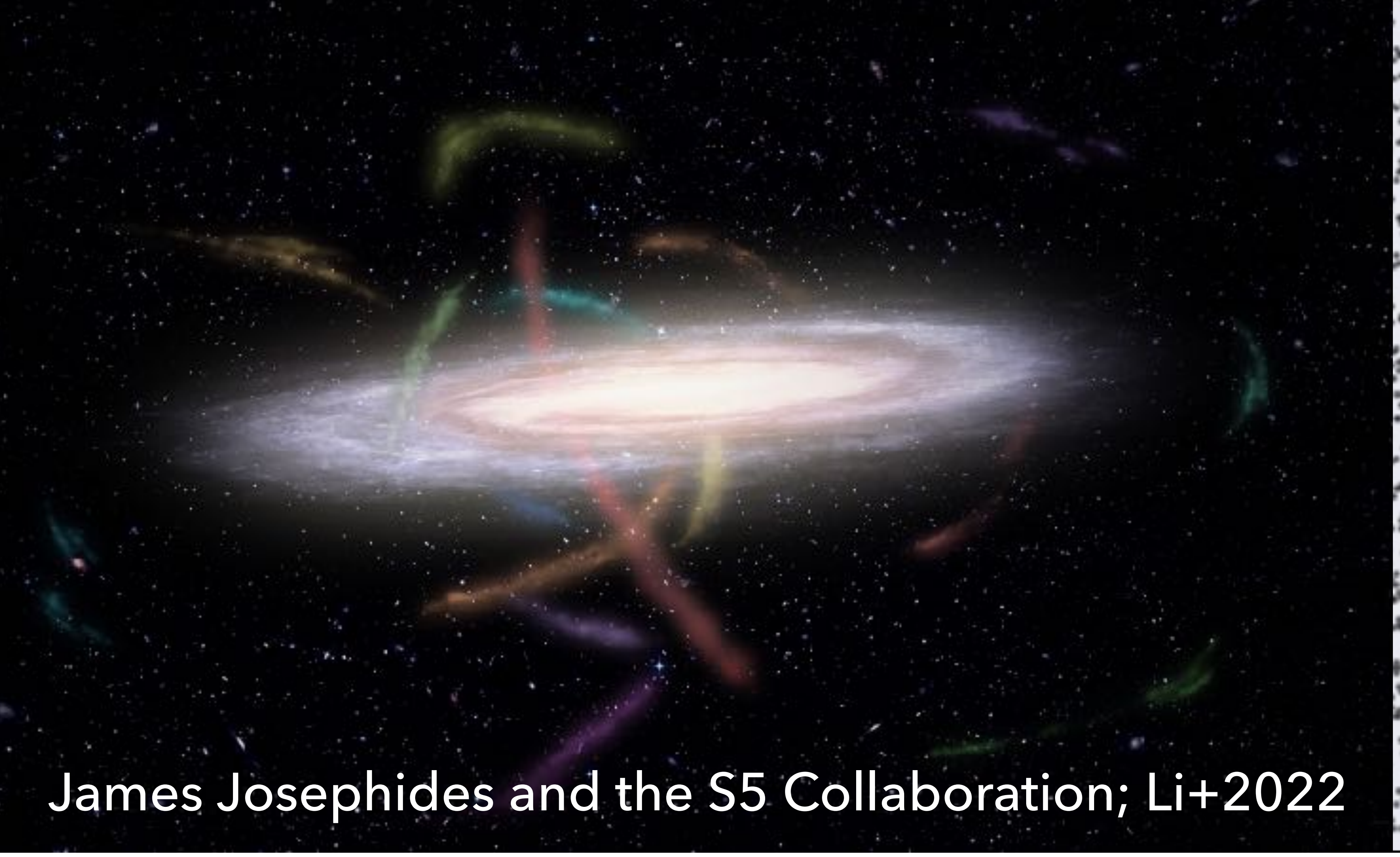
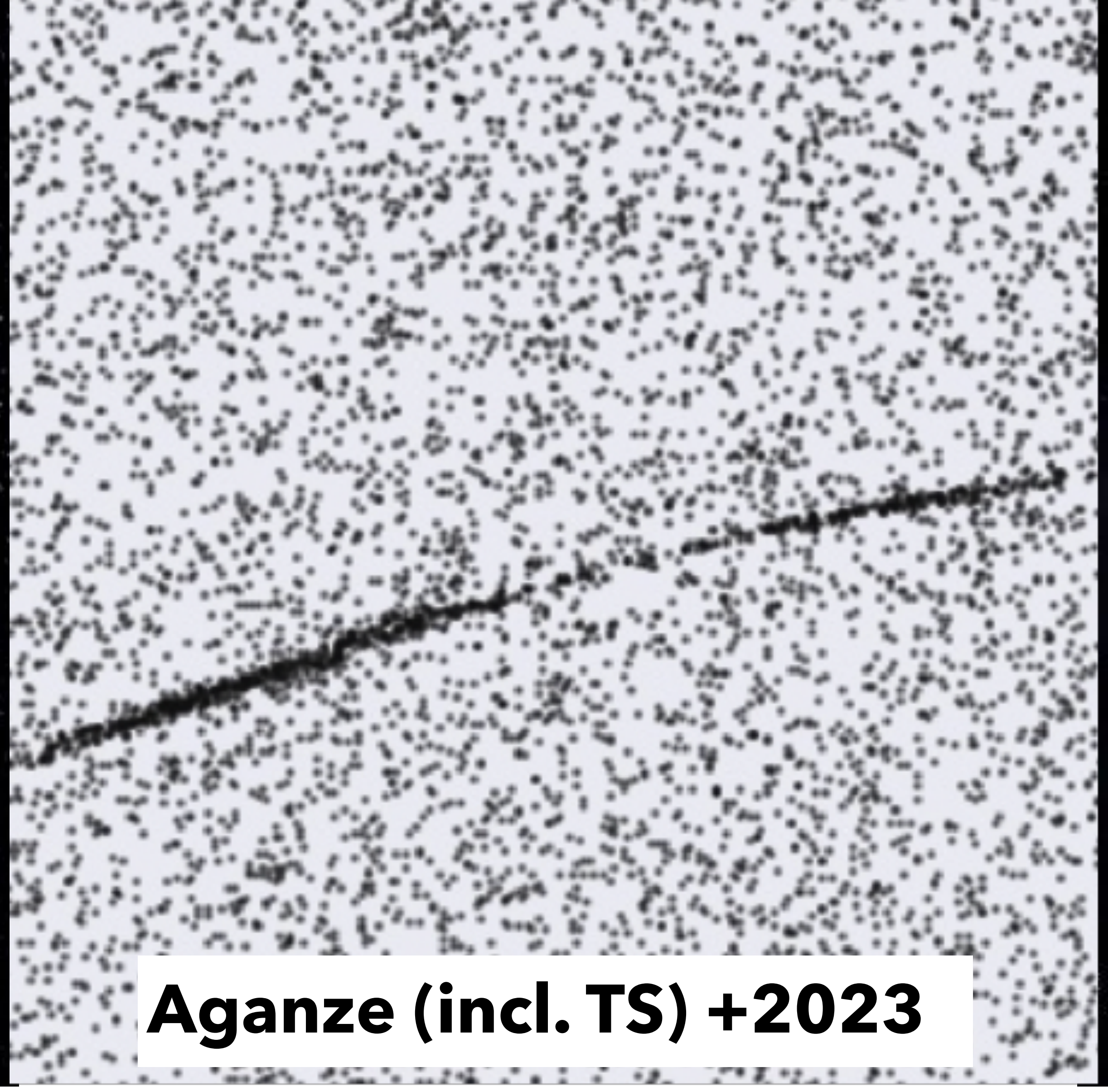




