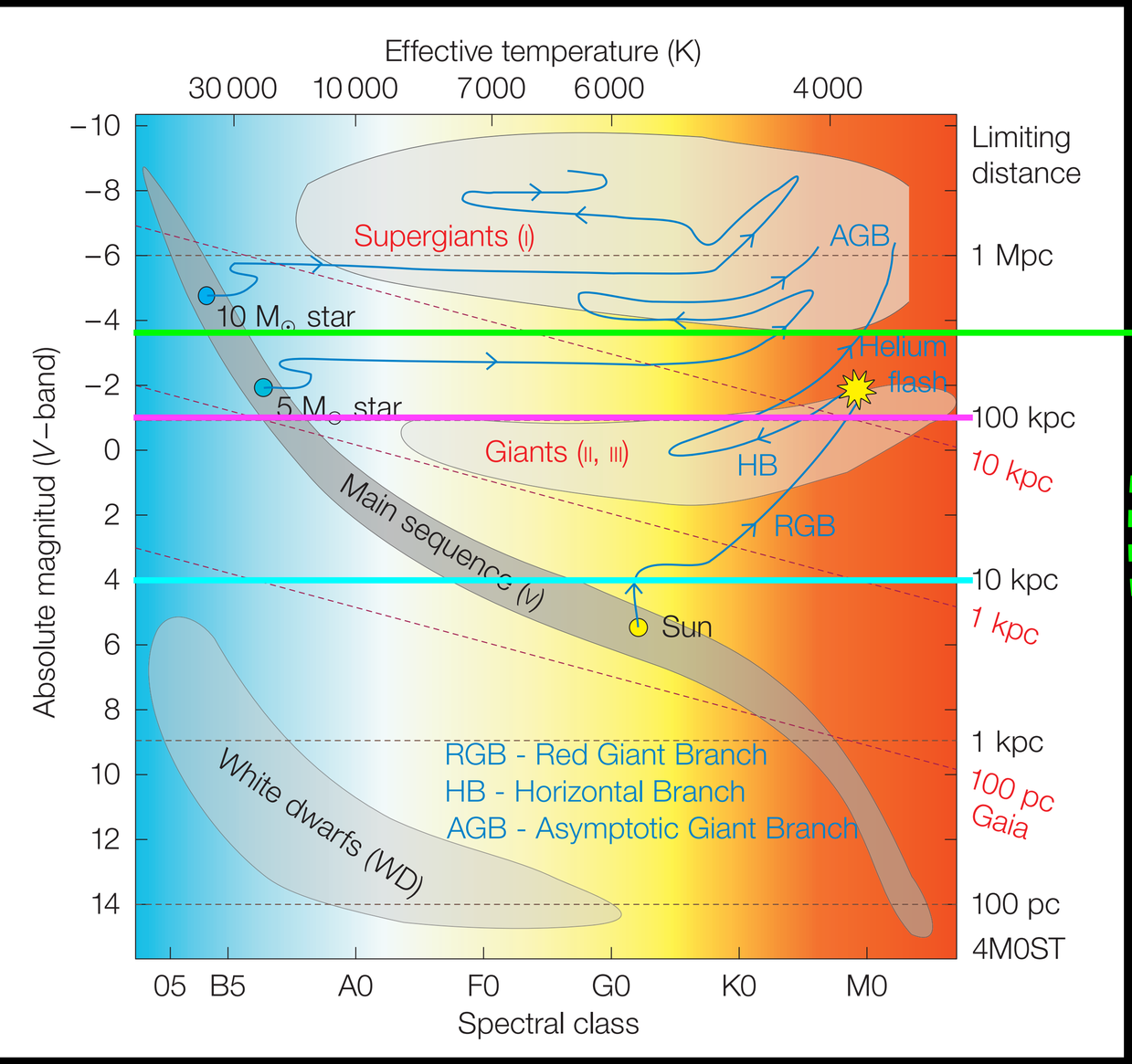
LSST
coadded depth
(m=26.7)

300 kpc (=Rvir?)

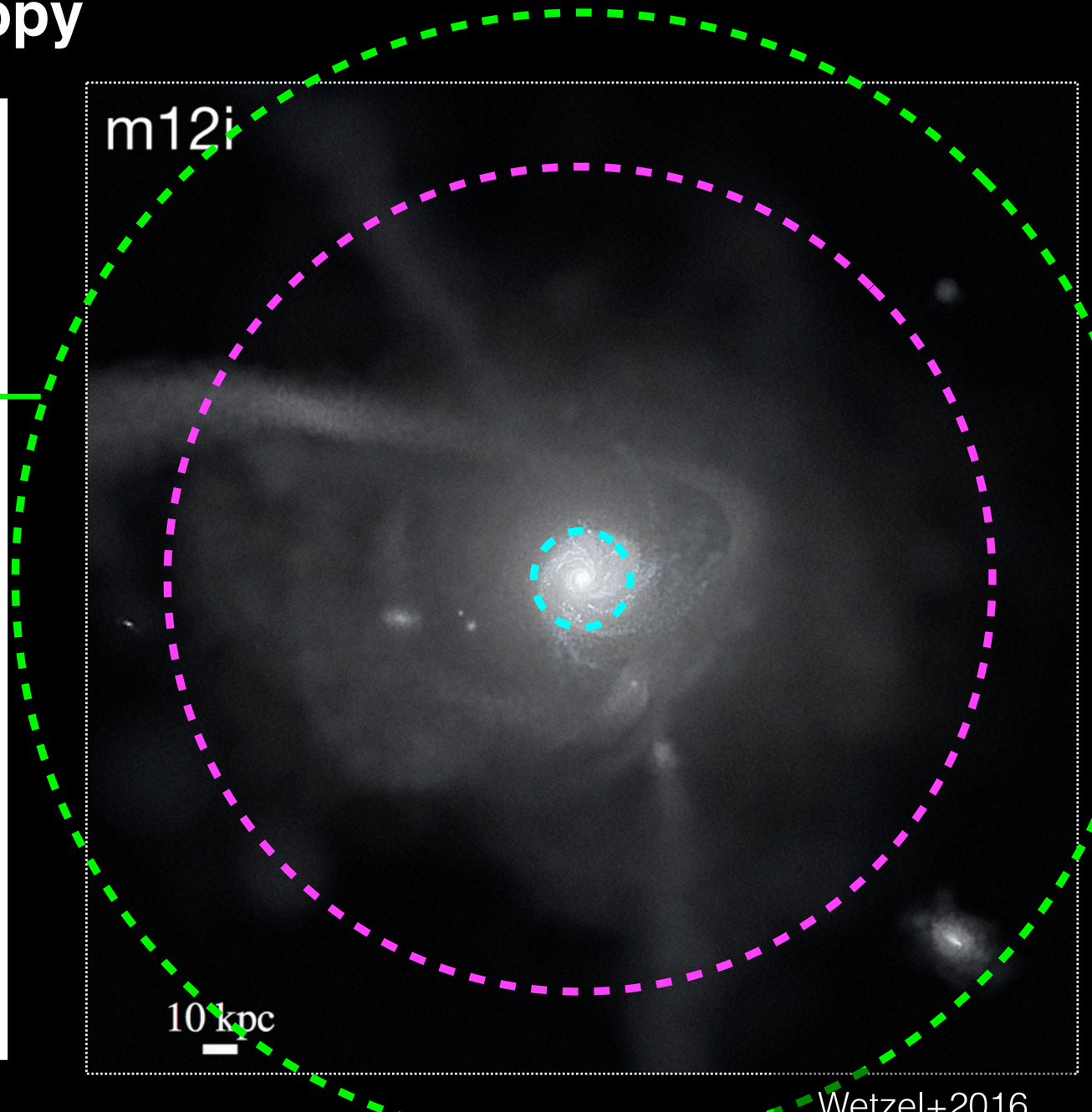
150 kpc
(extent of current
samples)

Figure courtesy Andrew Wetzel
Latte Simulation: arXiv:1602.05957

The Milky Way in 2028: spectroscopy



4MOST; De Jong 2011



Wetzel+2016

but…what do we DO with all this data?

Wetzel et al. 2016, movie credit: Phil Hopkins

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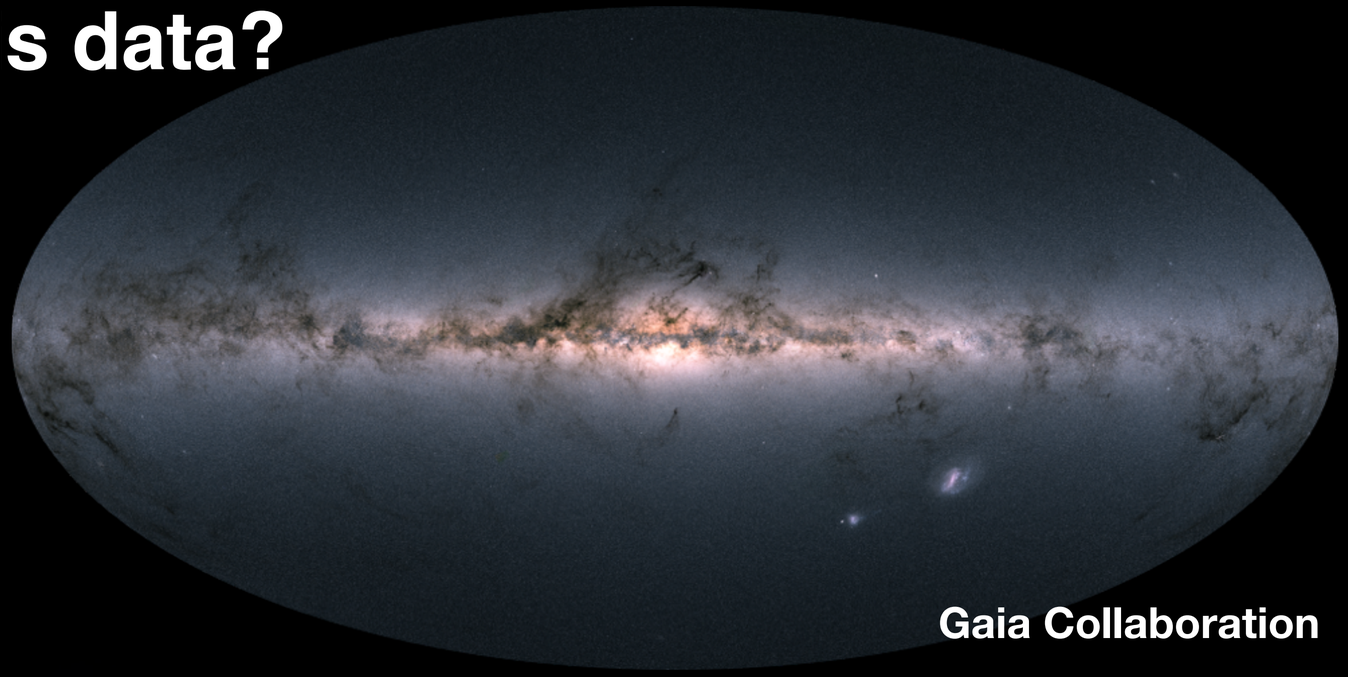
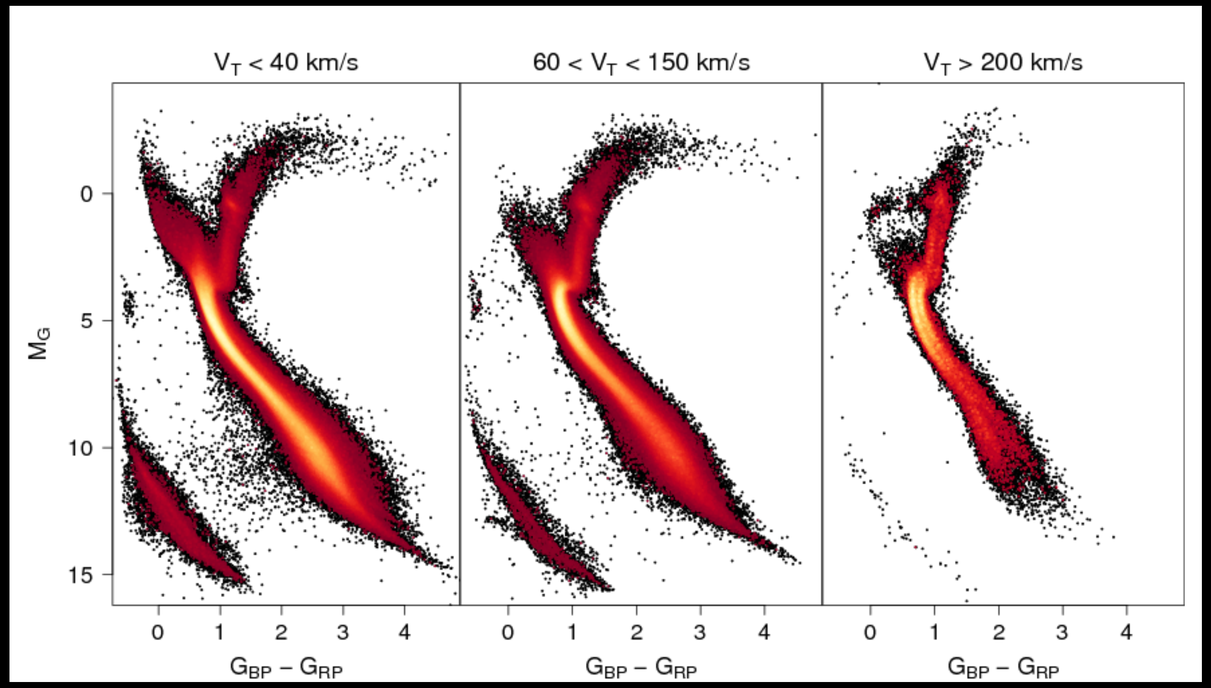


Gaia Collaboration

Wetzel et al. 2016, movie credit: Phil Hopkins



Babusiaux et al 2018

Making predictions for a 6+D galaxy

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Galaxy Simulation
(cosmology, DM model, gravity, gas physics, star formation, stellar feedback, …)

One particle = many “stars”
…with same age, abundances

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50 kpc

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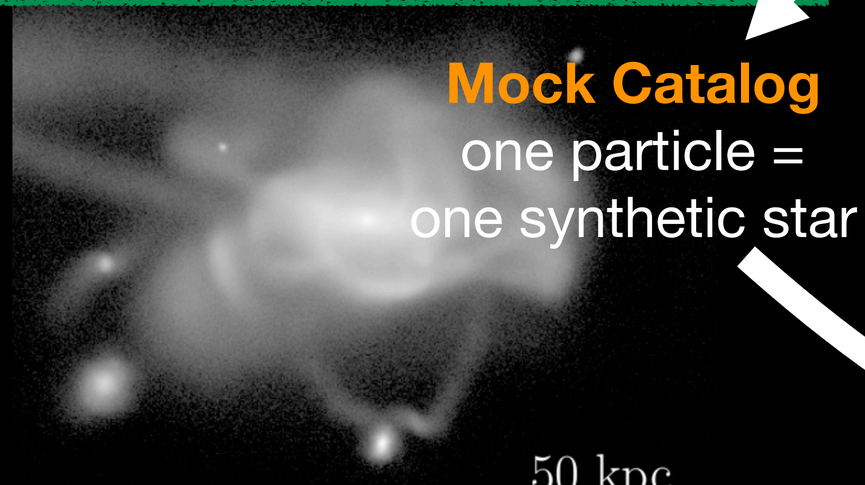
Phase-space density estimation
(kernel dimension, smoothing scales, ages, accretion history, …)

Mock Catalog
one particle = one synthetic star

Survey description
(Magnitude/color limits, extinction/reddening, selection function, error model, instrument model, …)

Synthetic Survey
one particle = one “observed” star

One particle = many “stars”
…with same age, abundances



Making predictions for a 6+D galaxy

- Mapping the DM halo of the Galaxy in the Gaia era & beyond
- Statistical effects of small-scale DM structure
- Interpreting chemodynamic structure in the solar neighborhood
- Resolving the stellar halos of nearby galaxies

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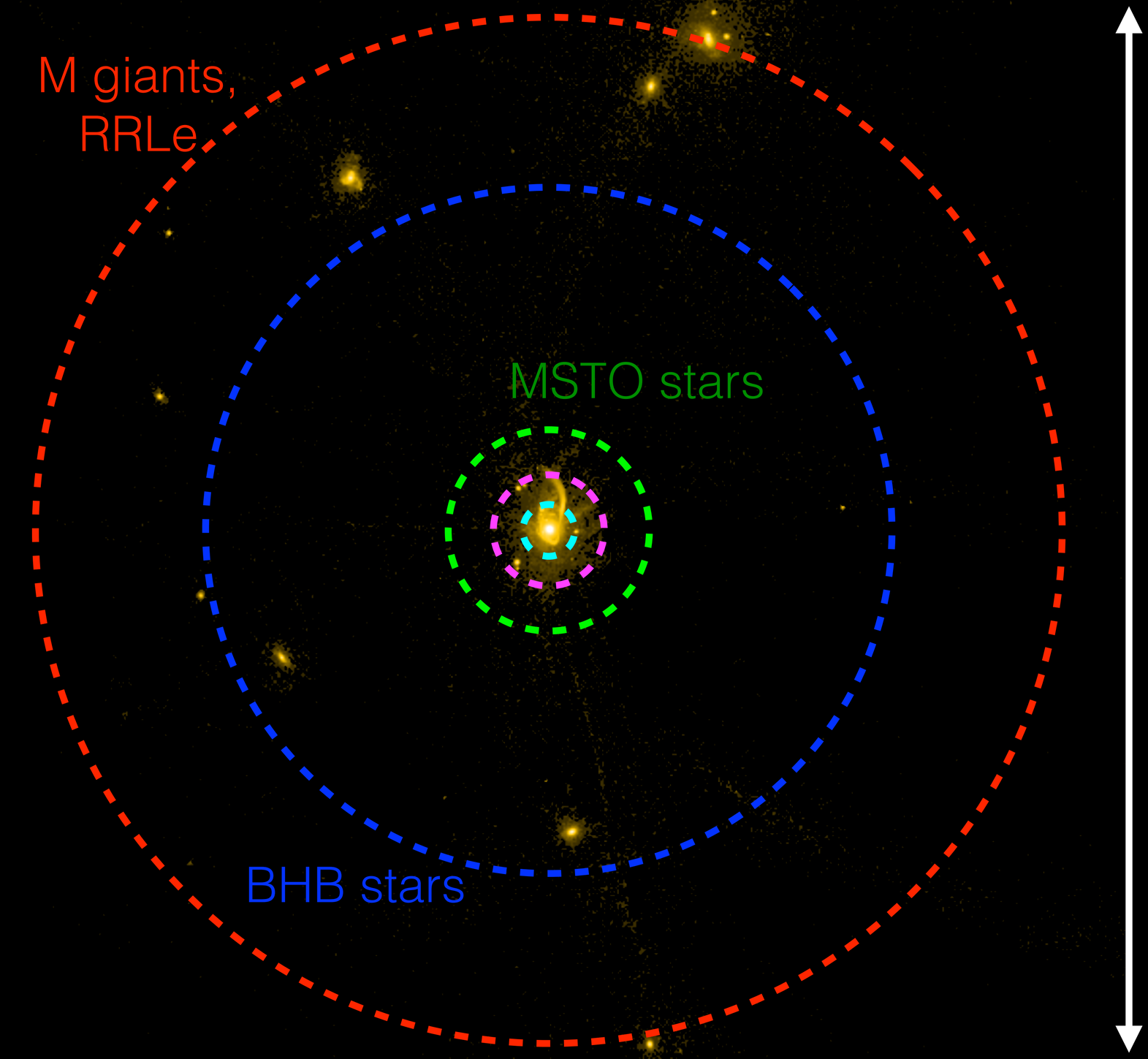

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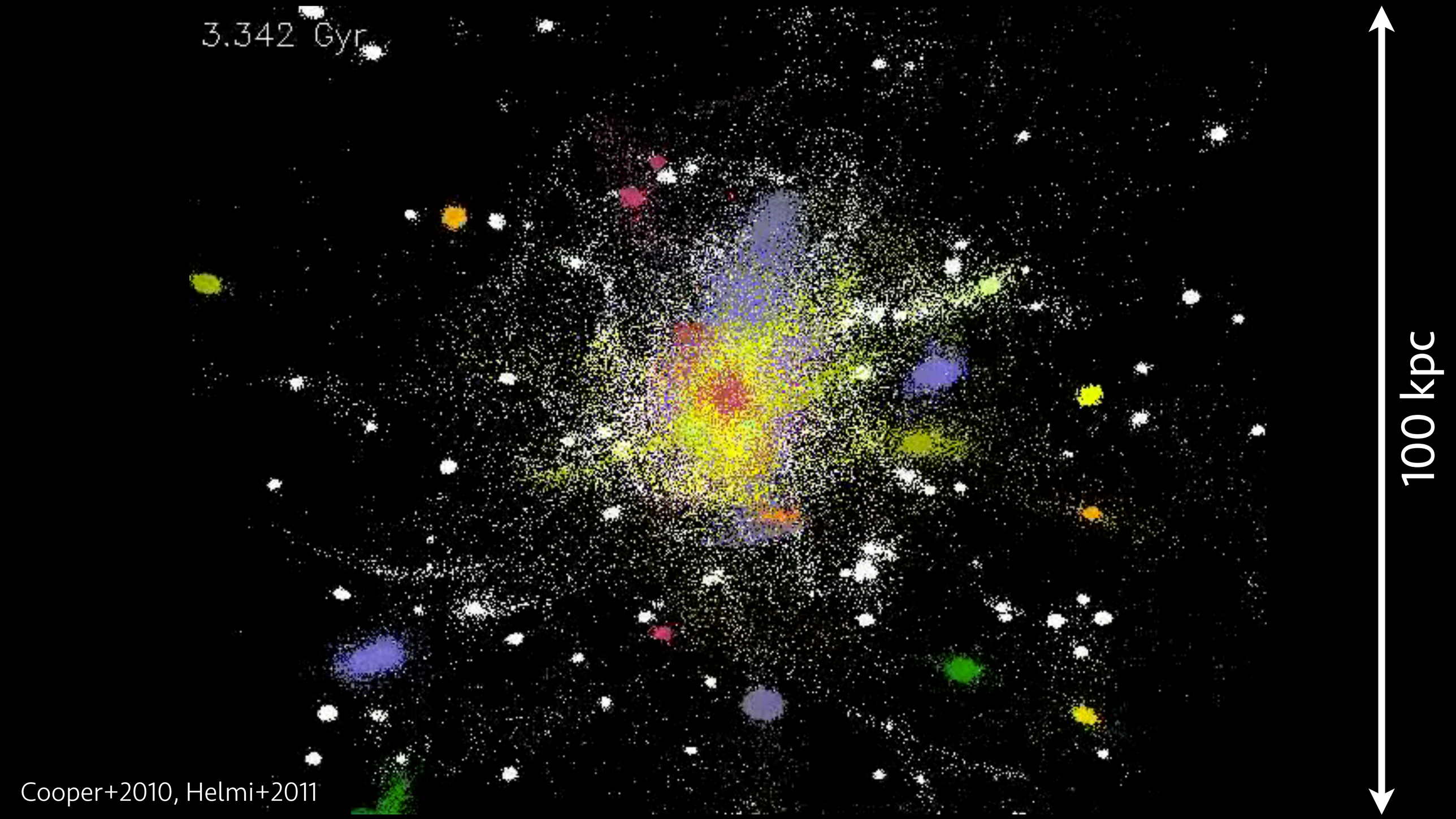
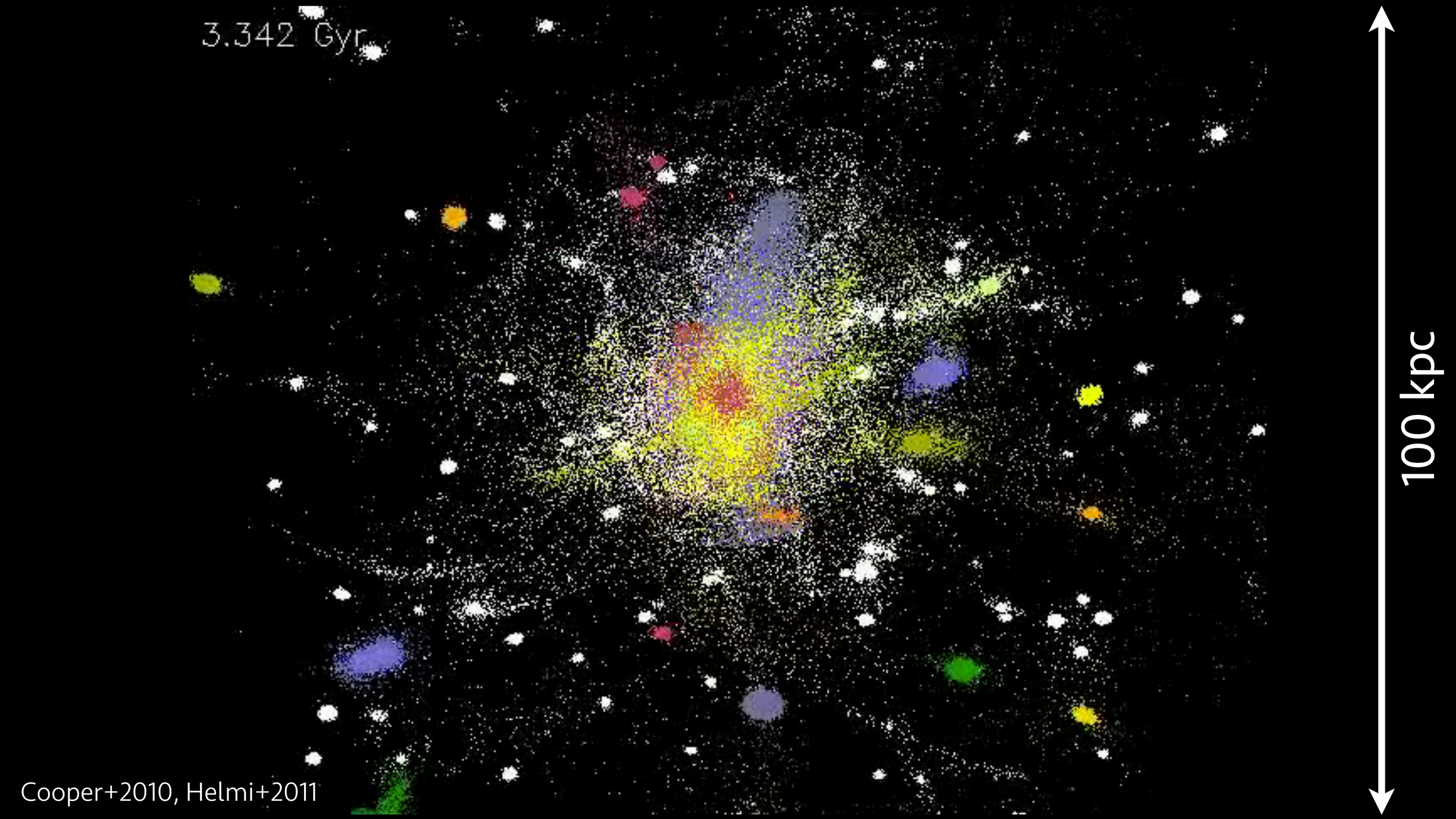


