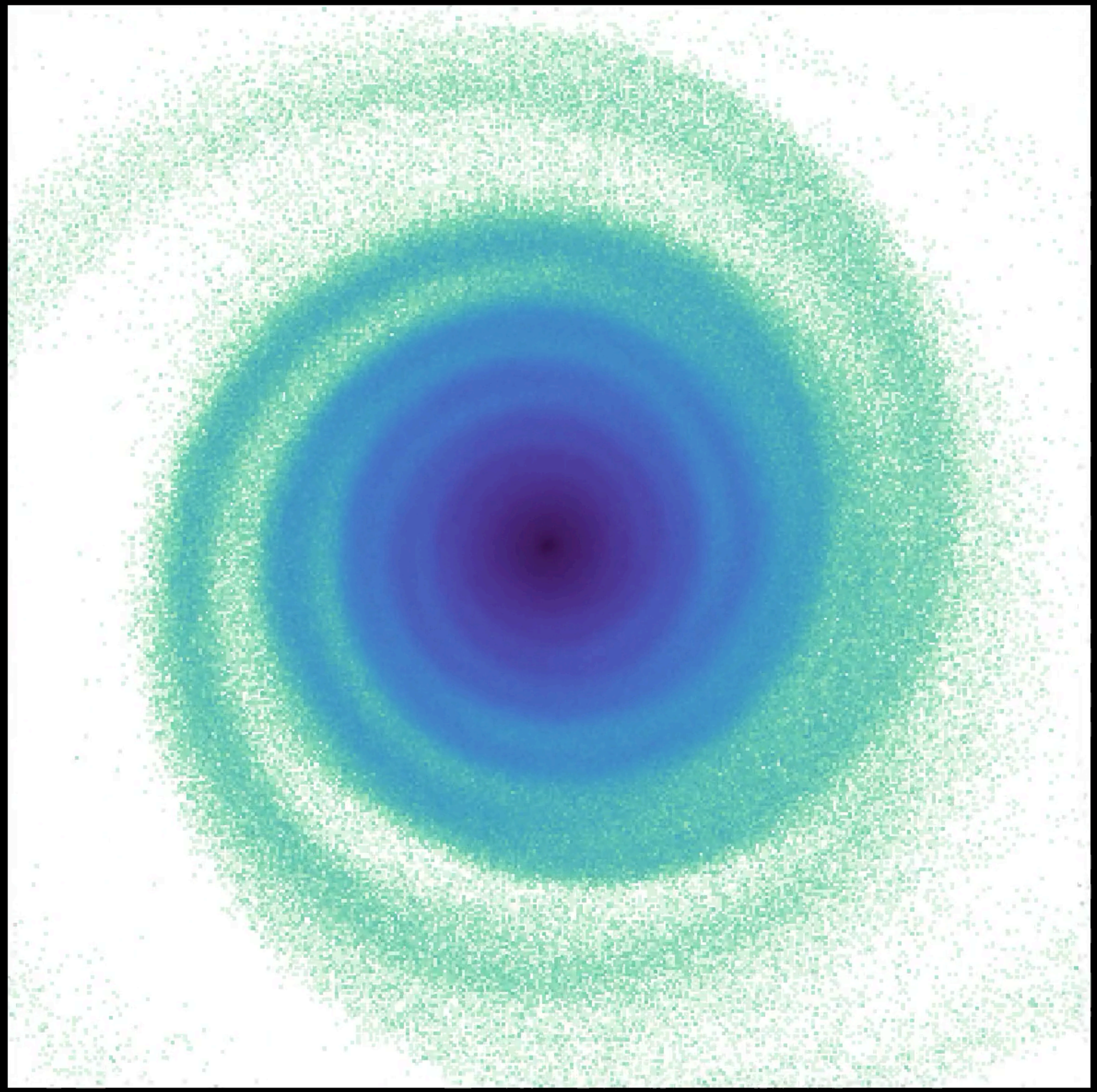
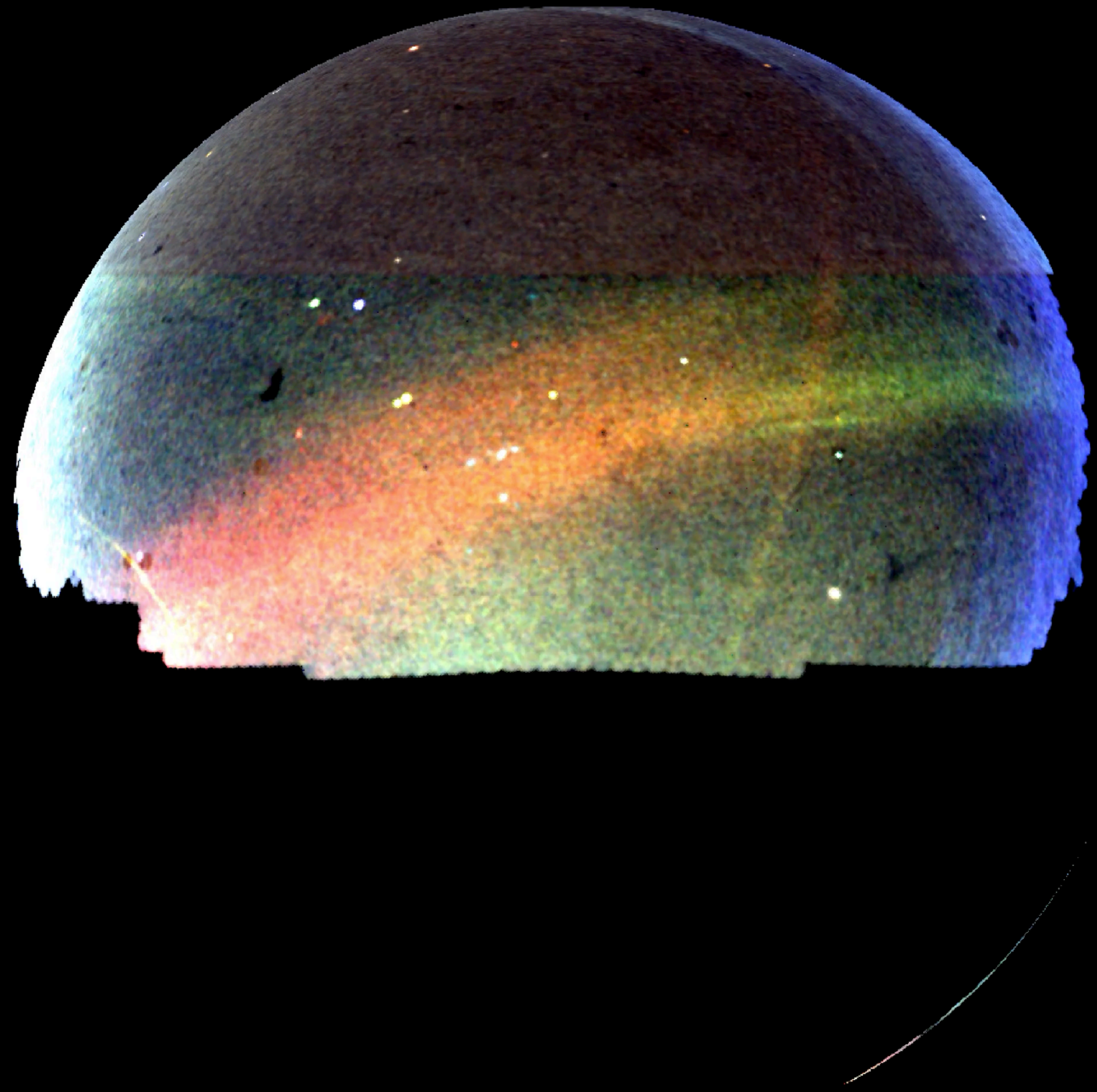
A New Era for Galactic Dynamics in the Milky Way

Adrian Price-Whelan
Flatiron Institute





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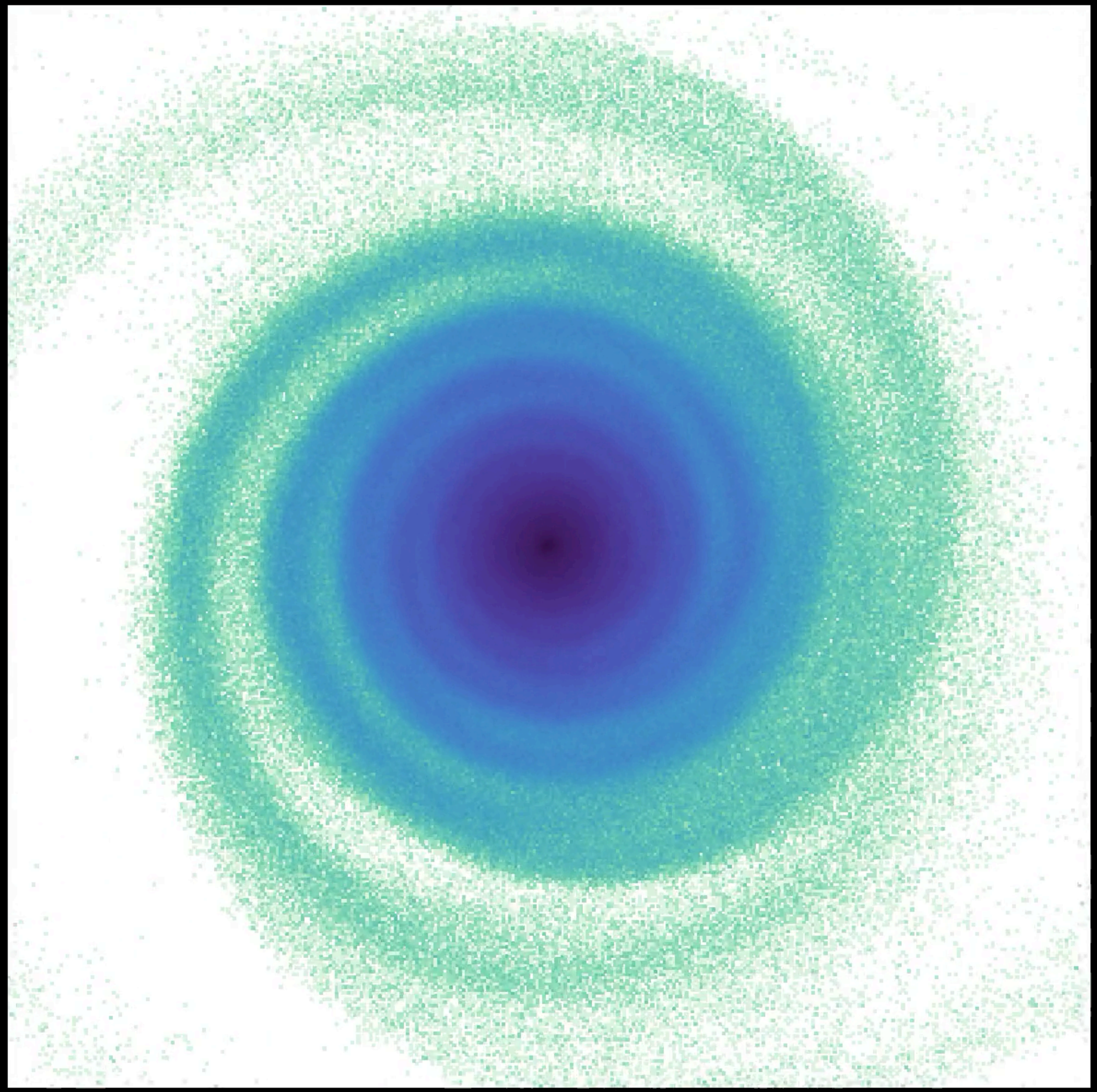
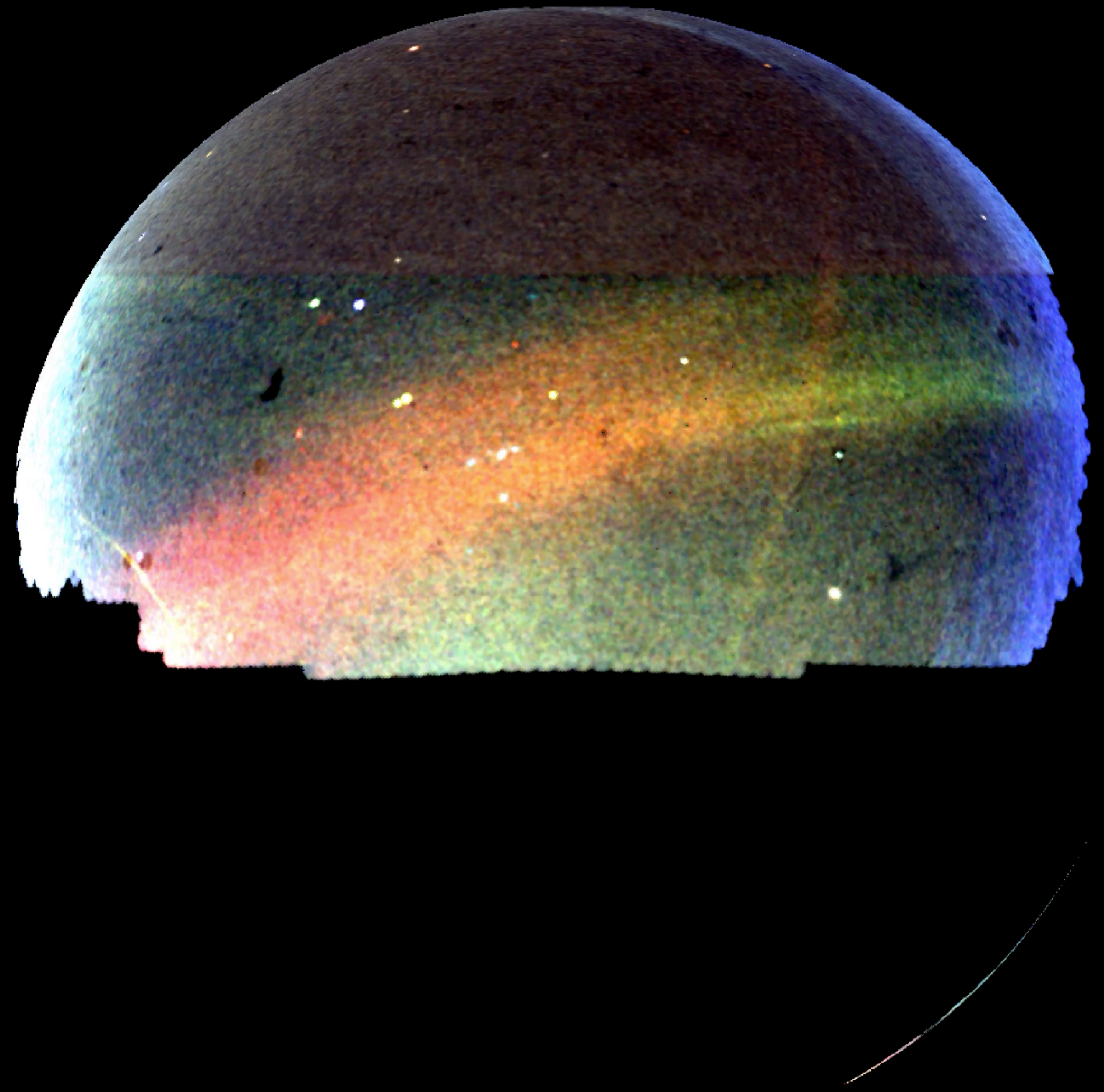




the past year...

Follow along: http://adrian.pw/aas237

Scope of This Talk

Galactic (stellar) Dynamics in the Milky Way:

- Front row seat to Galaxy evolution
- 3D view of mass distribution (visible and invisible)

Scope of This Talk

Galactic (stellar) Dynamics in the Milky Way:

Front row seat to Galaxy evolution

3D view of mass distribution (visible and invisible)

The Milky Way is *alive*: as a field of research and as a galaxy!

What are the main structural components of the Galaxy and how did they form? Are they long-lived or transient?

What are the dominant processes that have shaped the evolution of the Milky Way?

What are the properties of dark matter within the Galaxy and its satellites?

Surveys of Milky Way Stars

Surveys of Milky Way Stars

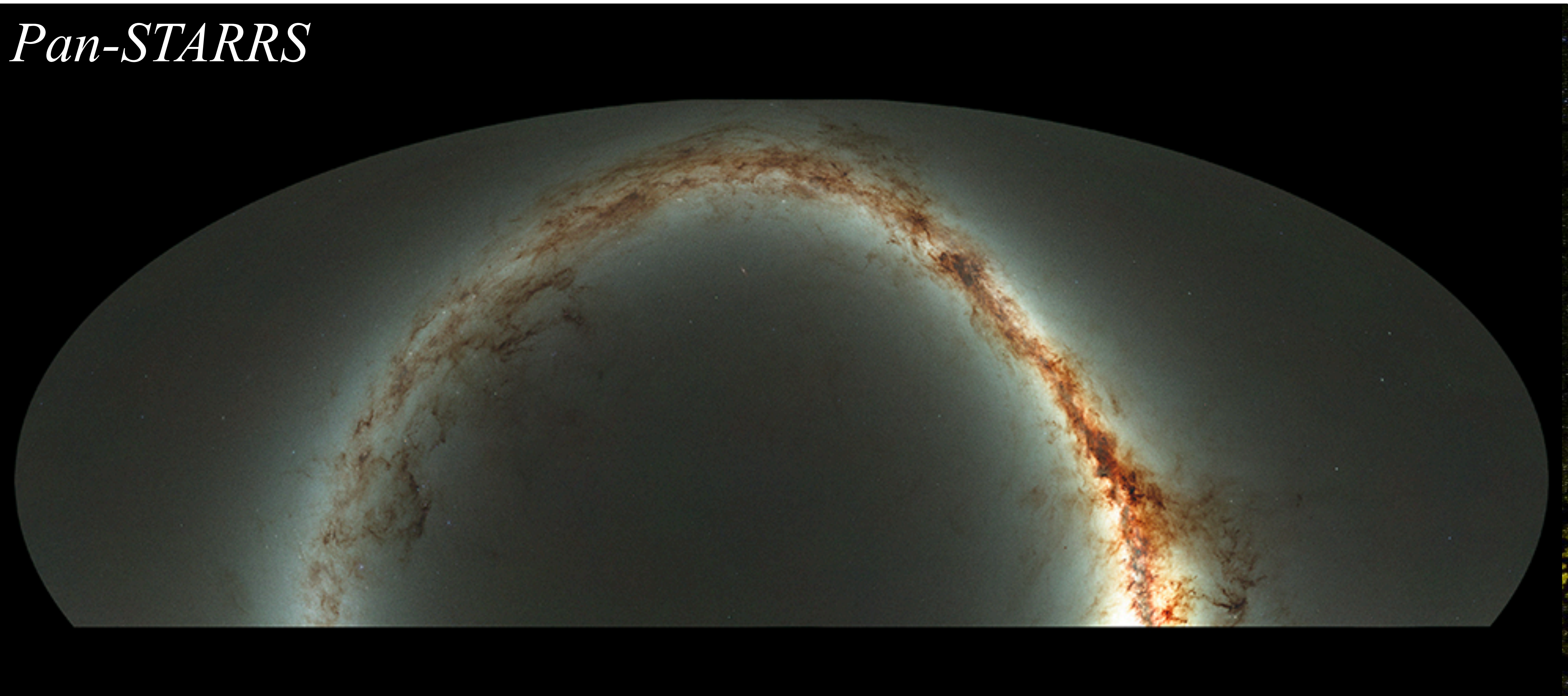
Deep, Wide-area Imaging

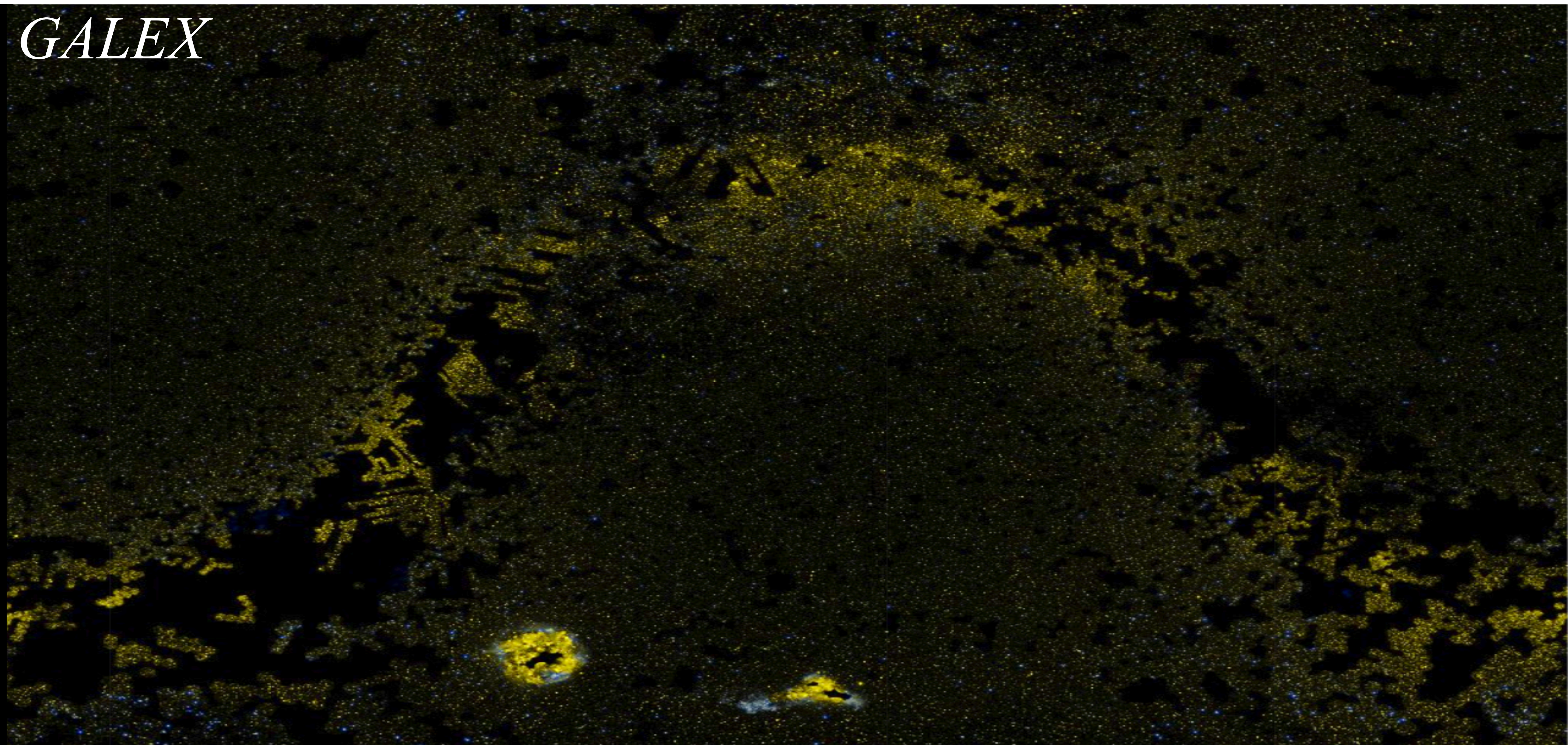
Multi-band photometry — source classification, rough stellar parameters

Time-domain imaging — variable stars

Pioneering surveys: 2MASS (near infrared), SDSS, PS1 (optical), GALEX (UV)

Now: *billions of resolved stars*





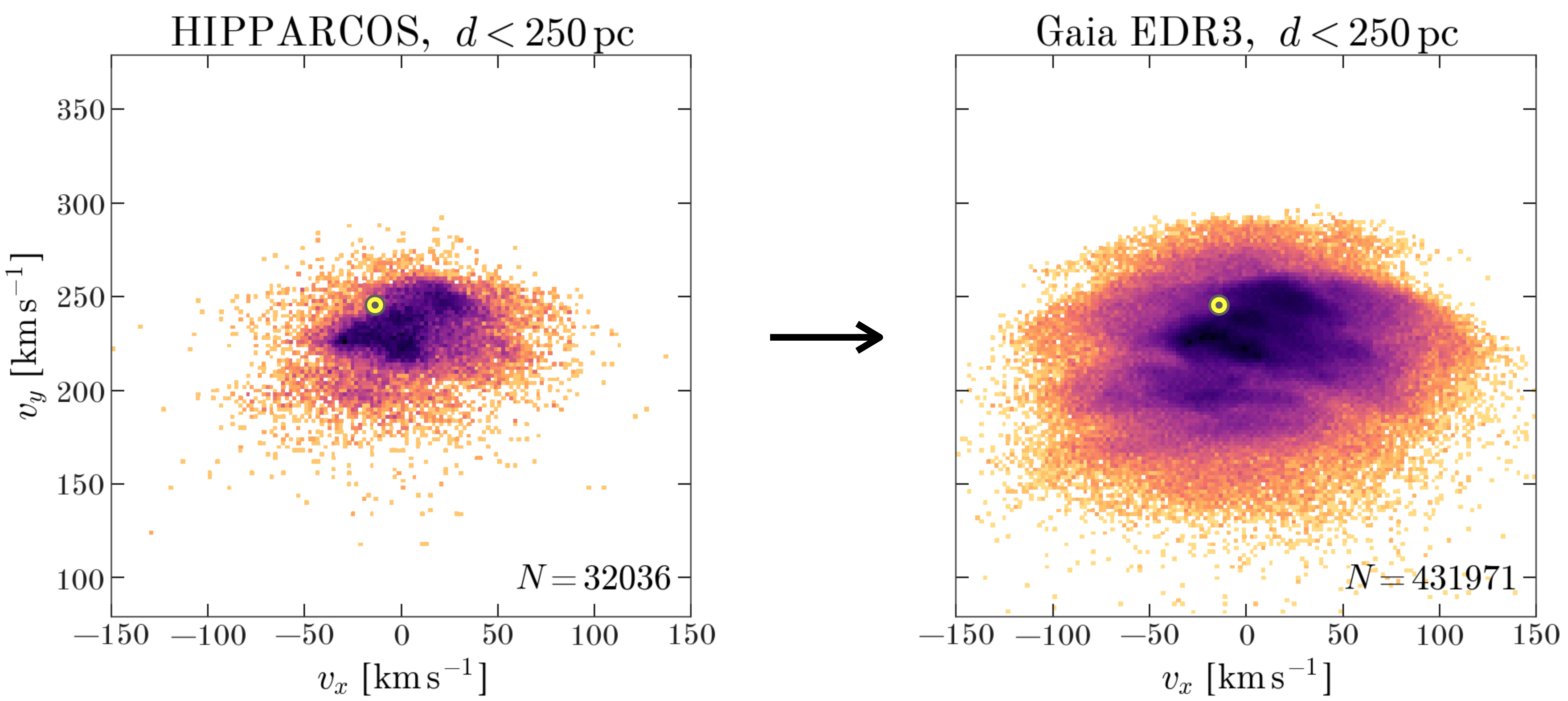
Surveys of Milky Way Stars

Astrometry

Parallax — distance

Proper motions — tangential velocities

Now: ***~1.7 billion stars*** (***Gaia***)



Surveys of Milky Way Stars

Medium/high-resolution Spectroscopy (R ≳ 5000)

Stellar parameters — surface gravity, temperature

Detailed surface abundances — >10s of elements

Precise radial velocities — kinematics, binarity

Pioneering surveys: RAVE (optical), APOGEE (near infrared), GALAH (optical)

Now: *~1 million stars* (APOGEE + GALAH)

Surveys of Milky Way Stars

Medium/high-resolution Spectroscopy (R ≳ 5000)