Globular cluster stellar streams beyond the Milky Way

Tjitske Starkenburg
CIERA, Northwestern University

In collaboration with:
Christian Aganze (Stanford), Sachi Weerasooriya (Carnegie),
Sarah Pearson (Copenhagen), Kathryn Johnston (Columbia),
Gabriella Contardo (SISSA), Emily Cunningham (Columbia)

STELLAR HALOS, SATELLITES AND TIDAL DEBRIS PROVIDE A WEALTH OF INFORMATION

- Stellar halos provide clues to a galaxy's past evolution and provide insights on low-mass galaxy formation (e.g. Helmi & White 1999; Cole+2000; Johnston+2001; Bullock+2001; Bullock & Johnston 2005; Bell+2008; Lowing+2015; Amorisco 2017; Monachesi+2019; Merritt+2020; Cook+2016; Helmi+2018; Donlon+2020; Renaud+2021; Bullock & Johnston 2005; Deason+2021; Cunningham+2021, …)

- Extended streams and shells trace the host potential providing key constraints on dark matter halo properties (e.g. Johnston+1999, 2001, 2002; Law & Majewski 2010; Varghese+2011; Lux+2013; Vera-Ciro+2013; Bonaca+2014; Sanders 2014; Bovy+2016; Sanderson+2017; Bonaca+2018; Reino+2020, Dey+2023 …)