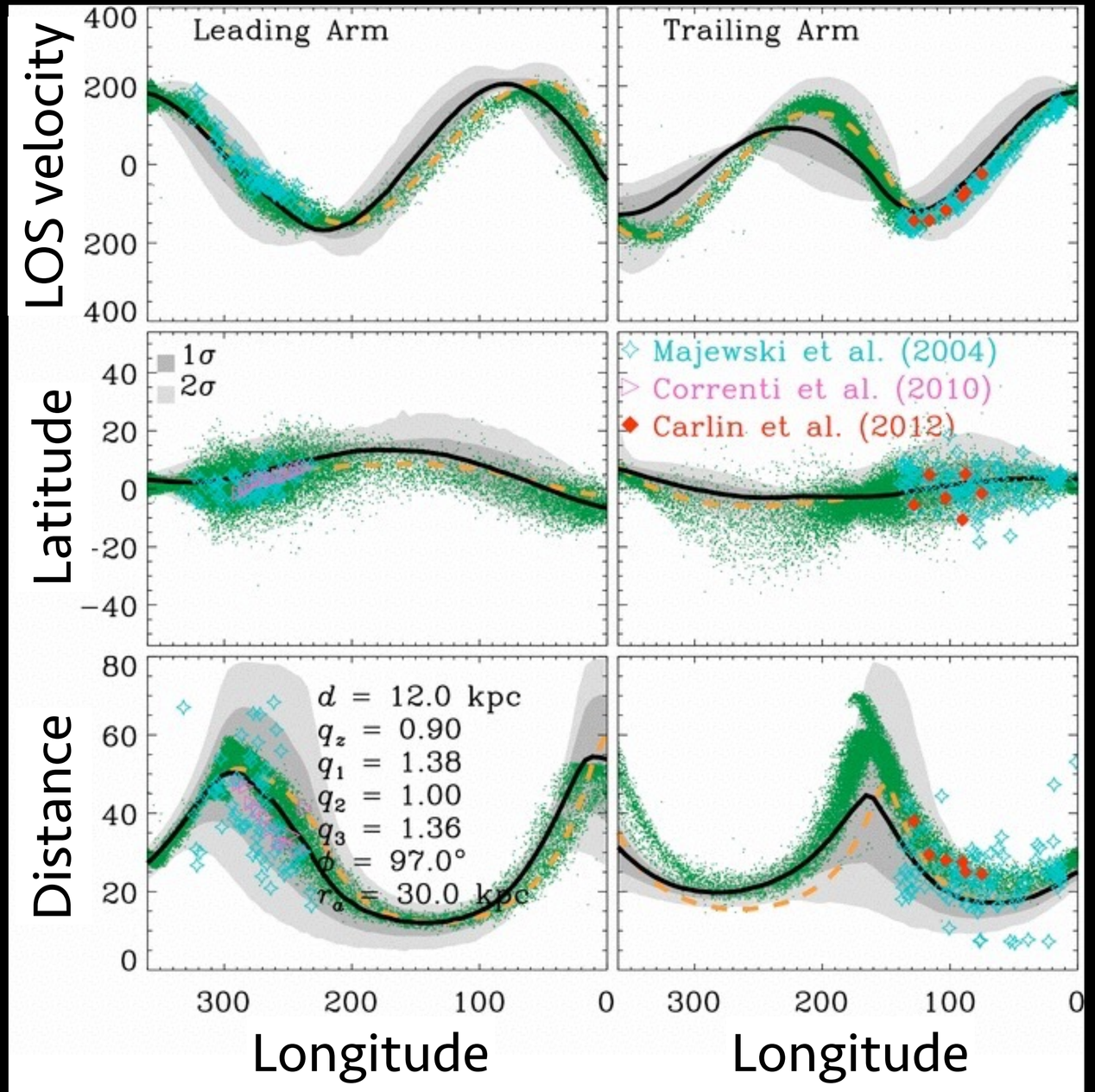
Cooper+2010, Helmi+2011



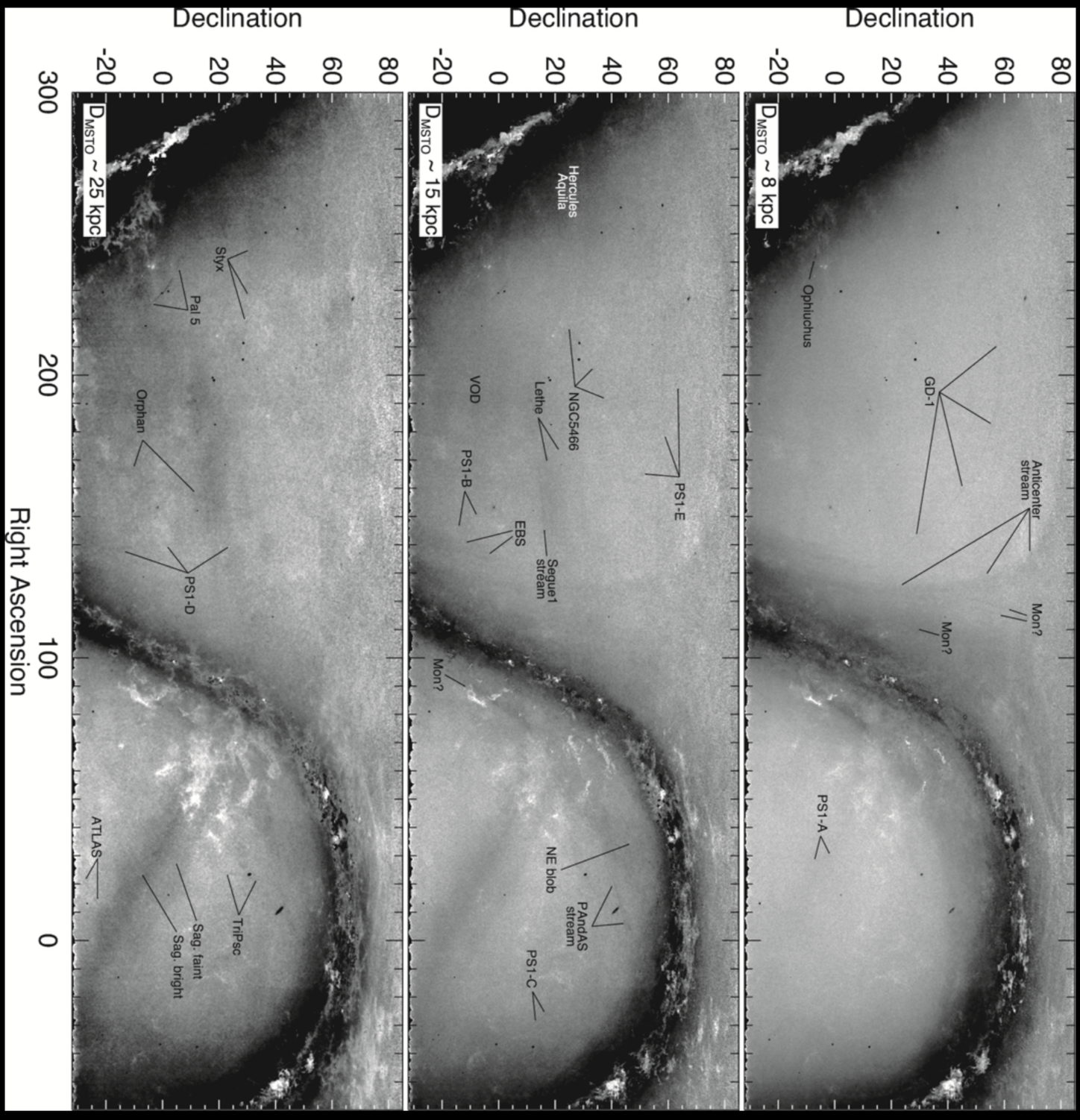
Cooper+2010, Helmi+2011

Constraints on the MW's shape with one stream are degenerate with the assumed functional form

Sagittarius Stream in triaxial dark matter halo:
Vera-Ciro & Helmi 2013;
Law & Majewski 2010



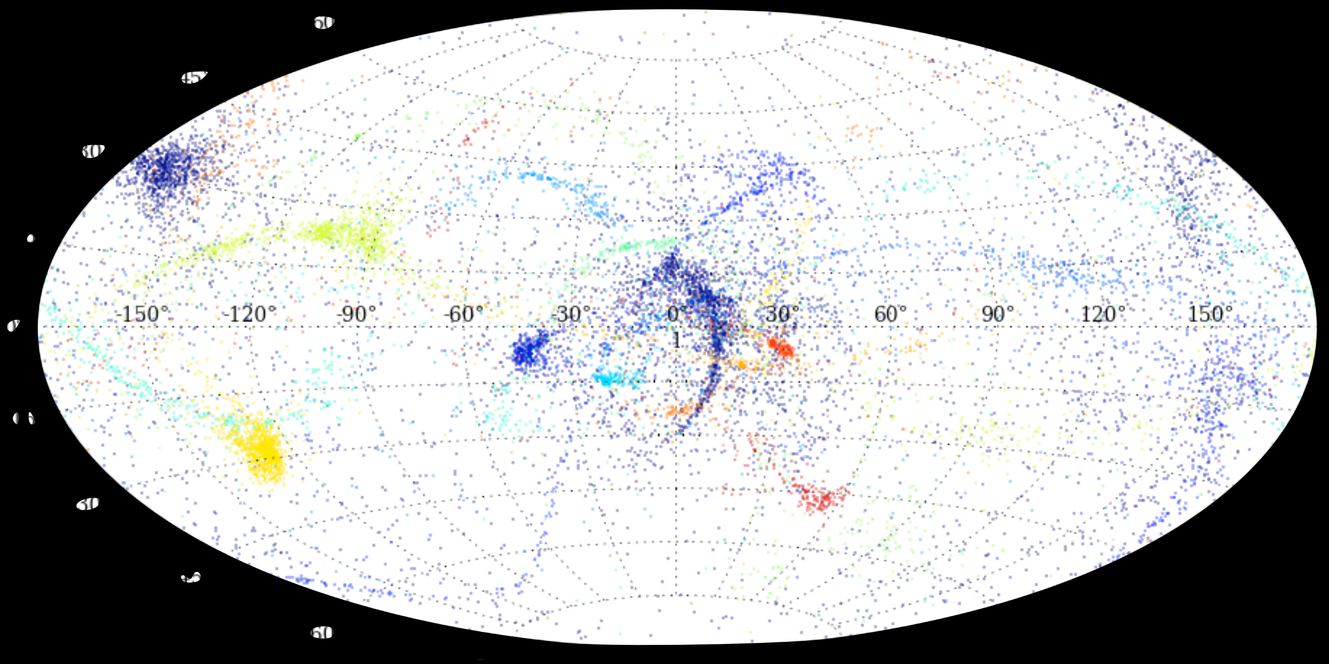
There are plenty of streams, even in the inner Galaxy



Bernard et al. 2016 (PanSTARRS)

The accreted stellar halo is clumpy in constants-of-motion space

Galactic coordinates



One particle = many stars

Sanderson, Helmi, & Hogg 2015
Sanderson et al. 2017a

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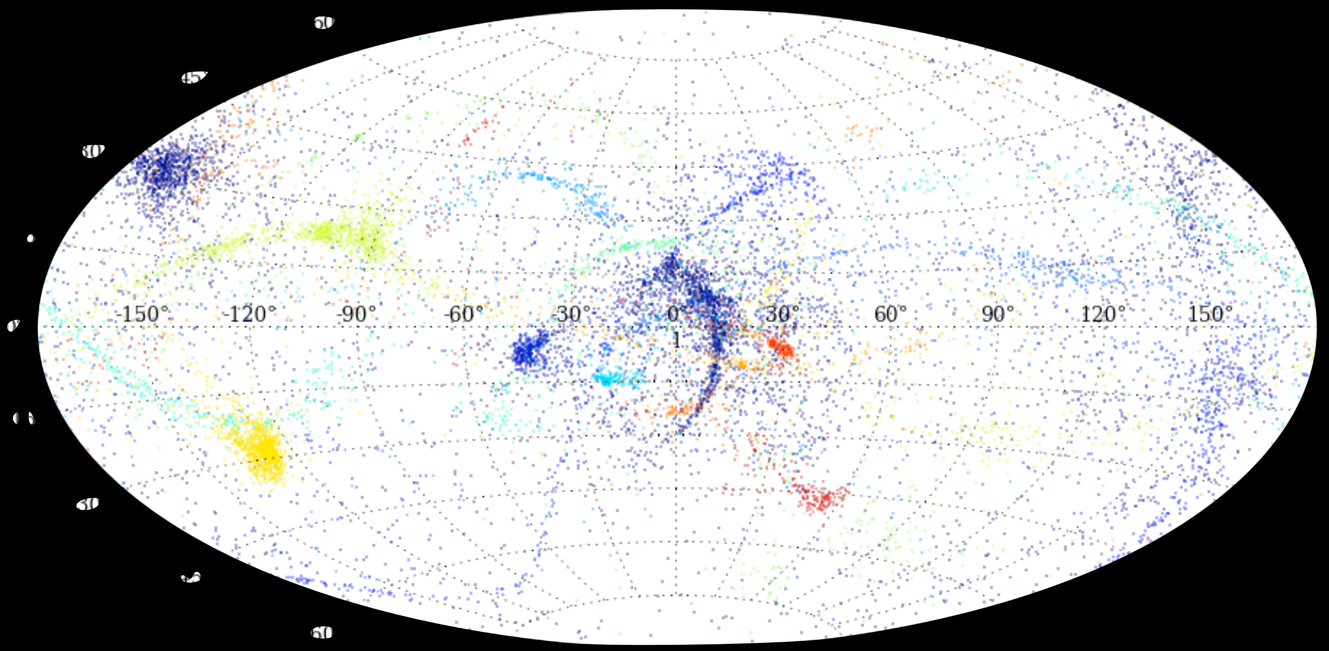

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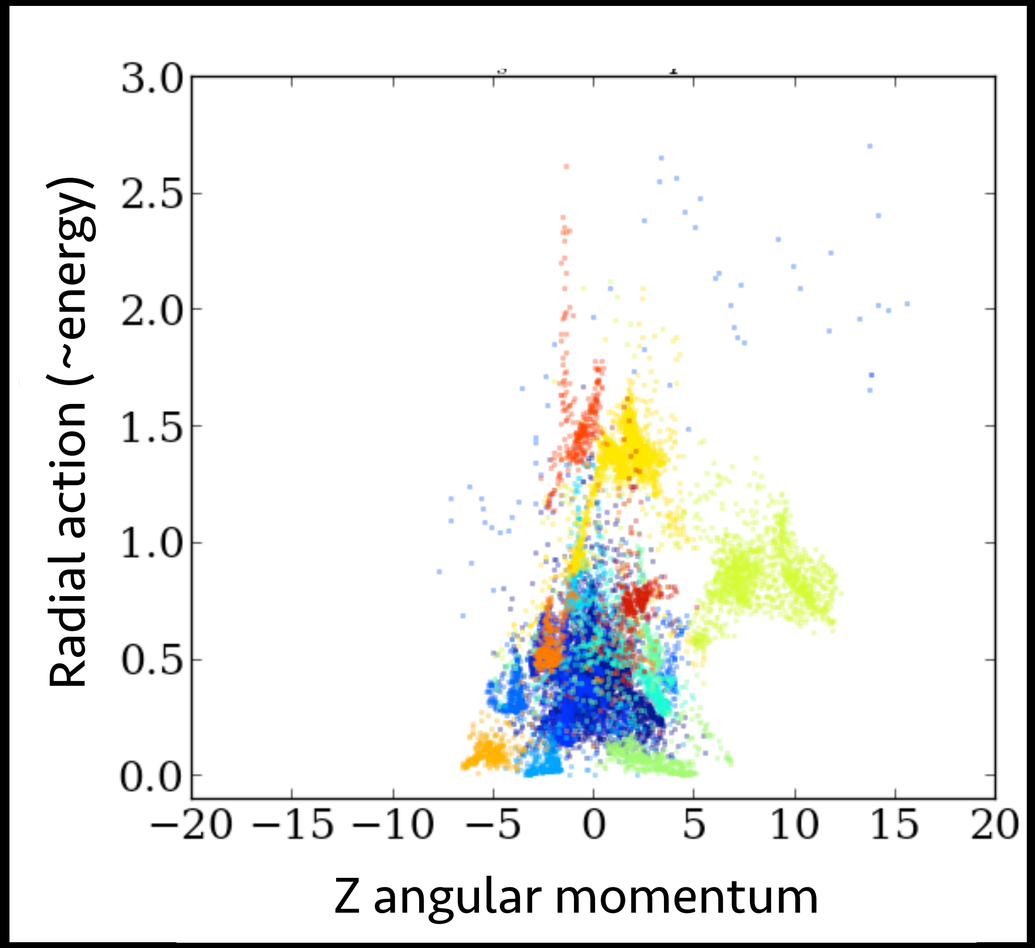
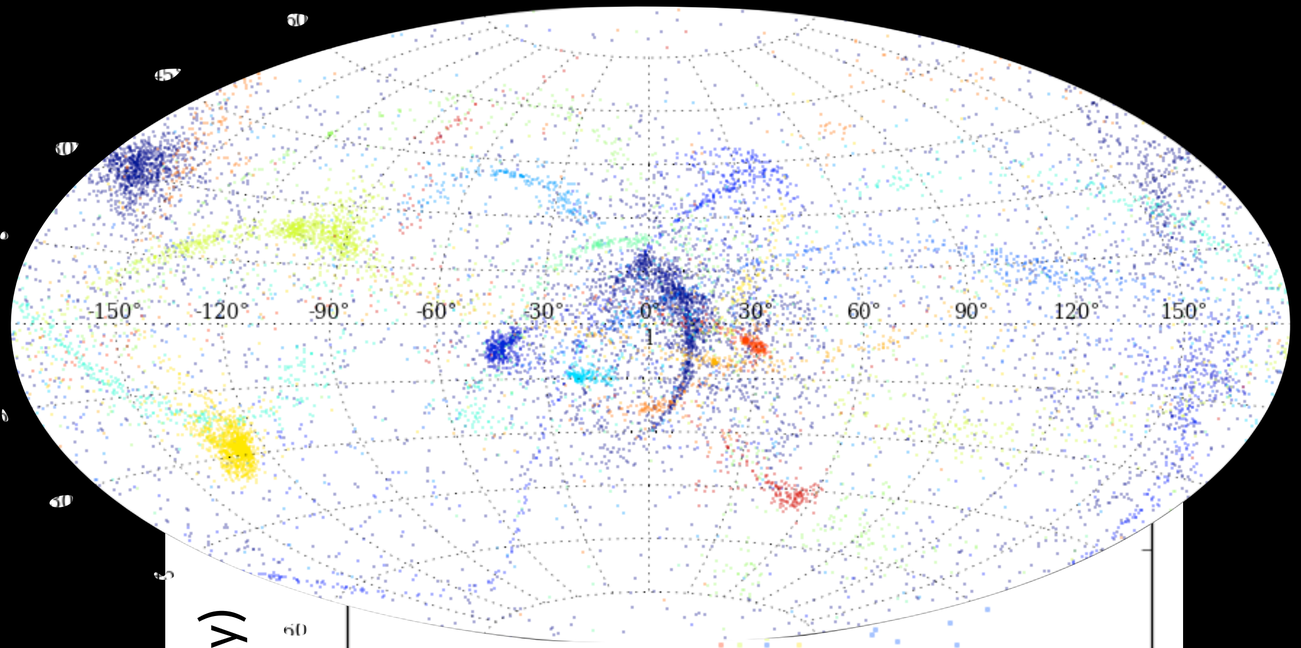
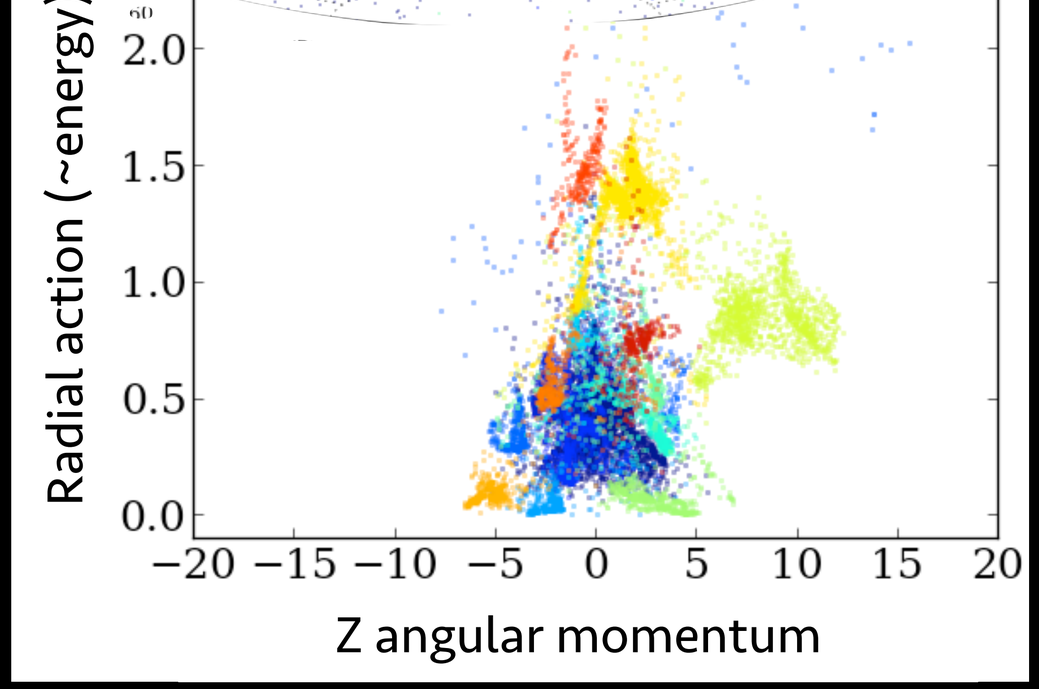


Constants of motion
(using best-fit mass model for host galaxy)