Stellar pa

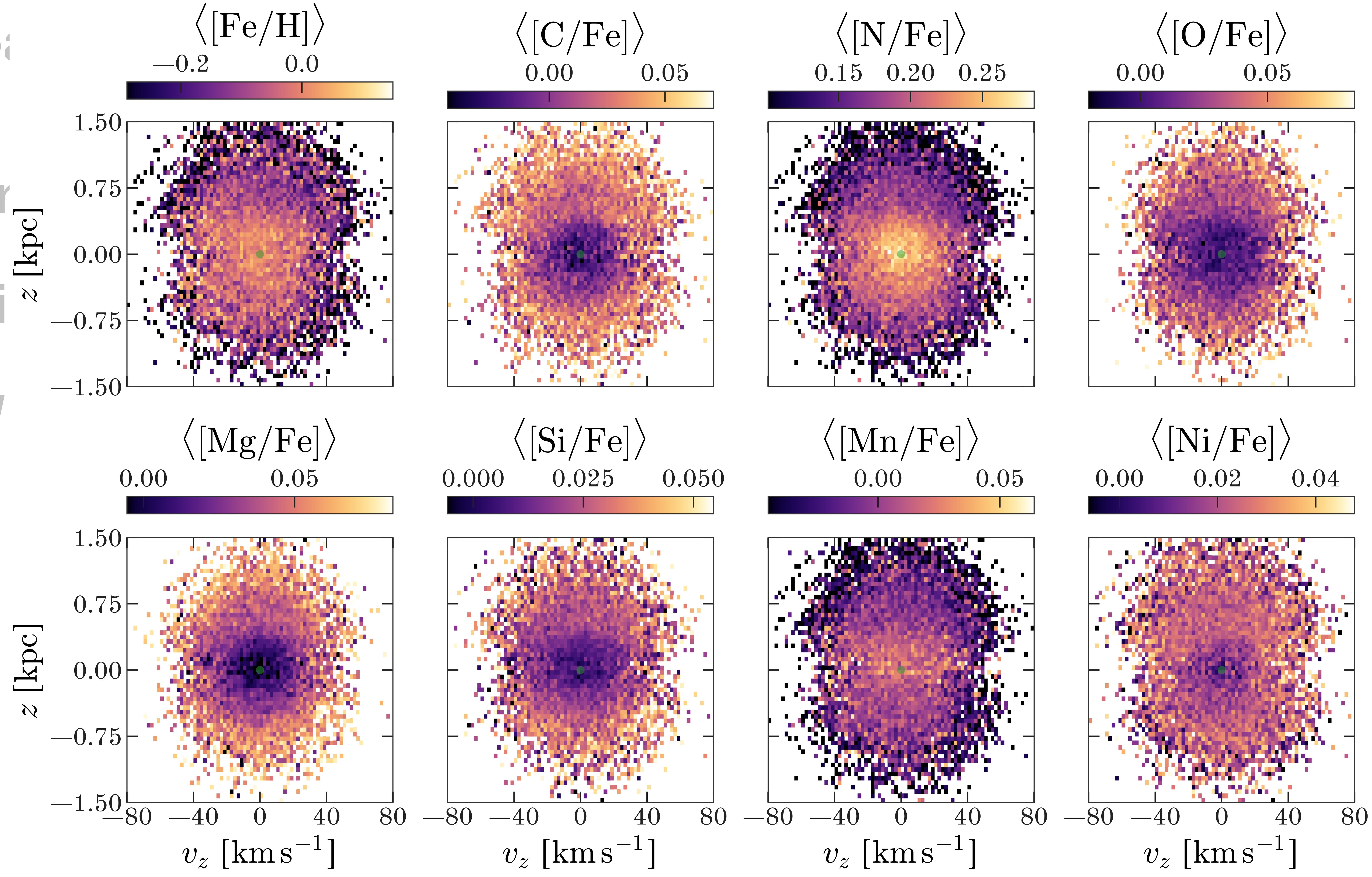
Detailed

Precise r

Pioneeri

l (optical)

Now: ~1



e.g., Price-Whelan et al. 2020

the Milky Way

A Milky Way Analog

NGC 6744
©M. Pugh

A Milky Way Analog

NGC 6744
©M. Pugh

A Milky Way Analog

A Milky Way Analog

NGC 6744
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A Milky Way Analog

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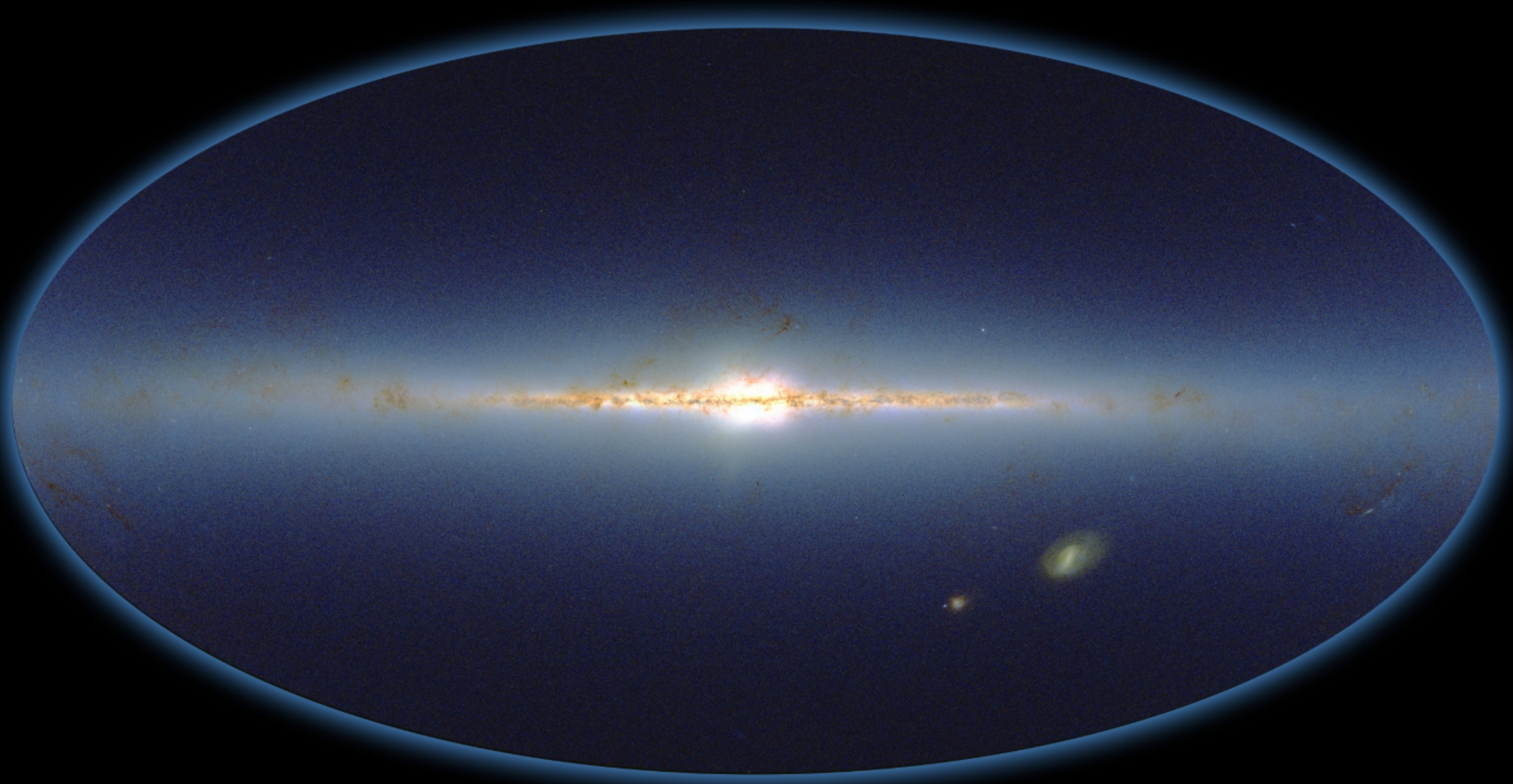
A Milky Way Analog

The Milky Way



Credit: 2MASS

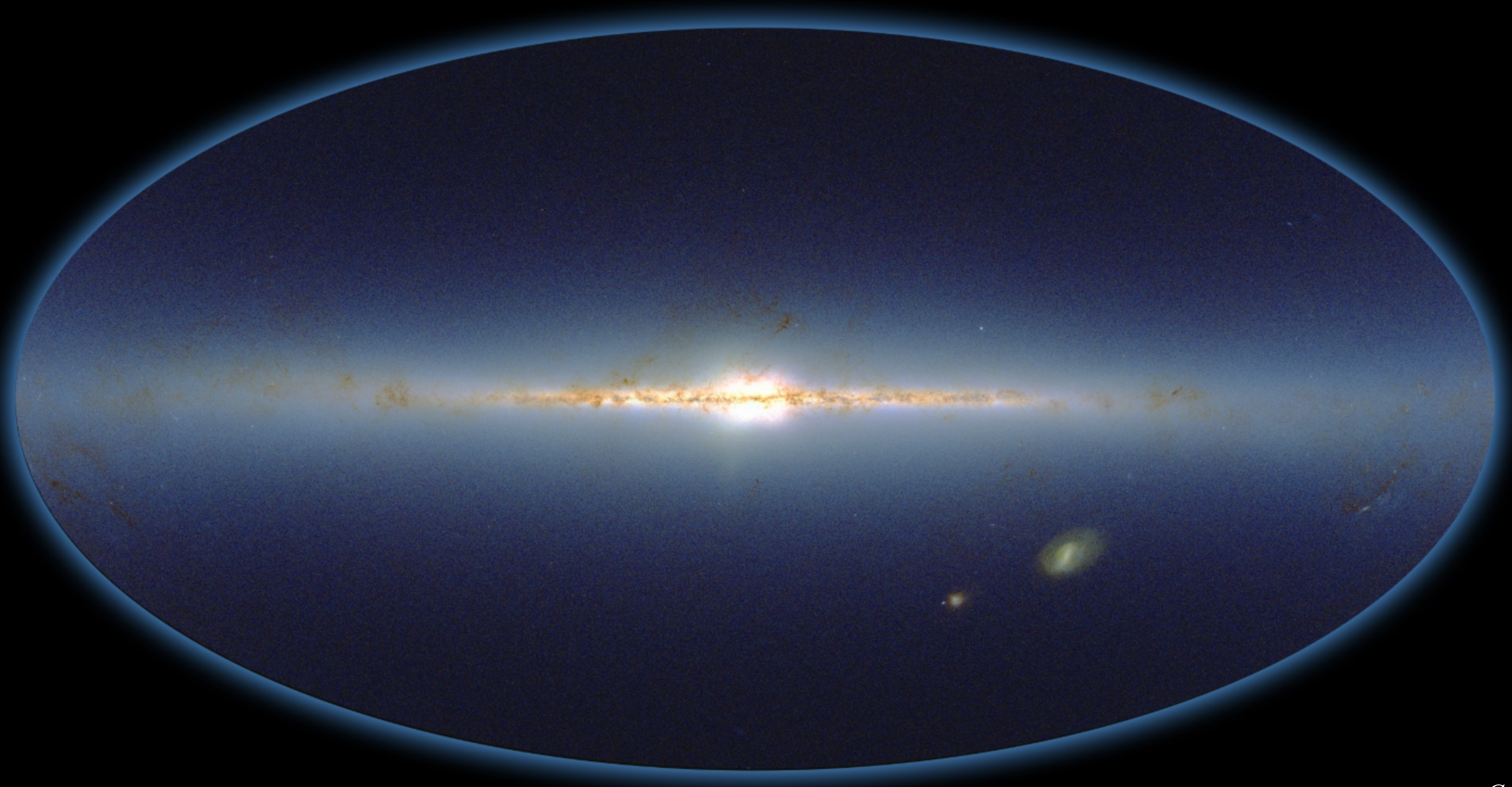
The Cartoon / Textbook Milky Way

Credit: adapted from K. Brauer
http://www.mit.edu/~kbrauer/

The Dark Matter (?)