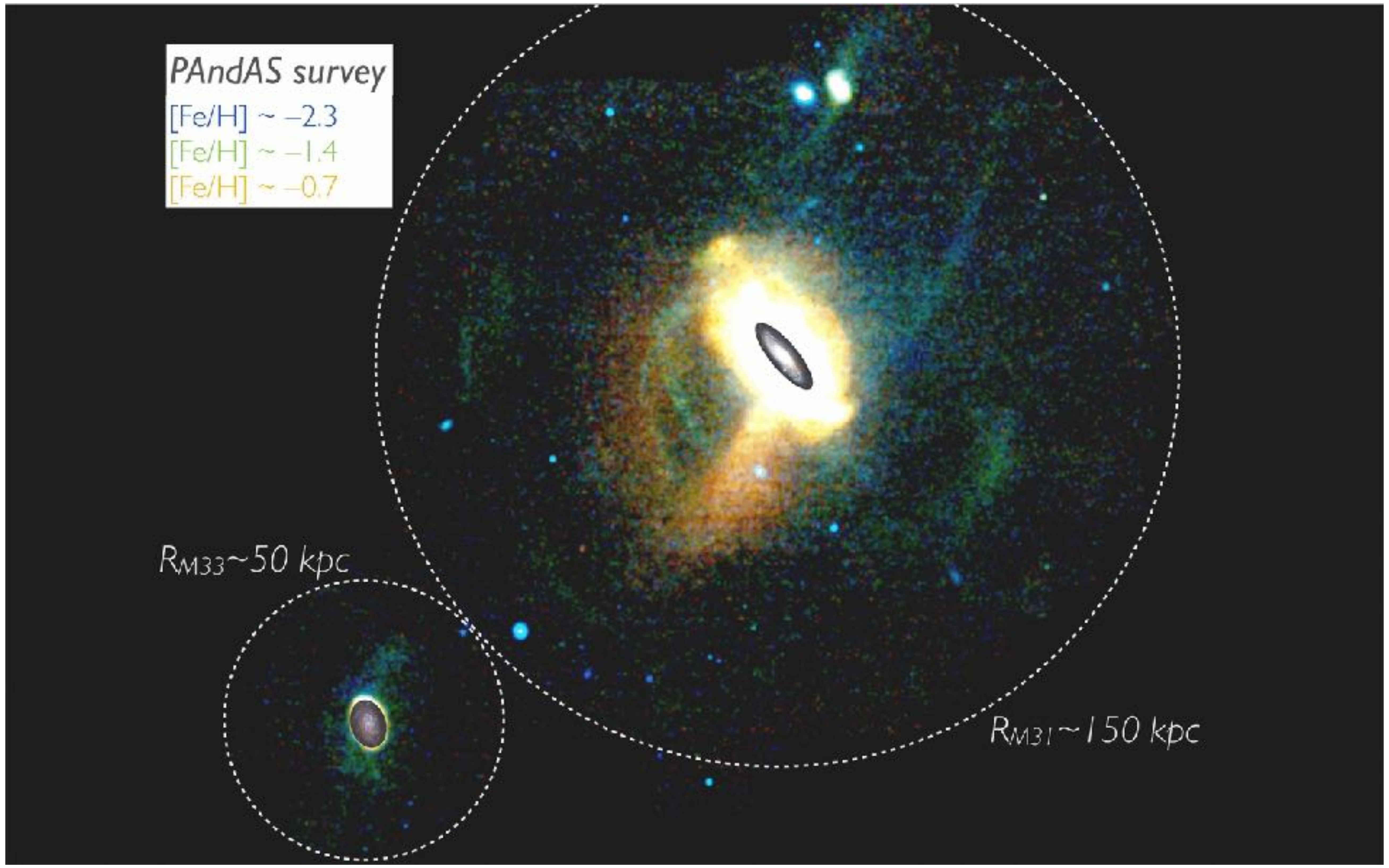