Sanderson, Helmi, & Hogg 2015
Sanderson et al. 2017a

The stellar halo constrains the MW's gravitational potential





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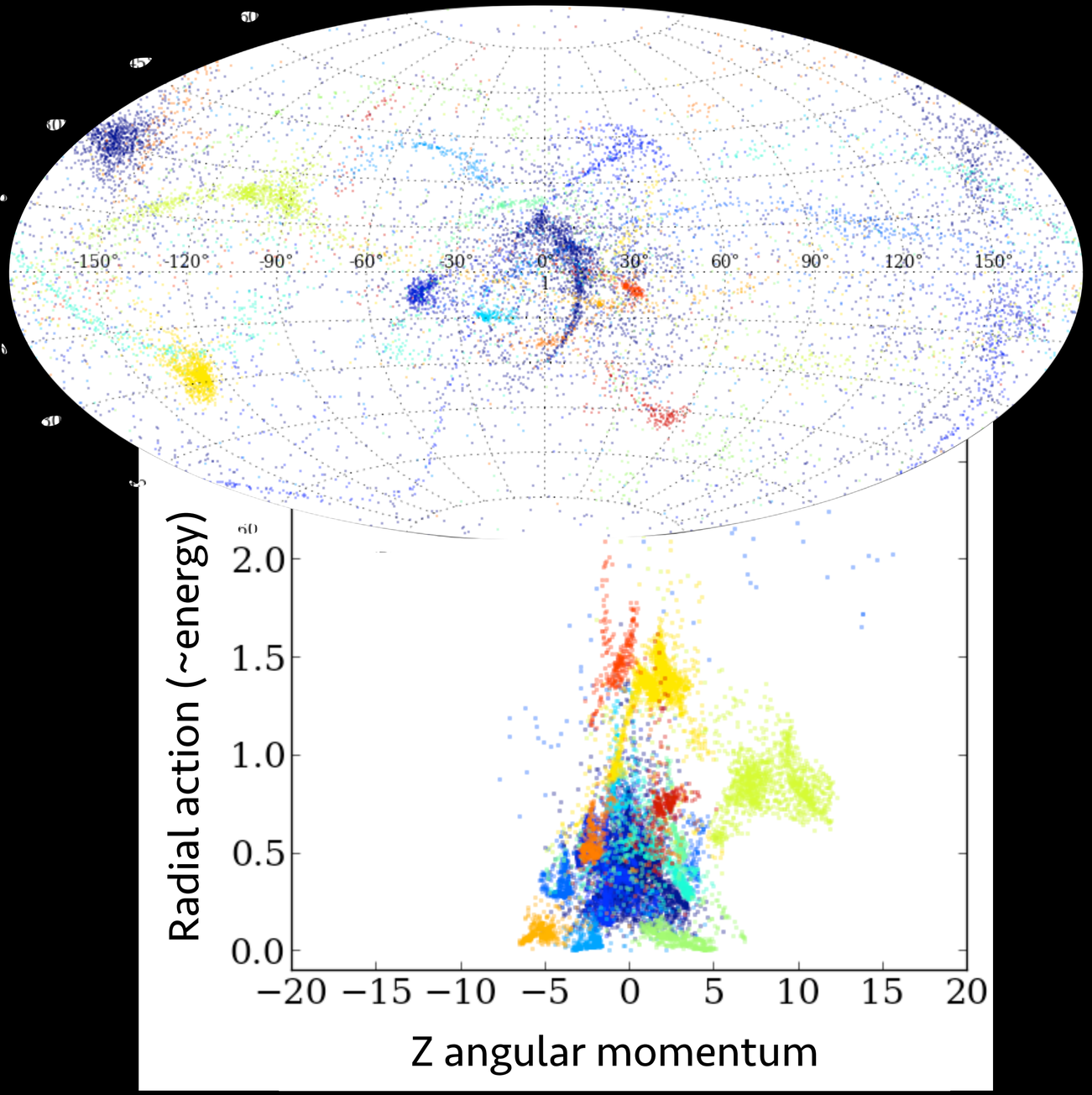
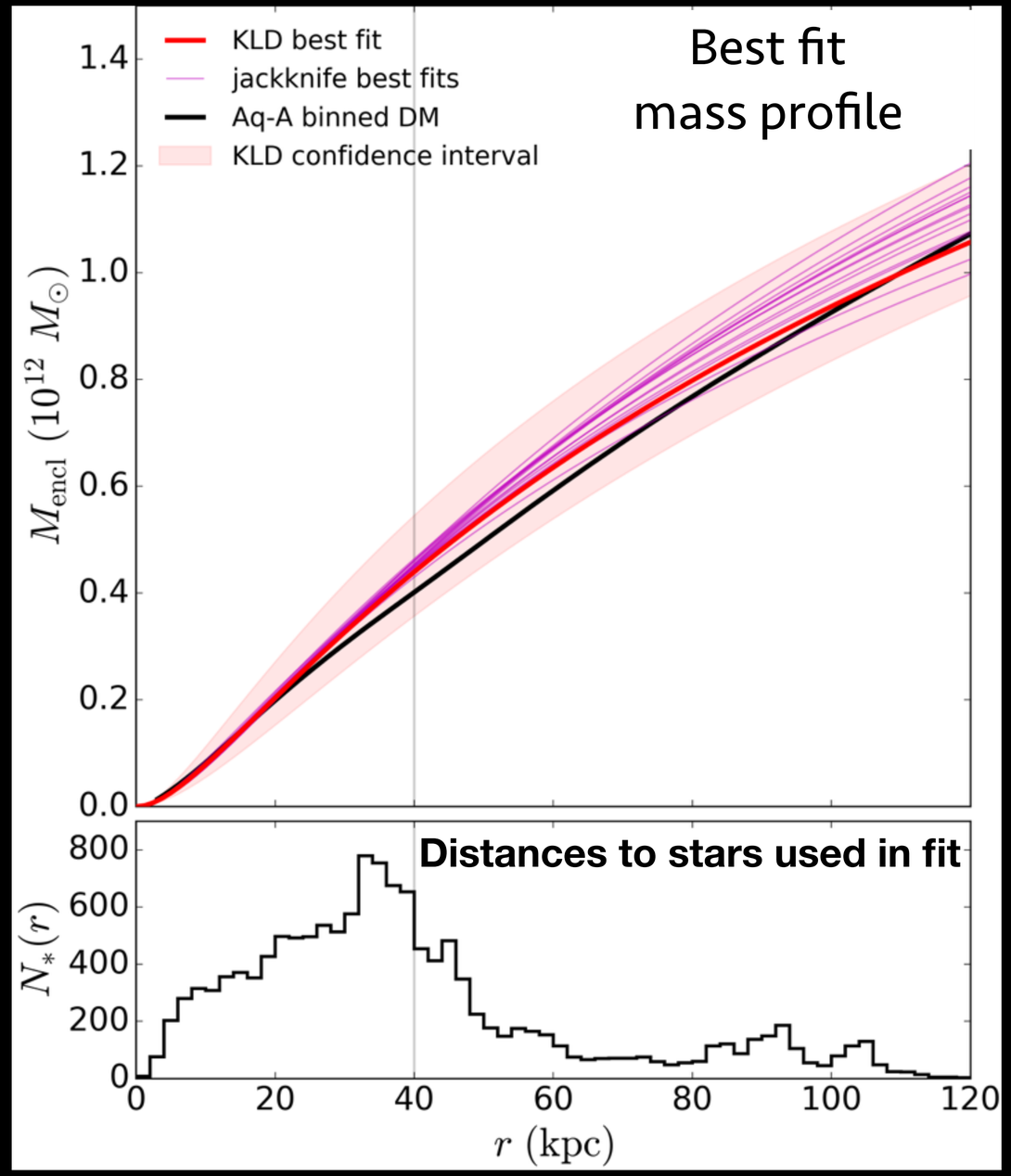
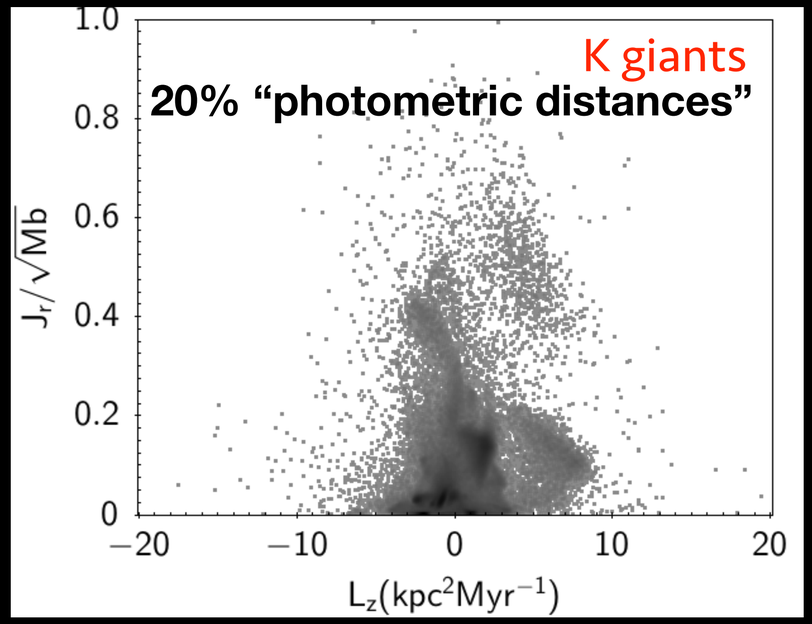
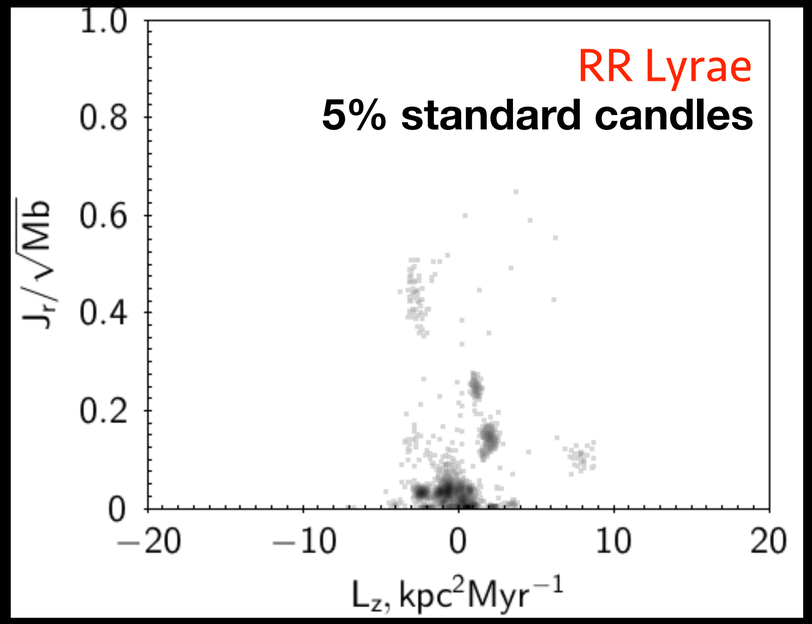




Sanderson et al. 2017a

The choice of stellar tracers matters





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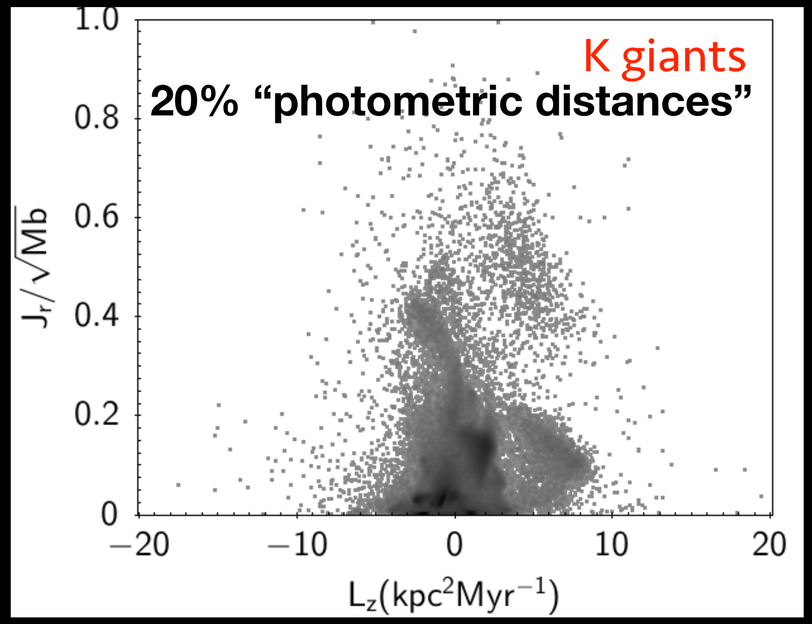
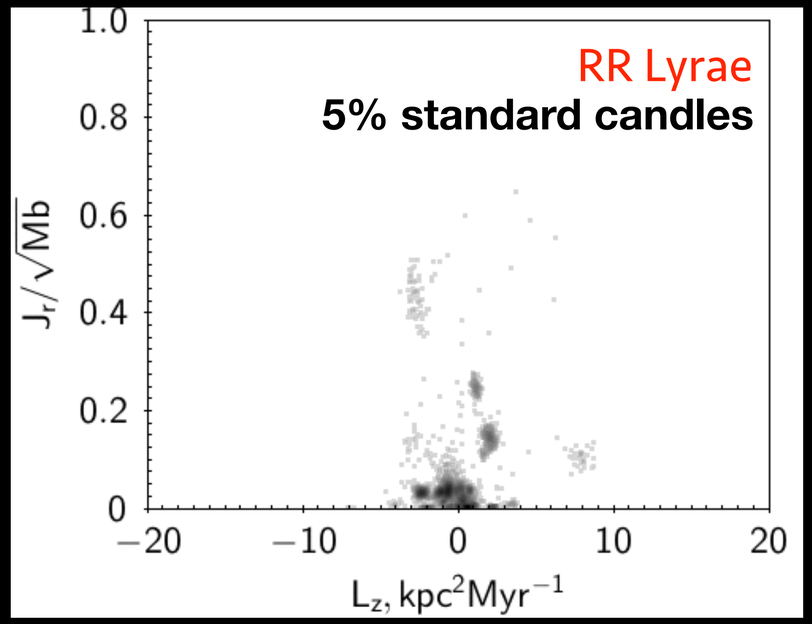
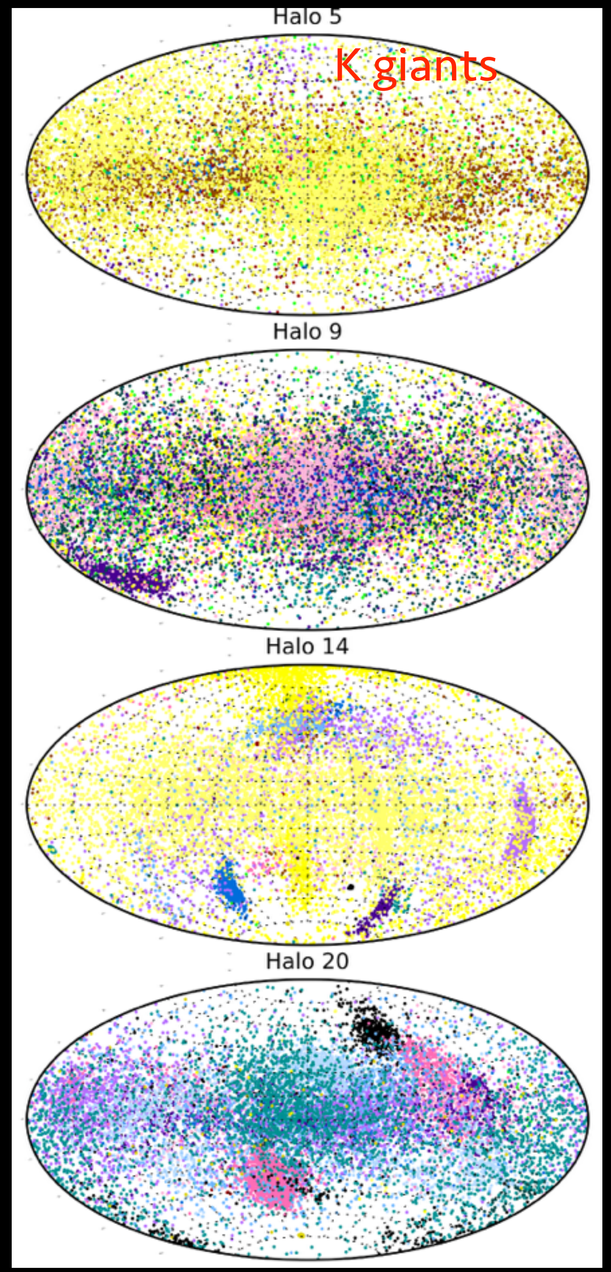
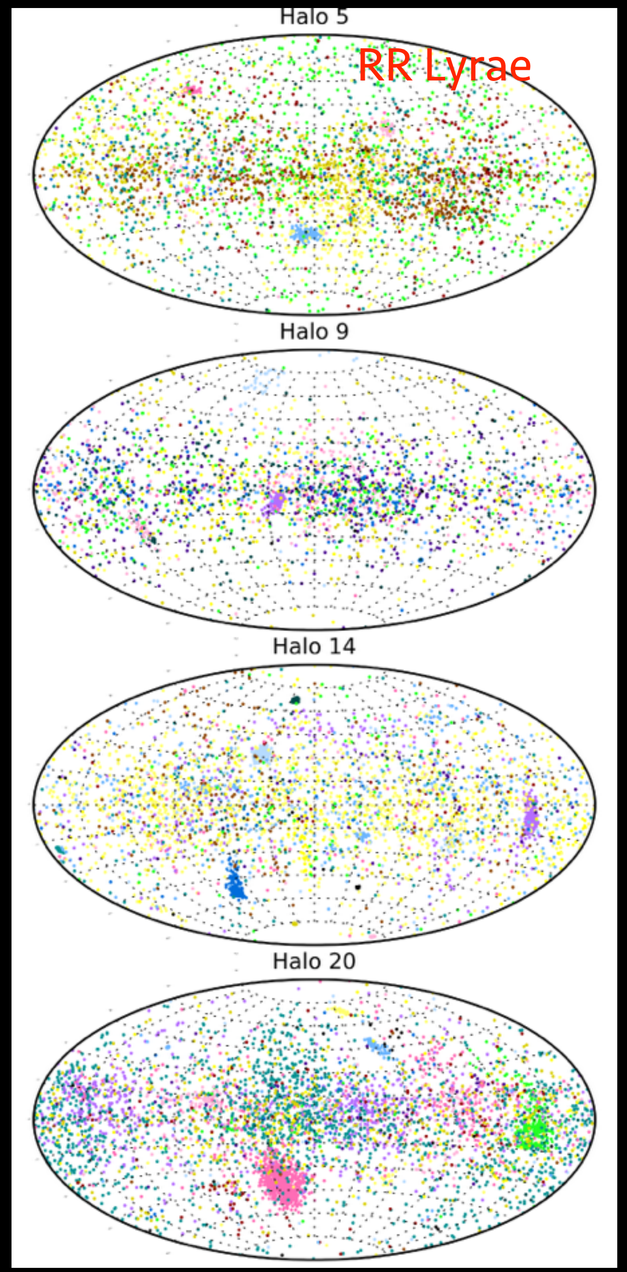




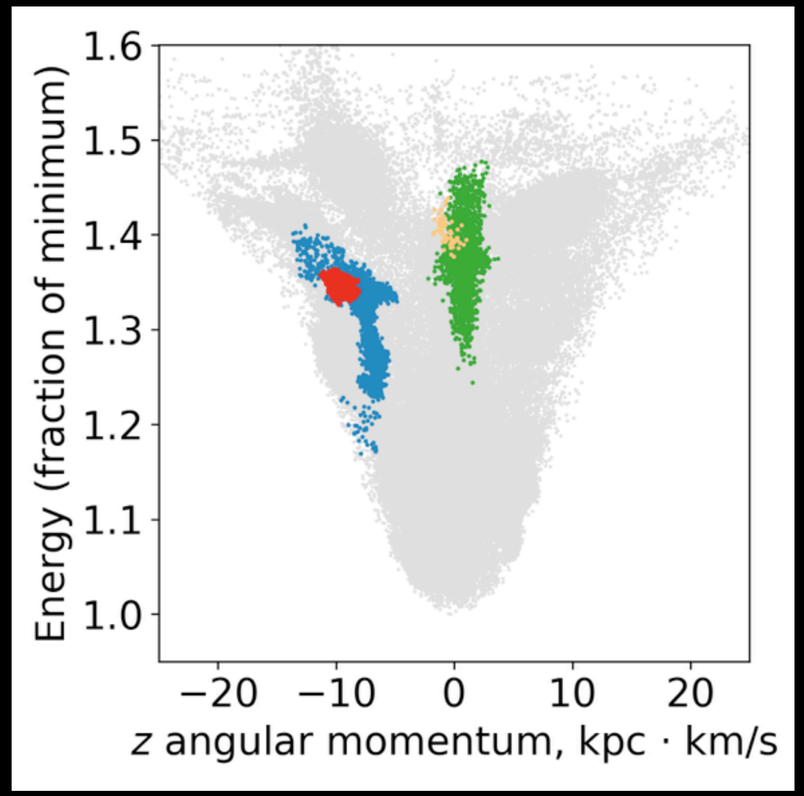
Sanderson 2016





Sanderson et al. 2017b

A route to untangling the stellar halo



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Sanderson et al. 2017c

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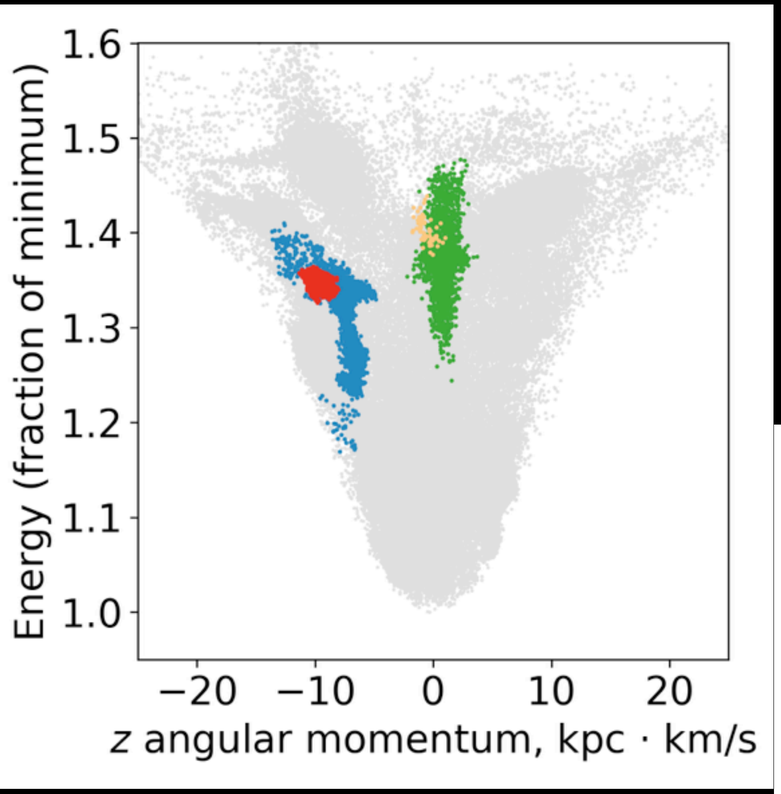

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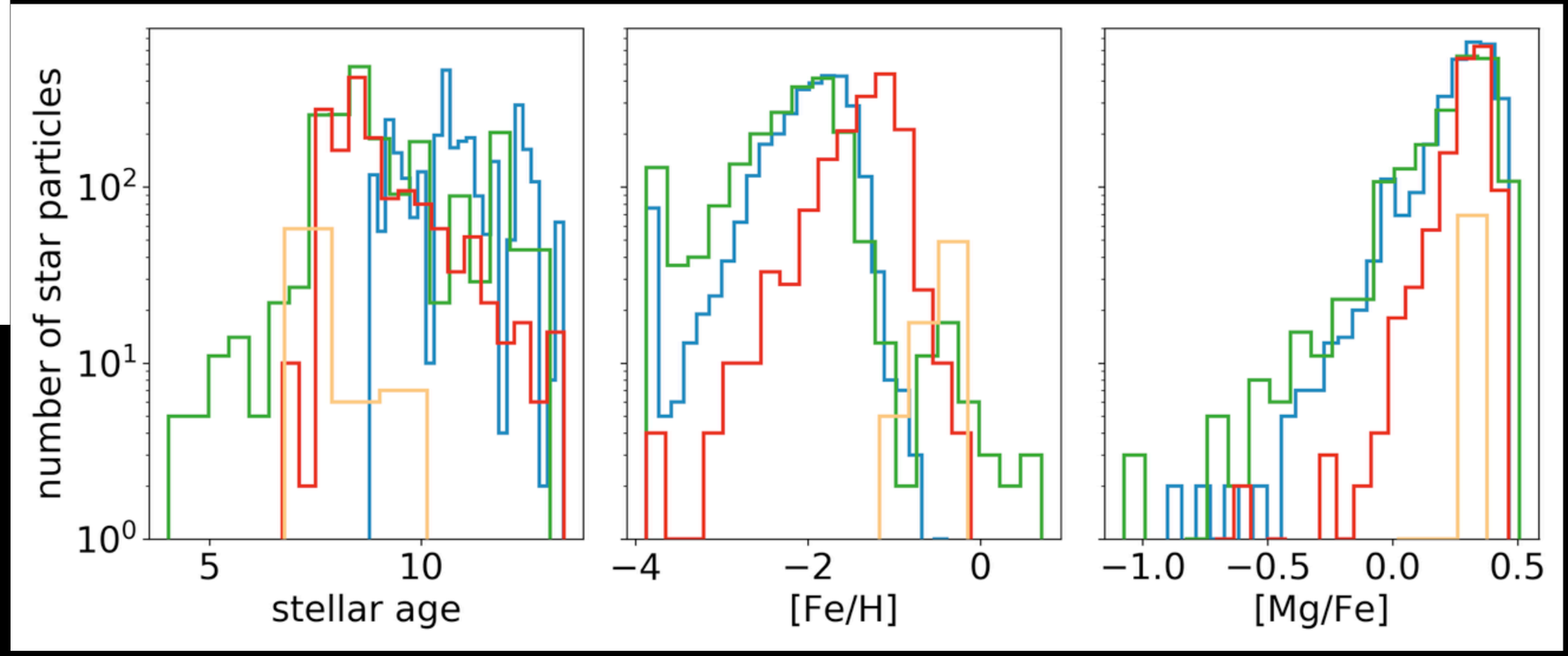
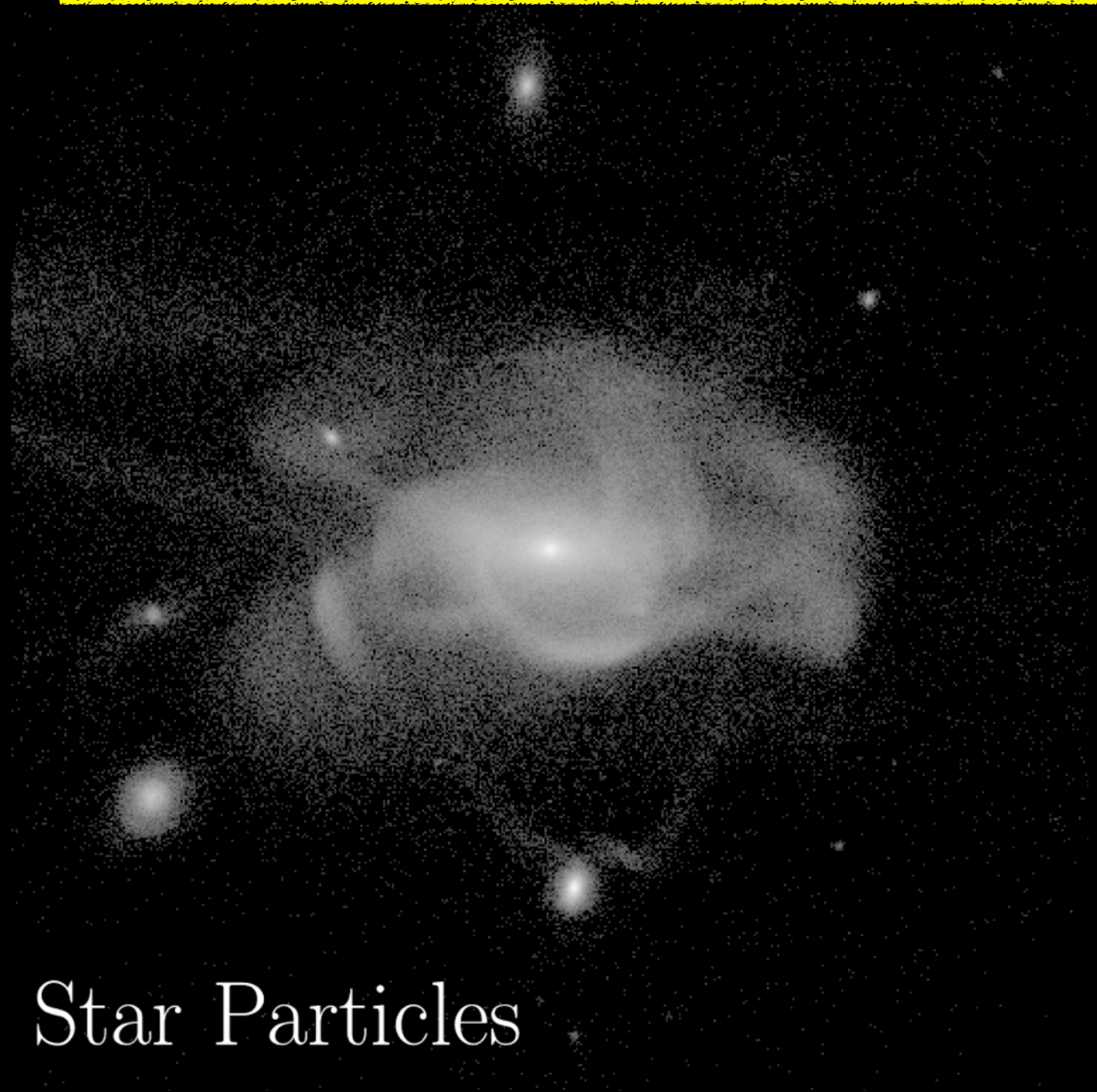


Sanderson et al. 2017c

Ananke
Sanderson, Wetzel, Loebman et al. in prep

- Cosmological sim with hydro —> realistic central MW
- 6D + 10 abundances + ages + …
- Complete stellar populations