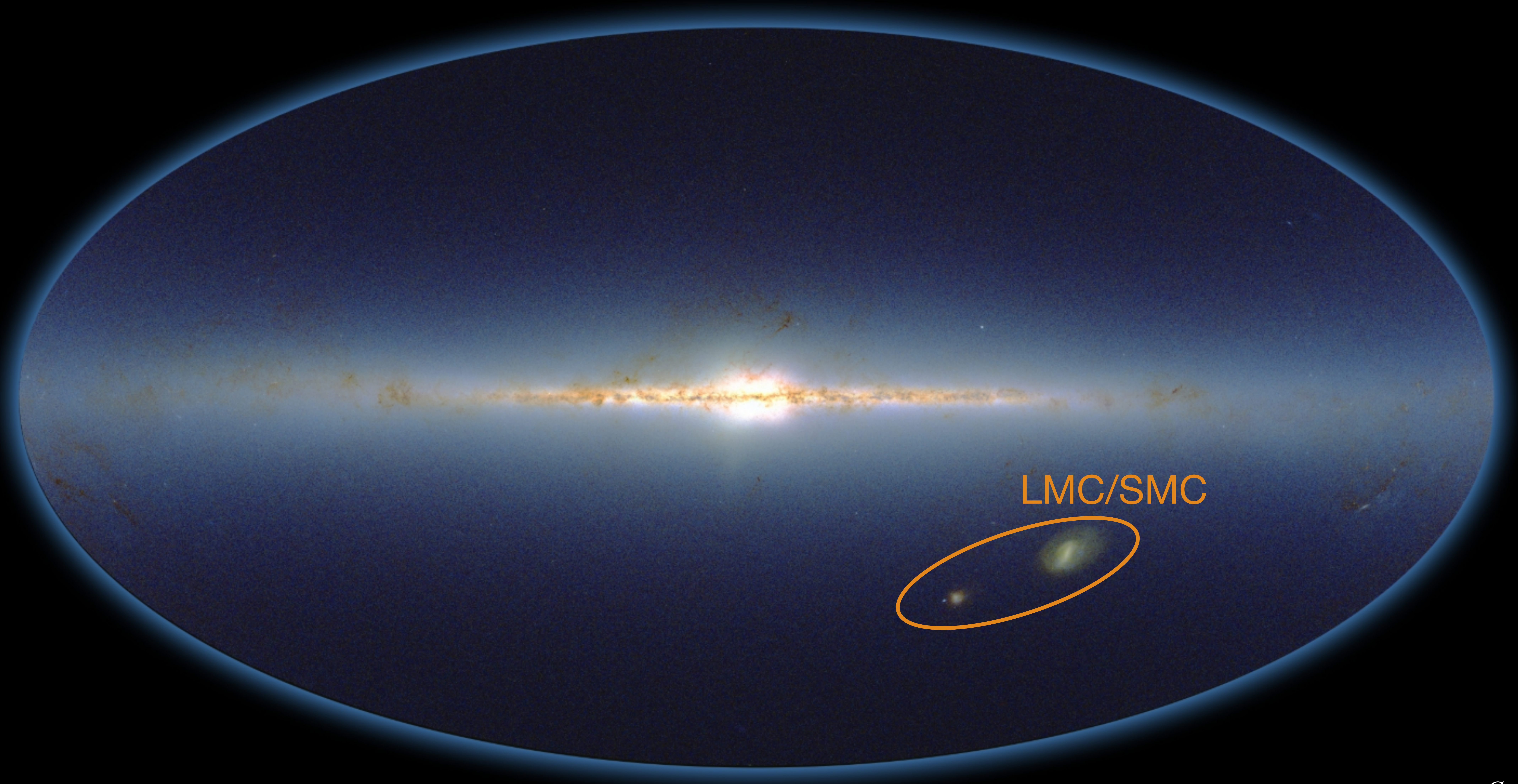
Diemand et al. 2008

The Milky Way



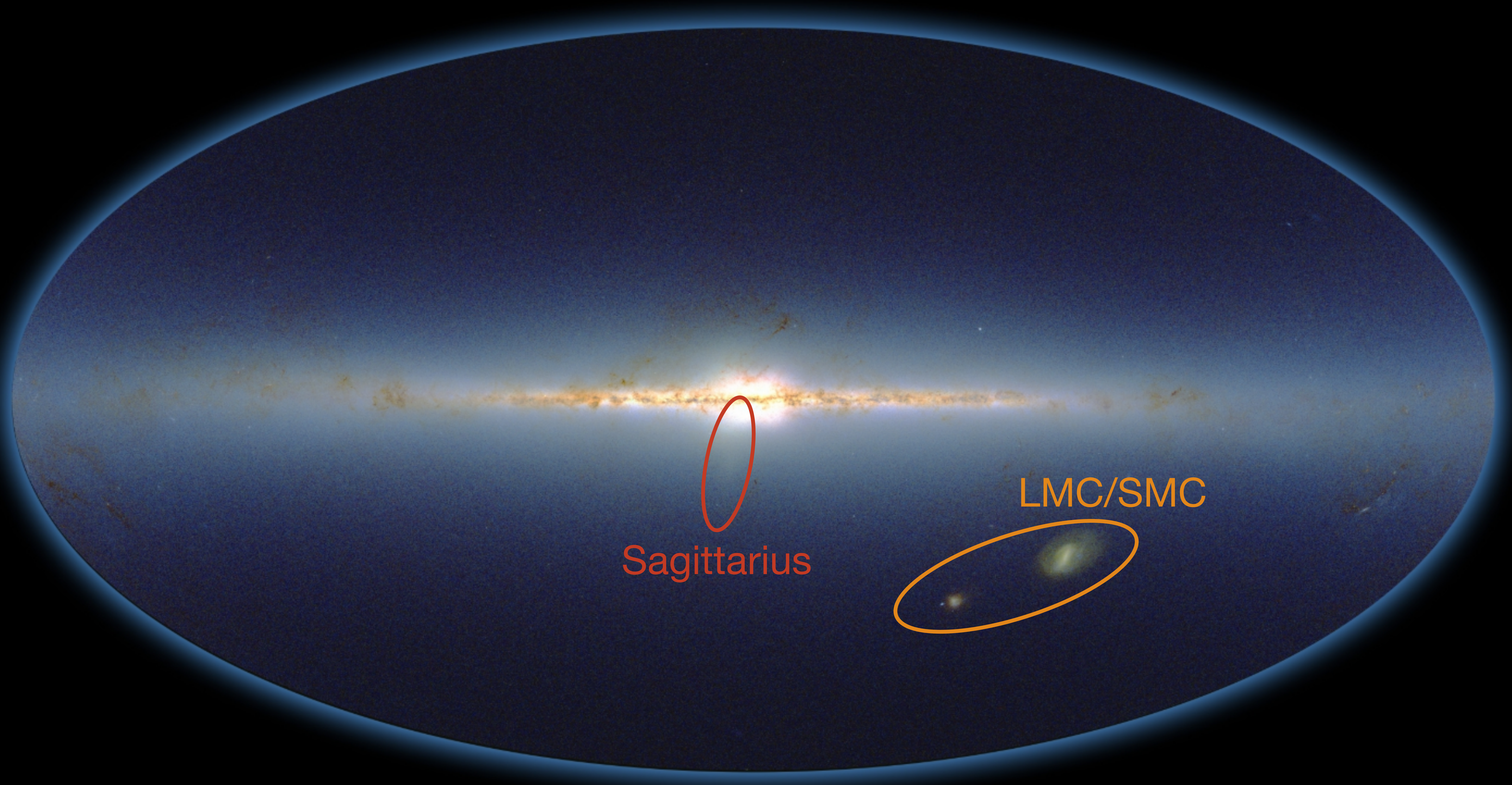
Credit: 2MASS

The Milky Way



Credit: 2MASS

The Milky Way

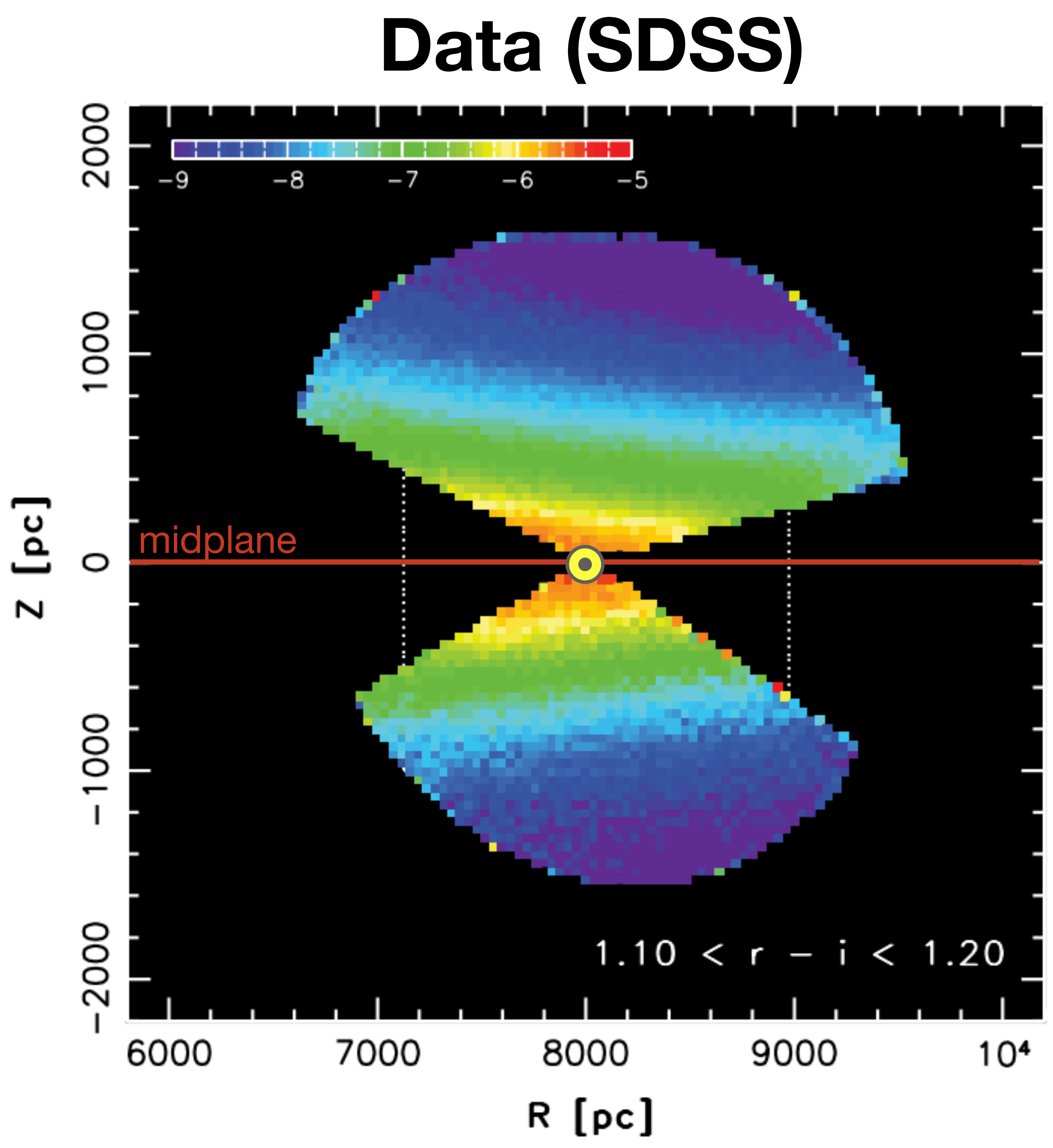


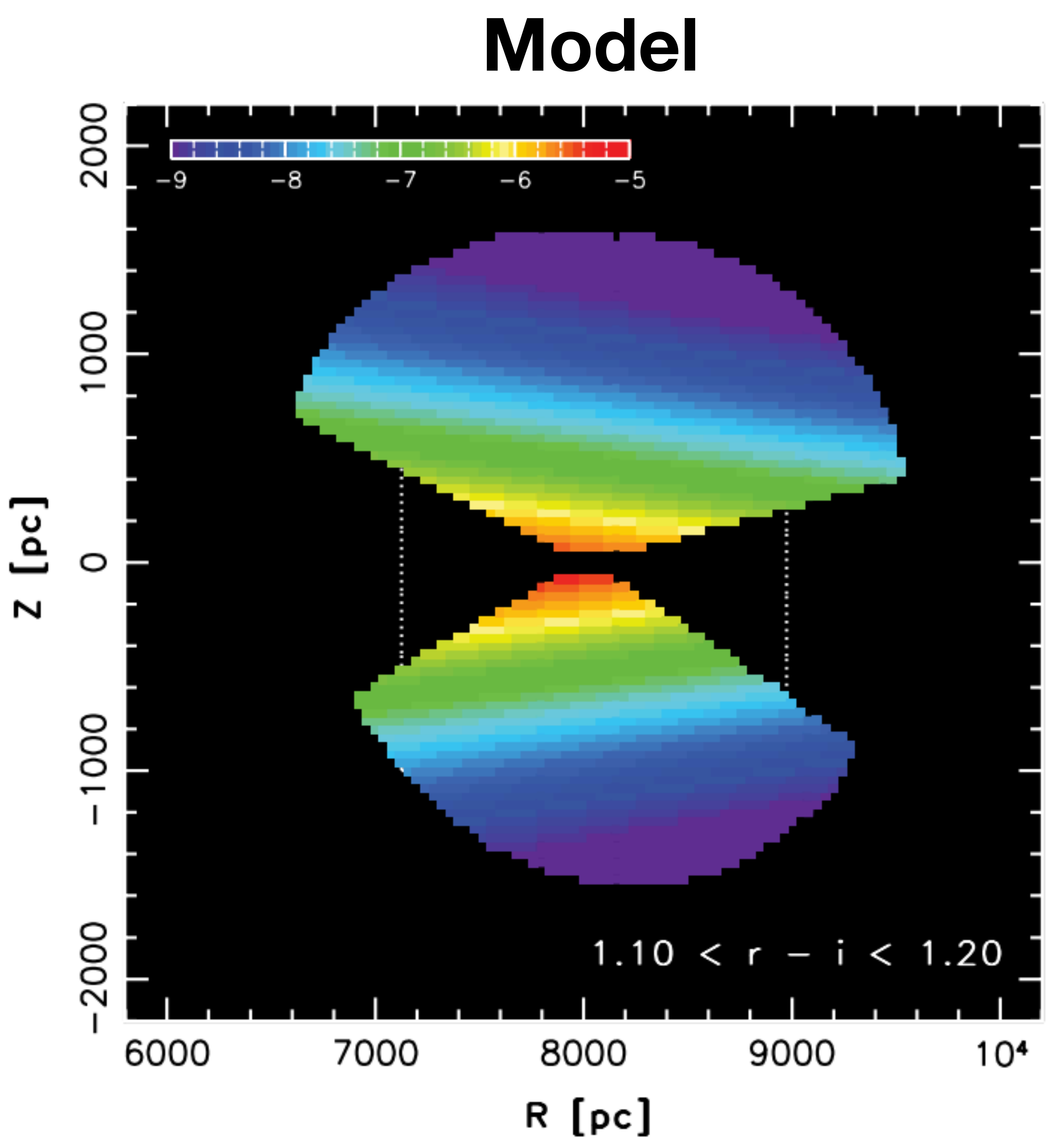
Credit: 2MASS

Milky Way Disk Structure

See also: Schönrich & Binney 2009; Bovy et al. 2012, 2013; Mackereth et al. 2017

Milky Way Disk Structure



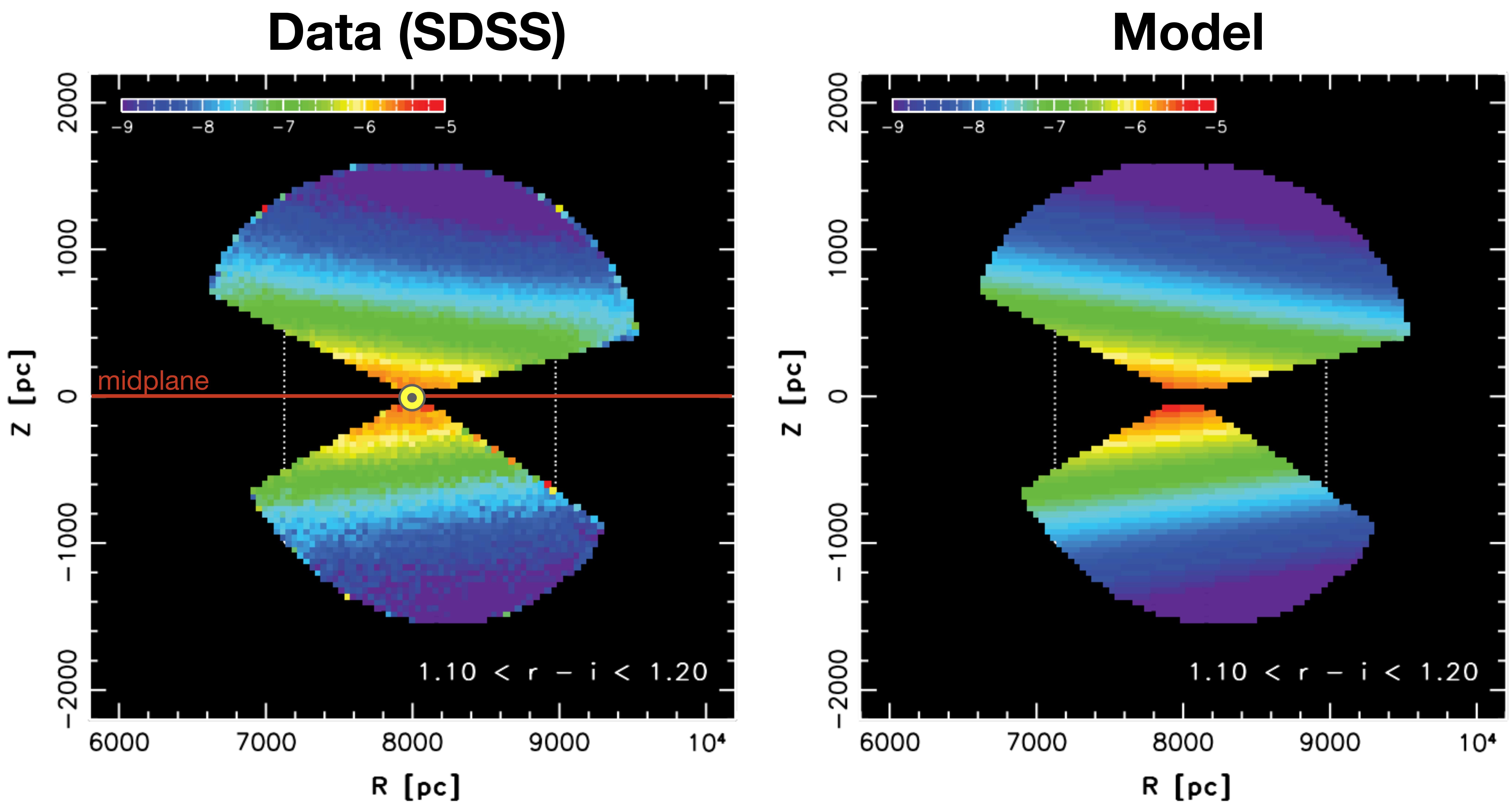


Jurić et al. 2008

See also: Schönrich & Binney 2009; Bovy et al. 2012, 2013; Mackereth et al. 2017

Milky Way Disk Structure

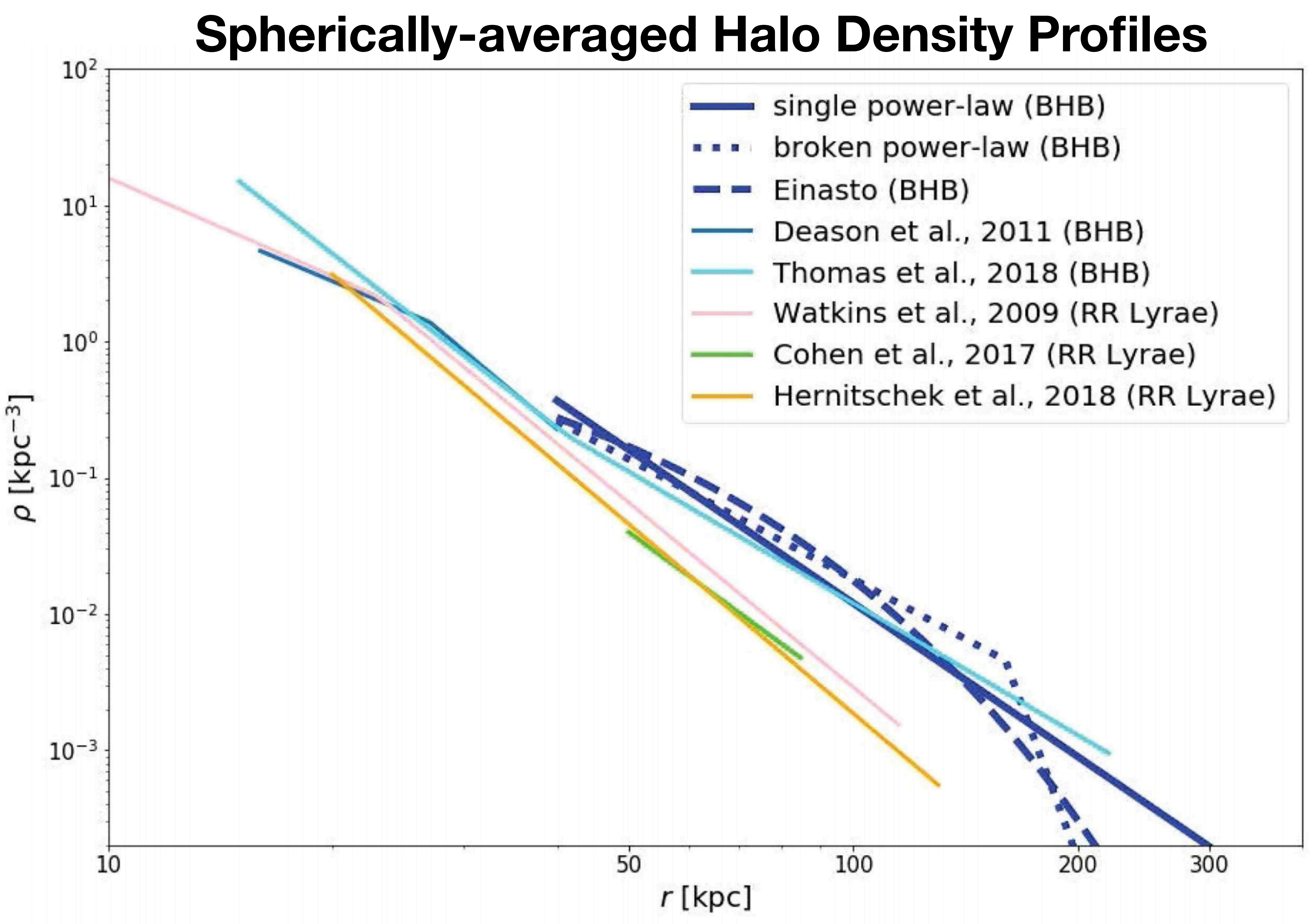
$$\rho_D(R,z) = \rho_1 \exp\left(-\frac{R}{h_{R,1}} - \frac{z}{h_{z,1}}\right) + \rho_2 \exp\left(-\frac{R}{h_{R,2}} - \frac{z}{h_{z,2}}\right)$$



Jurić et al. 2008

See also: Schönrich & Binney 2009; Bovy et al. 2012, 2013; Mackereth et al. 2017

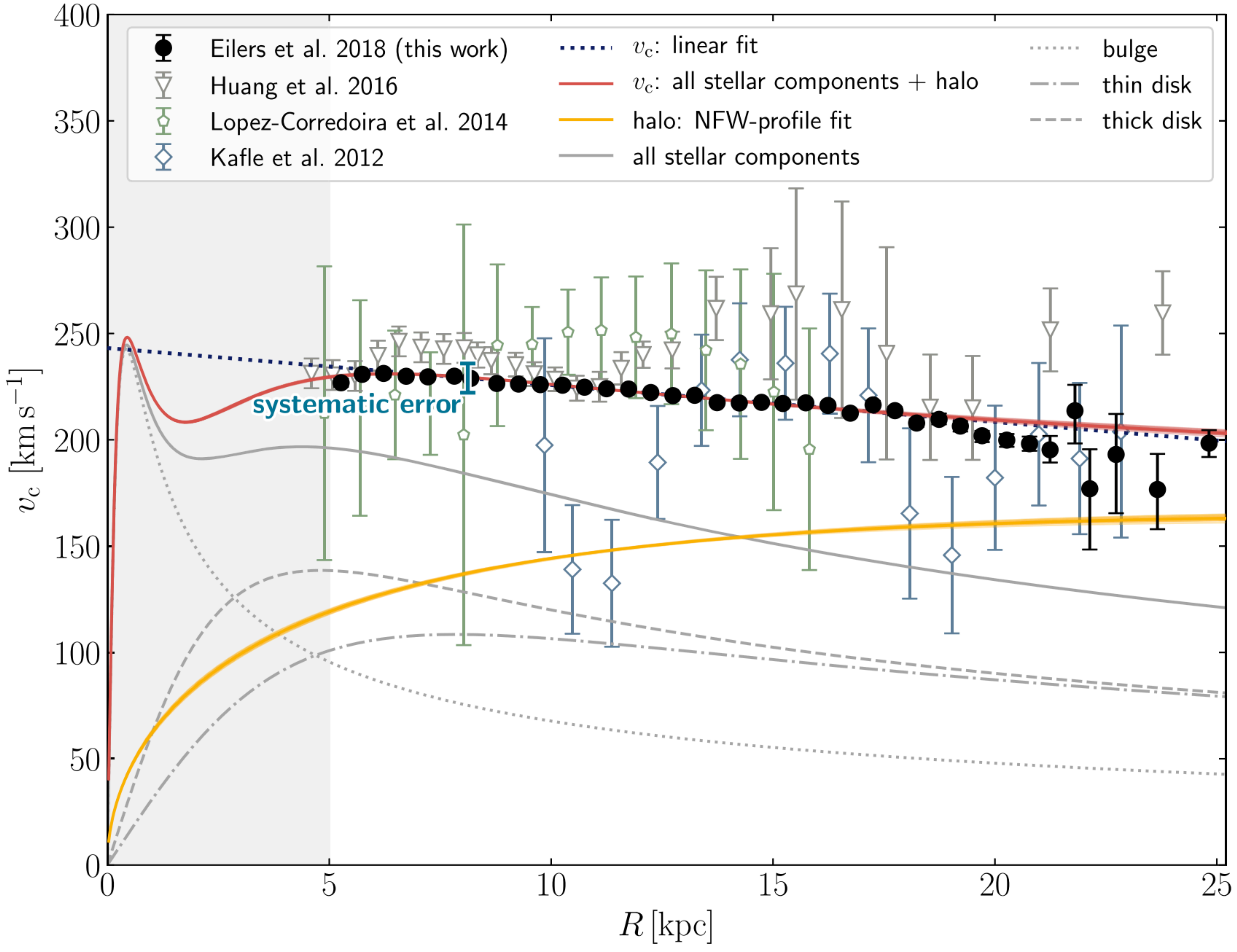
Milky Way Structure: Stellar Halo



Fukushima et al. 2019

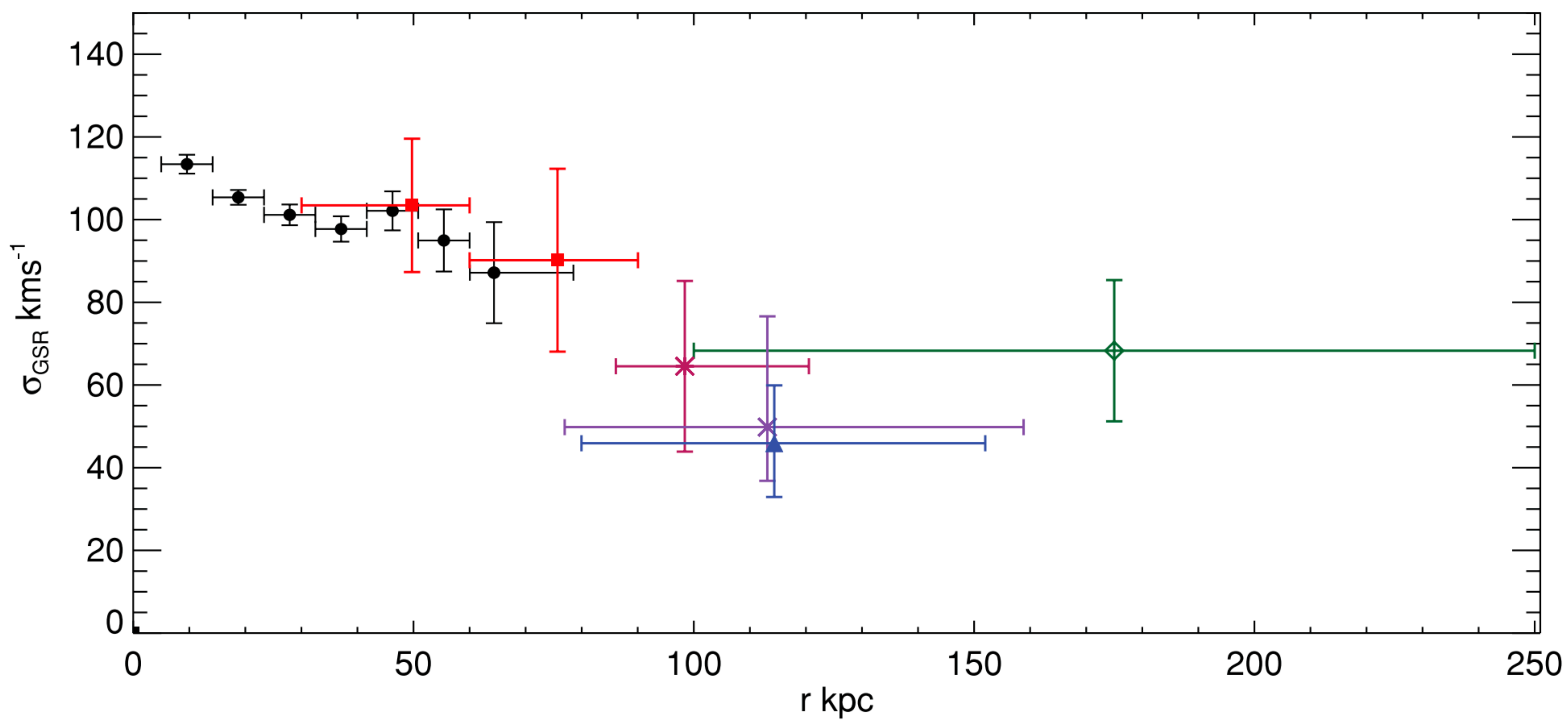
Milky Way *Kinematics*

Disk Rotation Curve



APOGEE; Eilers et al. 2019

Halo Velocity Dispersion Profile



SDSS; Deason et al. 2012

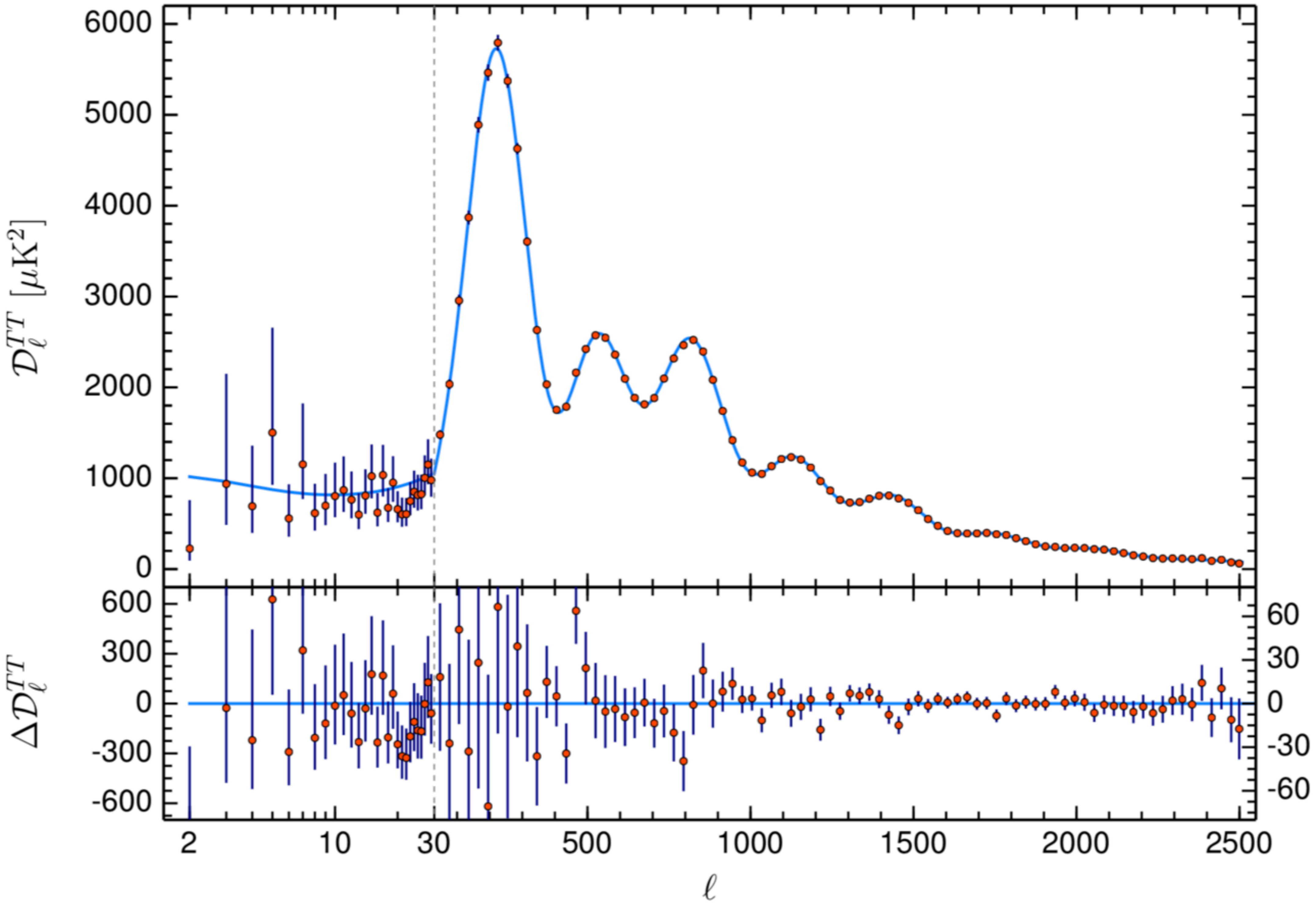
See also: Dehnen 2006; Cunningham et al. 2019; Bird et al. 2019

...let's remeasure with new surveys!?

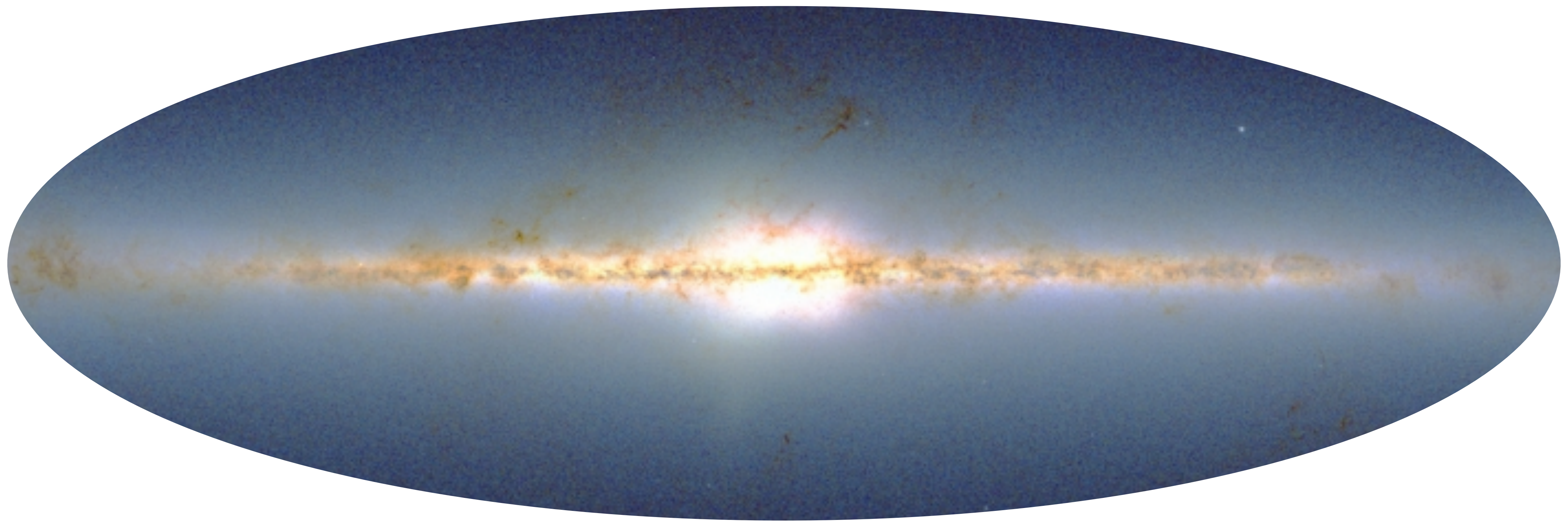
Cosmology vs. Milky Way Science

✓ Precise data
✓ Precise model

✓ Precise data
? Precise model



Planck Collaboration 2018

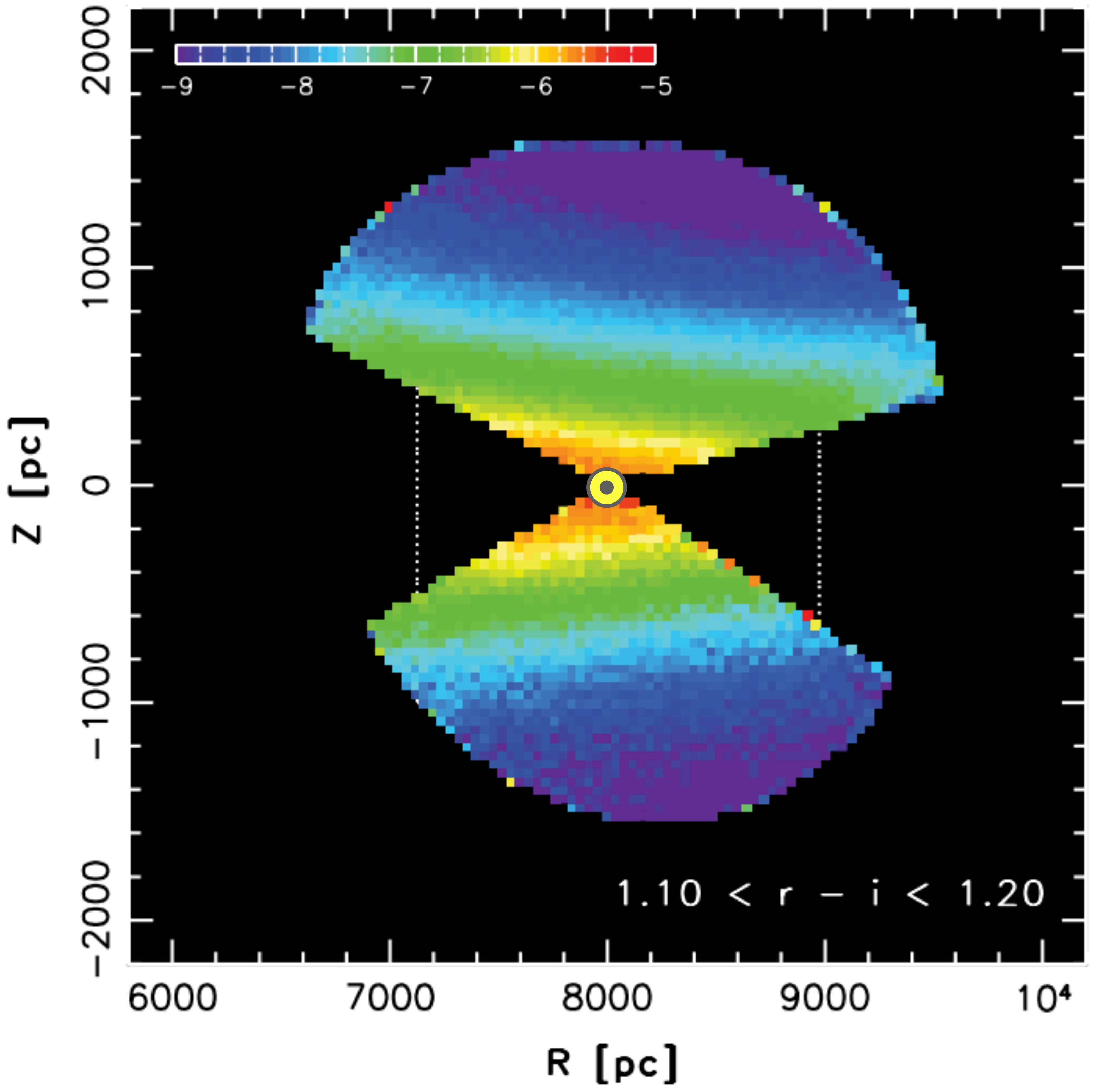


2MASS

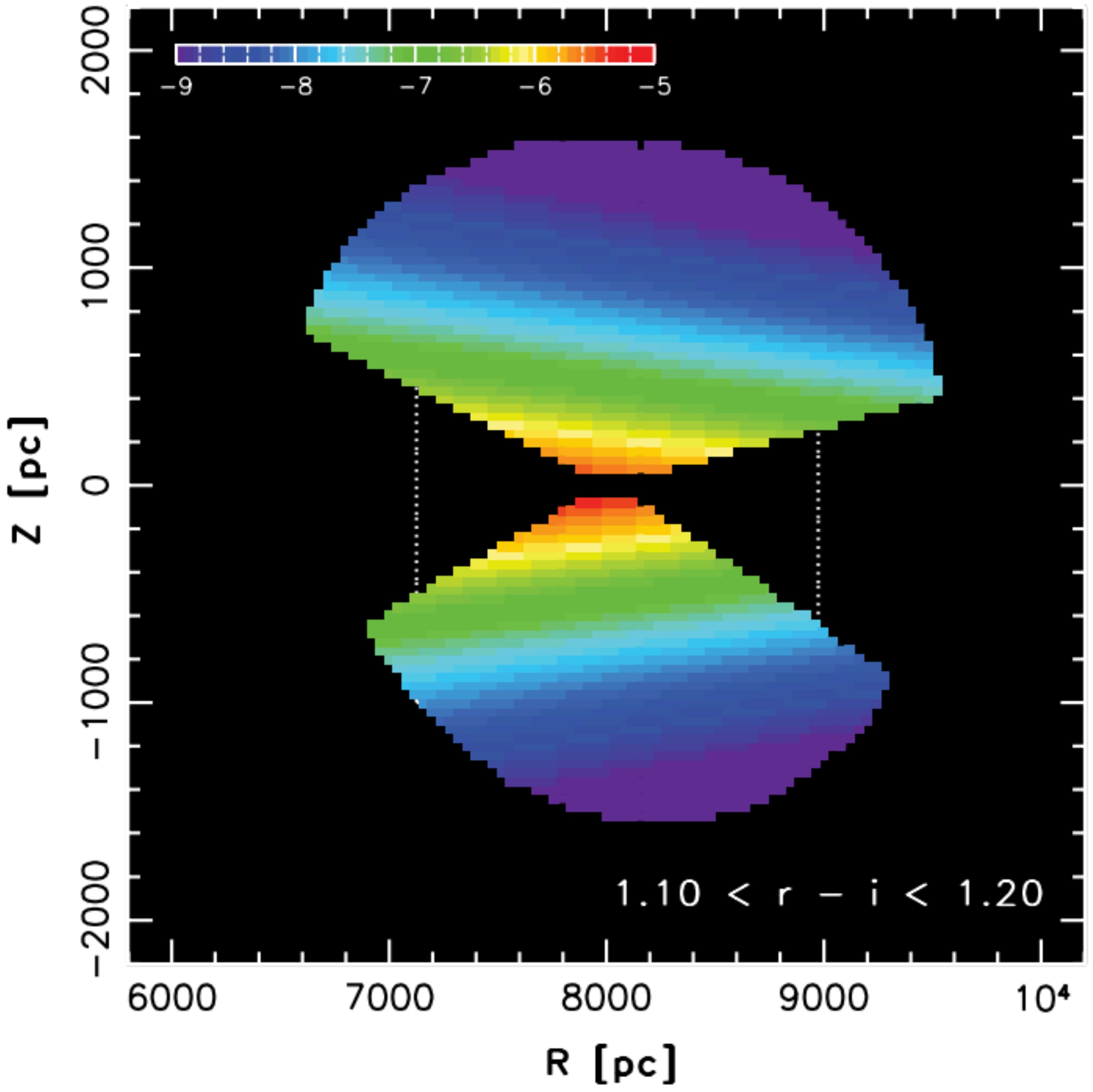
Milky Way *Sub*structure

Milky Way *Sub*structure

Data (SDSS)