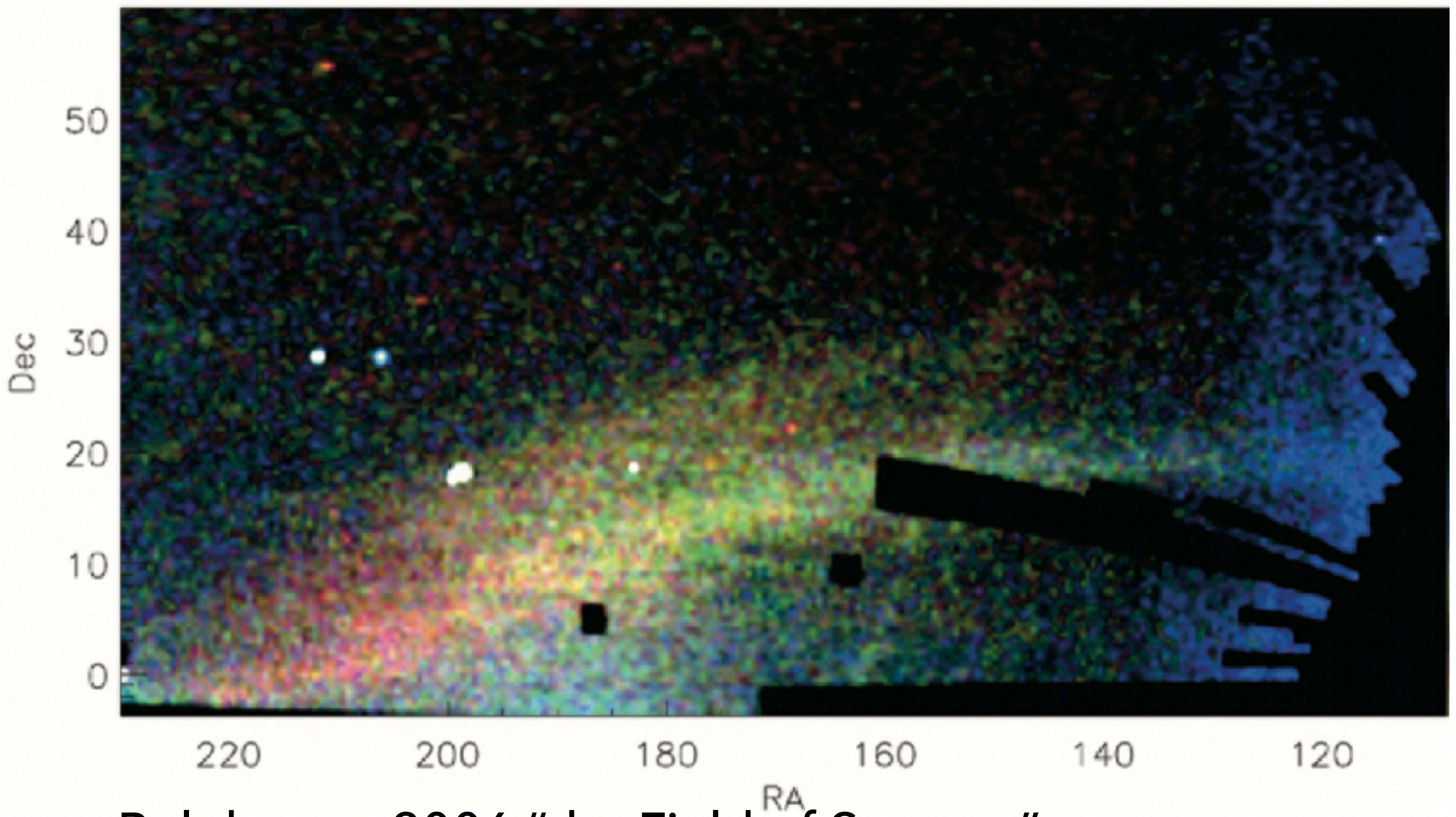