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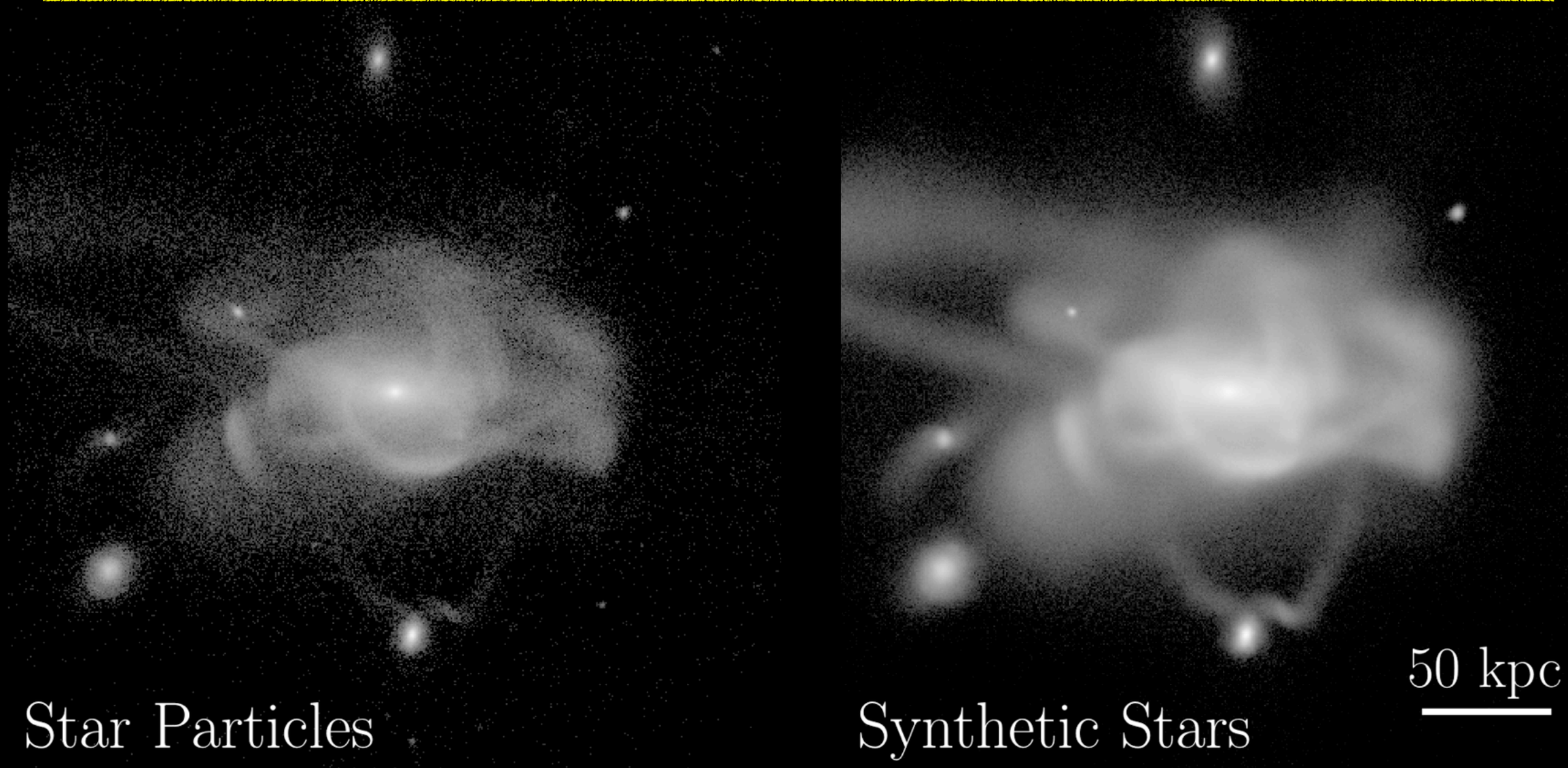

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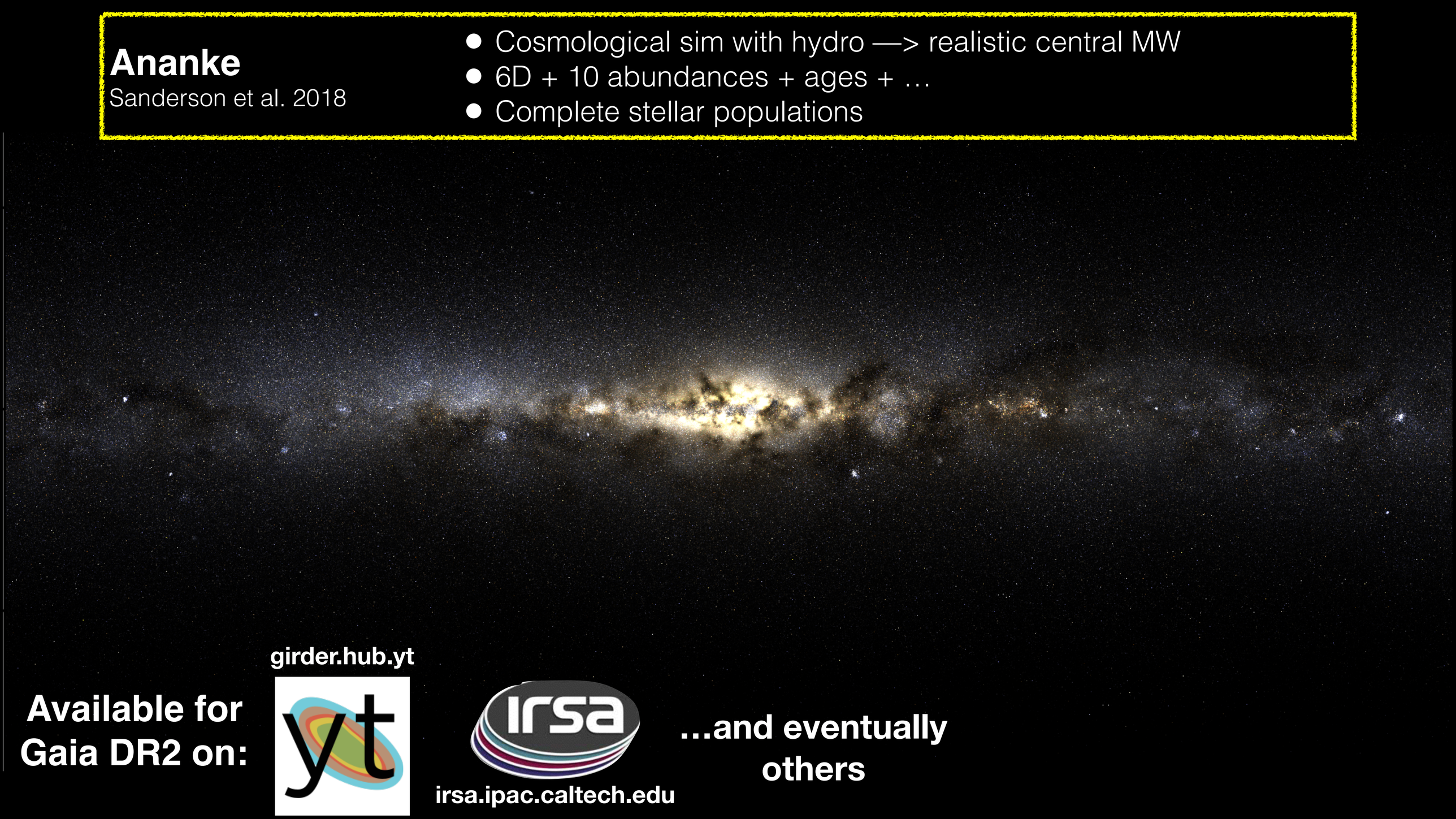
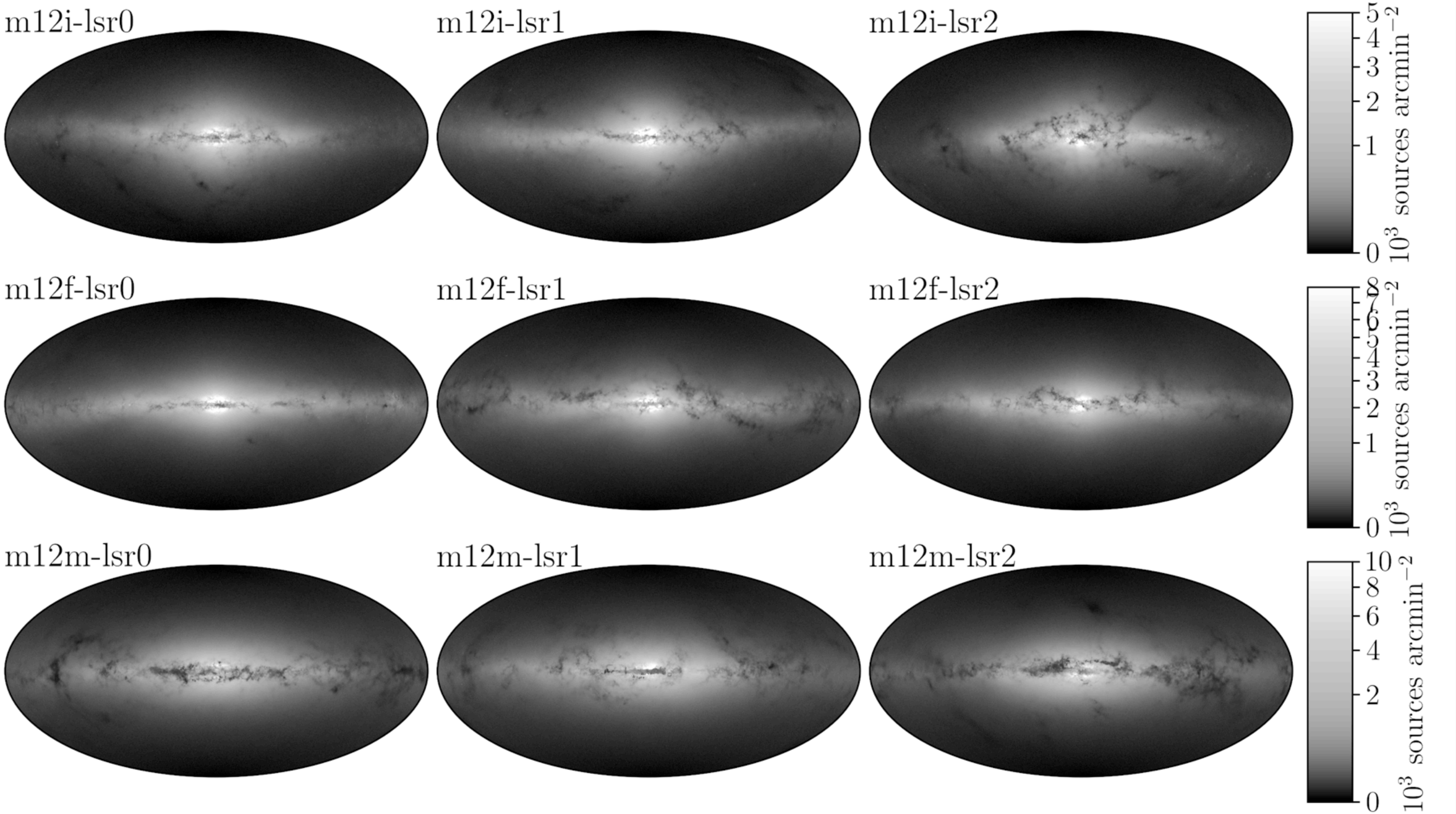


Available for Gaia DR2 on:

girder.hub.yt

irsa.ipac.caltech.edu

…and eventually others


m12i-lsr0
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m12m-lsr1
m12m-lsr2
0
1
2
3
4
5
10^3 sources arcmin^{-2}
0
1
2
3
4
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6
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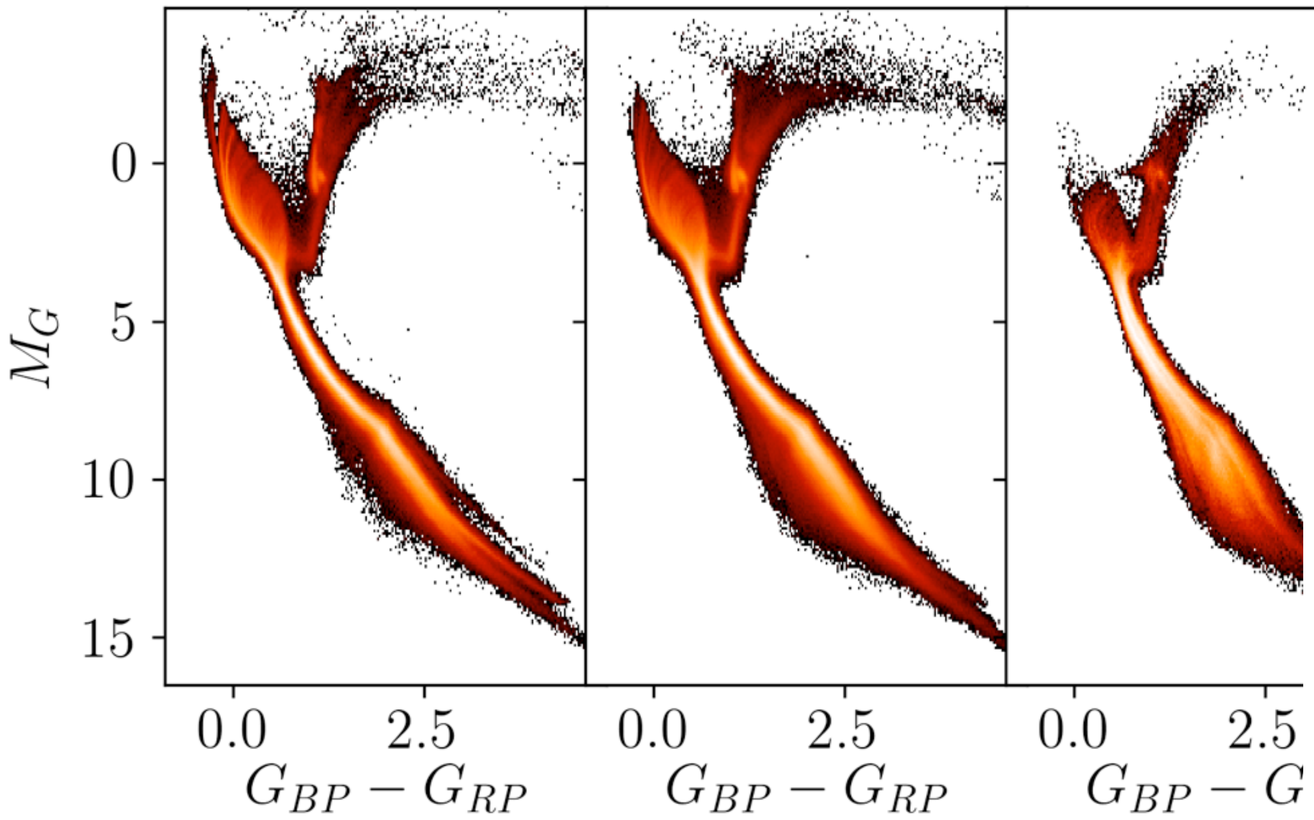
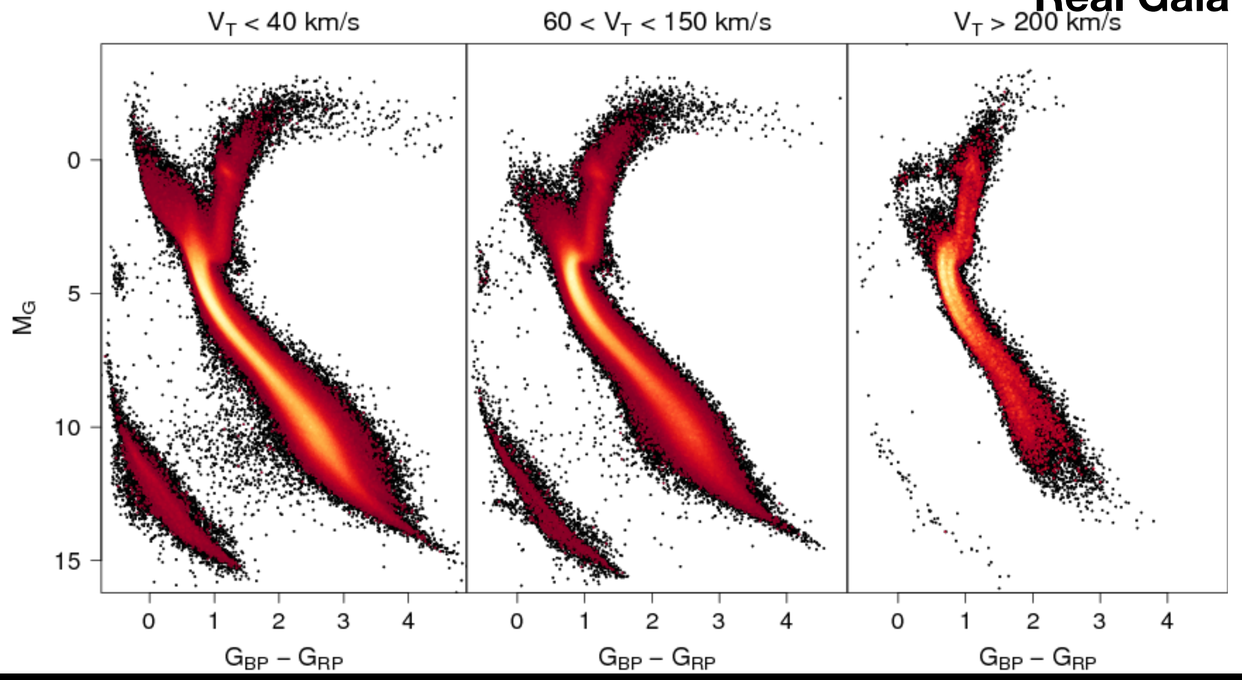
Mock Gaia $V_T < 40$ km s^{-1} $60 < V_T < 150$ km s^{-1} $V_T > 200$ km s^{-1}



Stars with:

- **10% or better parallax uncertainty**
- **extinction < 0.015 mag**
- **G mag uncertainty <0.22 mag**
- **G_{Bp}, G_{Rp} uncertainty < 0.054 mag**

Real Gaia



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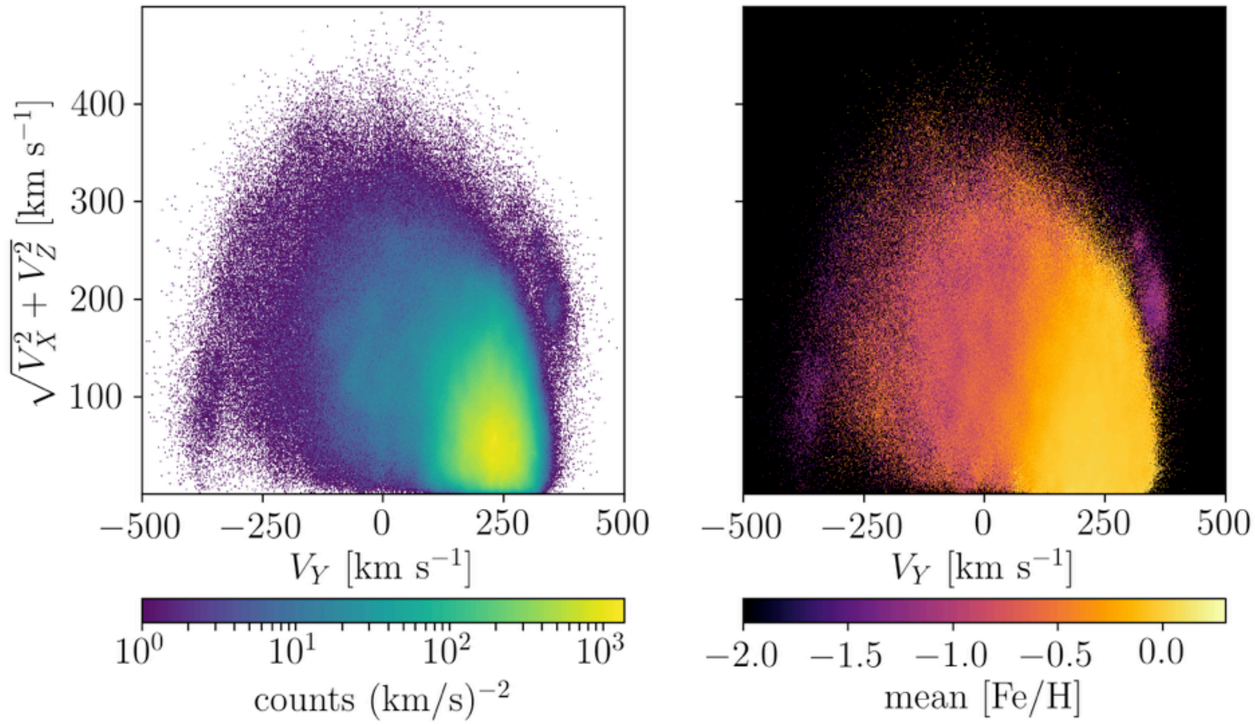
m12i-lsr0



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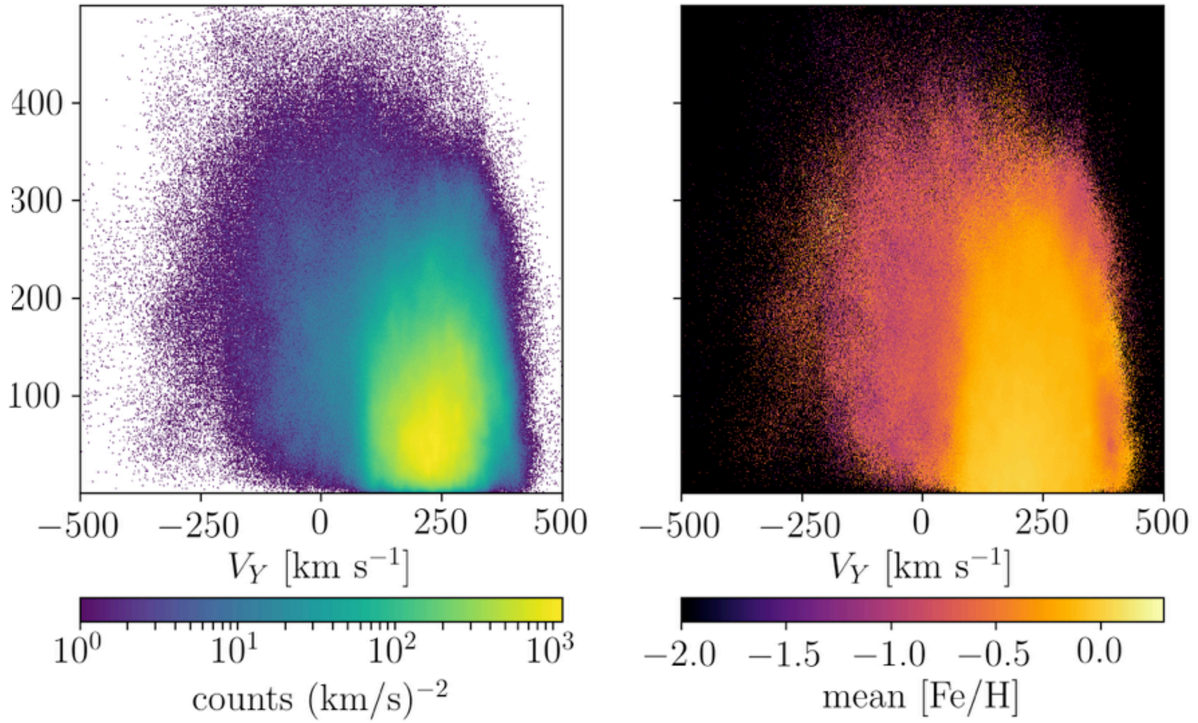
m12f-lsr2



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Ananke

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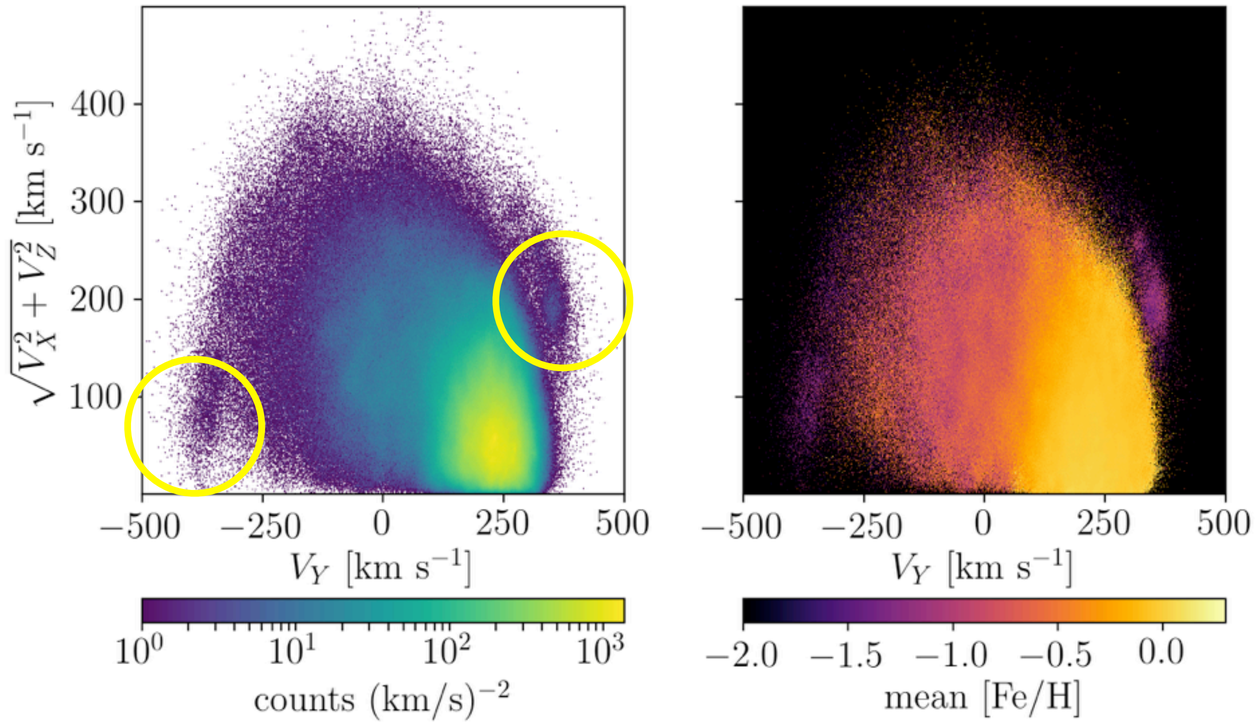