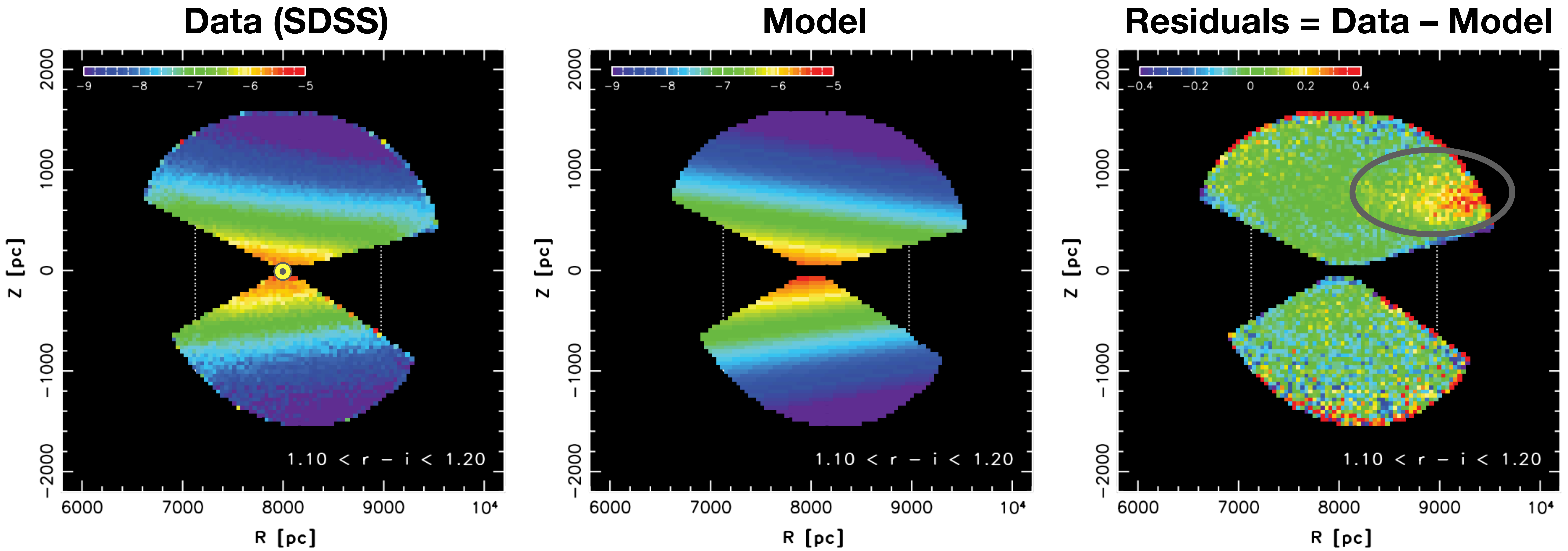


Model



Jurić et al. 2008

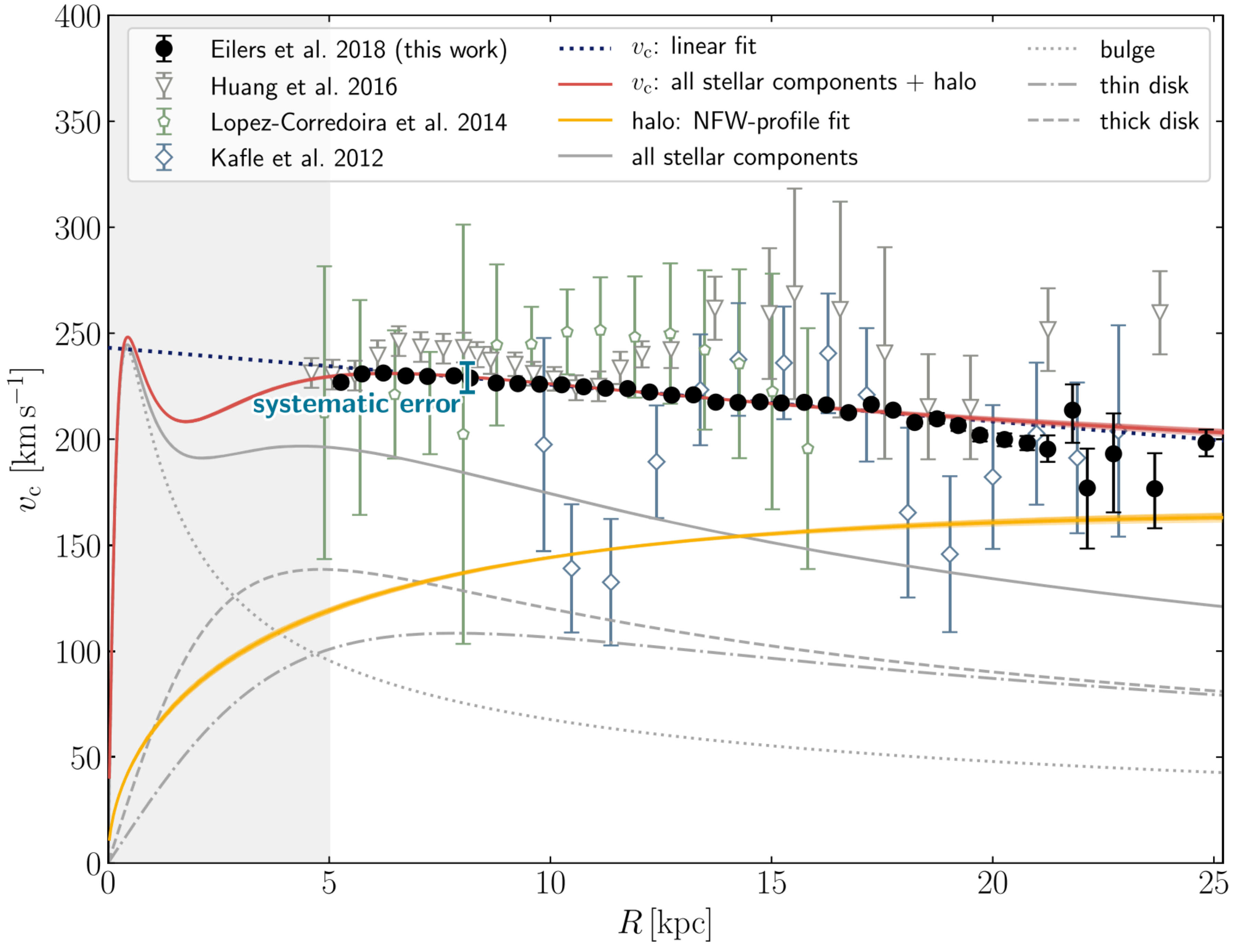
Milky Way *Sub*structure



Jurić et al. 2008

Milky Way *Sub*structure

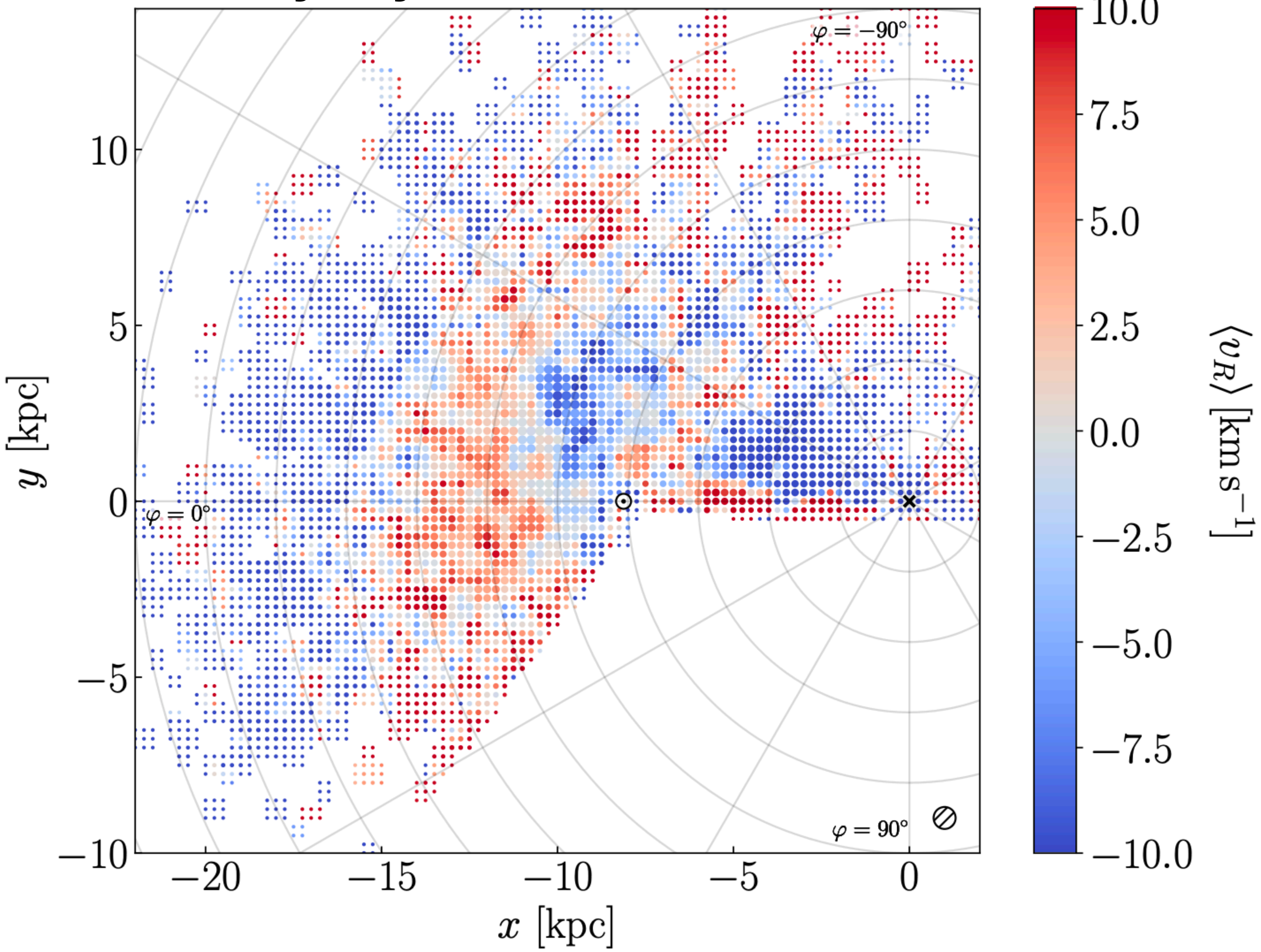
Disk Rotation Curve



APOGEE; Eilers et al. 2019

→

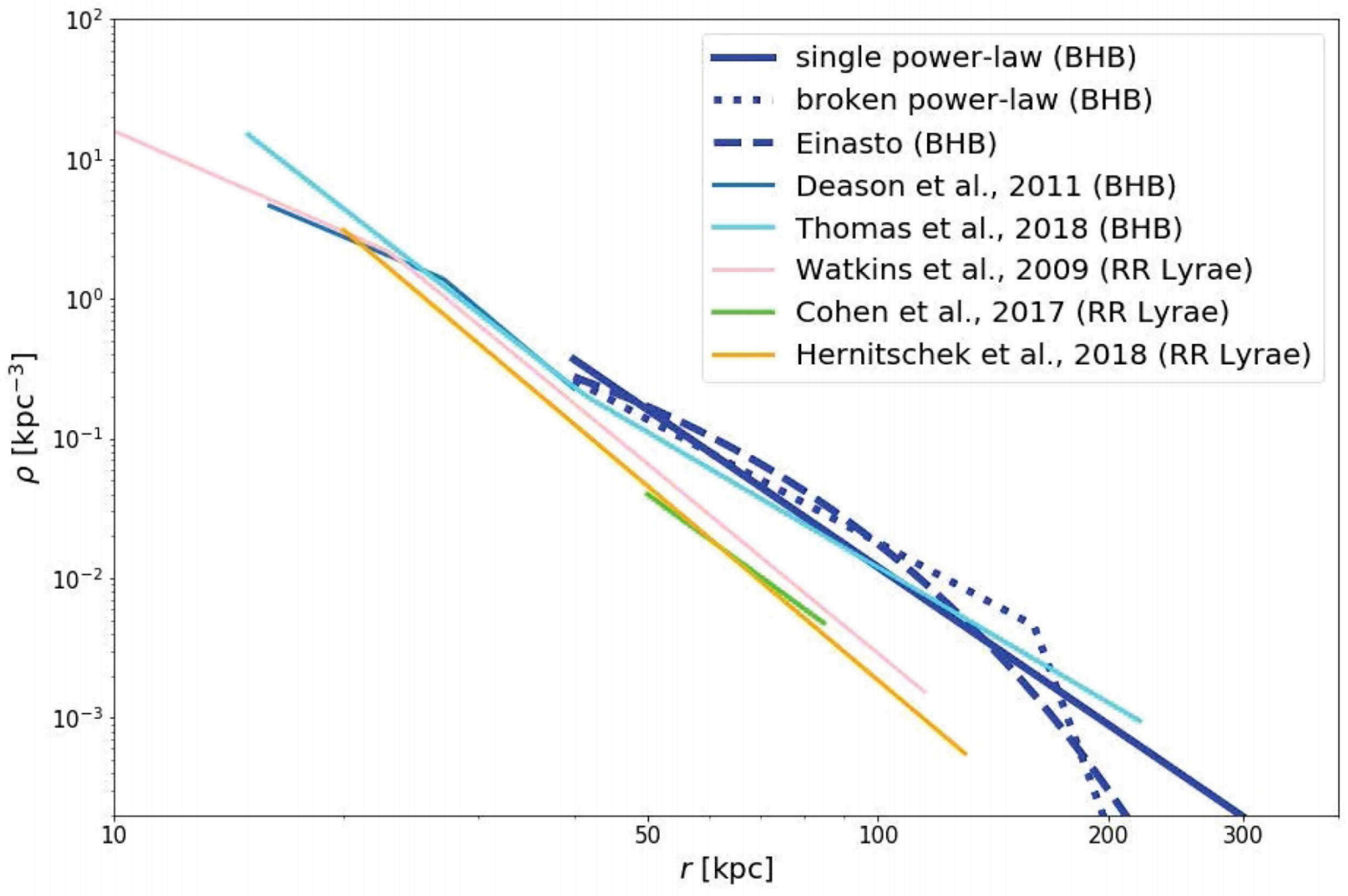
Velocity Asymmetries and Structure



APOGEE; Eilers et al. 2020

Milky Way *Sub*structure

Smooth Stellar Halo Profile



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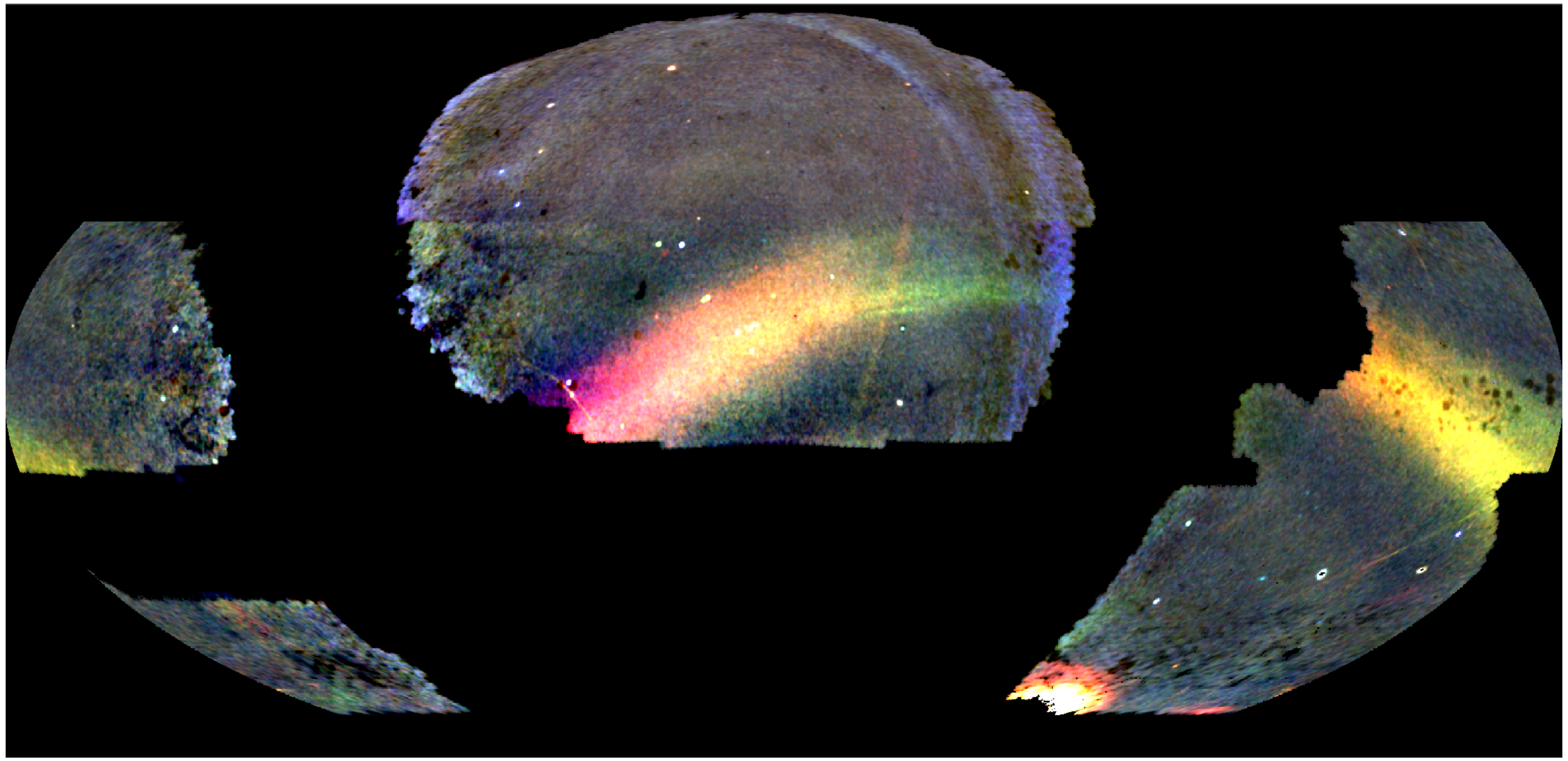
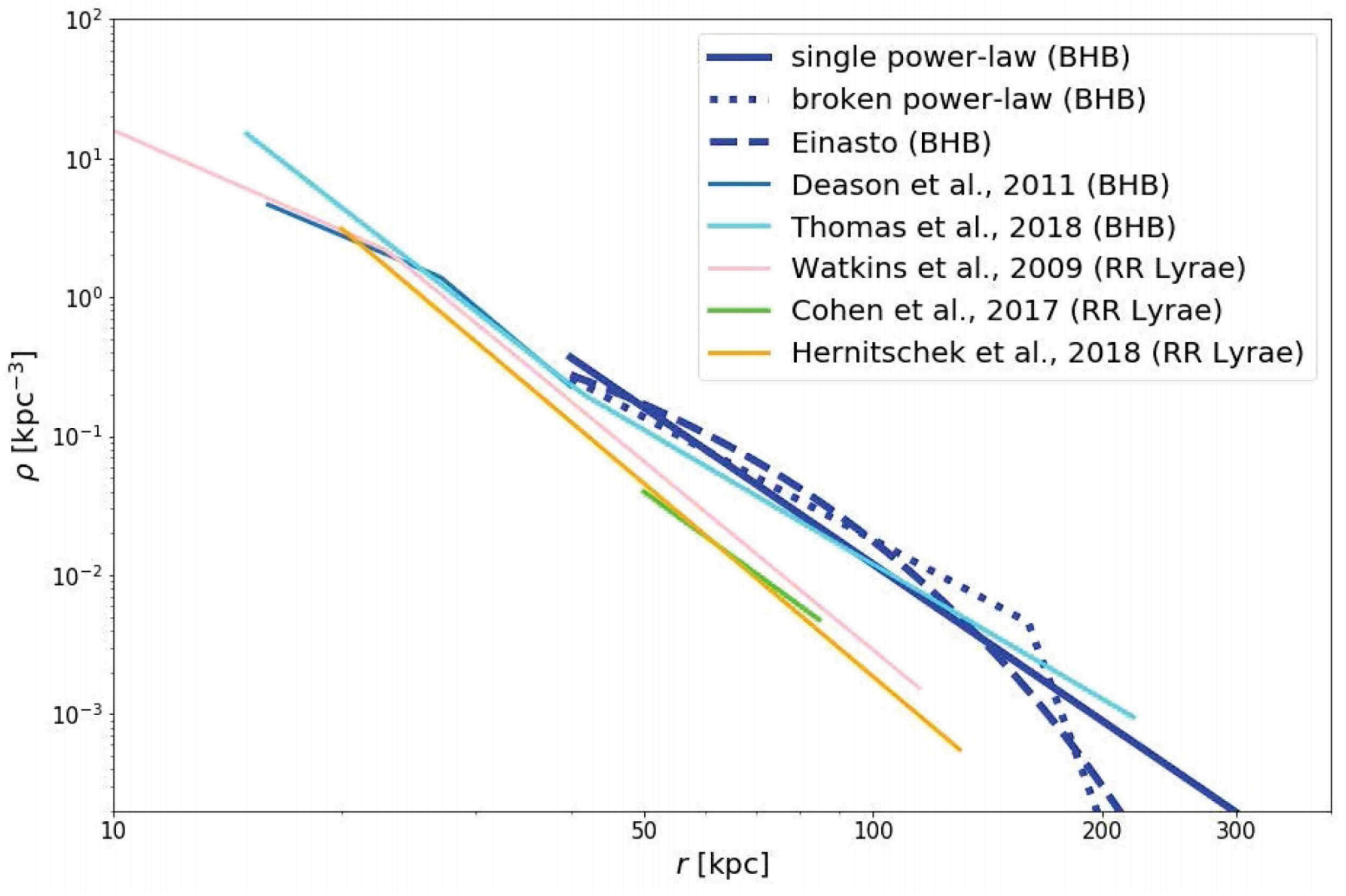
Stellar Streams and Substructures



Legacy Surveys; N. Shipp, A. Price-Whelan

Milky Way *Sub*structure

Smooth Stellar Halo Profile



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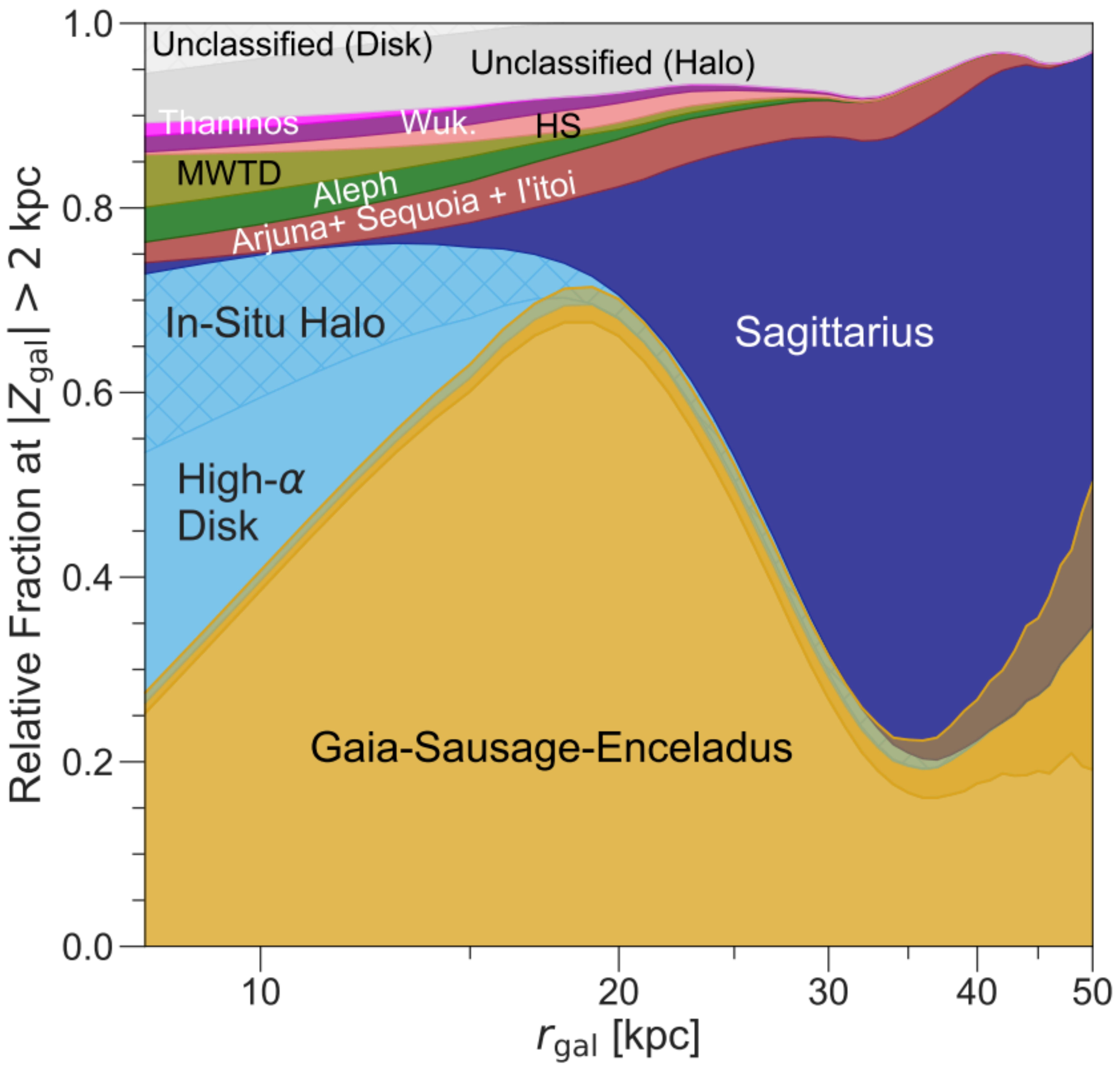


H3 Survey; Naidu et al. 2020

The future of Galactic dynamics will embrace and use this disequilibrium!

What dynamical processes shape the Milky Way?

What dynamical processes shape the Milky Way?