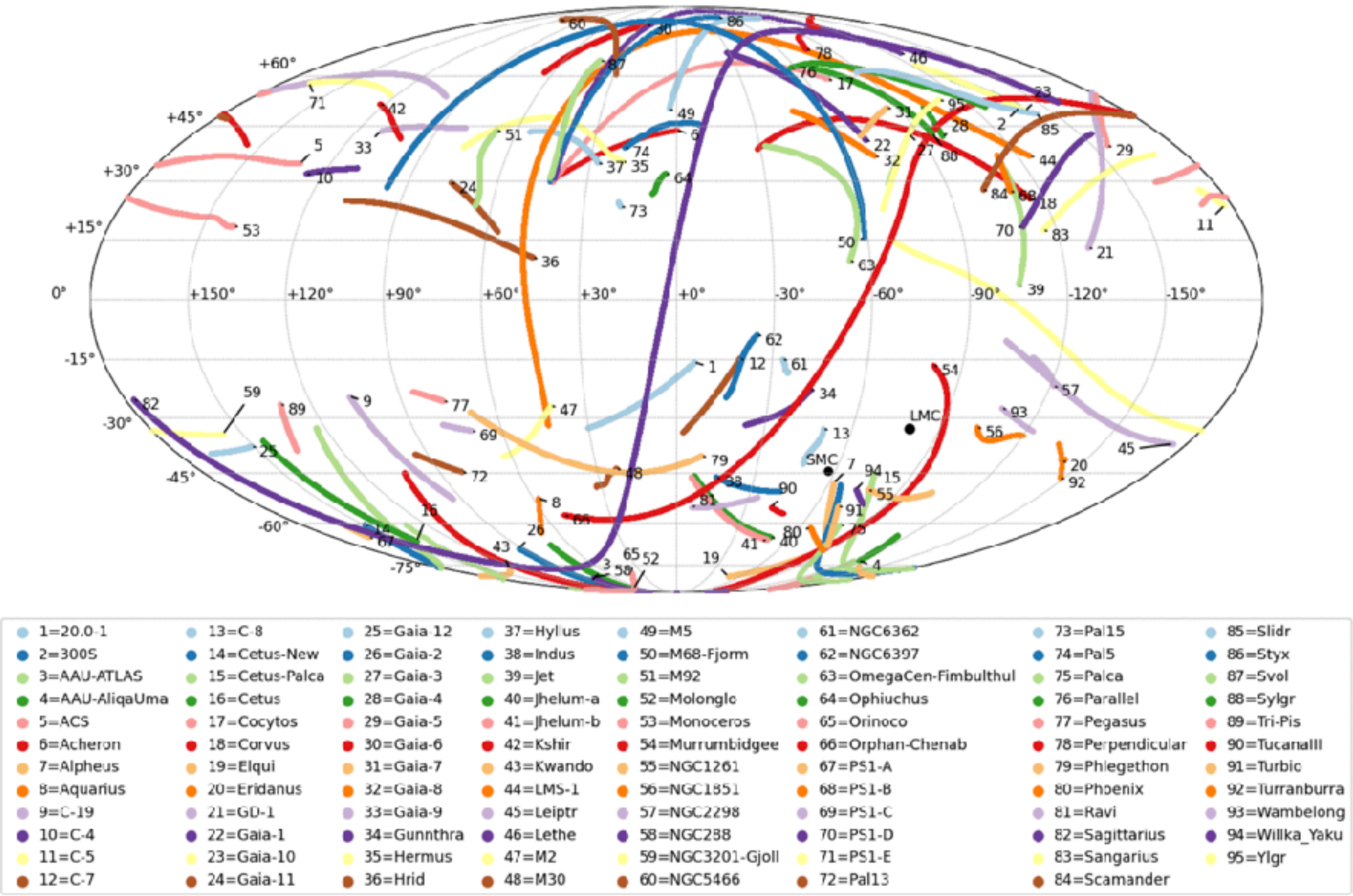
Figure from Martin+2013

THERE ARE MANY STELLAR STREAMS IN THE MILKY WAY



Belokurov+2006 “the Field of Streams”

Mateu 2022: galstreams: a python tidal stream library



With larger and deeper surveys, and especially with astrometry (Gaia) and the ability to speed up spectroscopic follow-up more and more streams are found in the Milky Way’s stellar halo.