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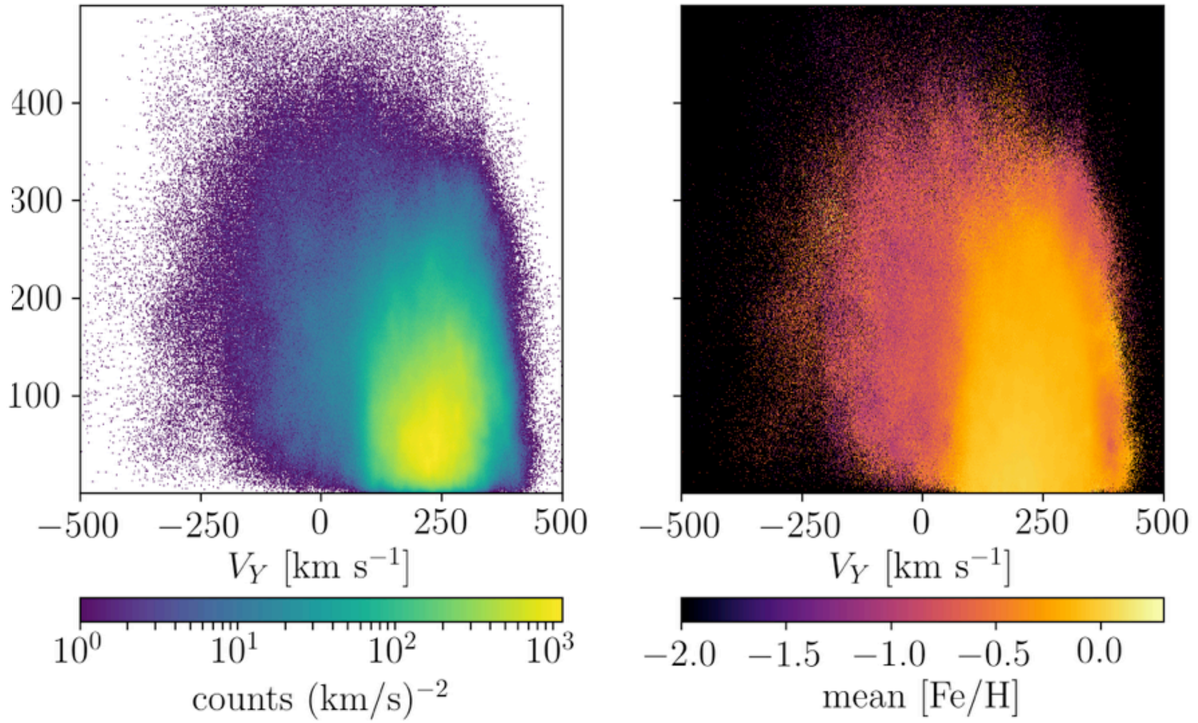

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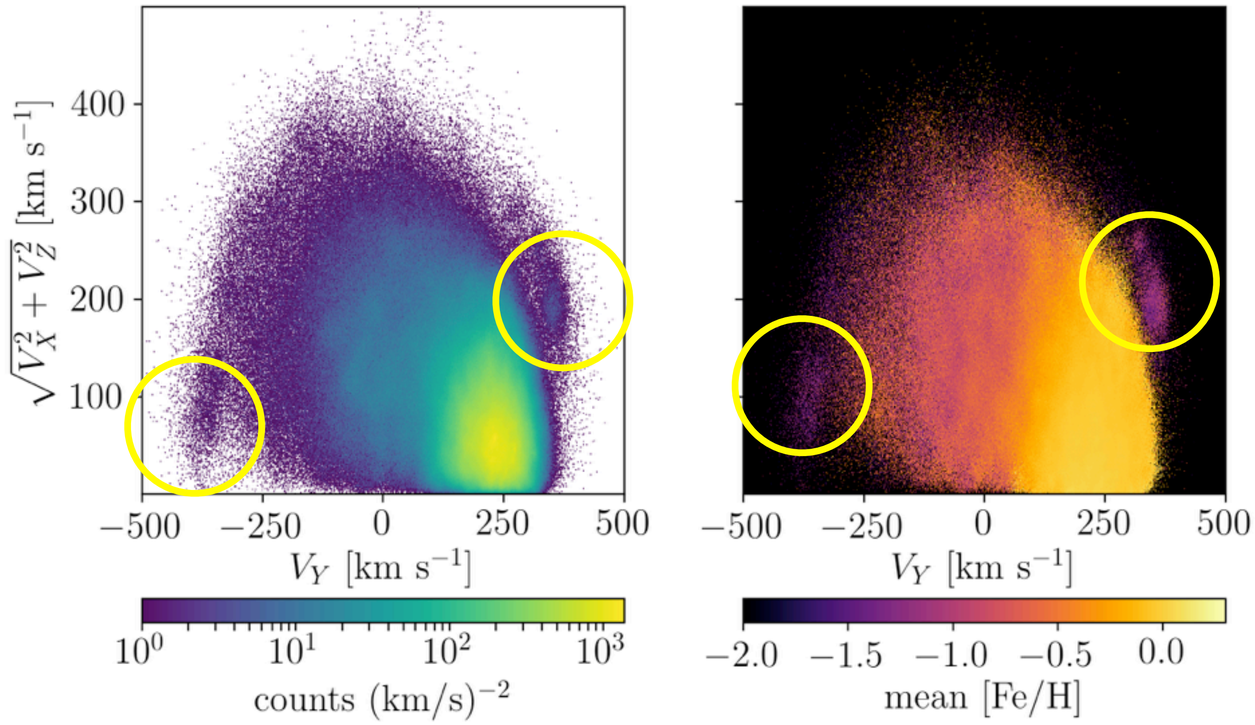

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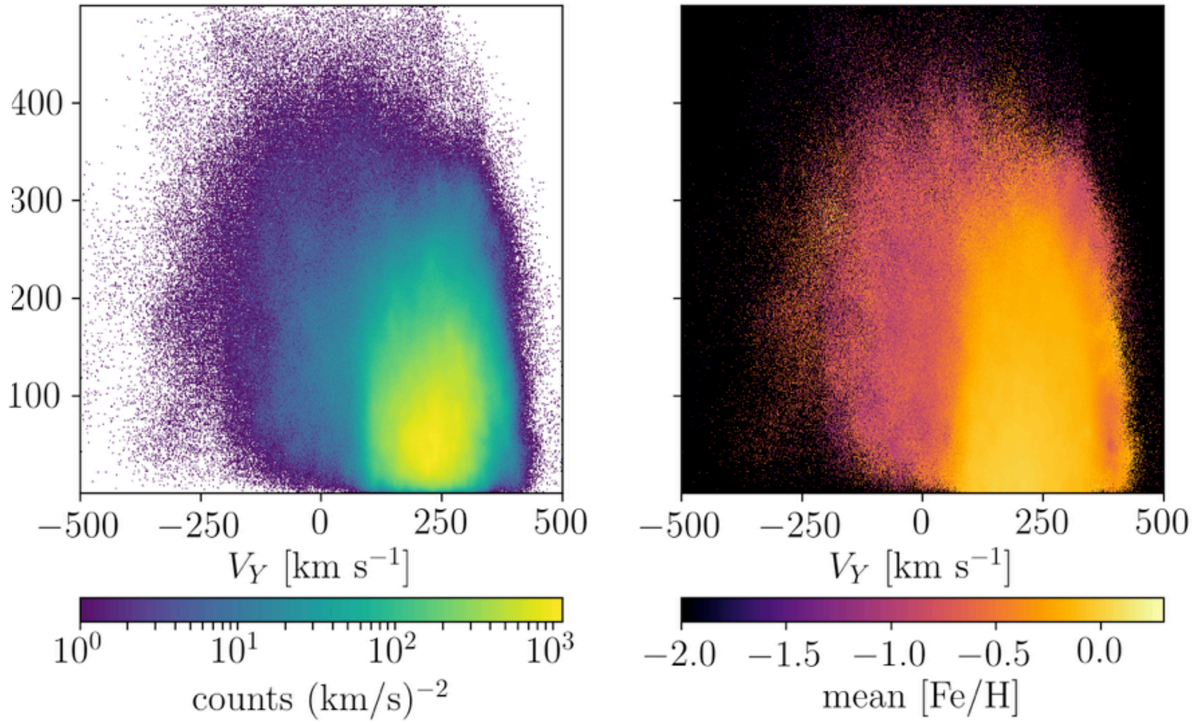
m12f-lsr2



Available for Gaia DR2 on:

girder.hub.yt

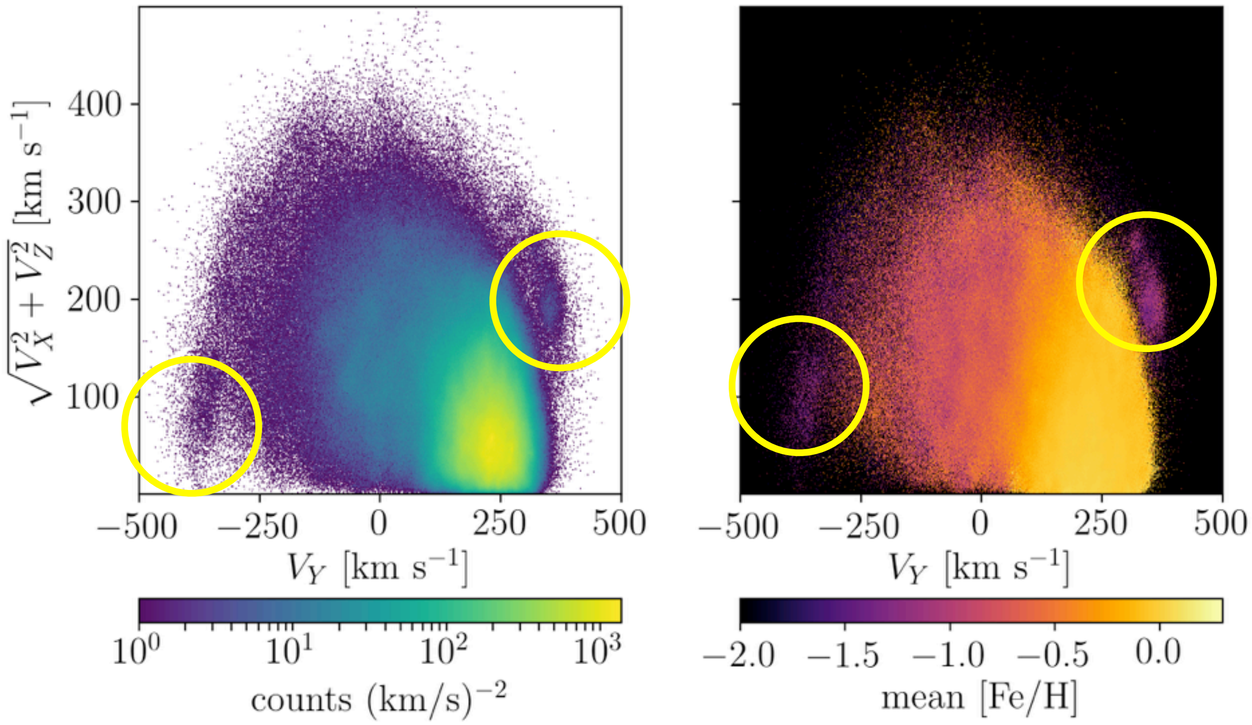
irsa.ipac.caltech.edu

Ananke

Sanderson et al. 2018

- Cosmological sim with hydro —> realistic central MW
- 6D + 10 abundances + ages + …
- Complete stellar populations

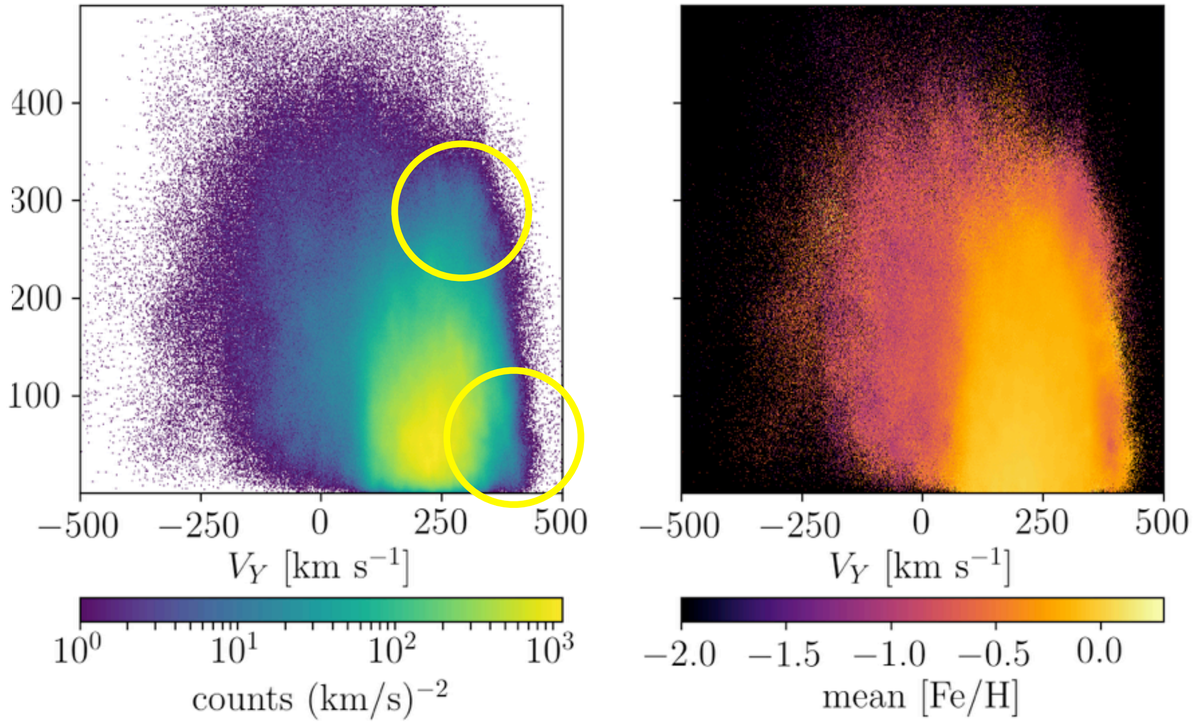
m12i-lsr0



Stars with:

- **10% or better parallax uncertainty**
- **extinction < 0.015 mag**
- **G mag uncertainty <0.22 mag**
- **G_{Bp}, G_{Rp} uncertainty < 0.054 mag**

m12f-lsr2



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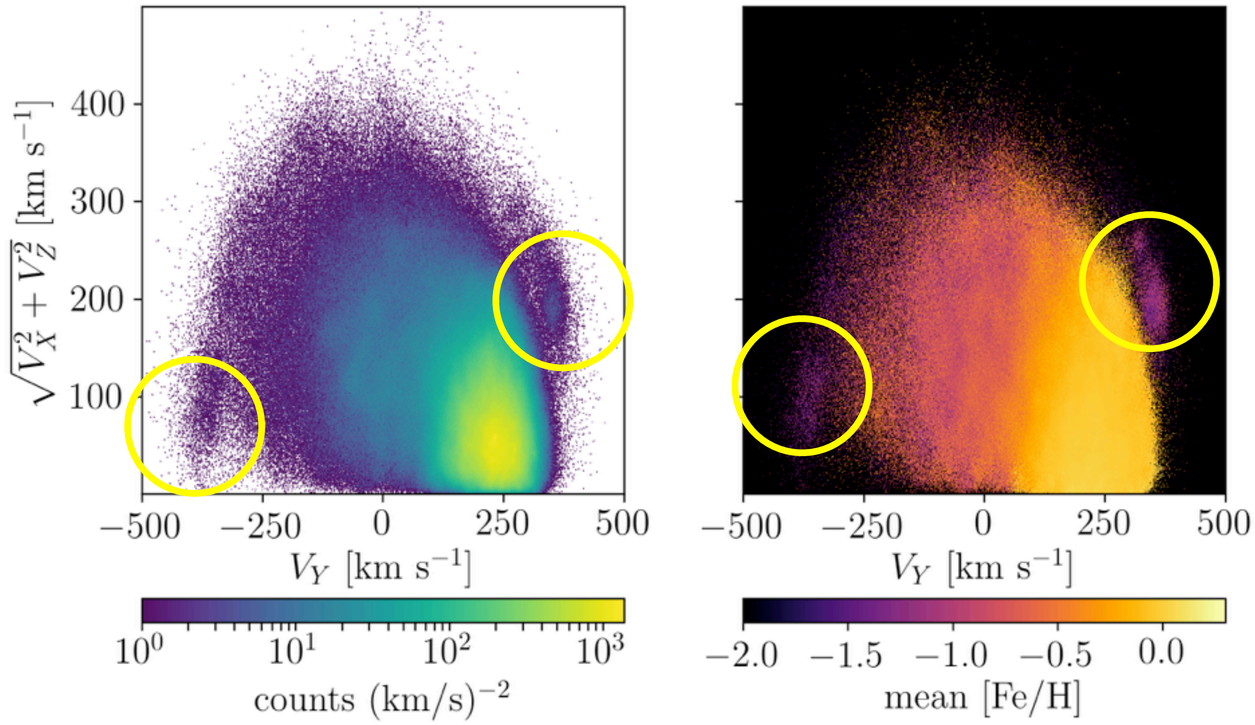

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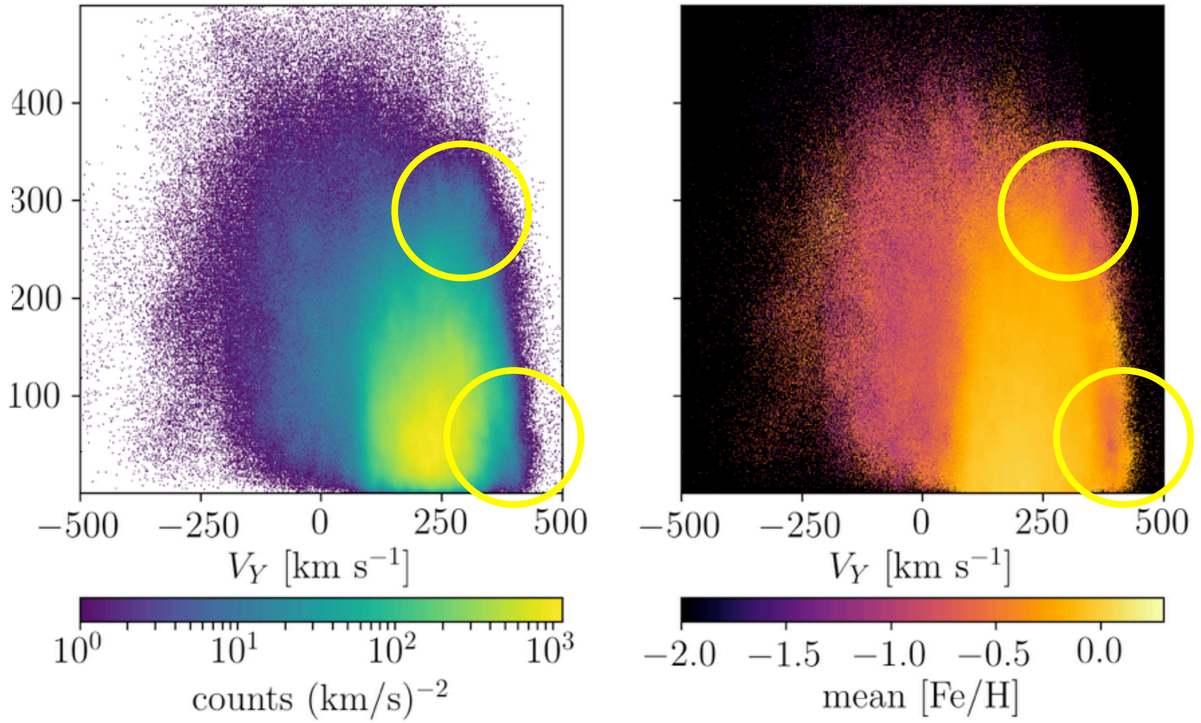

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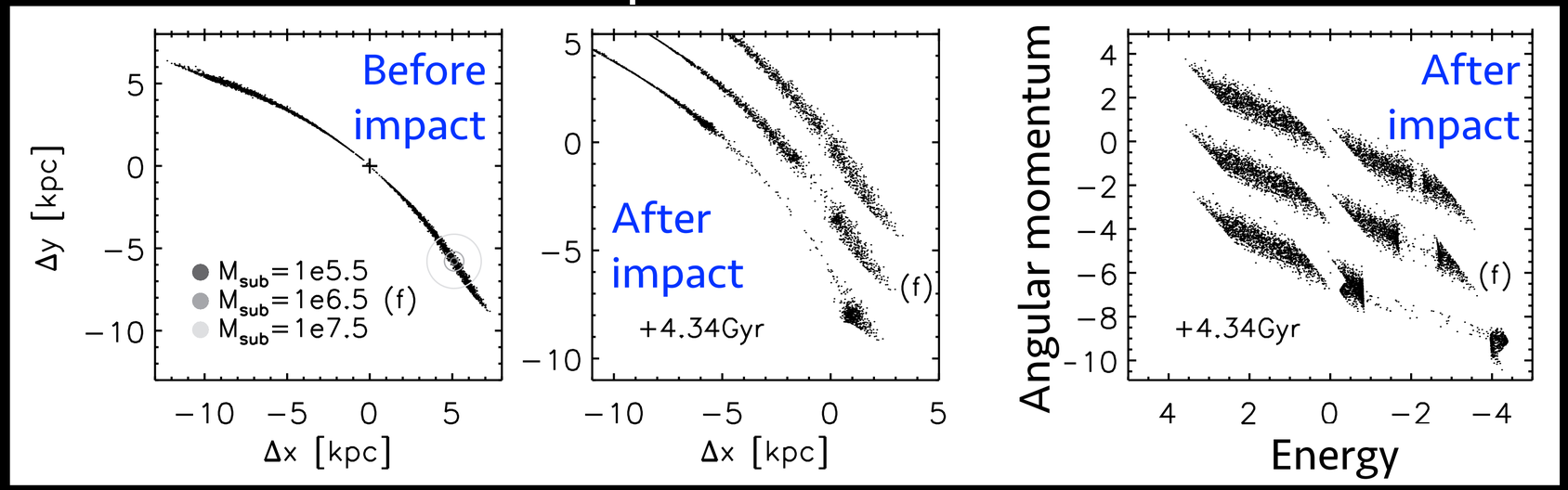
Cold tidal streams can be disrupted by dark substructure

Controlled numerical experiments



Yoon, Johnston, & Hogg 2011

Degree of disruption depends on
mass,
impact parameter,
velocity
of perturber

$$S \propto \frac{GM_{\rm sub}}{v_{\rm rel}^2 b}$$

for b ~ scale radius of perturber

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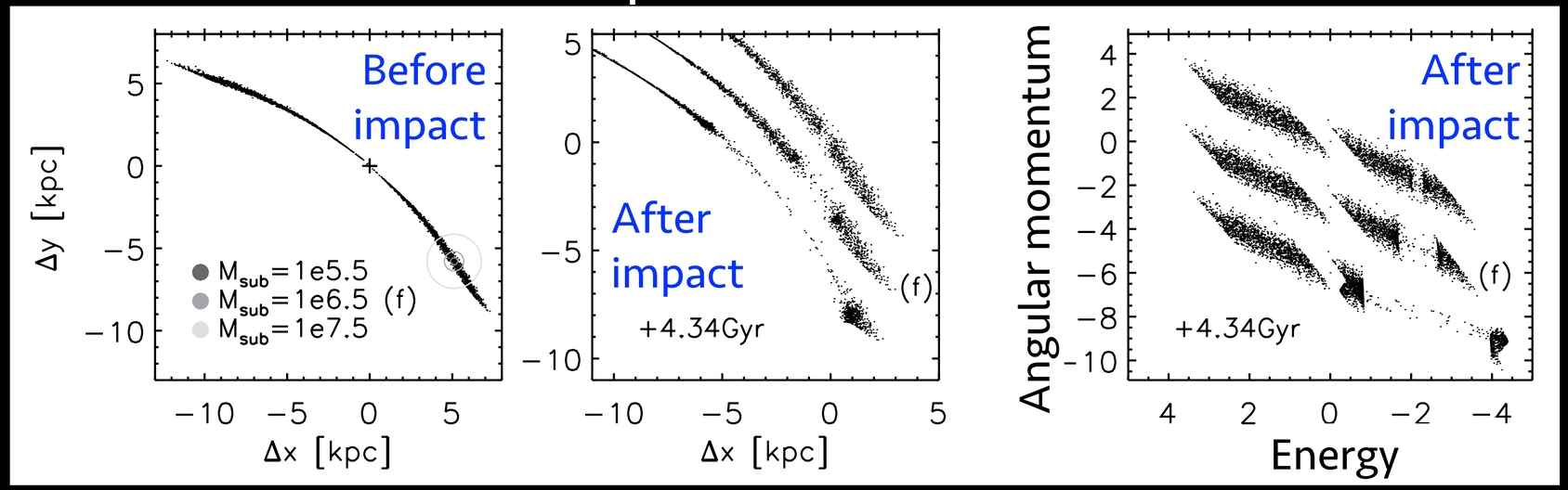