Satellites & Mergers

Satellites & Mergers

General picture (minor mergers):

- Satellite enters Milky Way
- Perturbs Milky Way disk / structure
- Disrupts and forms debris stream / substructure

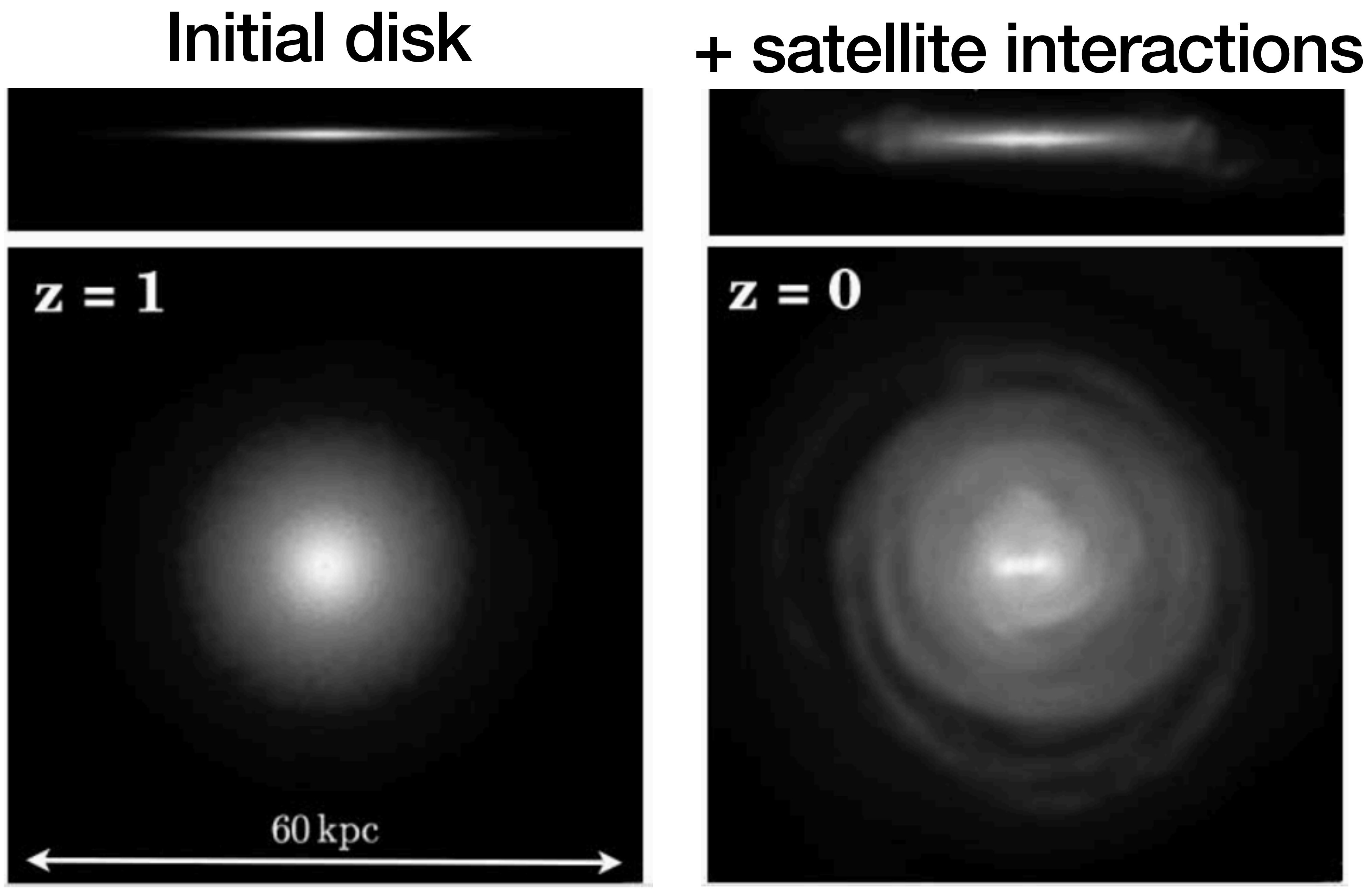
e.g. Weinberg 1989

Satellites & Mergers

Perturbs Milky Way disk / structure

Satellites & Mergers

Perturbs Milky Way disk / structure

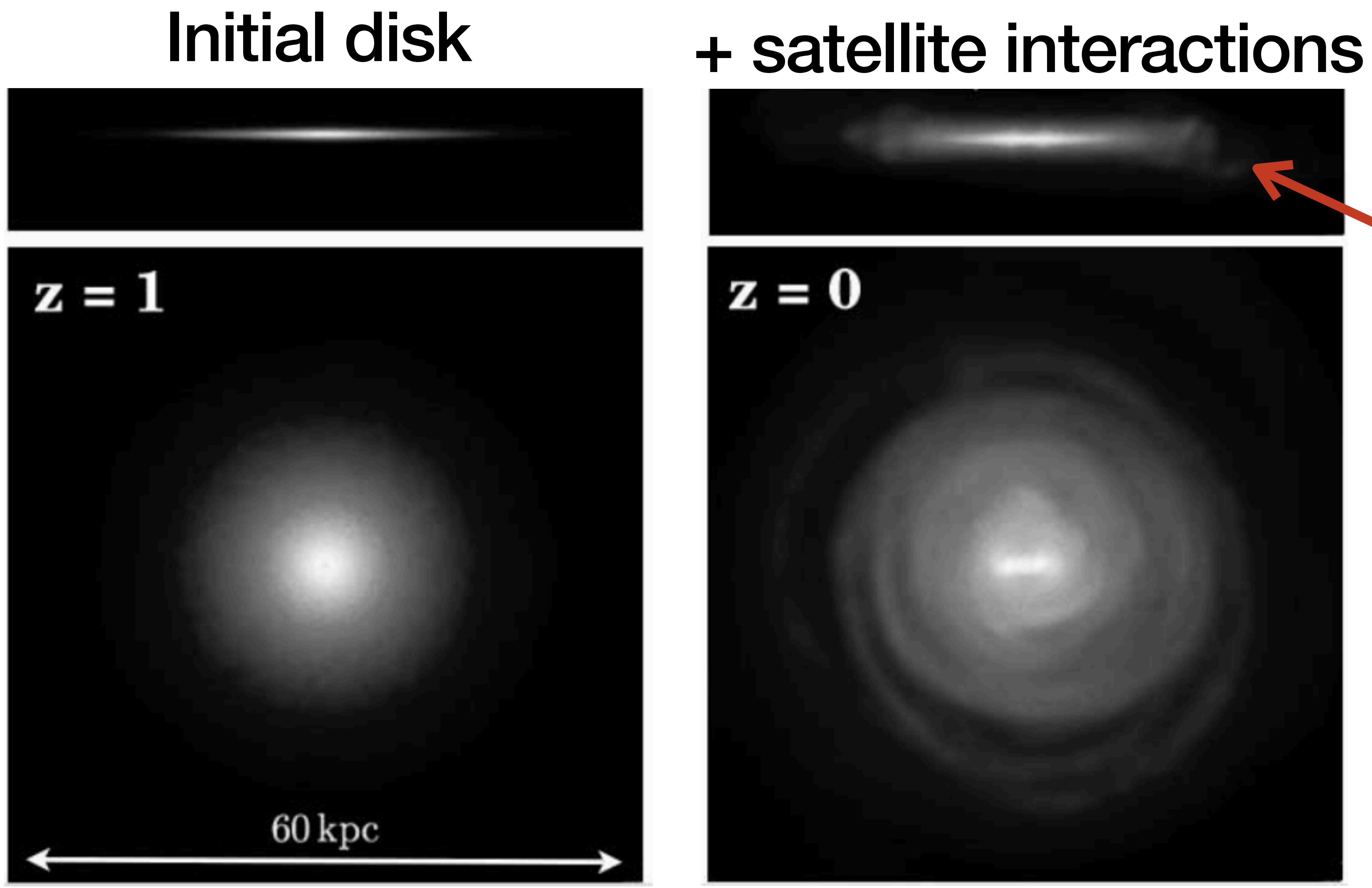


Kazantzidis et al. 2008

See also: Toth & Ostriker 1992; Hernquist & Quinn 1993; Veláquez & White 1999; Chakrabarti & Blitz 2009, ...+ many more!

Satellites & Mergers

Perturbs Milky Way disk / structure

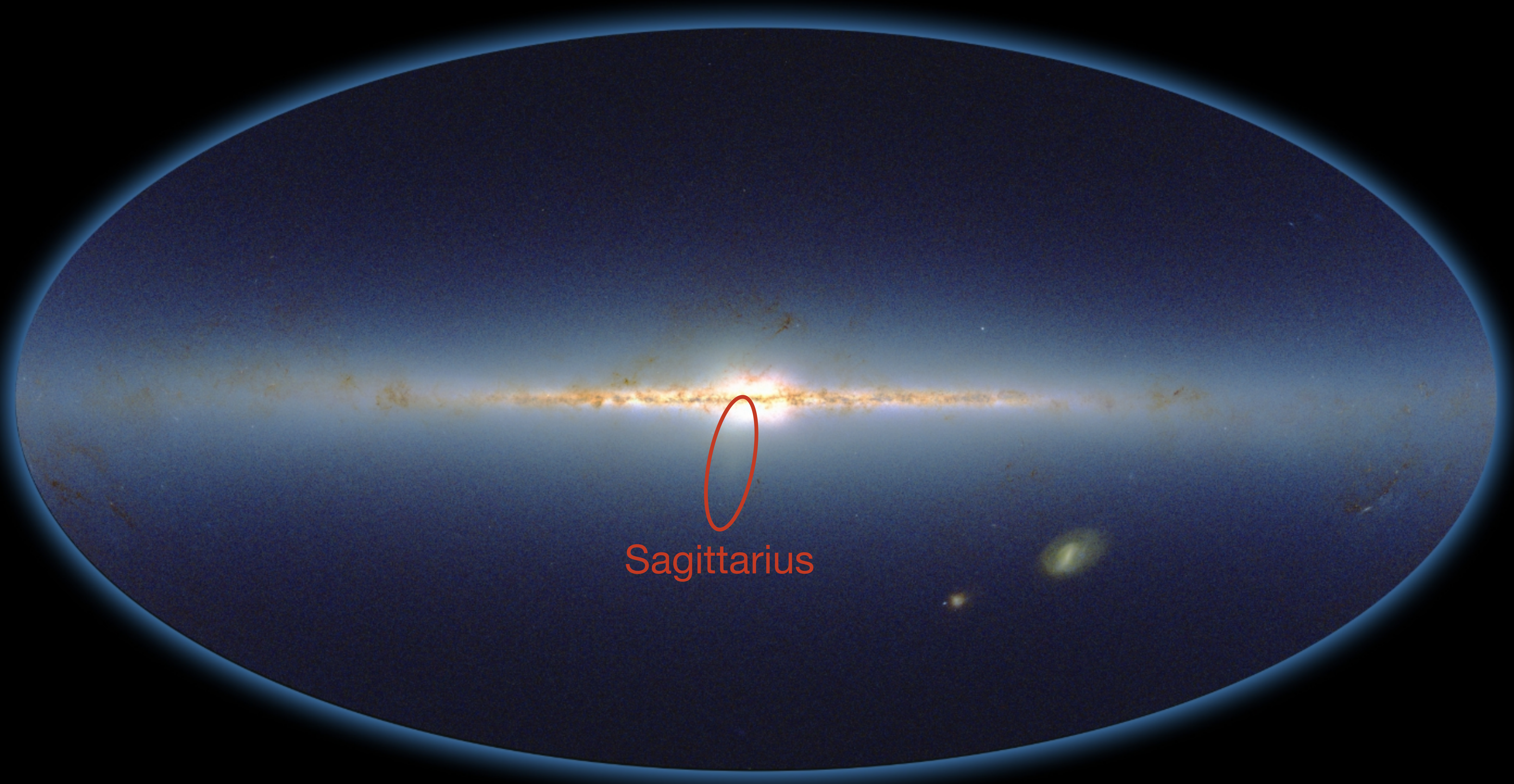


Kazantzidis et al. 2008

NGC 3628; Eric Coles and Mel Helm, 2017

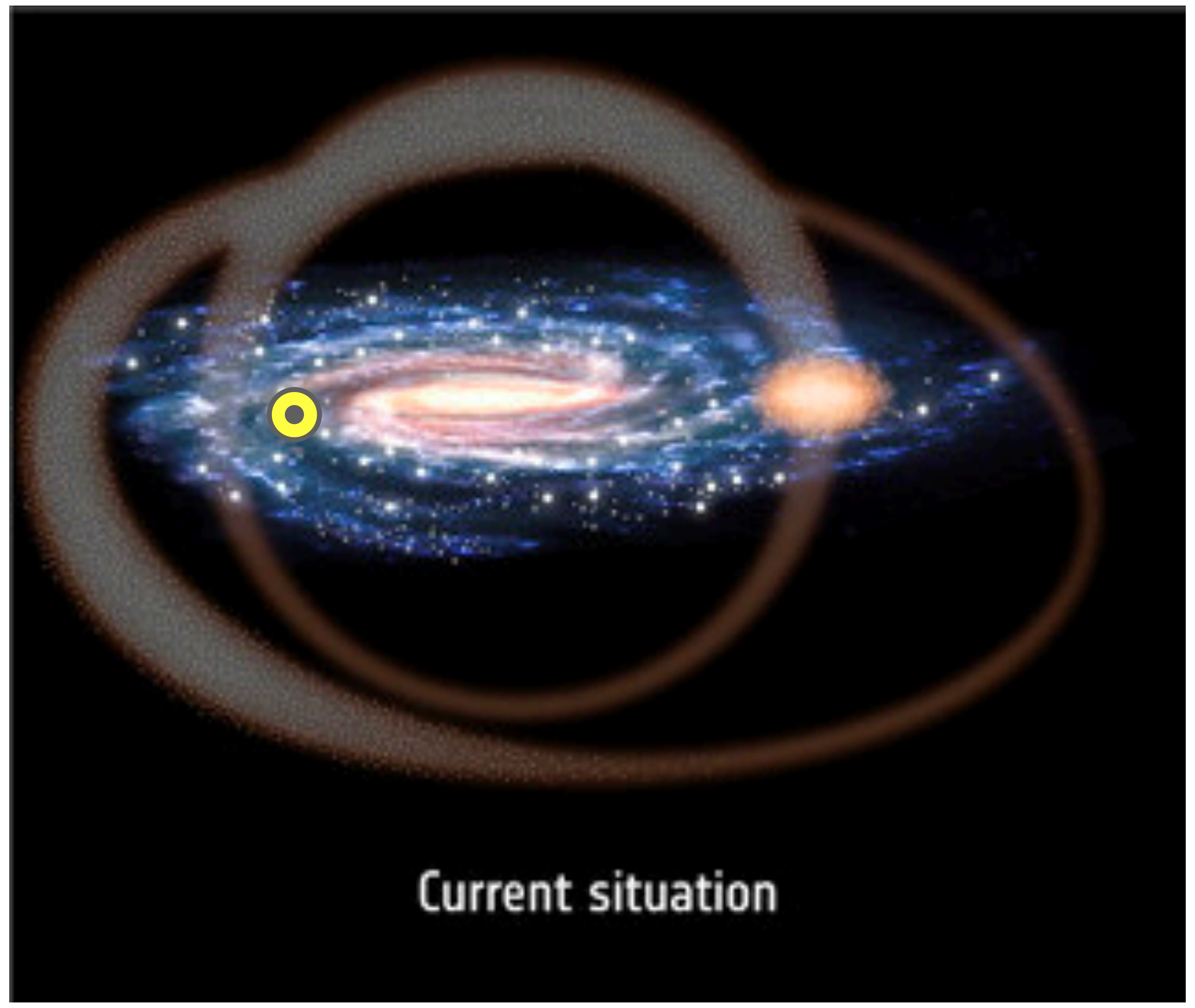
See also: Toth & Ostriker 1992; Hernquist & Quinn 1993; Veláquez & White 1999; Chakrabarti & Blitz 2009, ...+ many more!

Sagittarius + the Milky Way



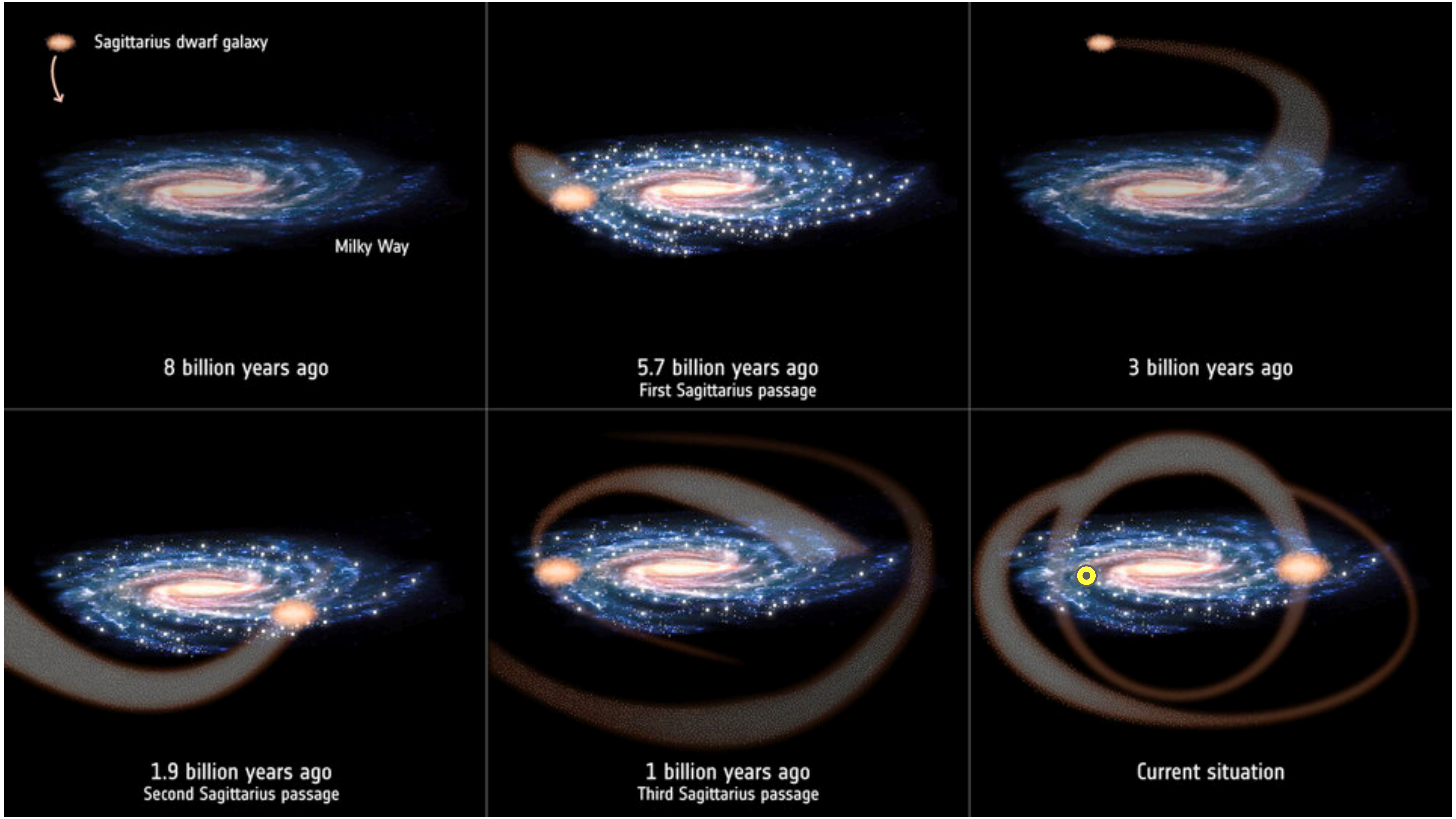
Credit: 2MASS

Sagittarius + the Milky Way



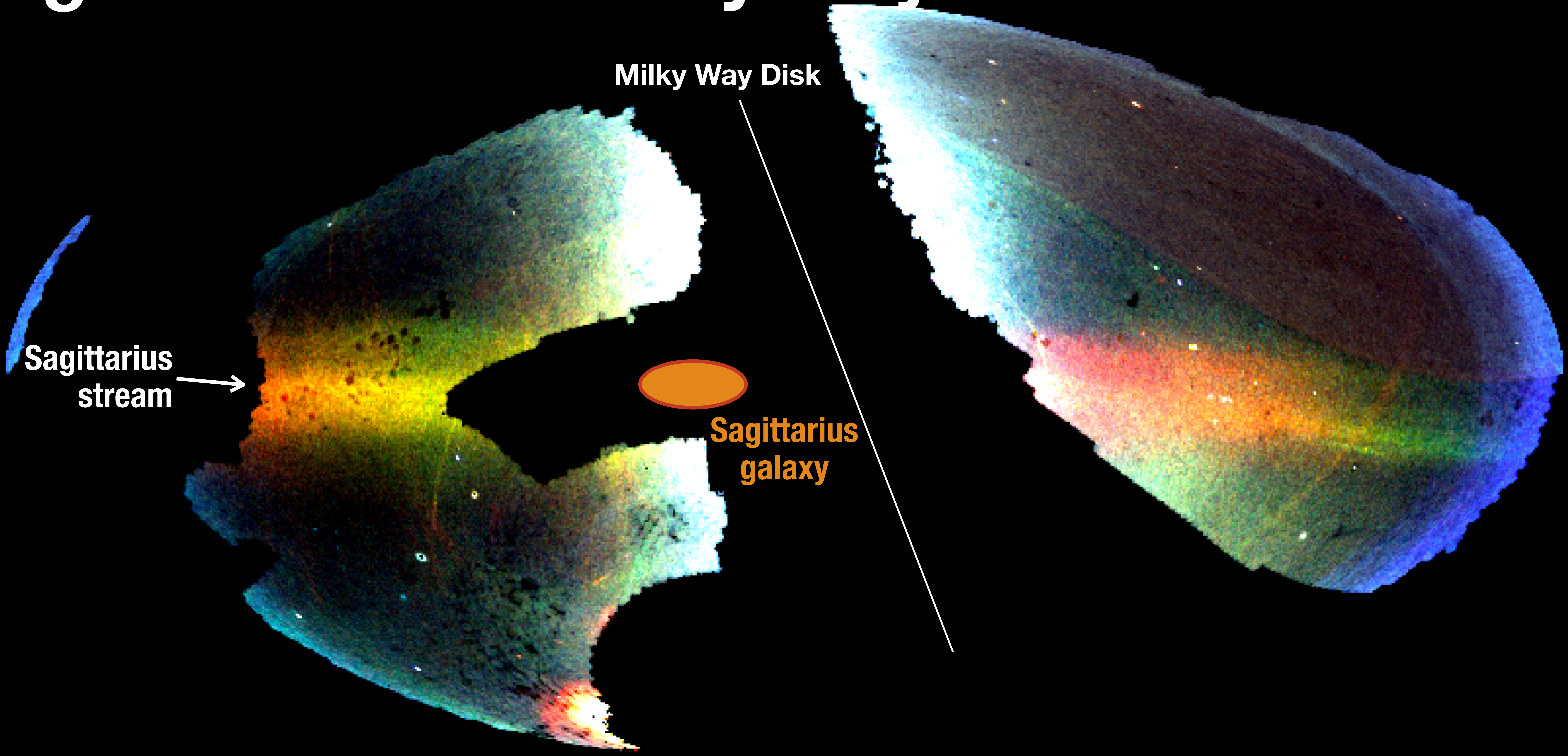
Credit: ESA; Ruiz-Lara et al. 2020

Sagittarius + the Milky Way



Credit: ESA; Ruiz-Lara et al. 2020

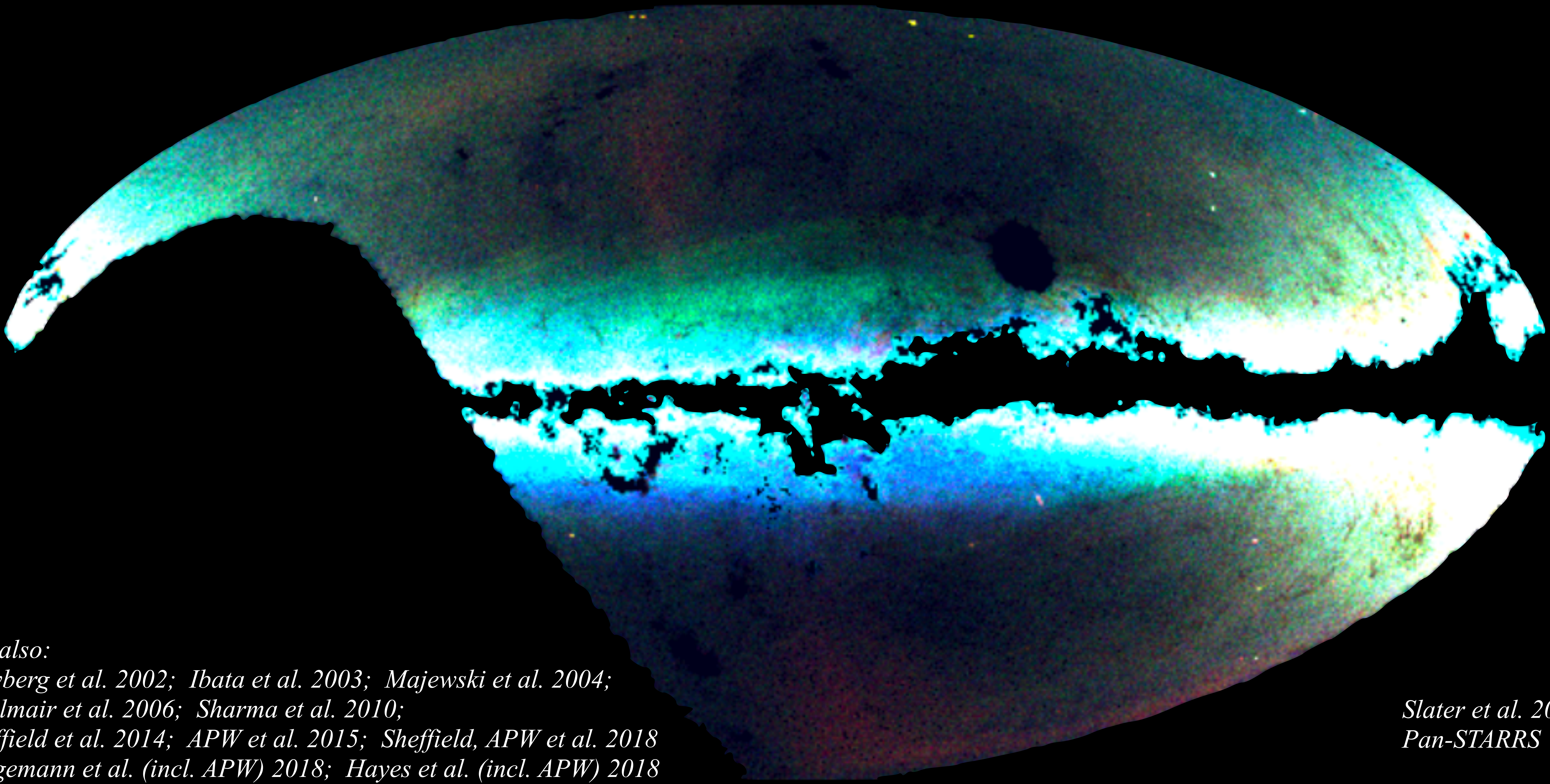
Sagittarius + the Milky Way



~10 kpc ~20 kpc >40 kpc

Legacy Surveys; N. Shipp, A. Price-Whelan

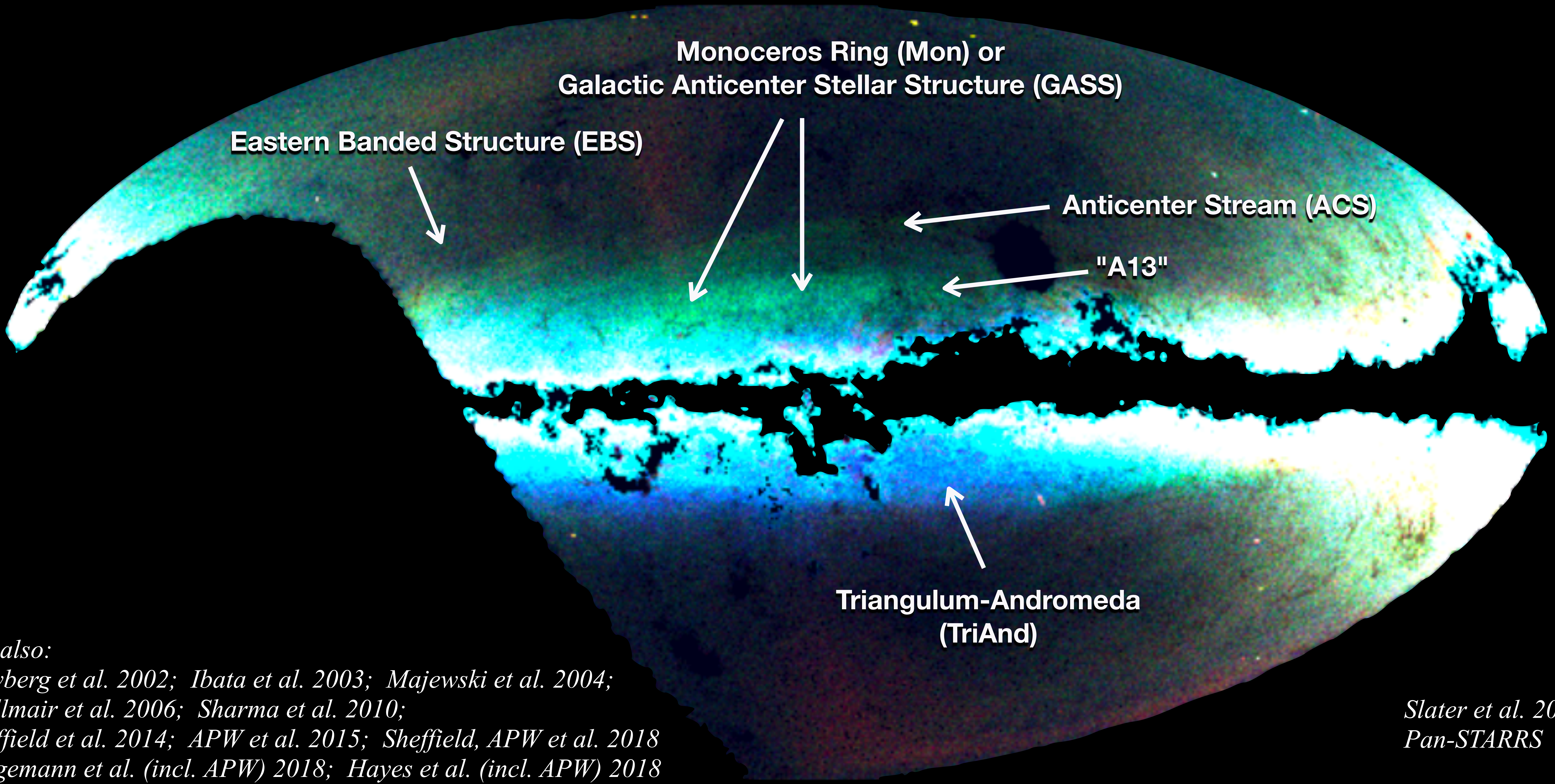
The Perturbed Galactic Anticenter



See also:
Newberg et al. 2002; Ibata et al. 2003; Majewski et al. 2004;
Grillmair et al. 2006; Sharma et al. 2010;
Sheffield et al. 2014; APW et al. 2015; Sheffield, APW et al. 2018
Bergemann et al. (incl. APW) 2018; Hayes et al. (incl. APW) 2018