See Pearson+2024 for a prediction of GC streams
In the Milky Way that we have not found yet.

STELLAR HALOS, SATELLITES AND TIDAL DEBRIS PROVIDE A WEALTH OF INFORMATION

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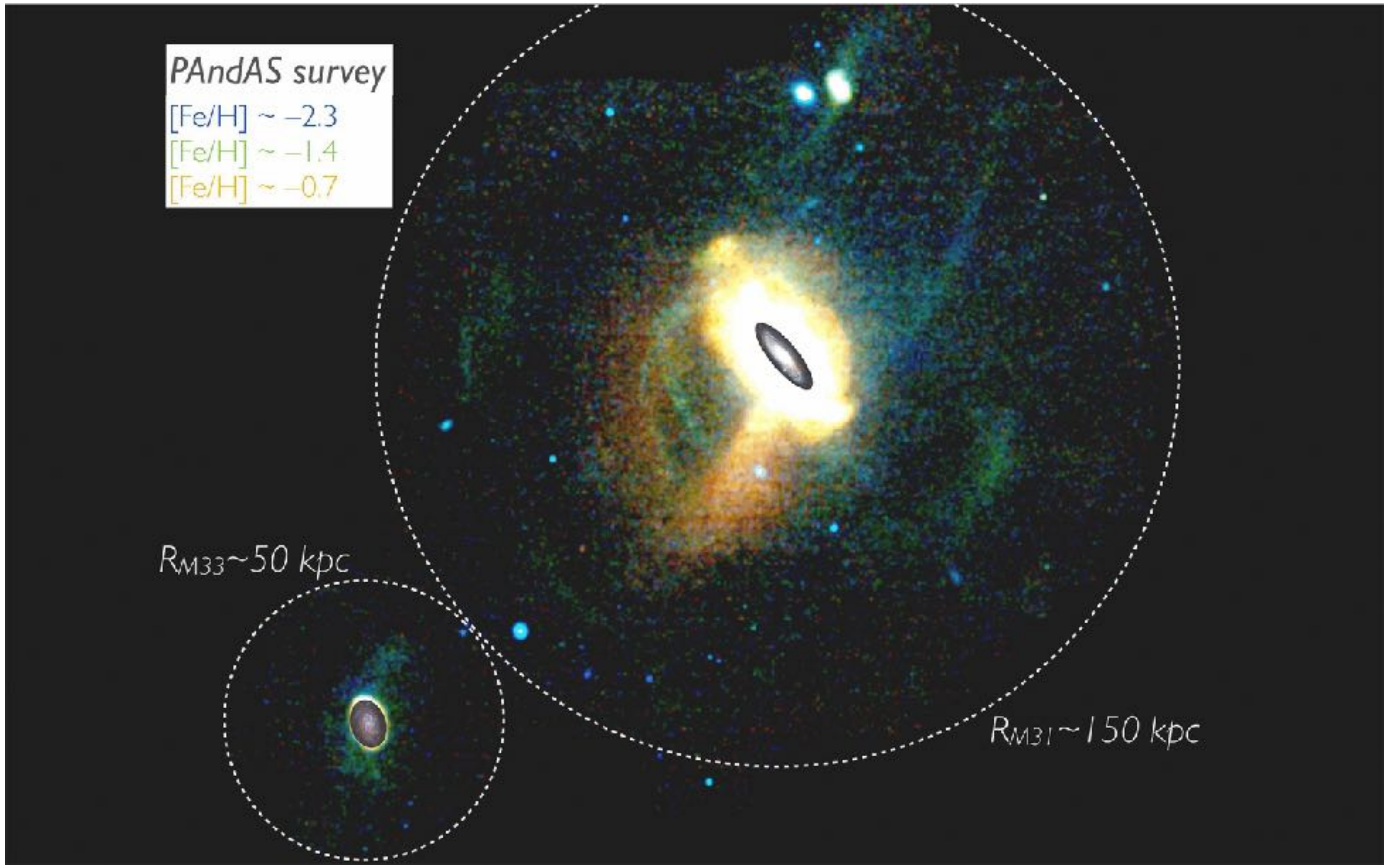