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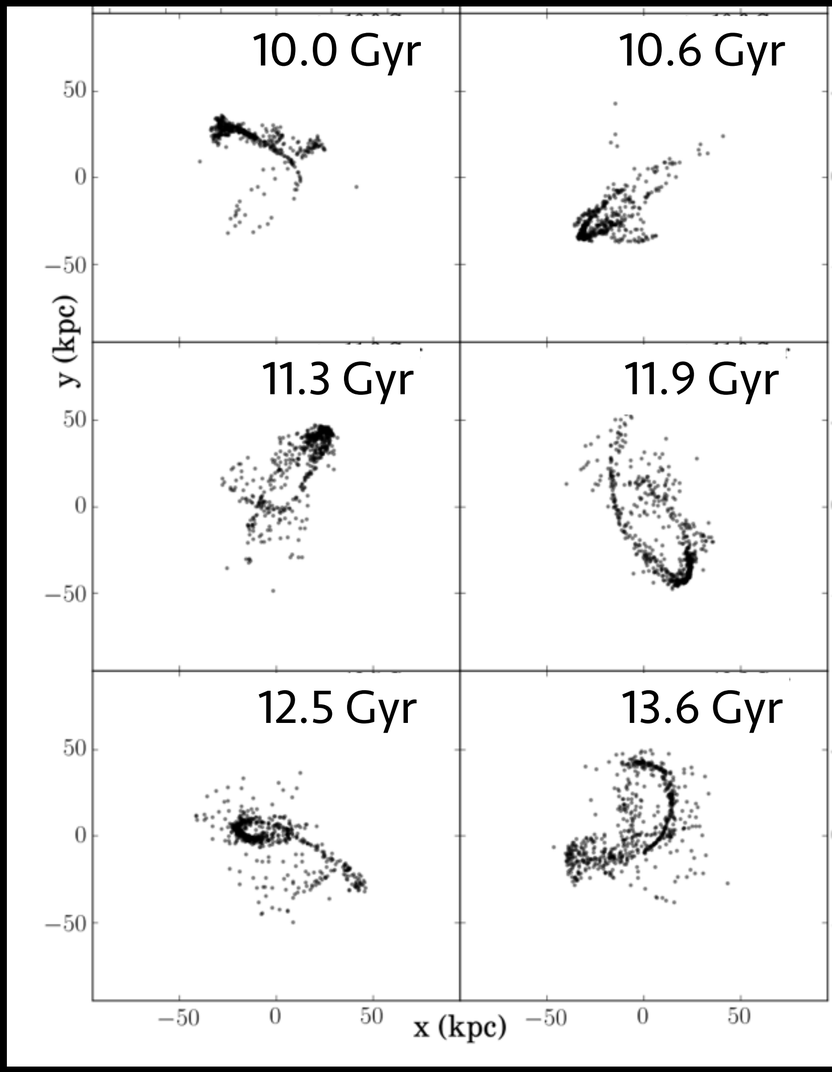
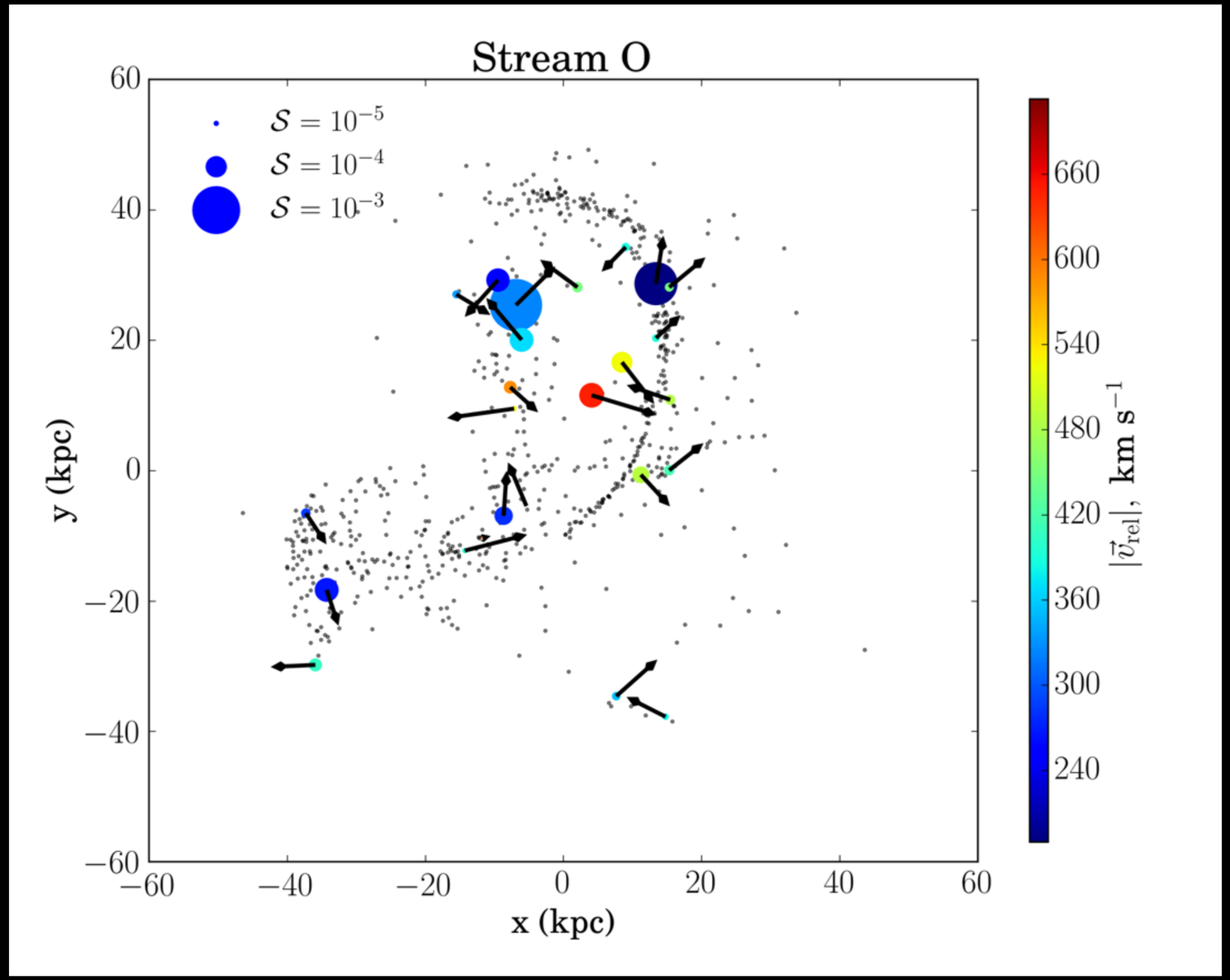
Cosmological simulations



Sanderson et al. 2016

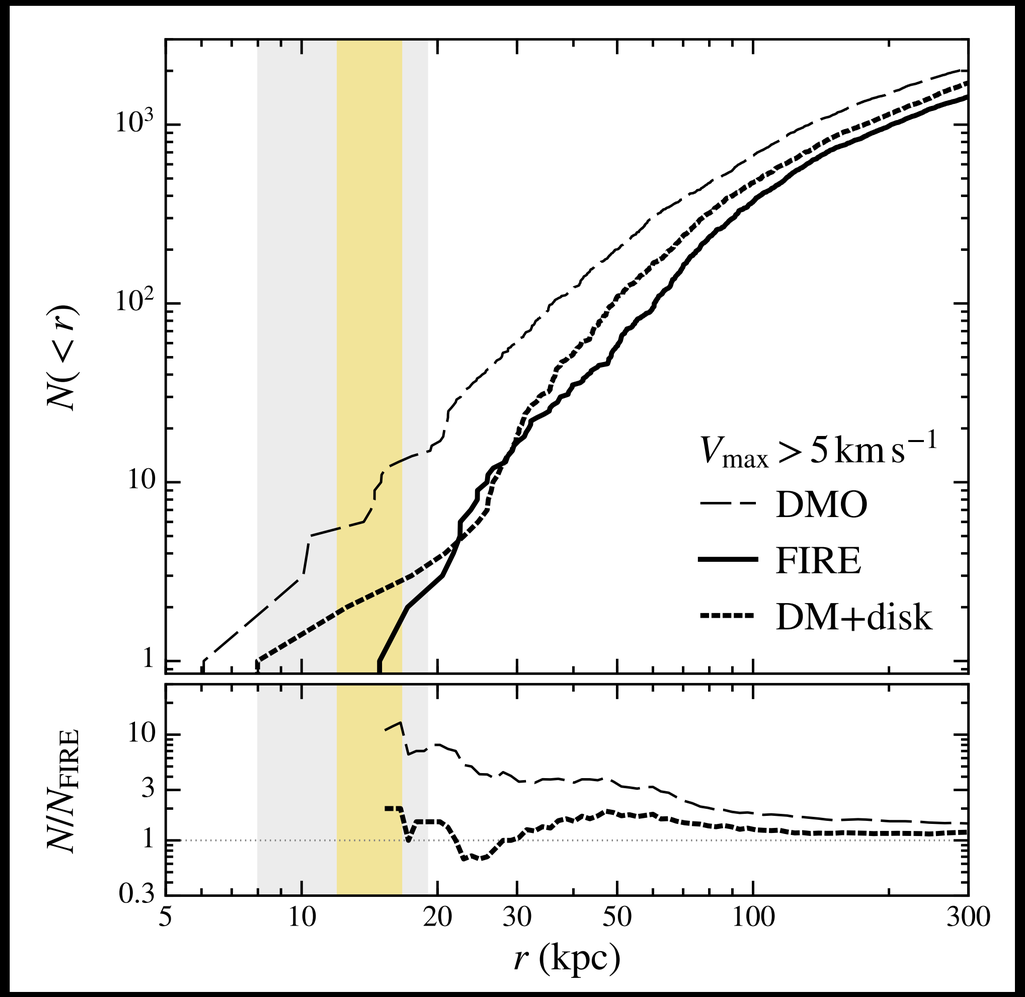
In Aquarius A, subhalos interact with streams frequently



Sanderson et al. 2016

Subhalos are likely depleted close to galaxy

Radial distribution of subhalos
in simulations with baryons



Garrison-Kimmel, .., Sanderson, et al. 2017

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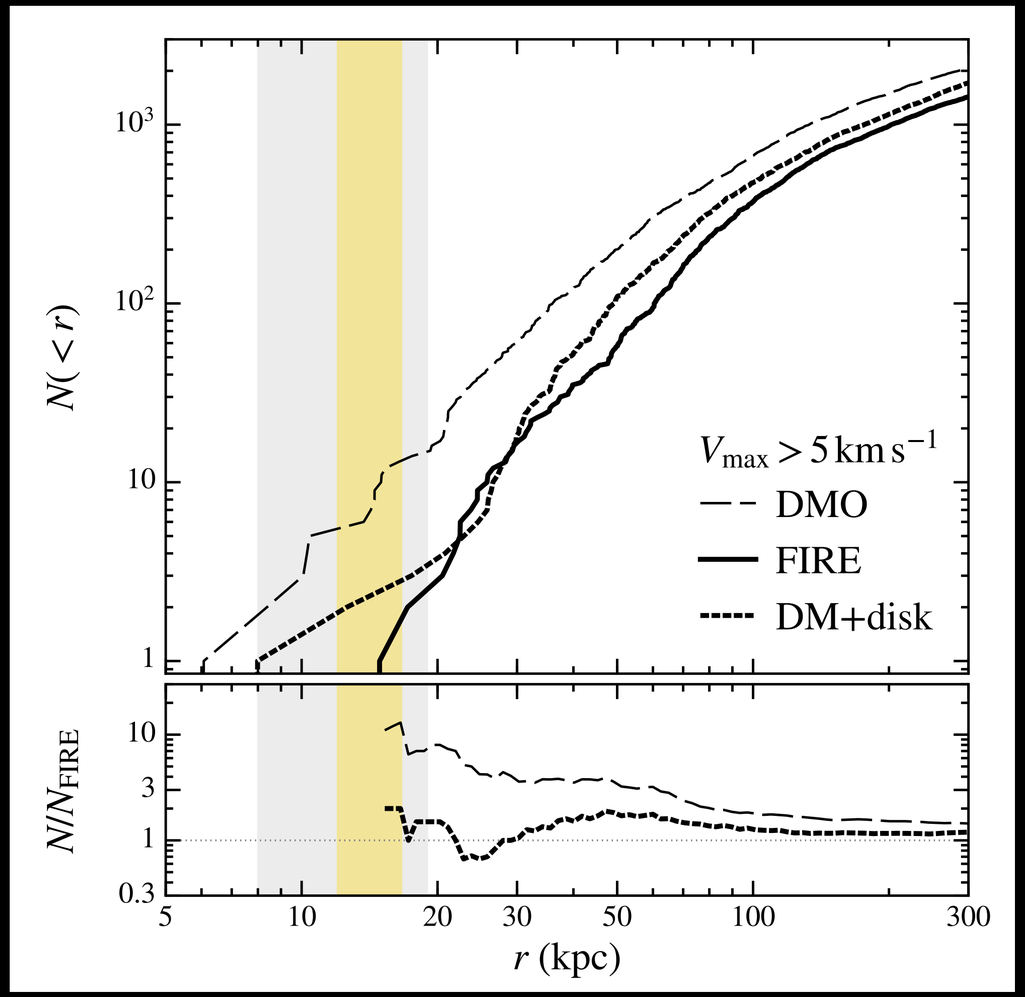
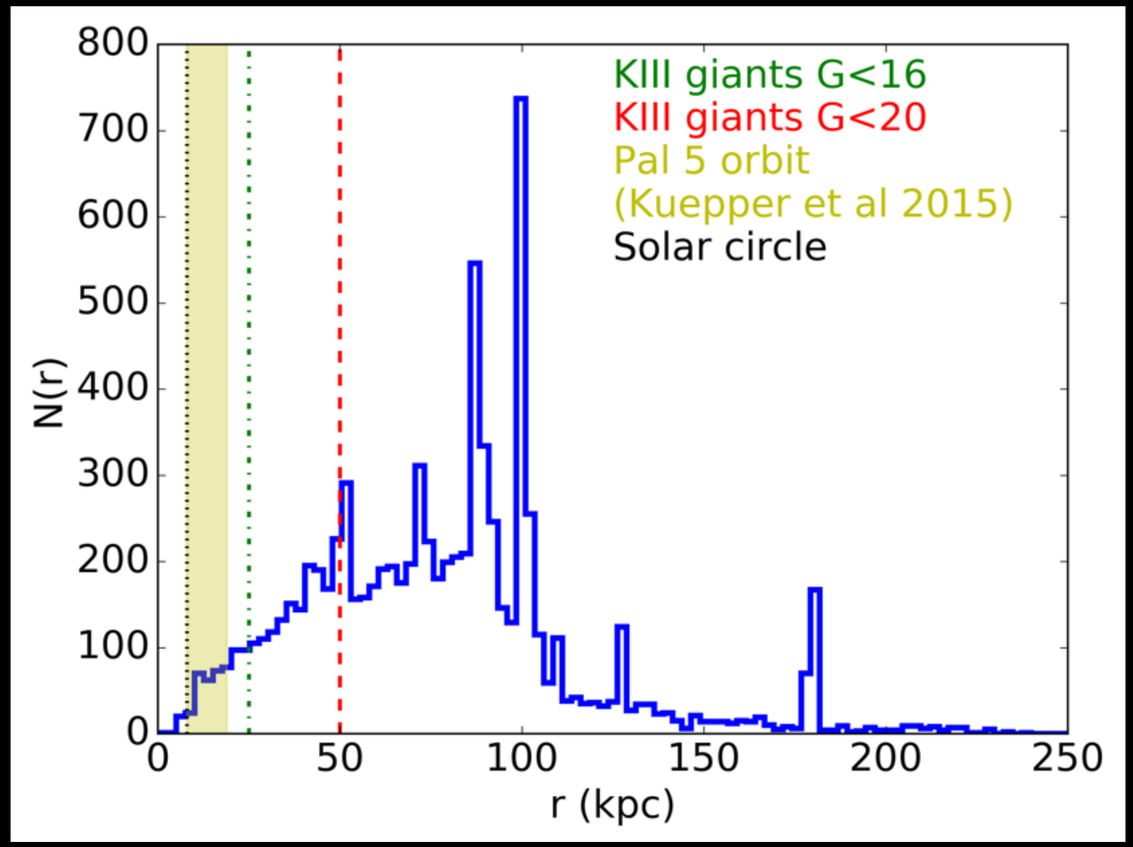


Garrison-Kimmel, .., Sanderson, et al. 2017

Radial distribution
of simulated streams
from disrupted satellites



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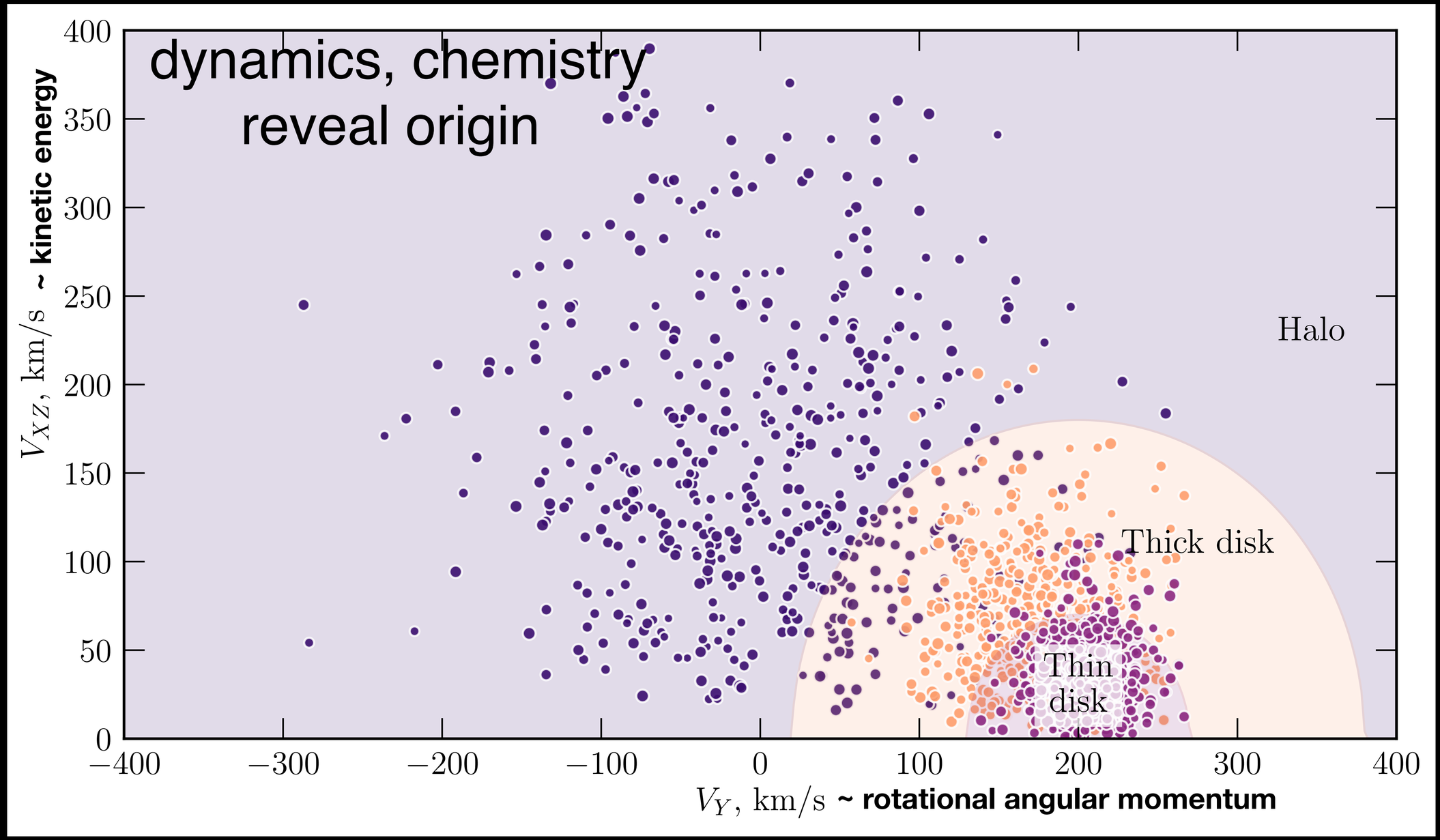
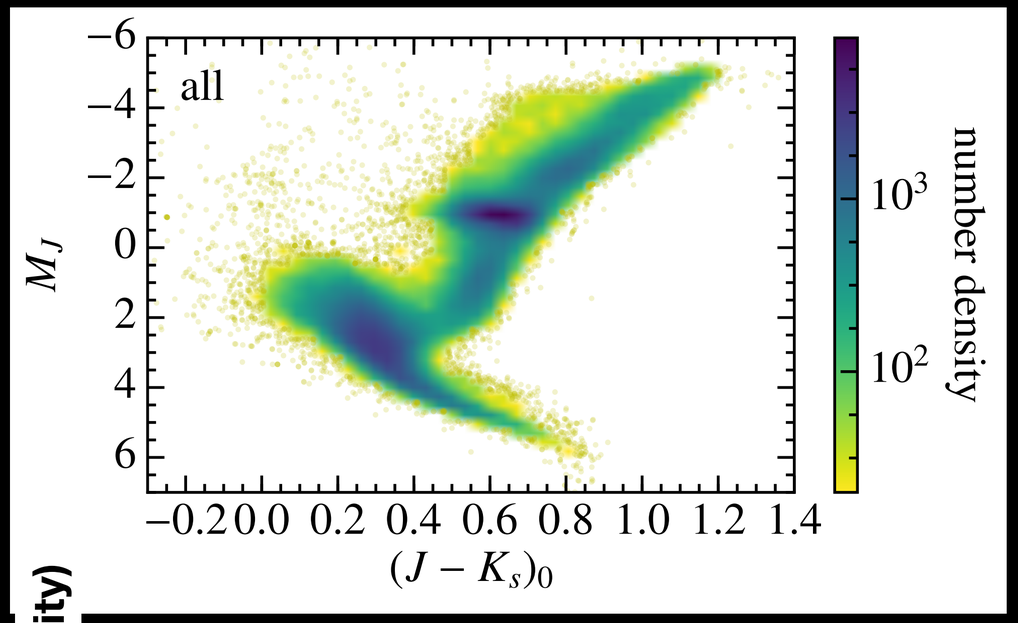
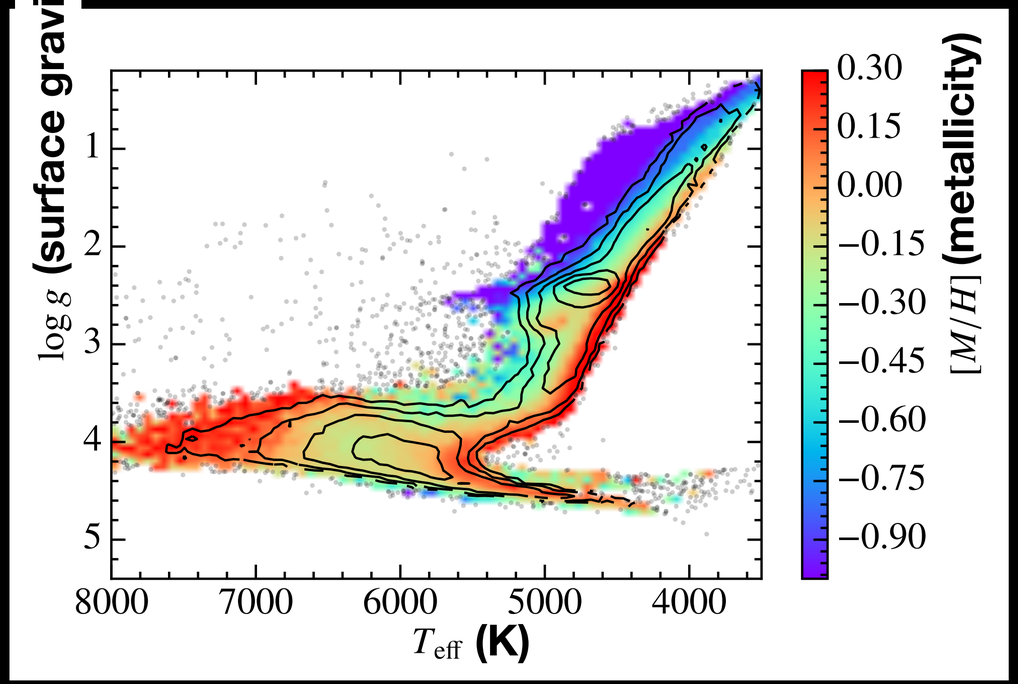
Classical picture of the Solar neighborhood