Slater et al. 2014
Pan-STARRS

The Perturbed Galactic Anticenter



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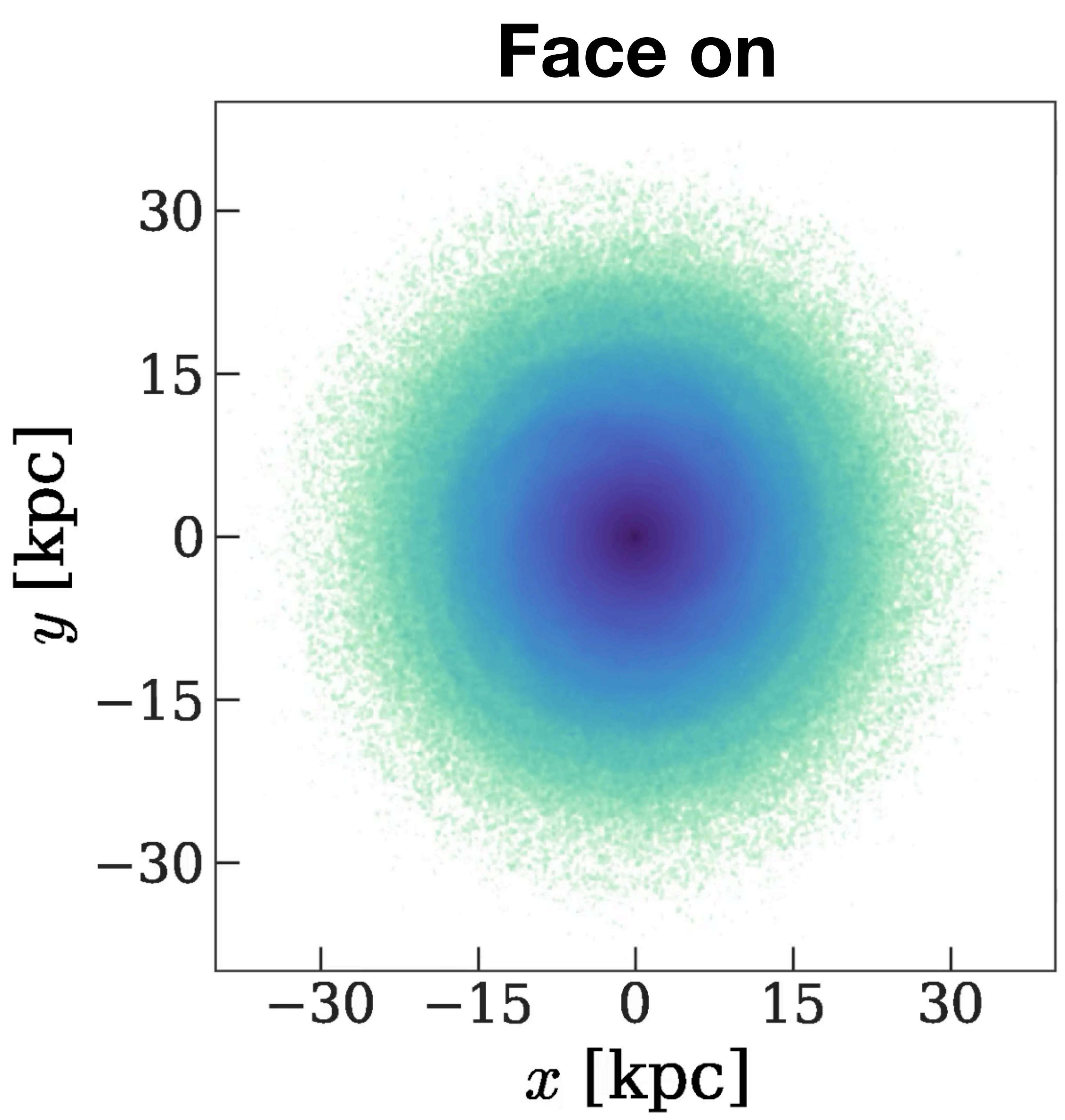
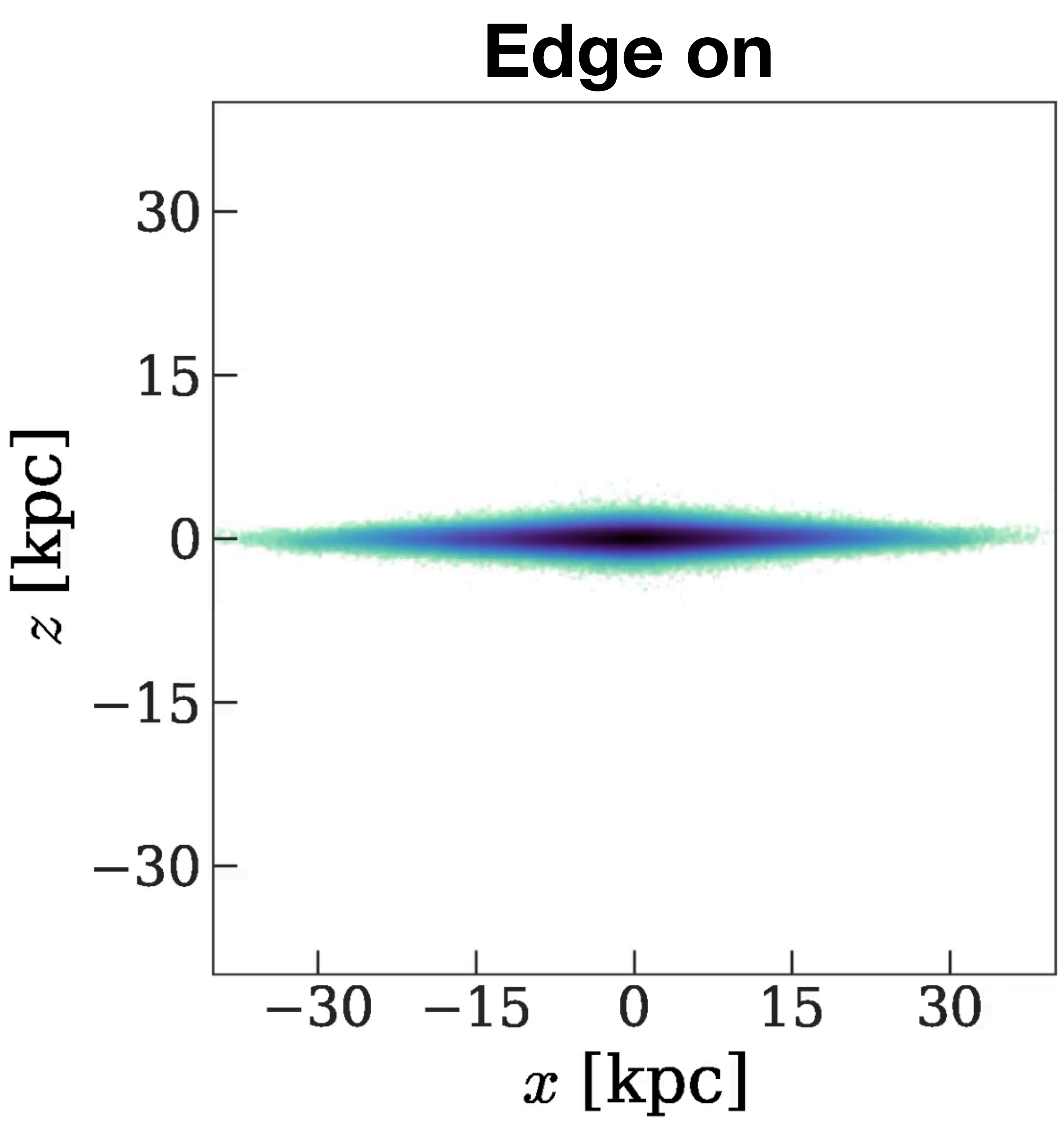
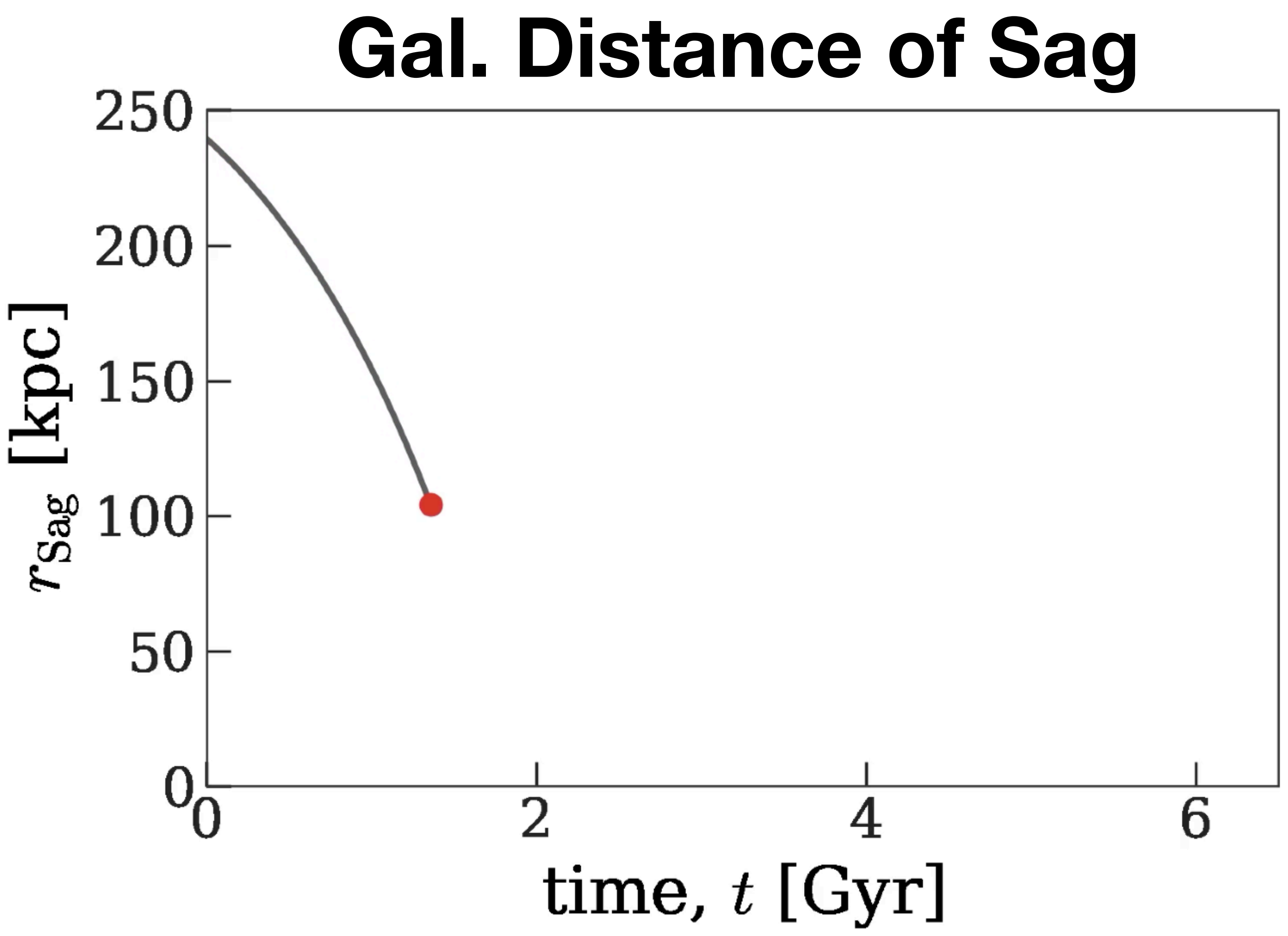
Slater et al. 2014
Pan-STARRS

Sagittarius + the Milky Way



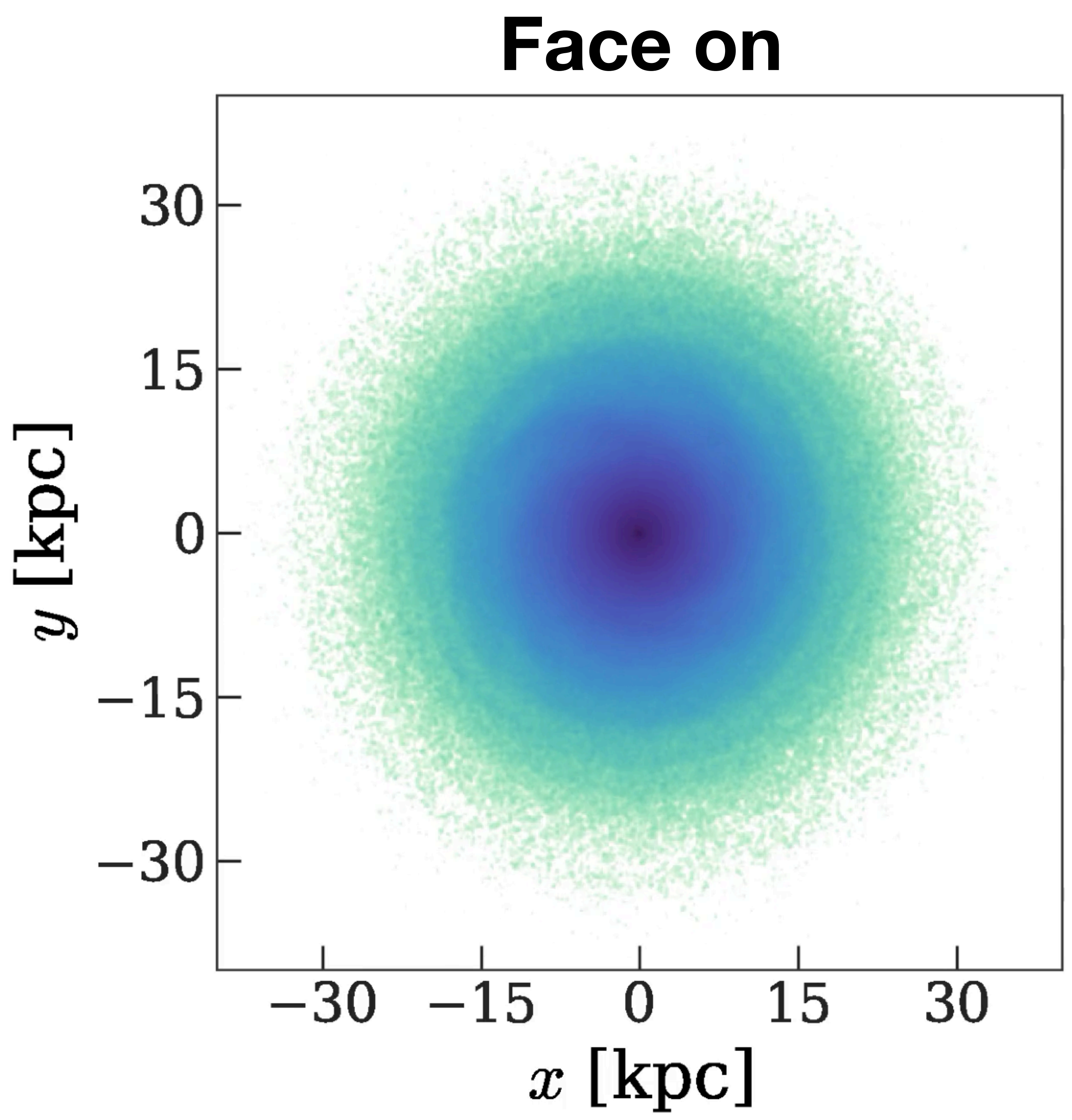


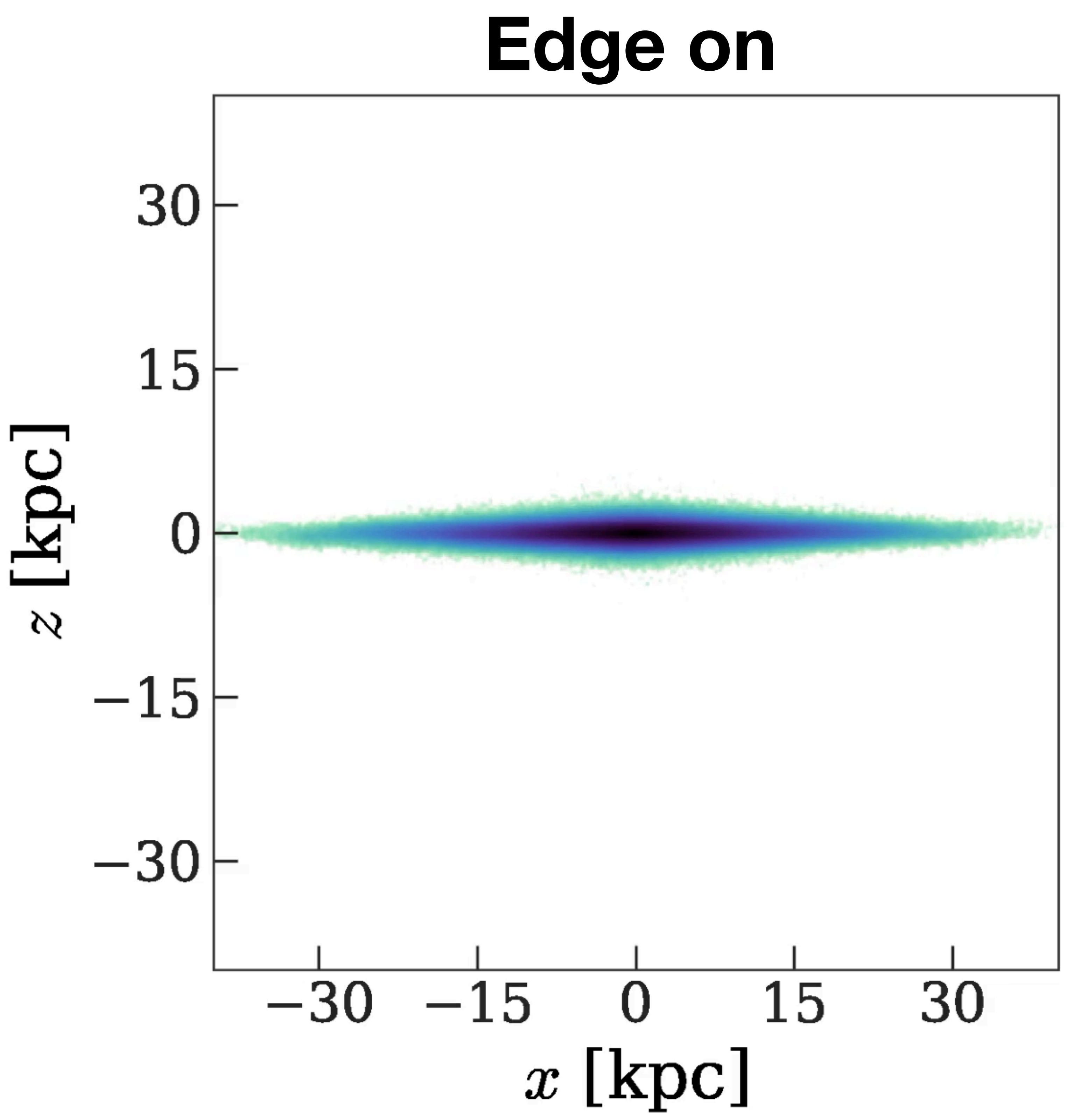


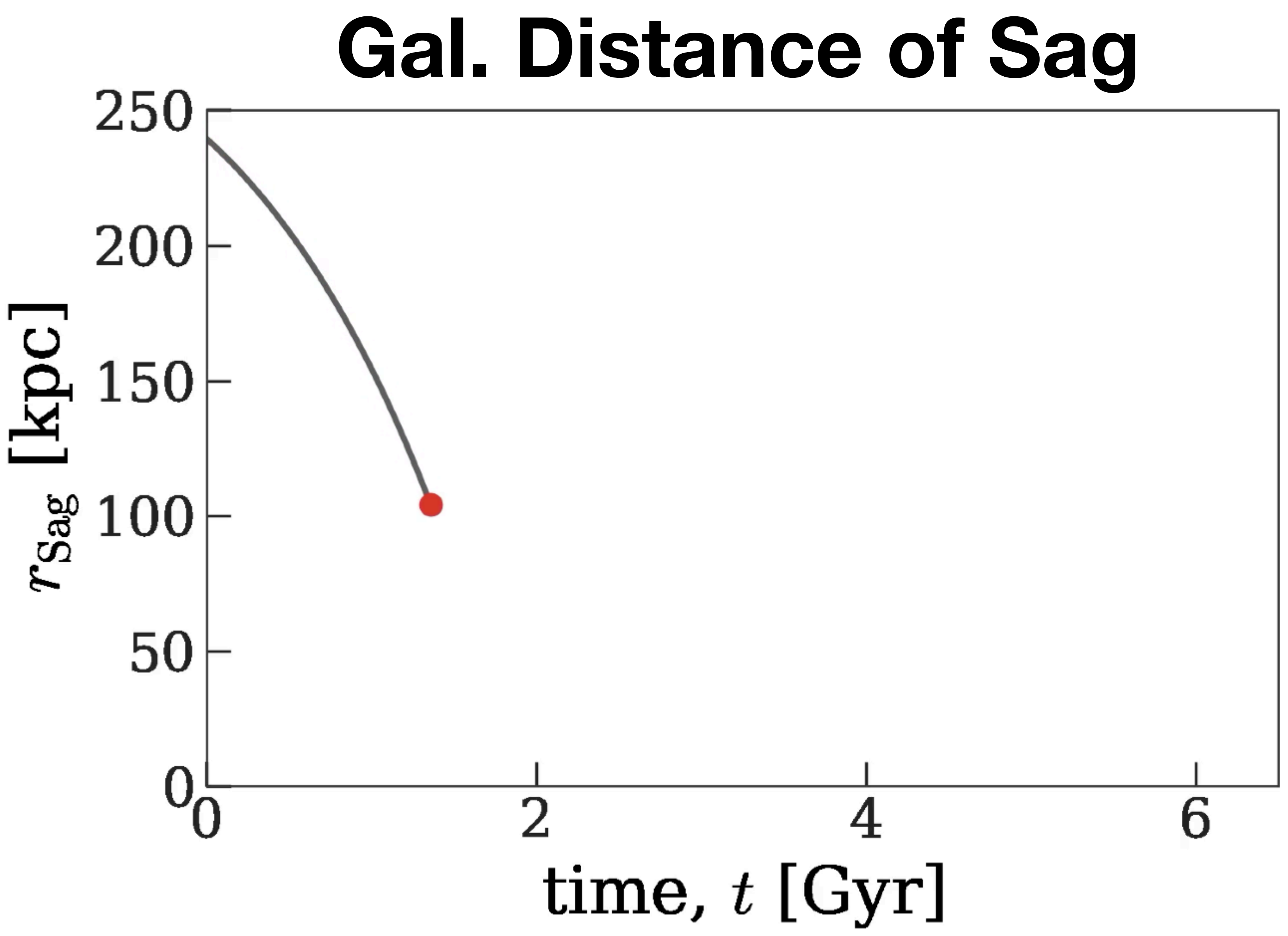
See also: Purcell et al. 2011; Gómez et al. 2013