Figure from Martin+2013

- Now: SAGA (Geha+2017, Mao+2021), Elves (Carlsten+2022), Stellar Streams Legacy Survey (Martinez-Delgado+2021), LIGHTS (Trujillo+2021), MADCASH (Carlin+2016,2021), LBT-SONG (Davis+2020, Garling+2021), Dwarfs gobbling dwarfs (Martinez-Delgado+2021)
- Coming: A low-surface brightness discovery space for Euclid, Rubin, and Roman

SPECTRUM OF THEORETICAL PREDICTIONS

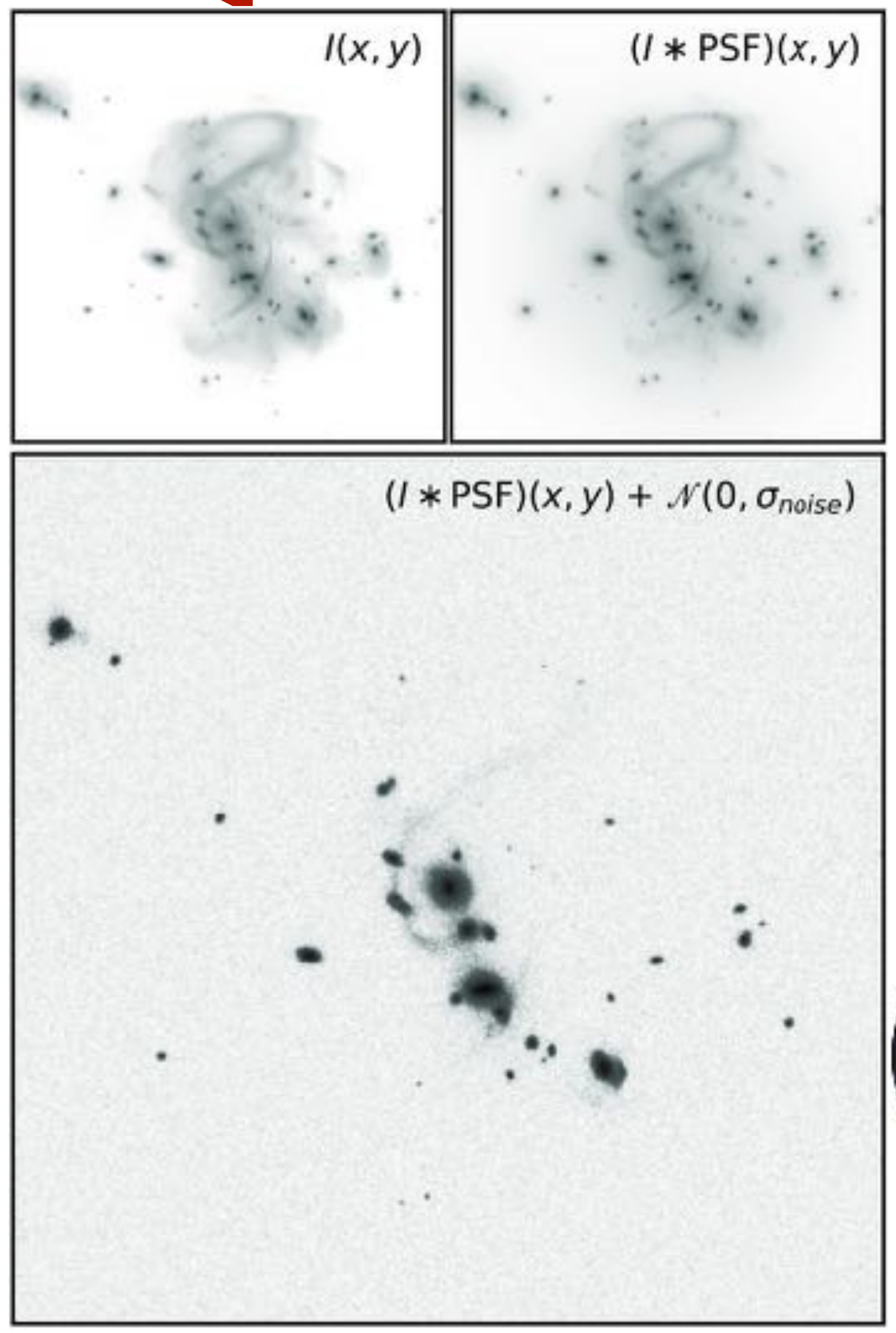
Cosmological,
large # of galaxies,
low resolution