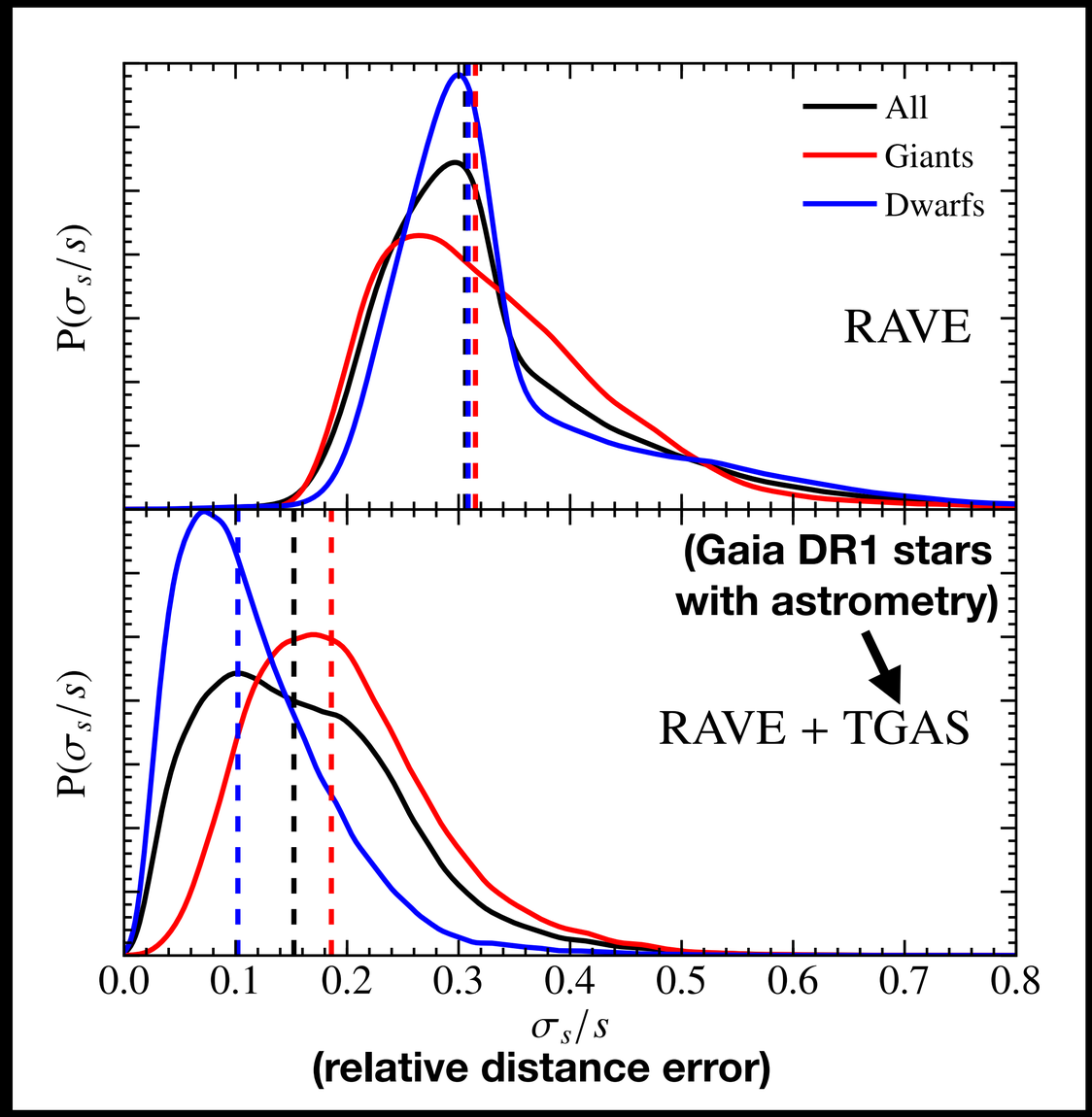


Sanderson et al. in prep

Gaia DR1 + RAVE already had complete 6+D information for >200k stars



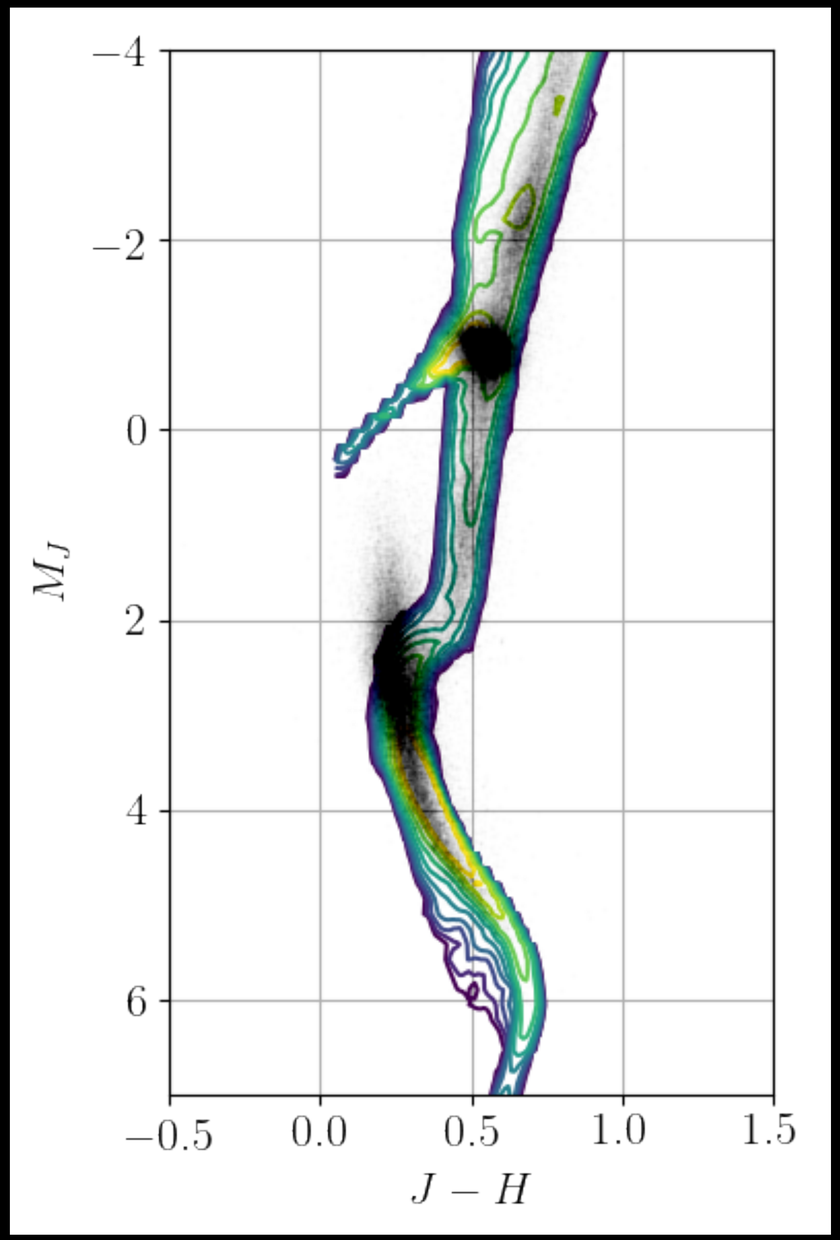




McMillan et al., arXiv:1707.04554

We synthesized this survey from a cosmological simulation (Latte)

Contours: mock catalog
Black dots: TGAS-RAVE crossmatch



Dwarf stars

Giant stars

1 kpc

Ananke

Sanderson et al. in prep

τ

Gaussian mixture modeling:

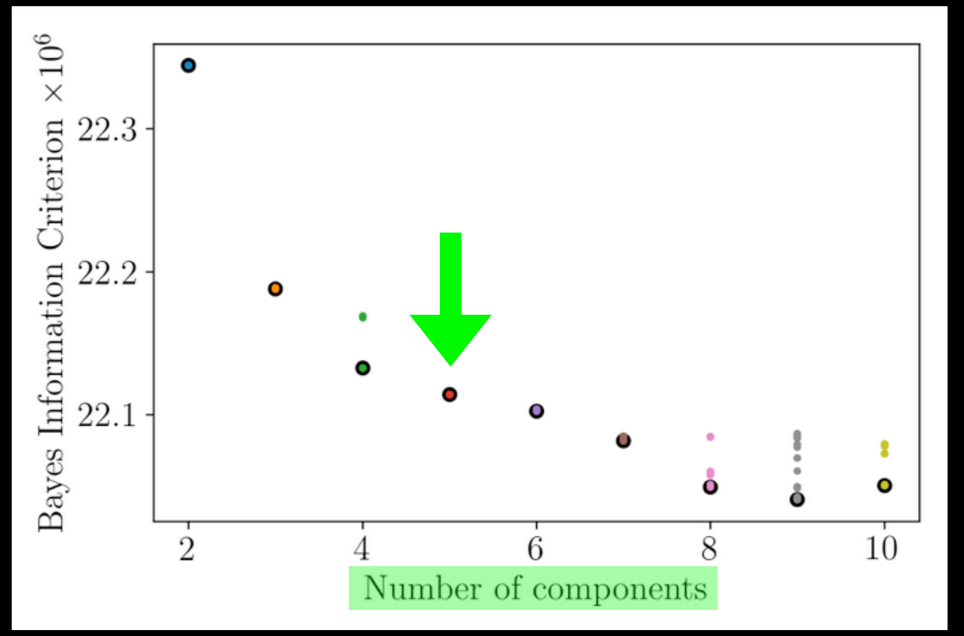
$$P(V_{XZ}, V_Y, [Fe/H]) = \sum_{i=1}^{n_c} \tau_i \mathcal{N}(V_{XZ}, V_Y, [Fe/H] | \vec{\mu}_i, \mathbf{\Sigma}_i)$$

Weights

Means

Covariances

Sanderson et al. in prep



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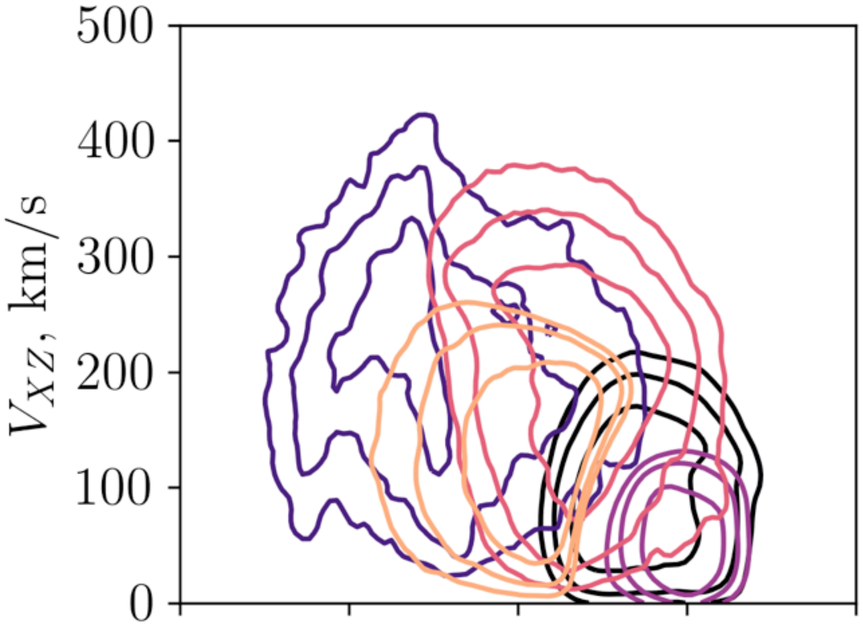

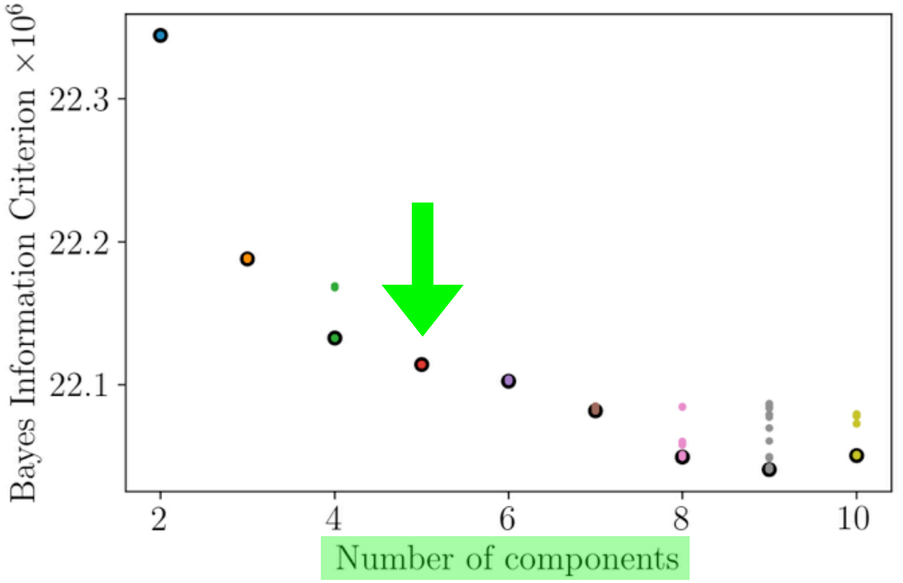

Thin-disk-like
Thick-disk-like
Thicker-disk-like?
Halo-like

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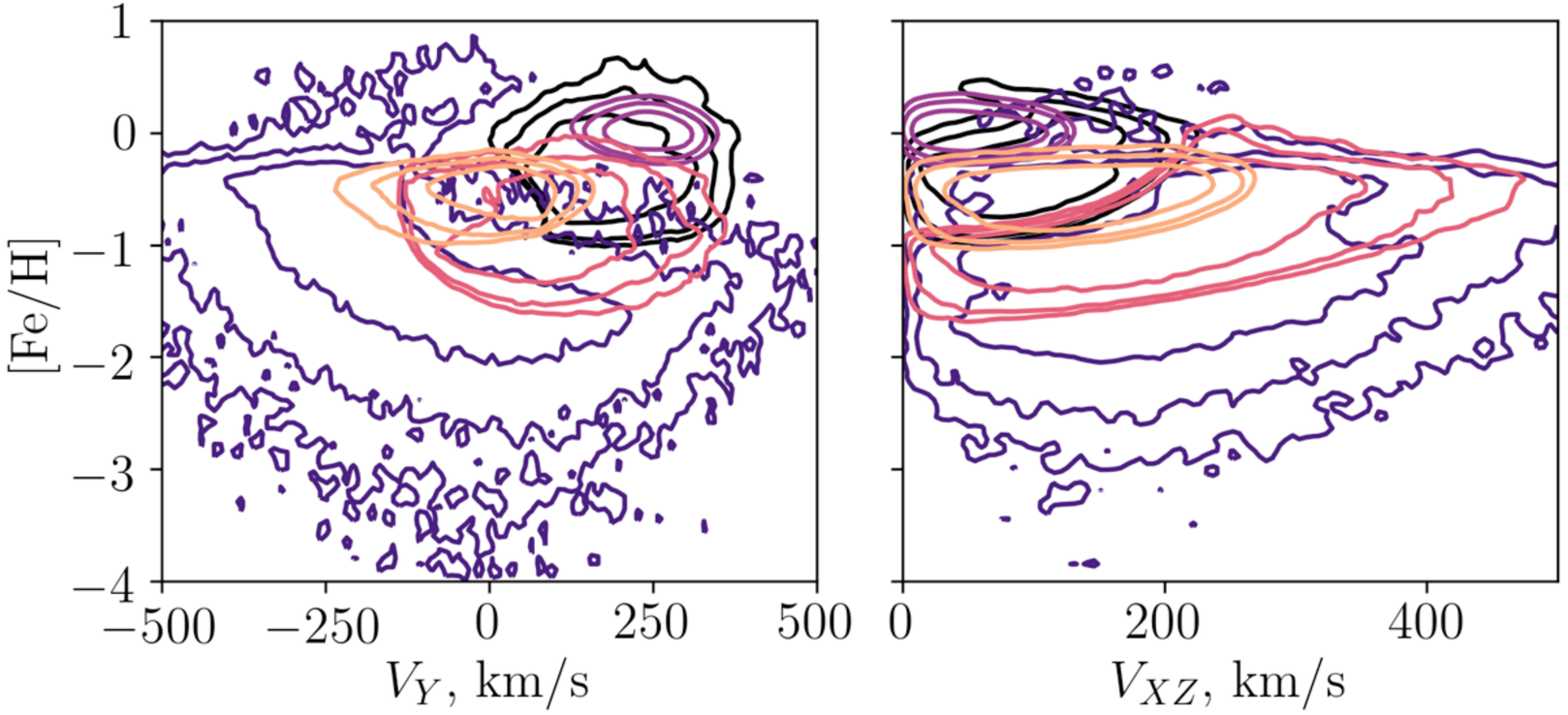

Sanderson et al. in prep

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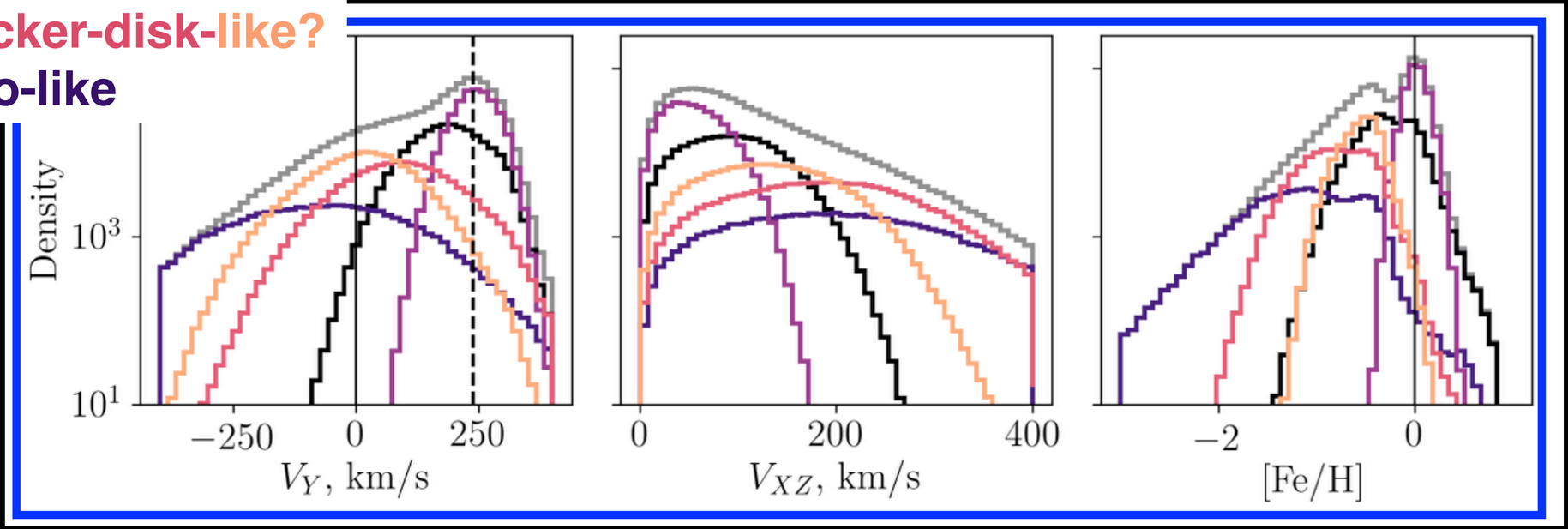
Where do stars in the different components really come from?



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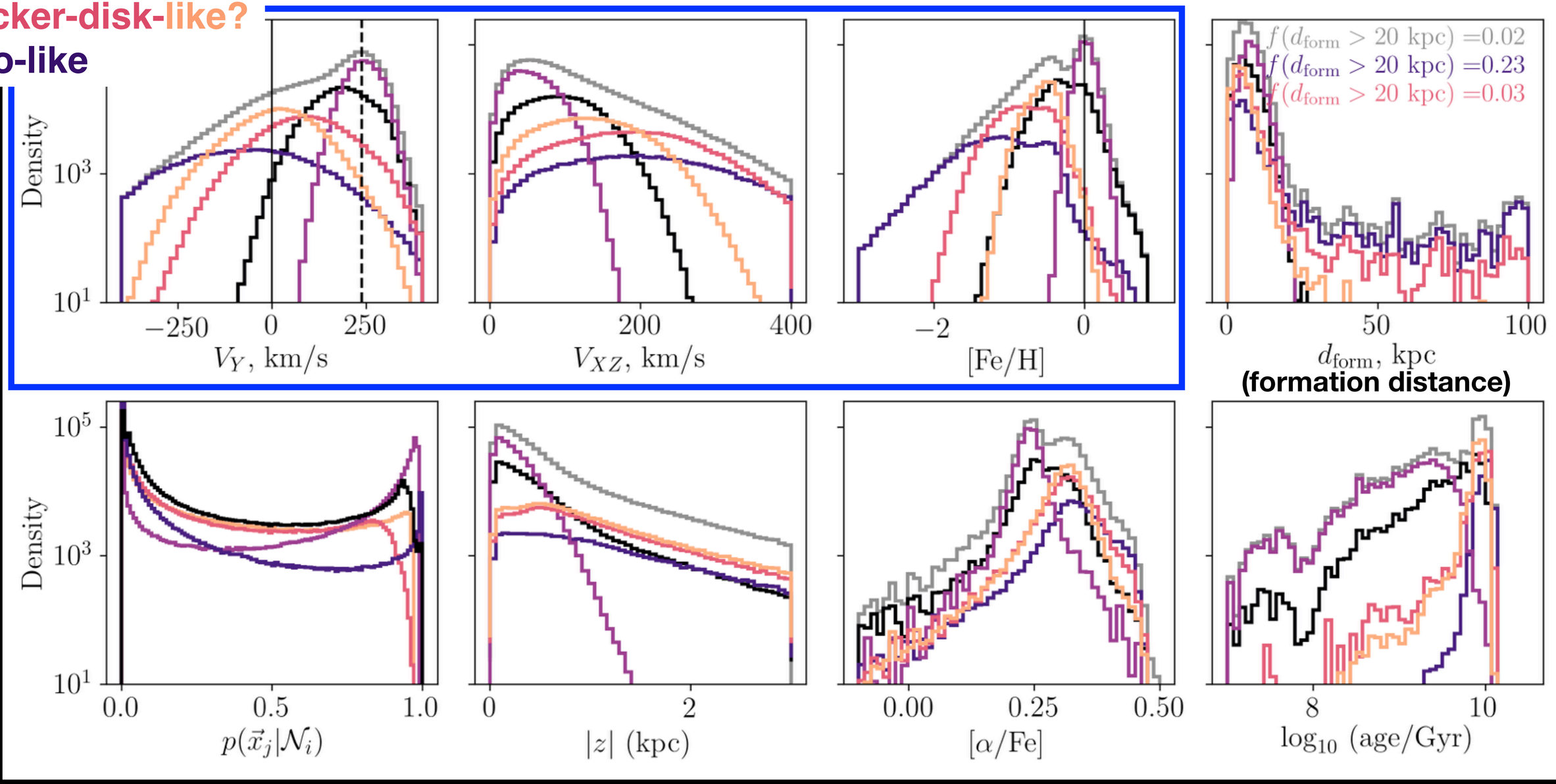
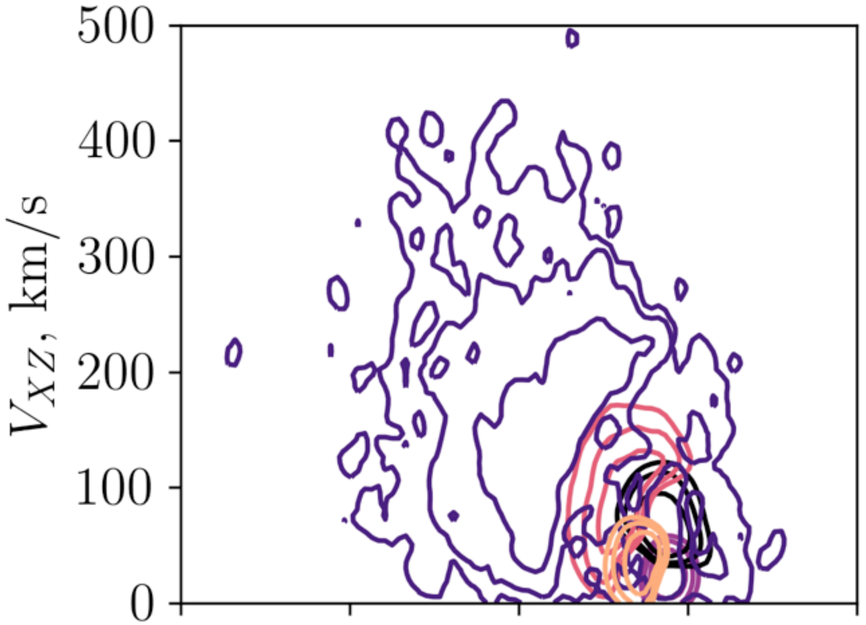
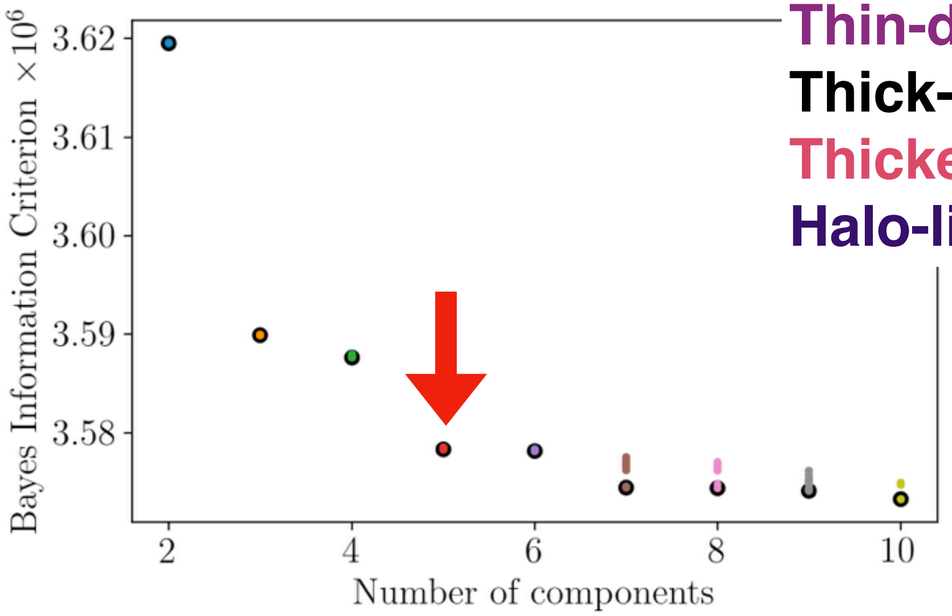


Sanderson et al. in prep

Mock data helps interpret the real data





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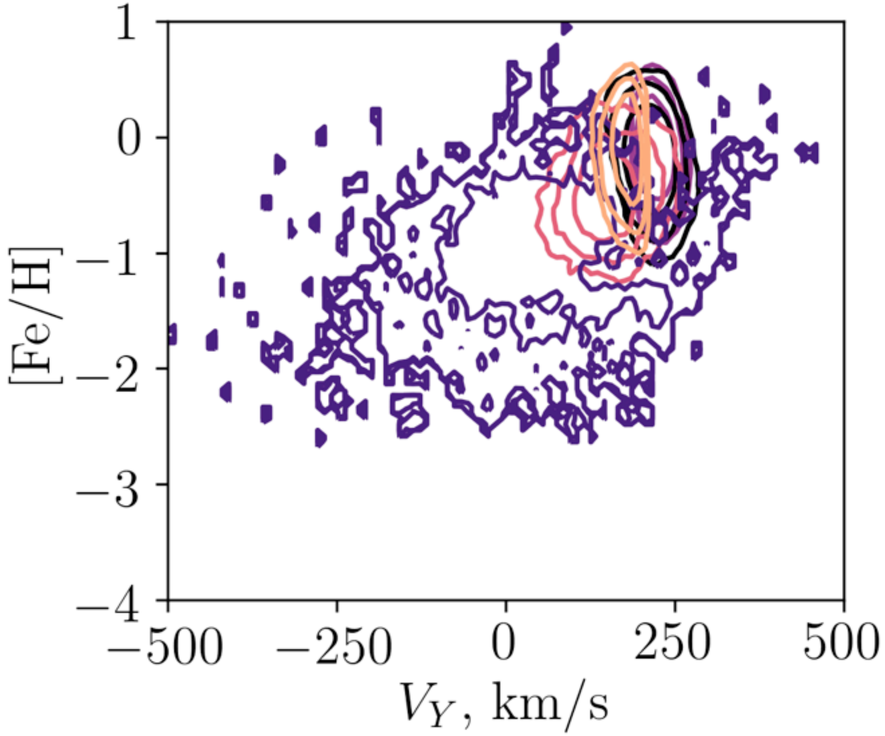