Simulation from Laporte et al. 2018

Sagittarius + the Milky Way







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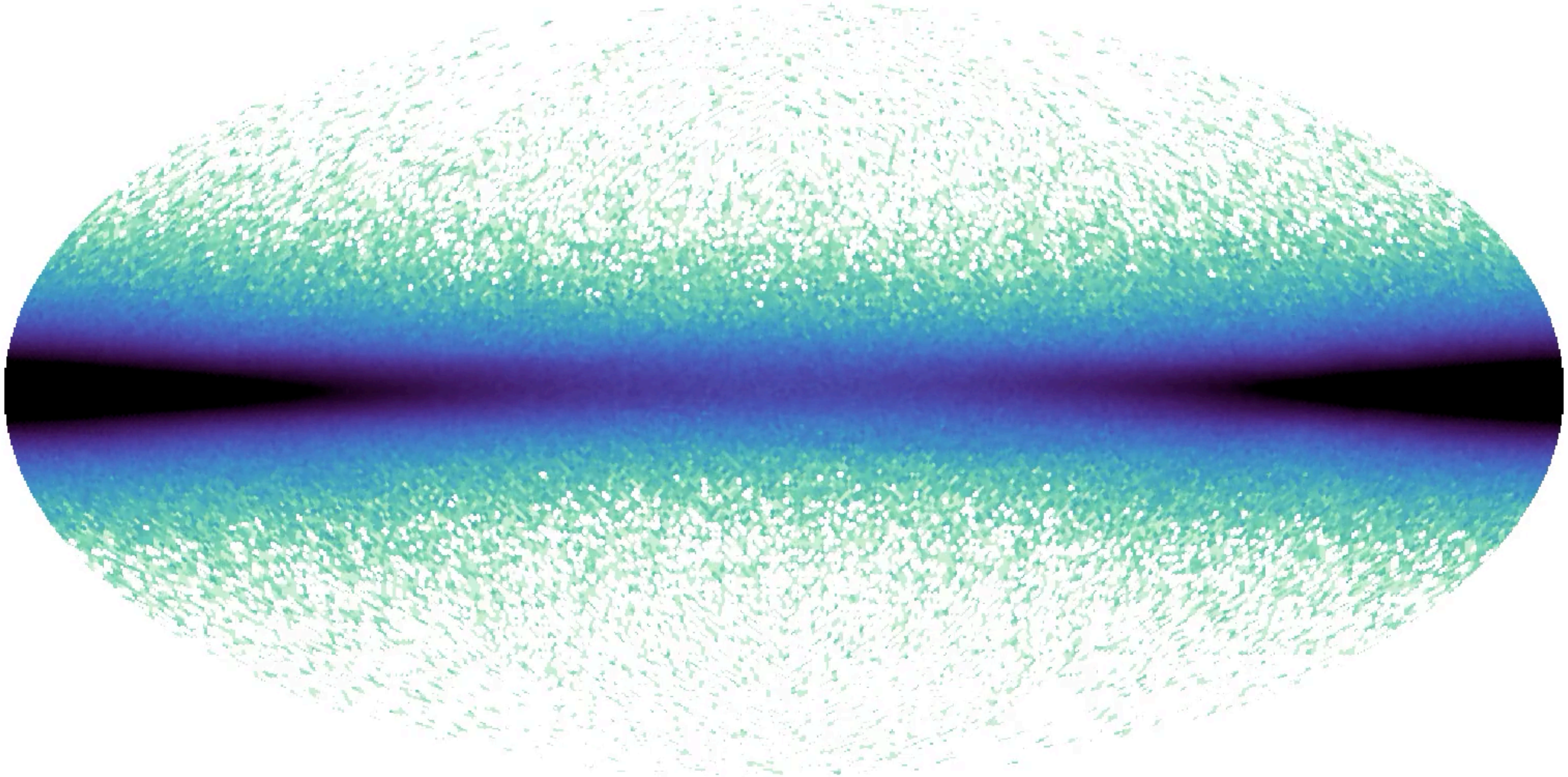
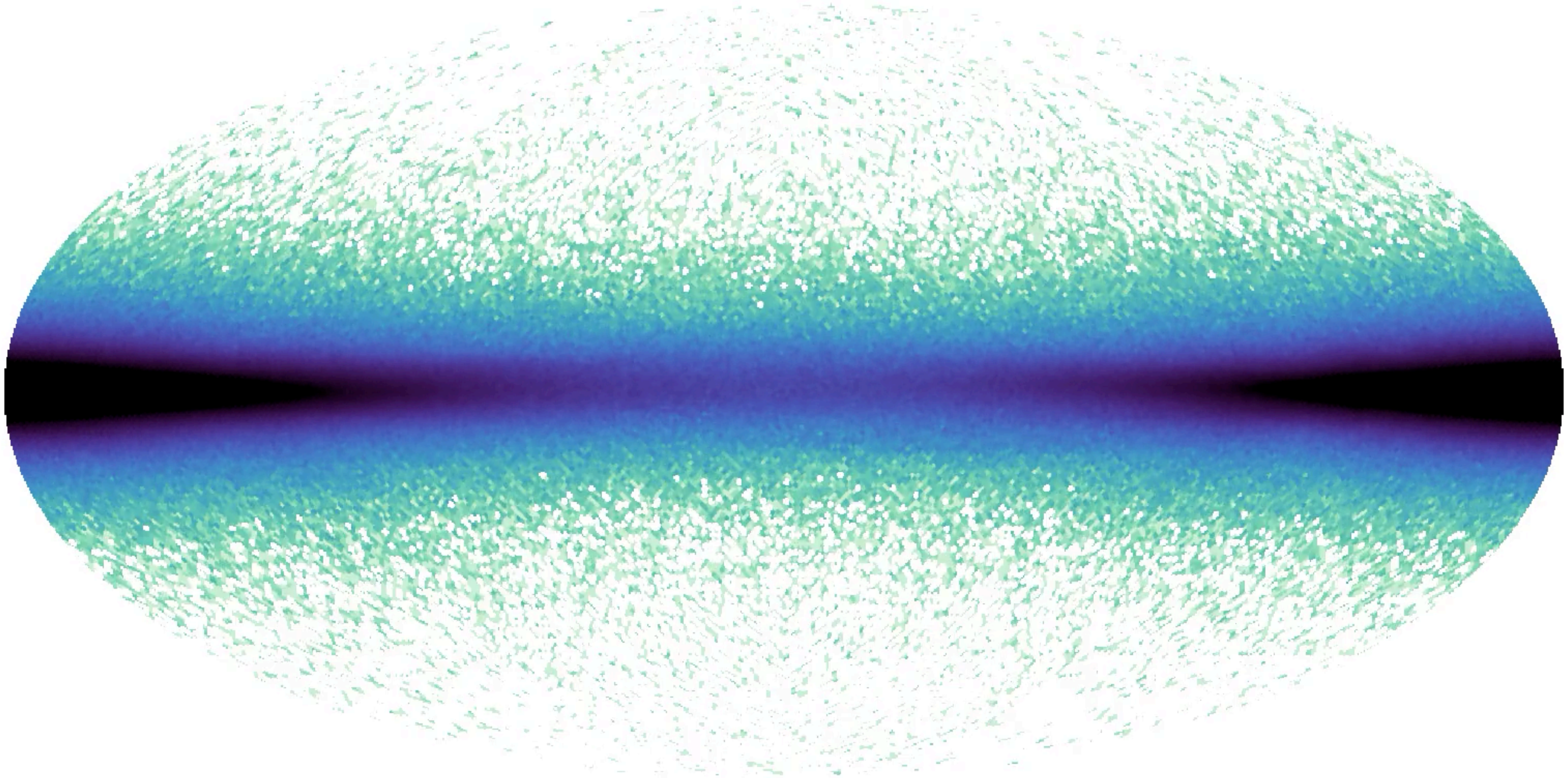
The (Simulated) Galactic Anticenter

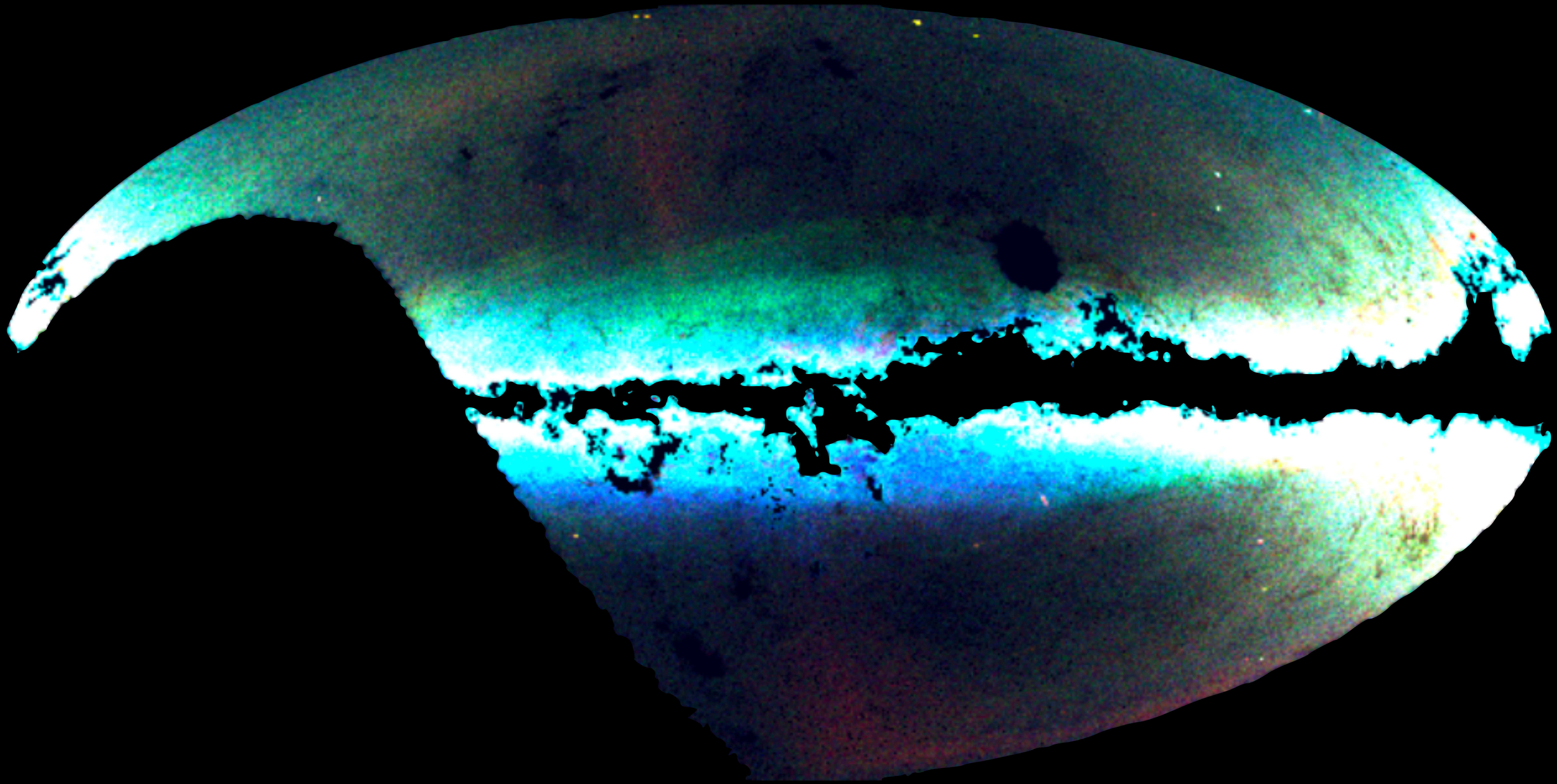


Simulation from Laporte et al. 2018

The (Simulated) Galactic Anticenter

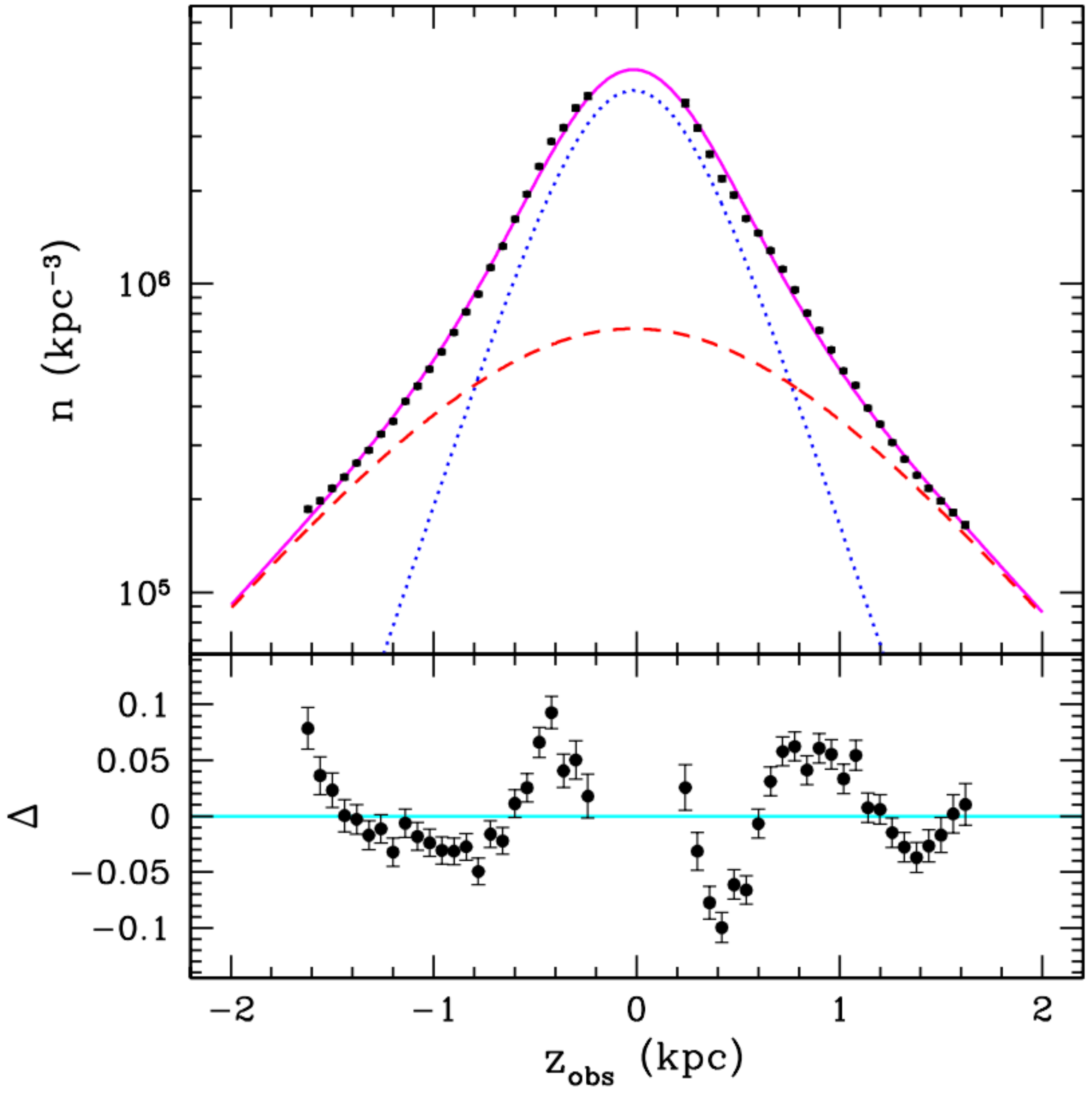


Simulation from Laporte et al. 2018



Stellar Density Variations and Asymmetries

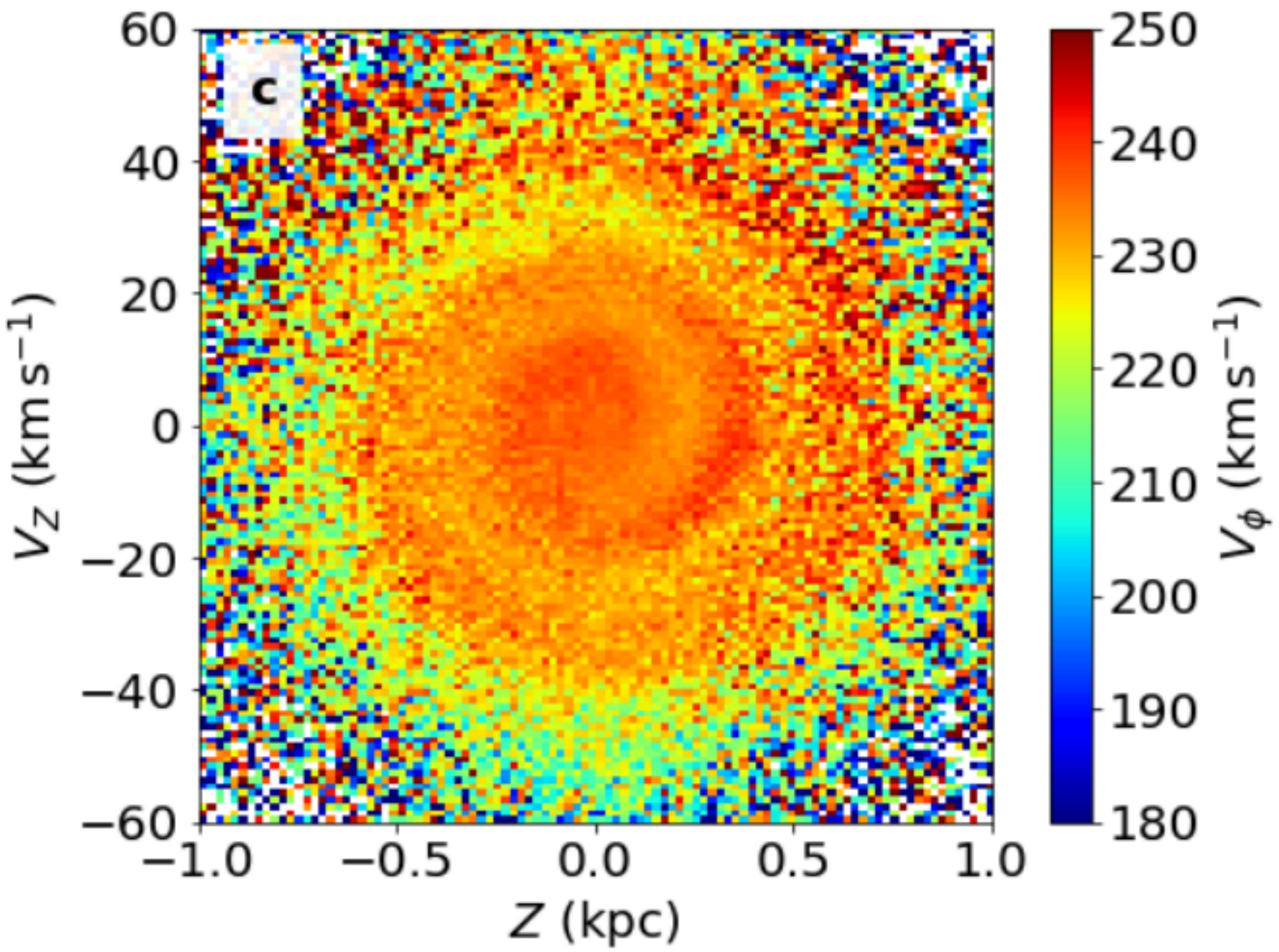
Stellar Density Residuals



SDSS; Widrow et al. 2012

See also: Goméz et al. 2012
Williams et al. 2013
Carlin et al. 2013

Gaia "phase spiral"



Gaia DR2; Antoja et al. 2018

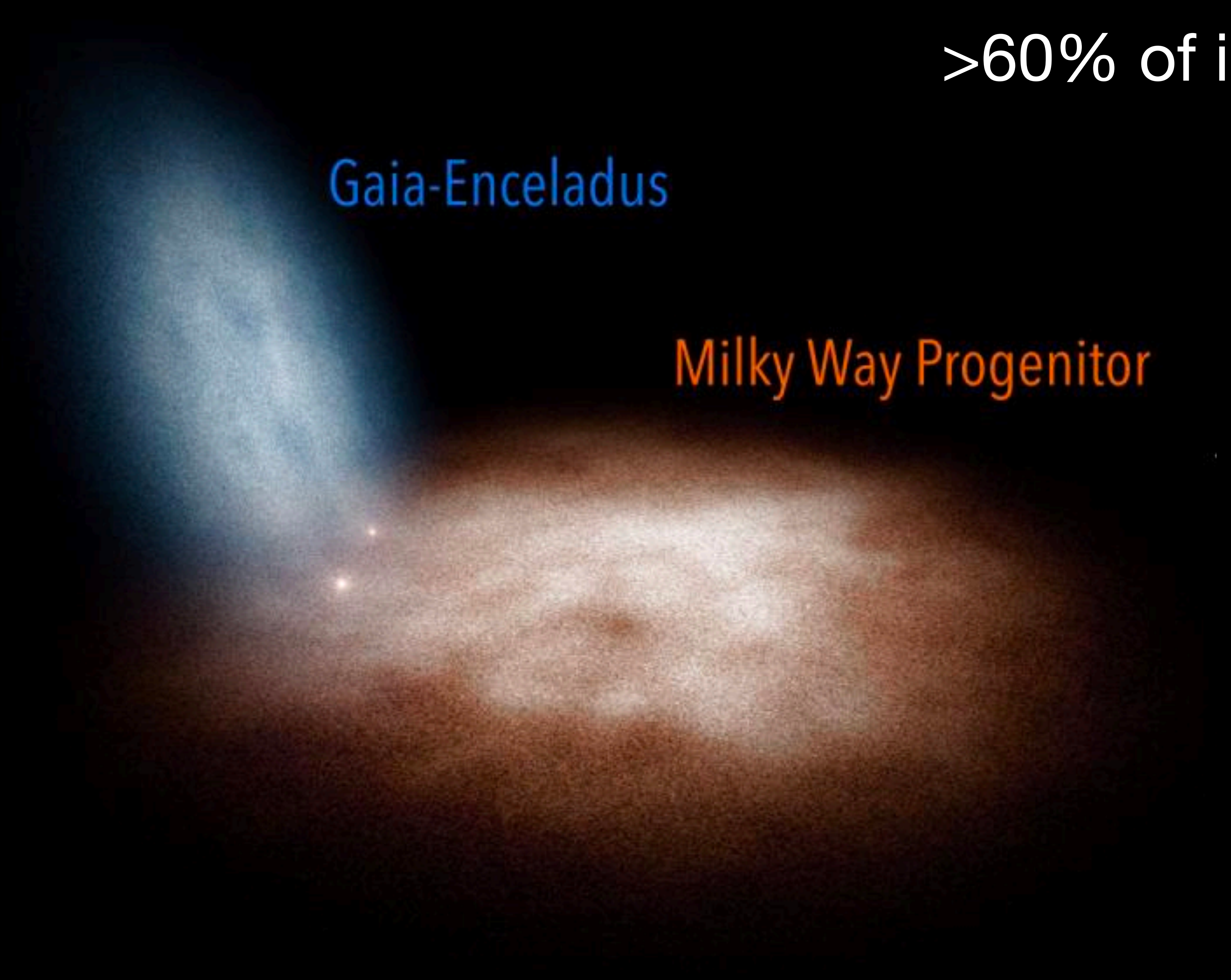
See also: Katz et al. 2018
Laporte et al. 2019
Darling & Widrow 2019
Zhao-Yu Li 2020

The Past: Gaia–Enceladus Merger

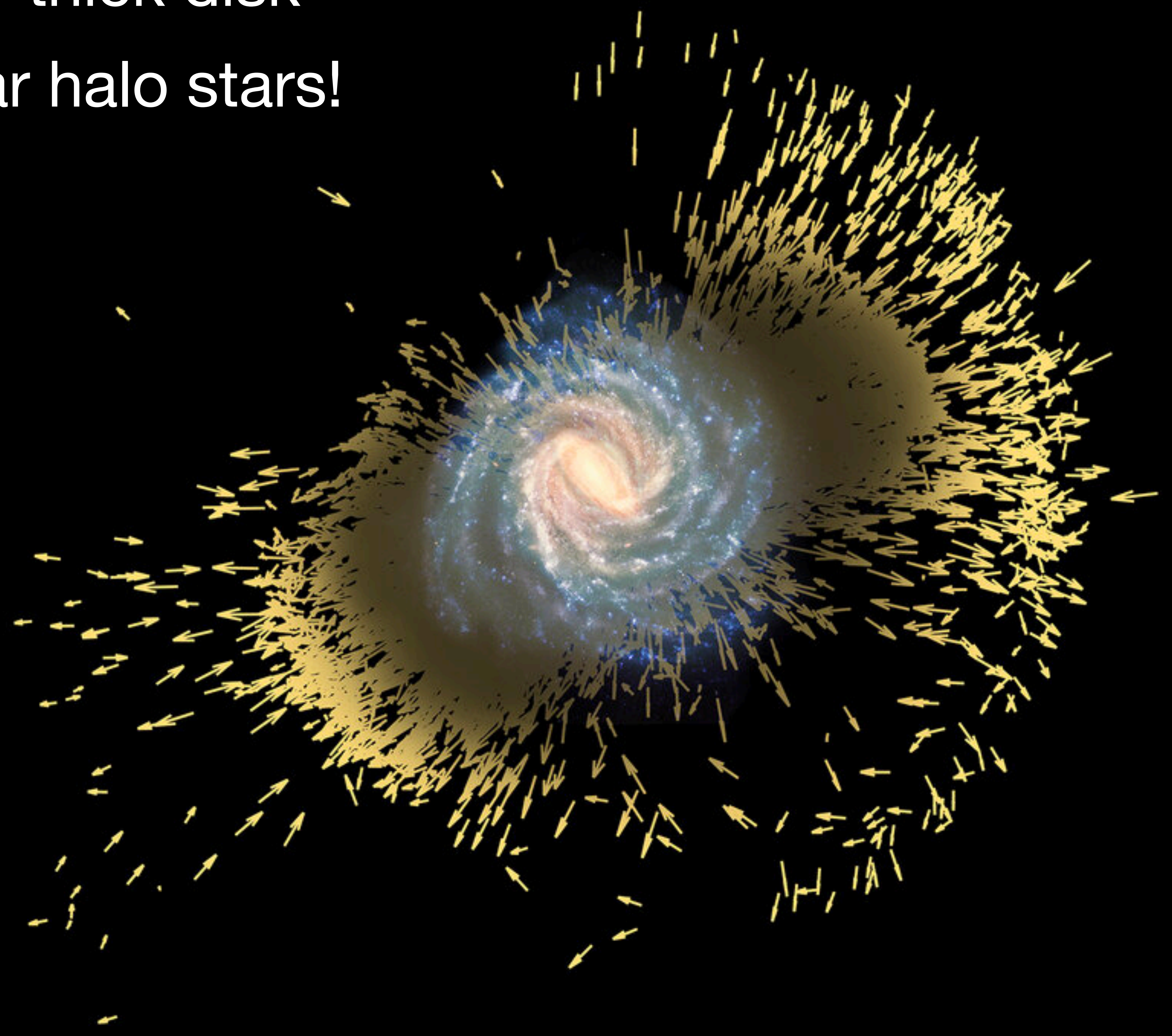
Merger ~8–10 Gyr in past

Led to formation of "thick disk"

>60% of inner stellar halo stars!

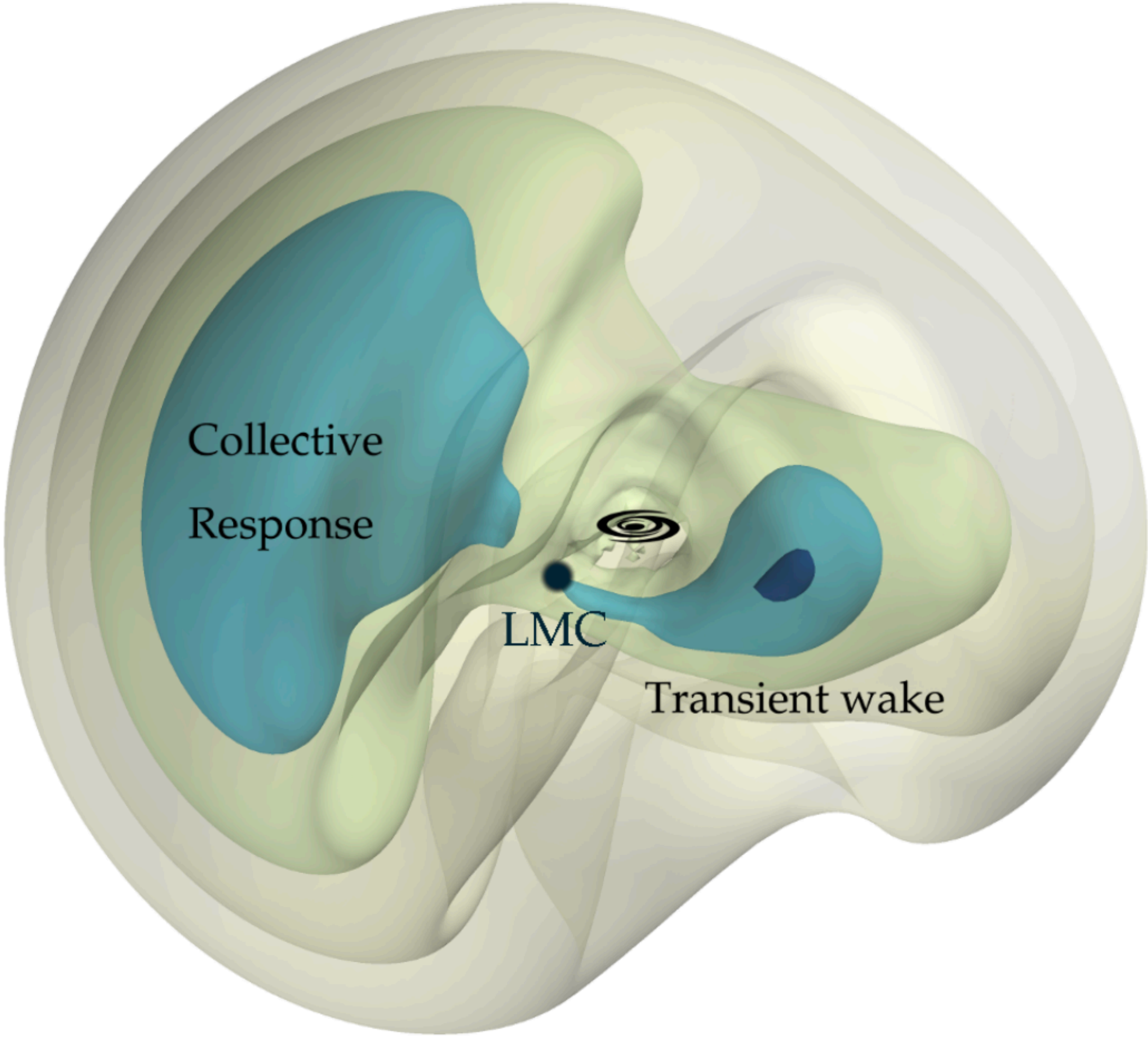


Gaia-Enceladus stars today



Belokurov et al. 2018; Helmi et al. 2018

The Future: the LMC/SMC Infall



Recent revelation: LMC is MASSIVE, comparable to enclosed mass in MW within its orbit

The Dark Matter distribution around the MW is likely responding to the infall of the massive LMC

Implications: MW disk offset and moving relative to outer halo!

The future stellar halo will be mostly LMC stars

Garavito-Camargo et al. 2019
Garavito-Camargo et al. (incl. APW) 2020

See also: Besla et al. 2010; Erkal et al. (incl. APW) 2019; Erkal et al. 2020; Petersen & Peñarrubia 2020a,b

Mergers Sculpt the Milky Way

Mergers Sculpt the Milky Way

Early MW

Gaia-Enceladus-Sausage

↓

High-α disk ("thick disk")

e.g., Helmi et al. 2018;
Belokurov et al. 2018

Mergers Sculpt the Milky Way

Early MW

Gaia-Enceladus-Sausage

↓

High-α disk ("thick disk")

e.g., Helmi et al. 2018;
Belokurov et al. 2018

Now

Sagittarius

↓

Thin disk / outer disk

e.g., APW et al. 2015;
Antoja et al. 2018;
Laporte et al. 2018, 2019

Mergers Sculpt the Milky Way

Early MW	***Now***	***Future MW***
Gaia-Enceladus-Sausage	Sagittarius	LMC / SMC
↓	↓	↓
High-α disk ("thick disk")	Thin disk / outer disk	Warp / DM halo distortions
e.g., Helmi et al. 2018; Belokurov et al. 2018	*e.g., APW et al. 2015; Antoja et al. 2018; Laporte et al. 2018, 2019*	*e.g., Garavito-Camargo et al. 2019, 2020; Petersen & Peñarrubia 2019, 2020; Erkal et al. 2020*

New Directions for Galactic Dynamics

New Directions for Galactic Dynamics

"...most disk stars have completed over forty revolutions, and it is reasonable to assume that the Galaxy is now in an approximately steady state."

— Binney & Tremaine (2008)

New Directions for Galactic Dynamics

~~*"...most disk stars have completed over forty revolutions, and it is reasonable to assume that the Galaxy is now in an approximately steady state."*~~

— Binney & Tremaine (2008)

"...most disk stars have completed only about forty revolutions, and mergers continue to impact the disk, so it is not reasonable to assume that the Galaxy is in steady state."

New Directions for Galactic Dynamics

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~~It's too complex / it's weather / we can't learn anything~~

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There is immense *opportunity* in the phase-coherent structures in the Galaxy!

How can we study the mass (dark matter) in the Milky Way?

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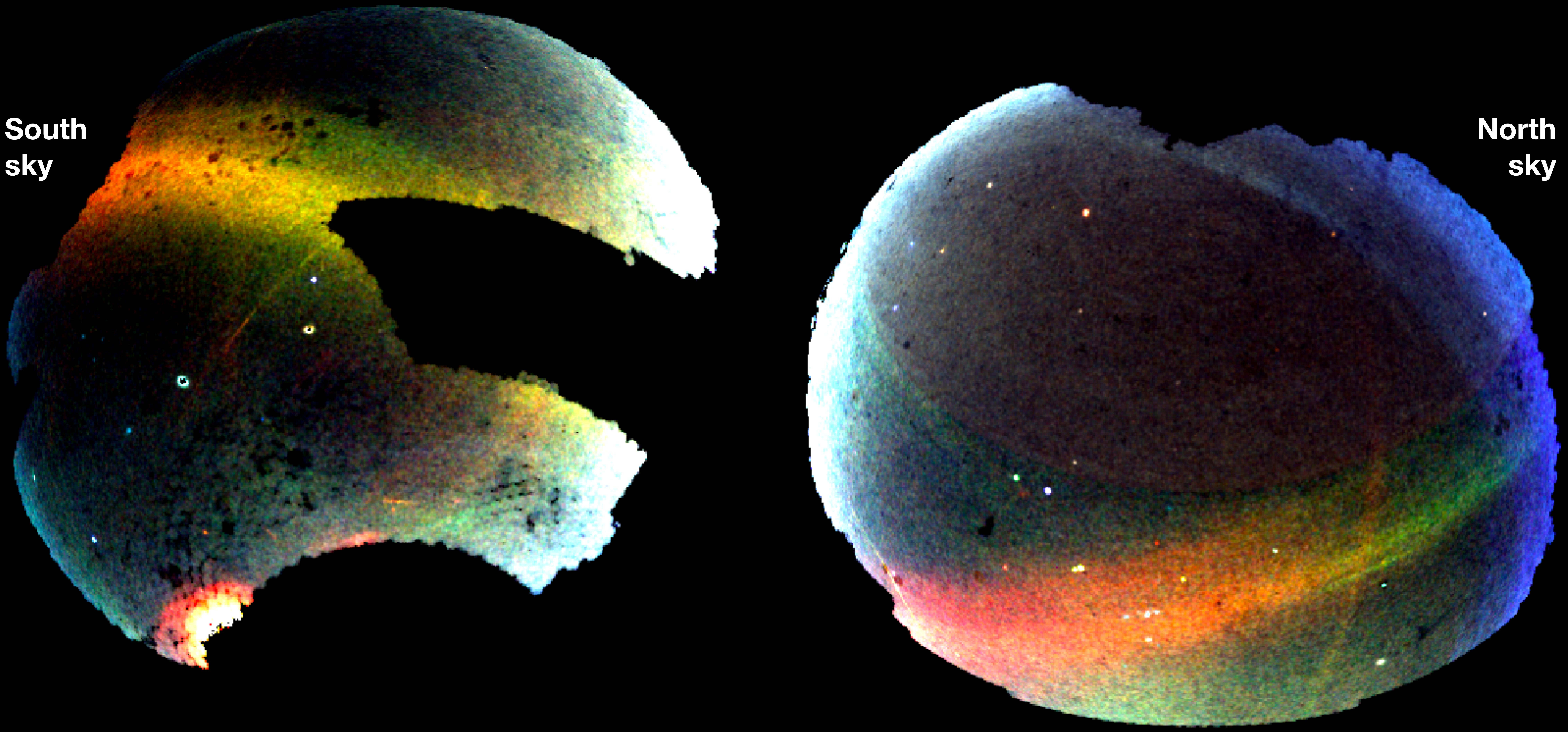
Satellites & Mergers, again!

Stellar Streams Around the Milky Way



Legacy Surveys; N. Shipp, A. Price-Whelan

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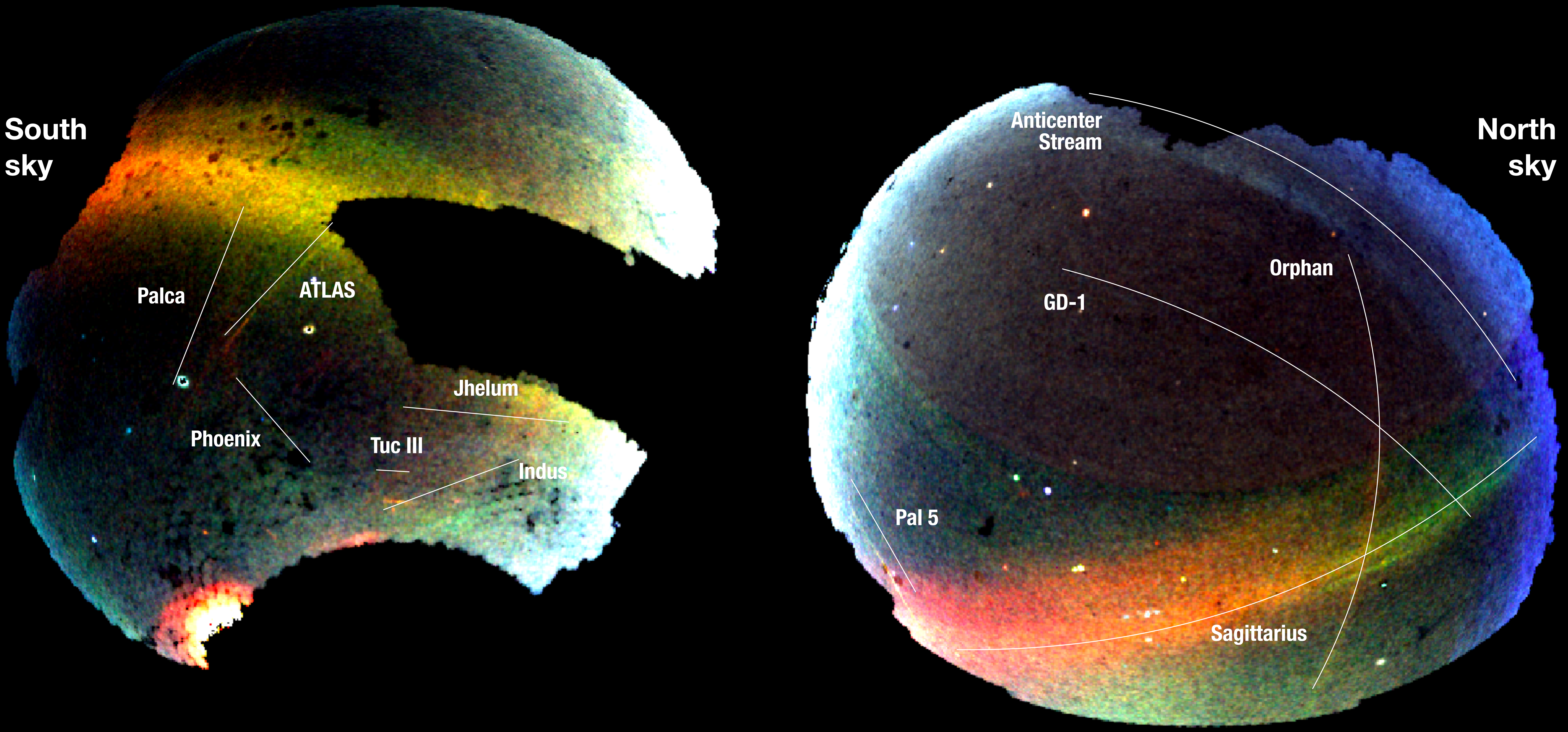
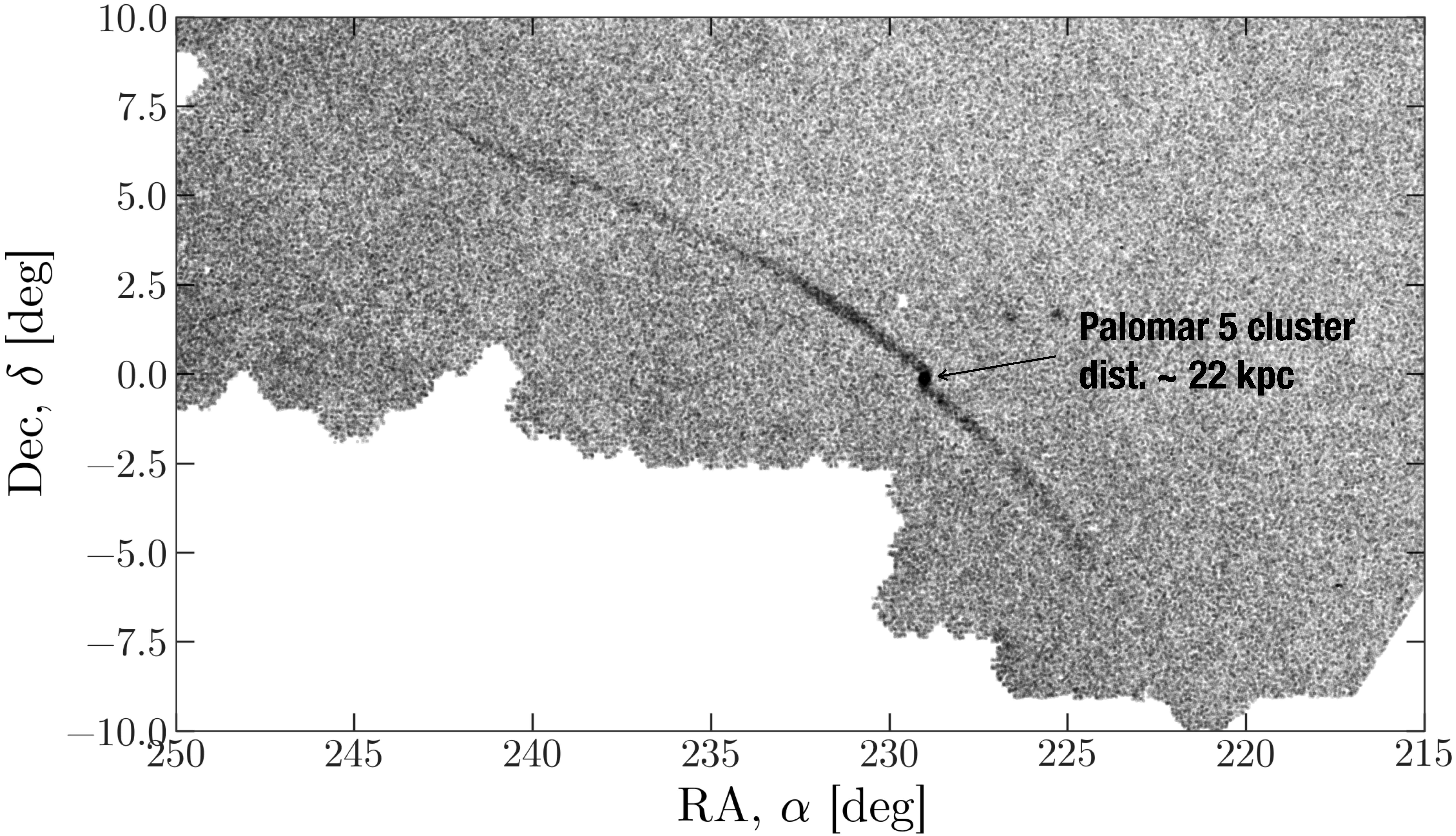


~10 kpc ~20 kpc >40 kpc

Legacy Surveys; N. Shipp, A. Price-Whelan

The Exemplar: Palomar 5



Data: Legacy Surveys

Bonaca, Pearson, APW et al. (2019)

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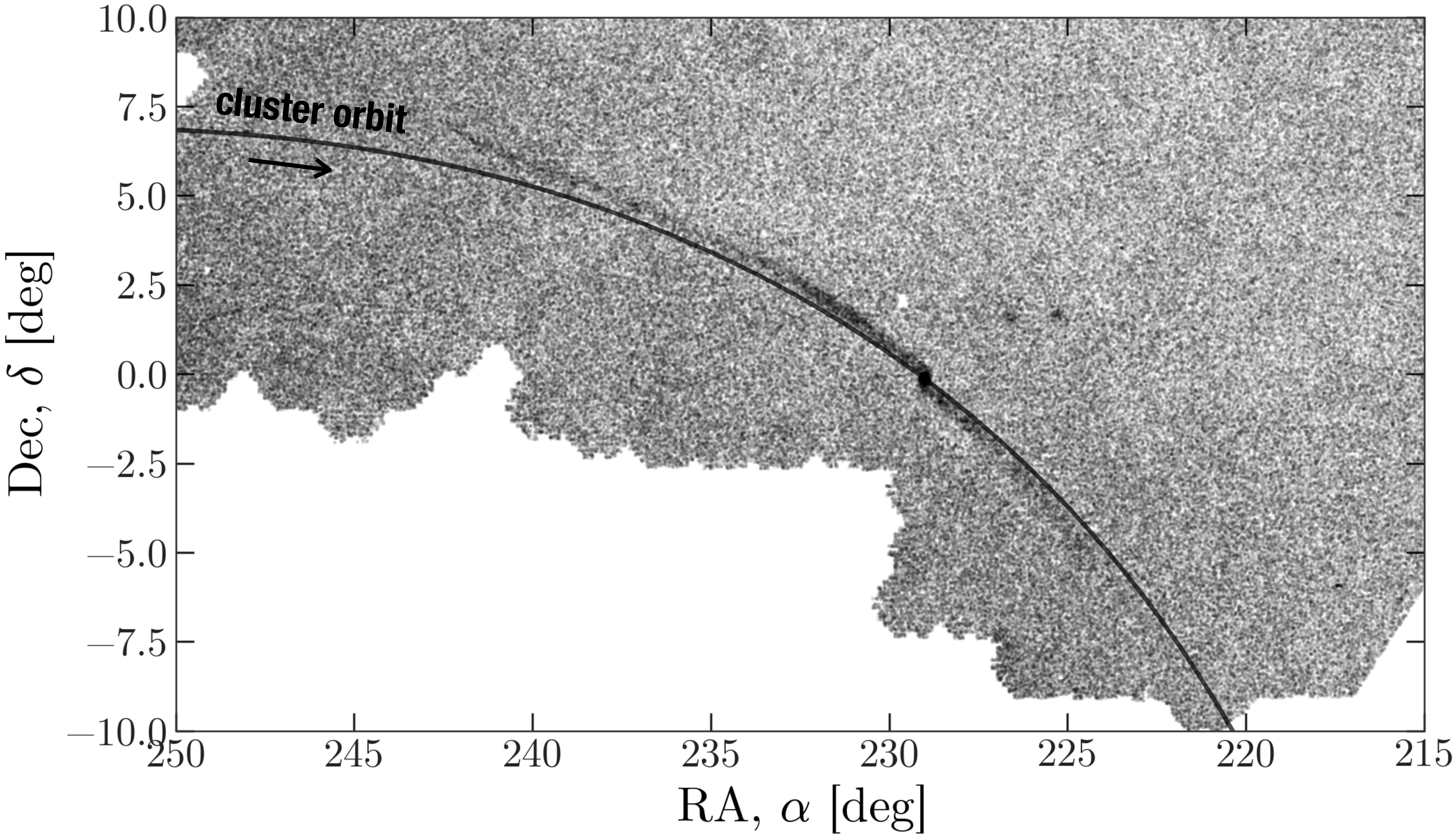

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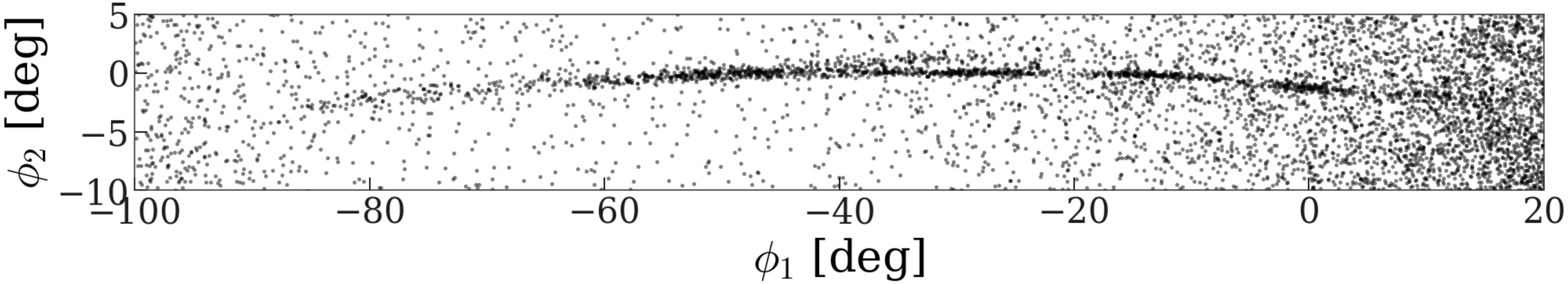
Streams *also* have Substructure!

e.g.,

GD-1 Stream

(APW & Bonaca 2018)



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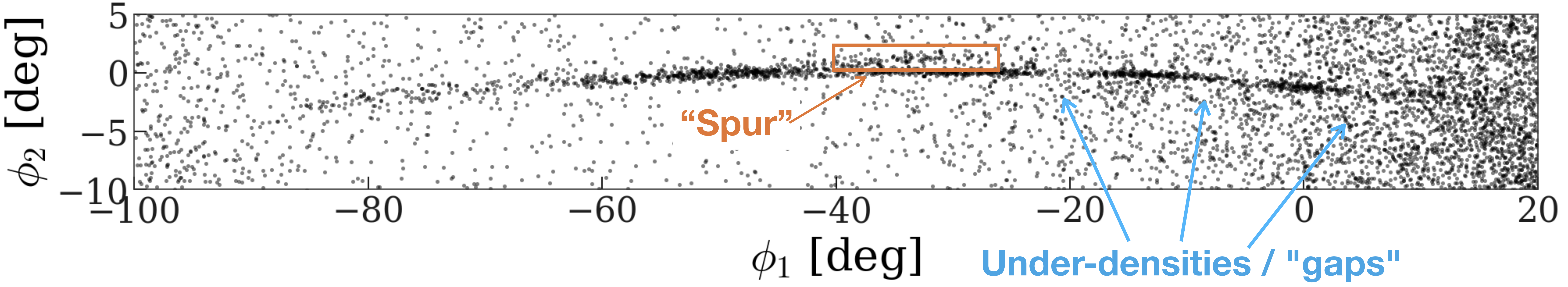

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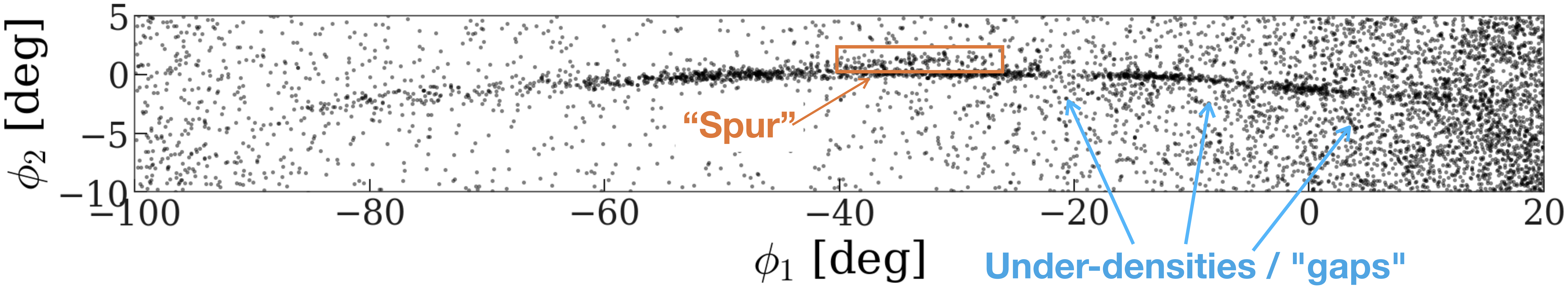
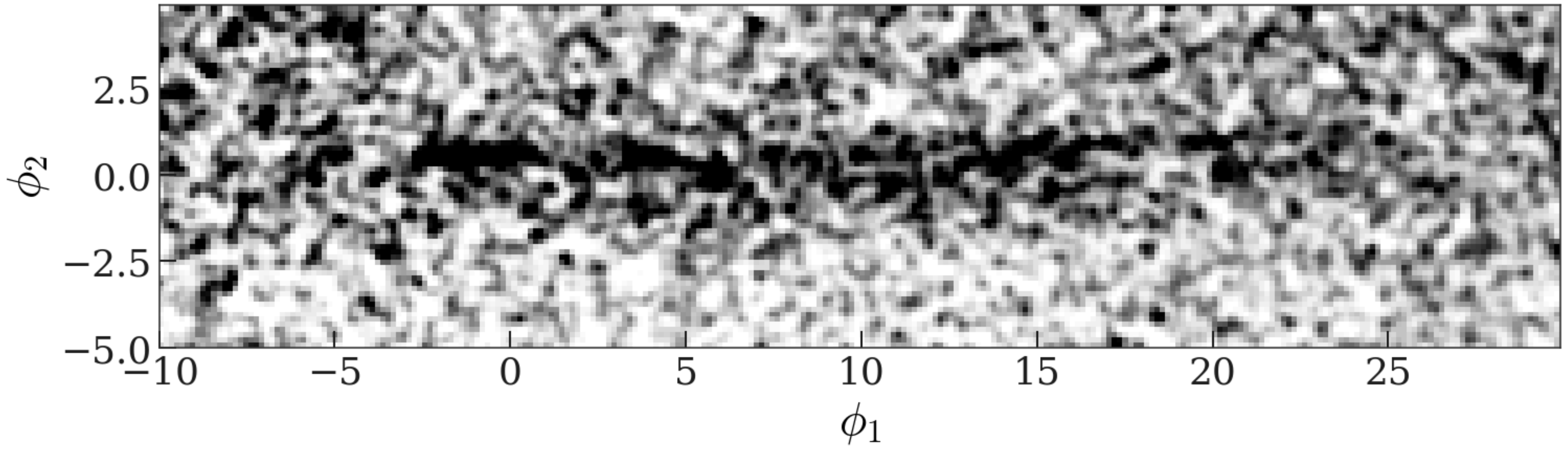


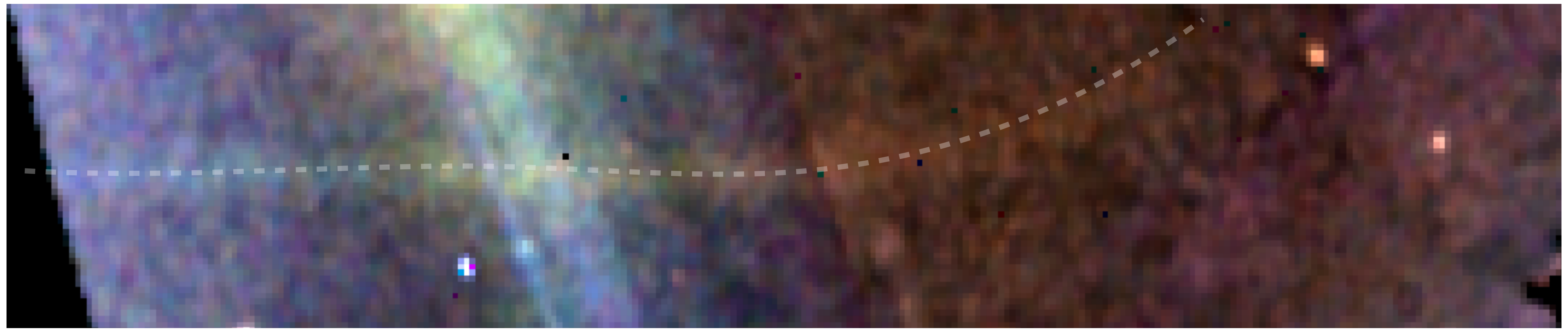
Jhelum Stream

(Bonaca, APW et al. 2019)



Orphan Stream

(Koposov, APW et al. 2019; Erkal, APW et al. 2019)



Streams *also* have Substructure!

Stream Name	Substructure	Dynamical Source	
GD-1	spur, gaps	interaction with dark matter subhalo	*APW & Bonaca 2018* *Bonaca, APW + 2019, 2020*
Pal 5	asymmetric tails	Galactic bar	*Pearson, APW + 2017* *Bonaca, Pearson, APW + 2019*
Orphan	twist, proper motions don't follow stream	LMC/SMC	*Koposov, APW + 2019* *Erkal, APW + 2019*
Ophiuchus	short / truncated, diffuse surrounding stream stars	Galactic bar	*Sesar, APW + 2016* *APW + 2016a, b* *Caldwell, Bonaca, APW + 2020*
Sagittarius	bifurcation / two streams?	triaxiality? LMC? two streams???	*Hayes, APW+2018* *Vasiliev + 2020*
Jhelum	thin and thick components	???	*Bonaca, APW + 2019*
ATLAS/Aliqa Uma	Broken / discontinuous stream?	???	*Shipp + 2018* *Li + 2020*

Stellar Streams in the 2020's

Stream population

↓

Accretion history

e.g., Helmi et al. 1999
Bullock & Johnston 2005
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Bovy 2016

Stream perturbations & substructure

↓

Small-scale DM / DM models

e.g., Ibata et al. 2002
Yoon et al. 2011
Carlberg 2012
Erkal et al. 2017
Bonaca et al. (incl. APW) 2019, 2020

Main Points

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Time-dependence and disequilibrium are prevalent in the Milky Way, and modern surveys are enabling new efforts to quantify and model the Galaxy in this context.

Satellite mergers are a dominant driver of structure and time-dependence, and have been important throughout Galactic history.

Studying merger signatures will allow us to better constrain the mass distribution and dynamical evolution of the Galaxy.

Mergers leave behind streams: phase-coherent structures that provide an important way of constraining dark matter properties.

Equilibrium dynamics will be superseded by methods that directly model these phase-coherent structures and deliver more precise constraints on the evolution and dark matter content of the Galaxy.

Invaluable Collaborators & Thanks

Mentors: David W. Hogg, Kathryn Johnston, Hans-Walter Rix, Melissa Ness, David Spergel, Mike Blanton

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\+ ***Gaia*, APOGEE, SDSS, Legacy Surveys teams!**

Software and Open Science

The Astropy Project

APOGEE

SDSS

github.com/adrn