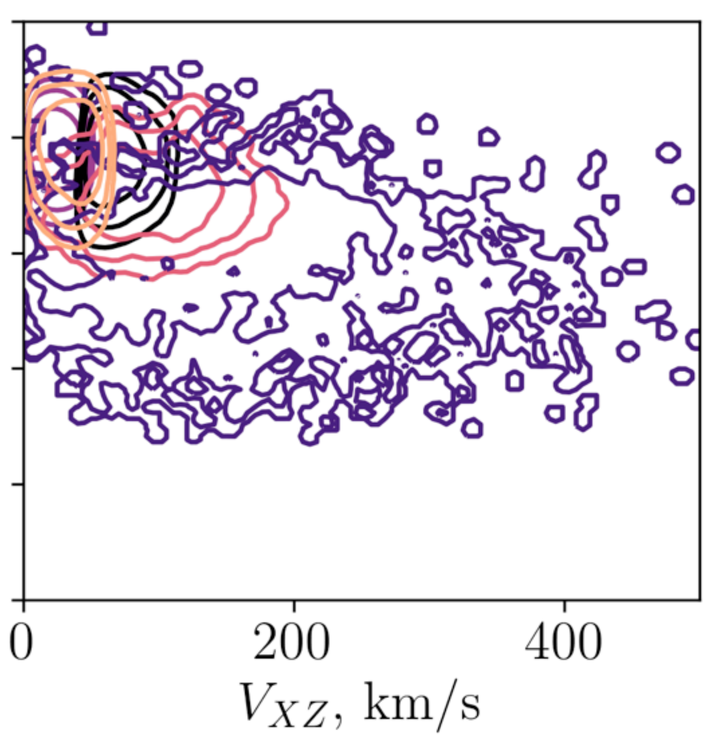

Sanderson et al. in prep

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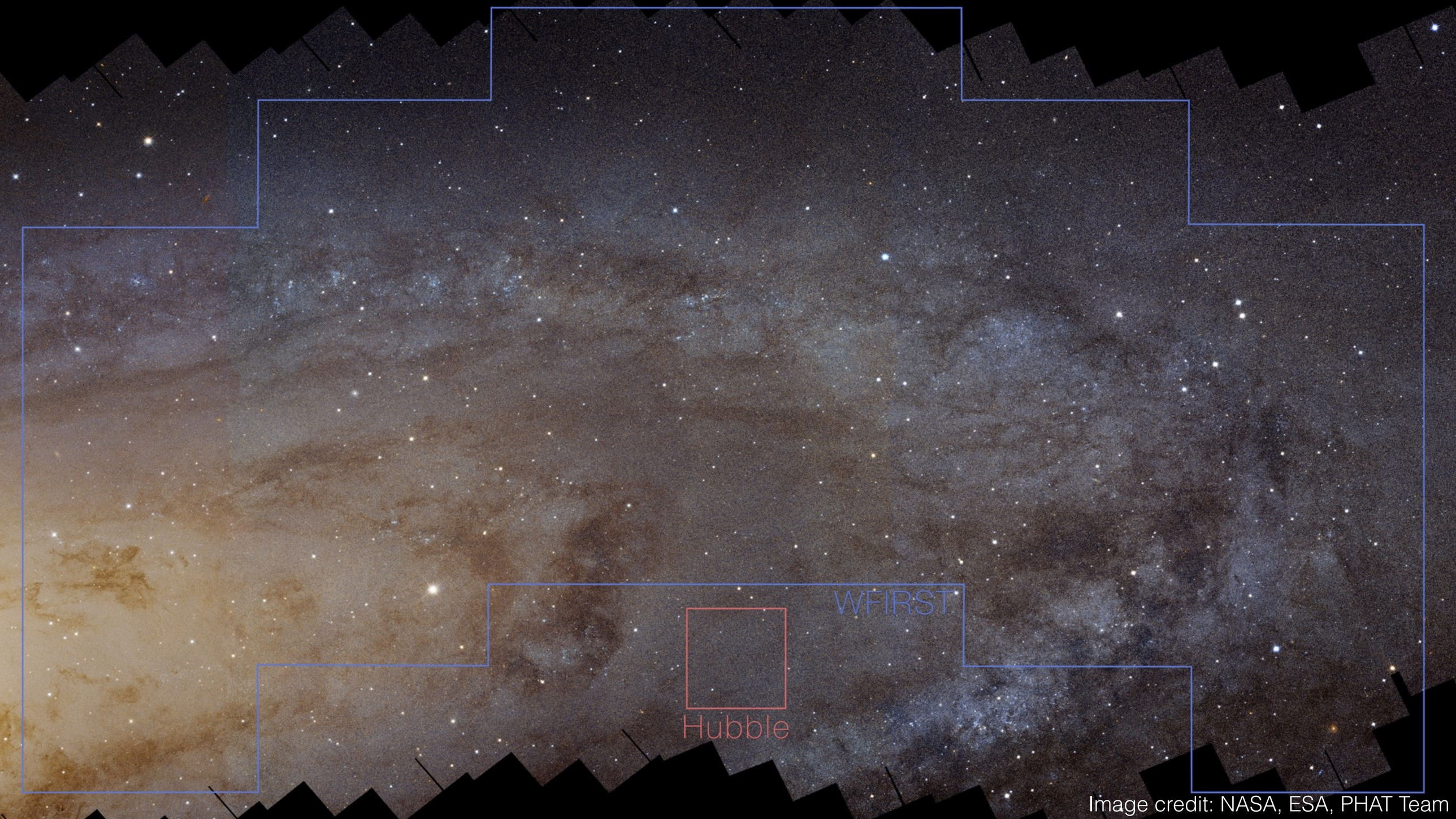
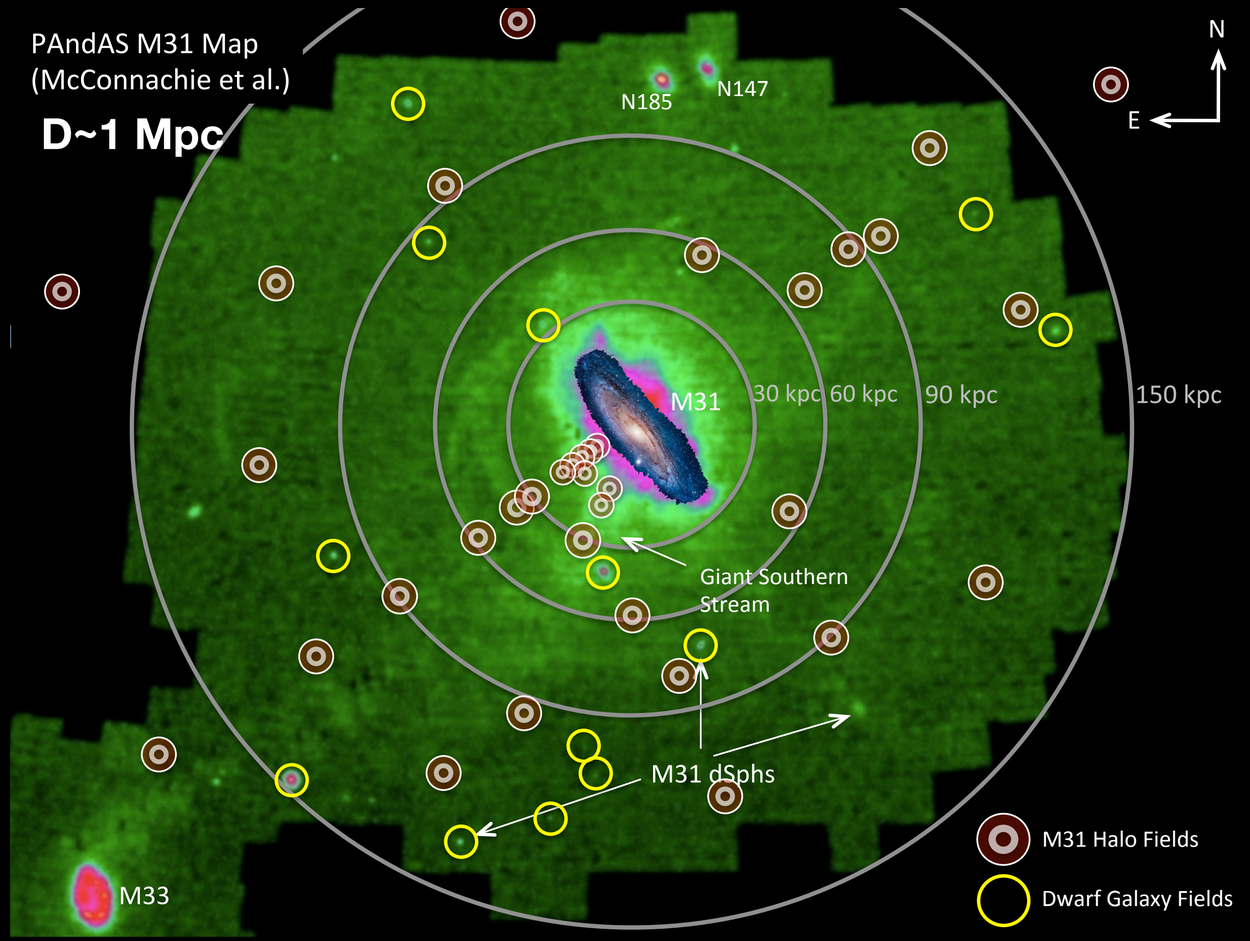
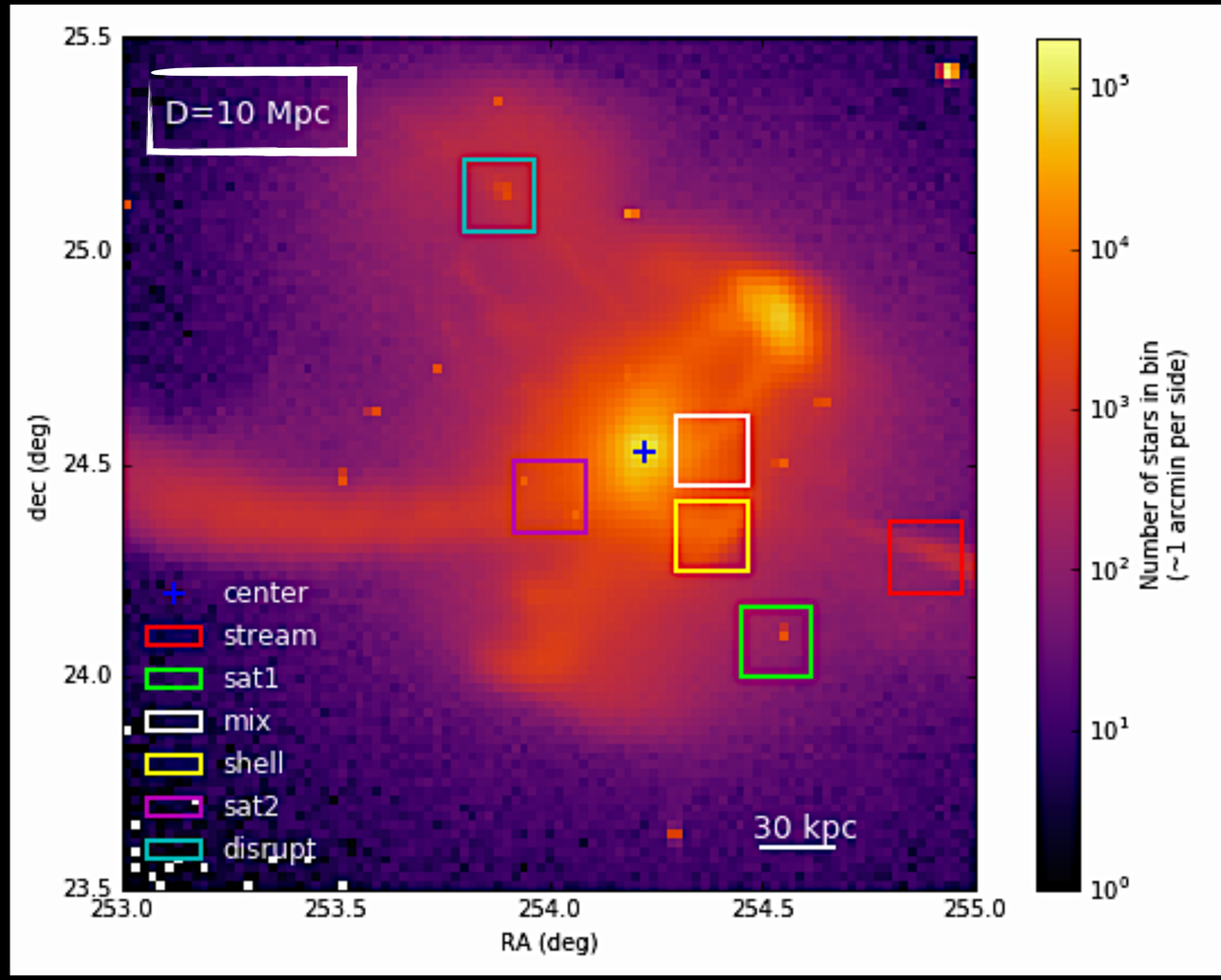


Image credit: NASA, ESA, PHAT Team

WFIRST will resolve stellar populations in 100 nearby MW-like galaxies

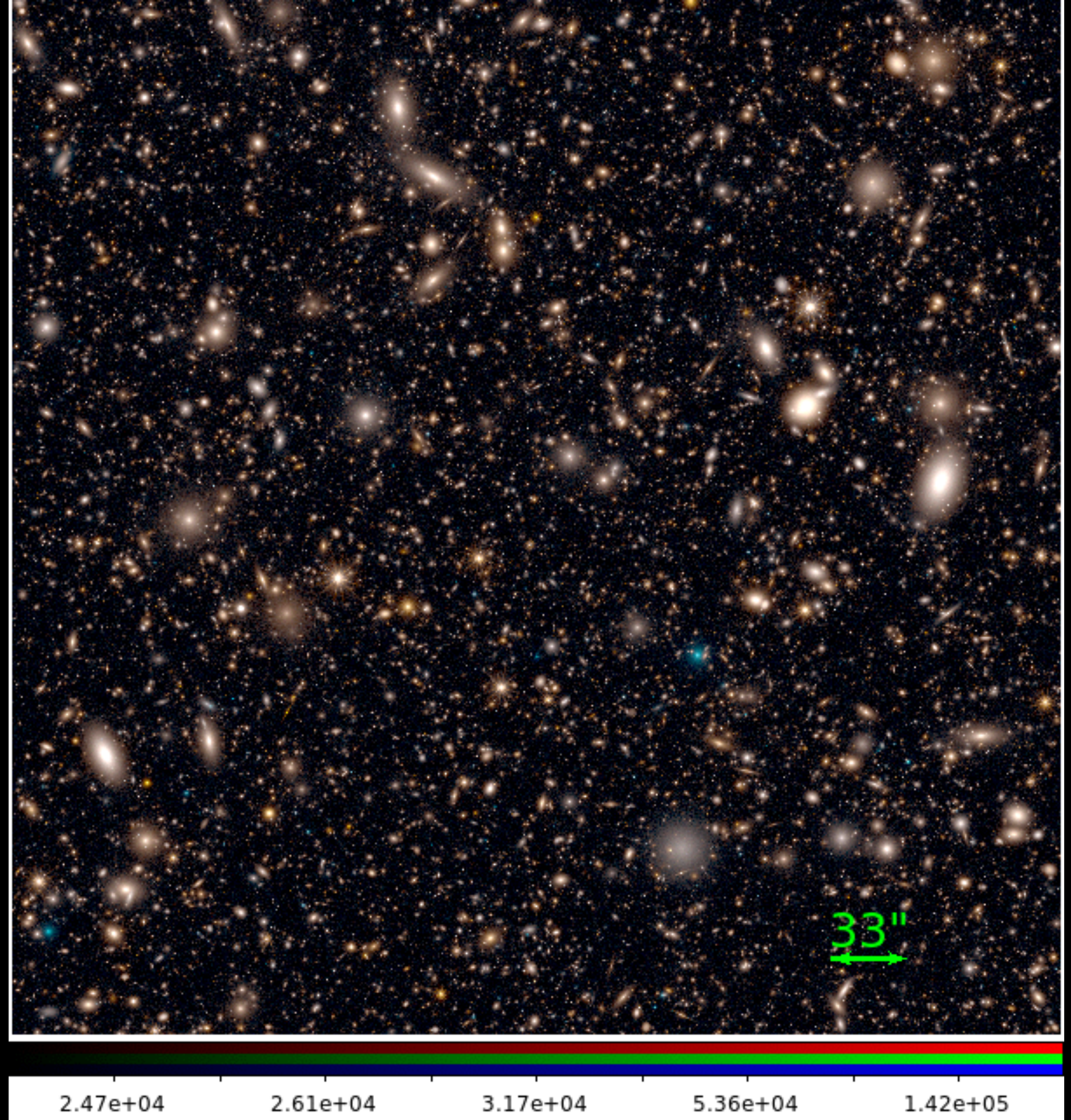




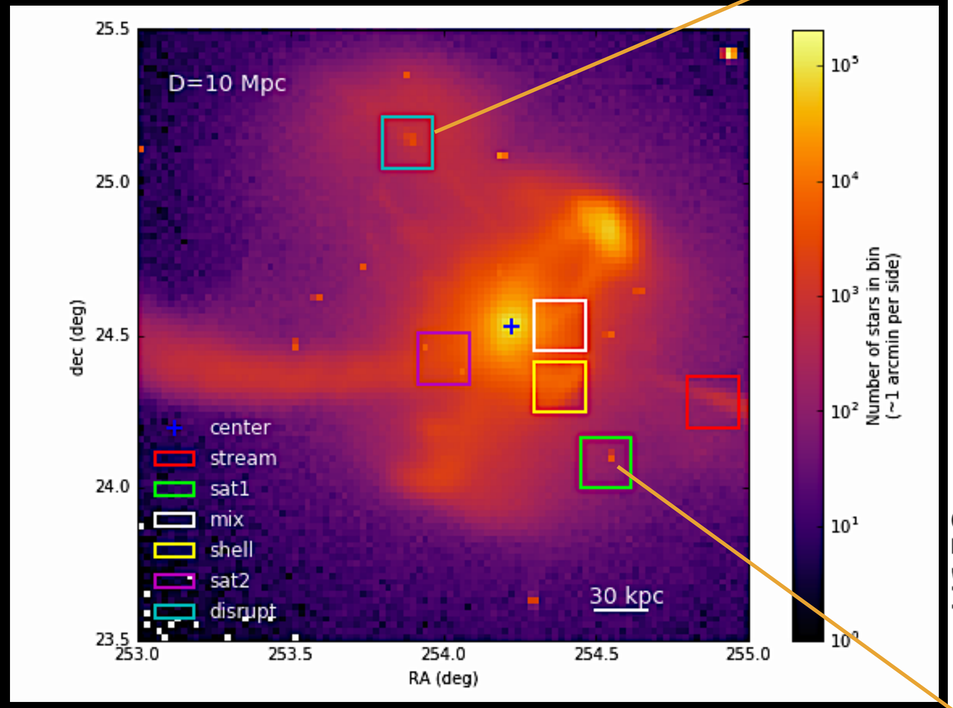
Simulated image on 1 WFIRST chip (of 18!) (courtesy Rubab Khan, Ben Williams)

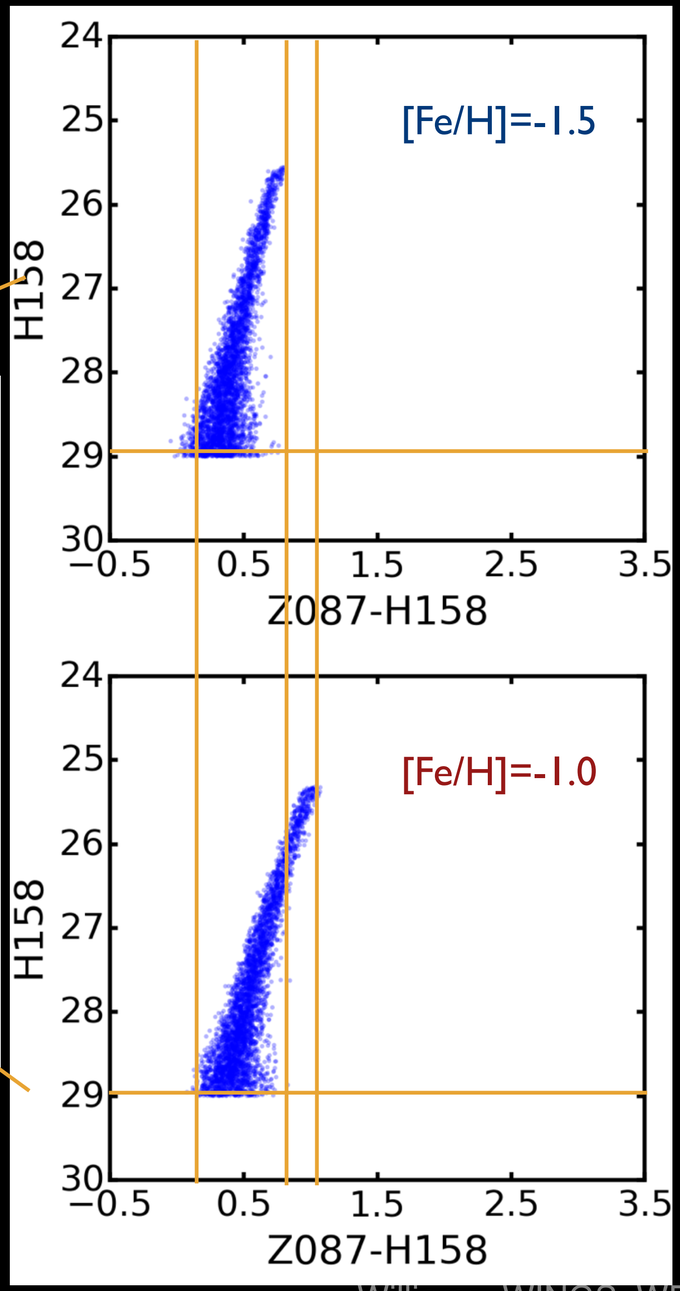
Stars: from mock stellar halo catalog at 5 Mpc (Me, Kathryn, Sol)

Galaxies: from CANDELS (courtesy Eric Bell), randomly distributed



Recovering Populations Δ[Fe/H]=0.5 dex





Z087 and H158 Colors

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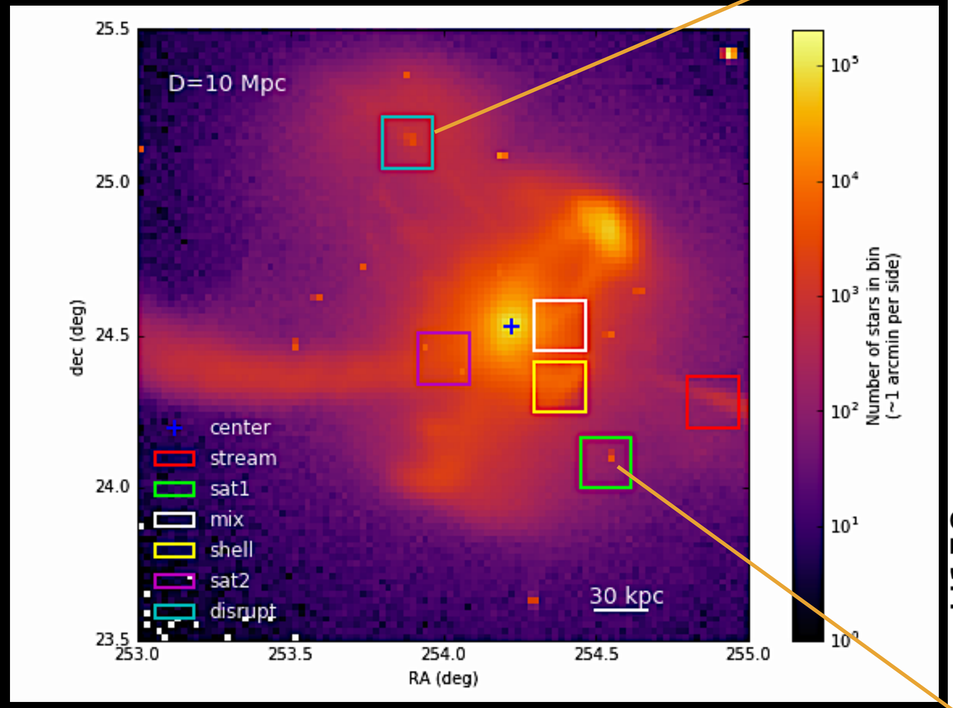

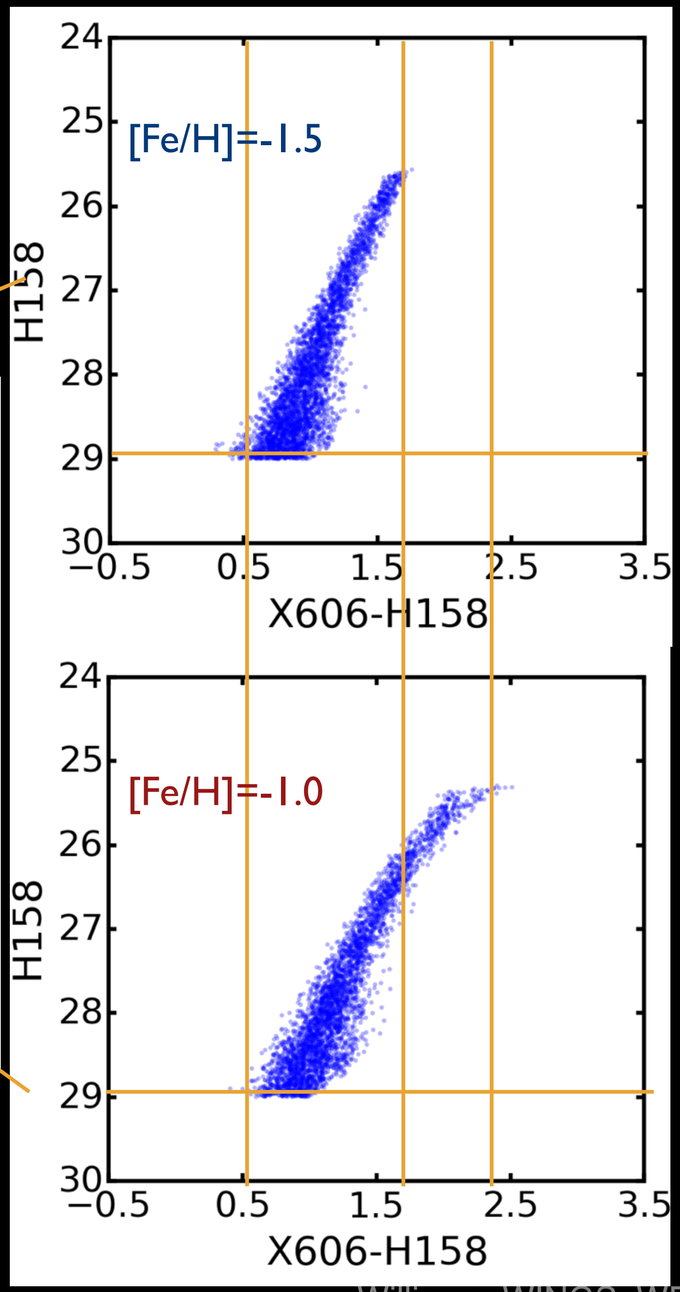

X606 and H158 Colors

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