Cosmological,
Few galaxies,
High resolution to resolve dwarfs, satellites and streams

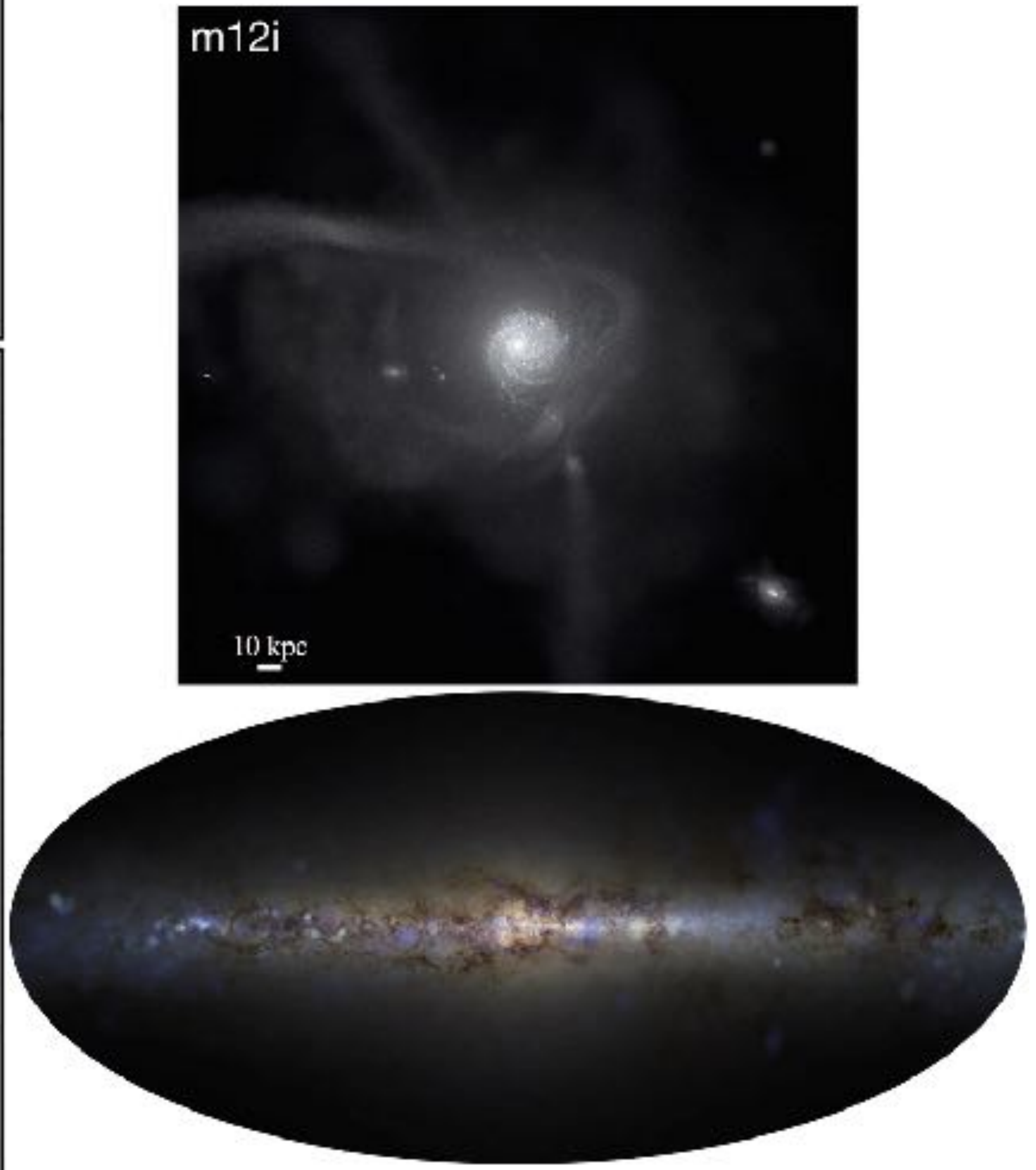
Cosmological, more galaxies, high DM resolution, flexible empirical models

Semi-analytic galaxy evolution models: large statistical samples, no spatial resolution

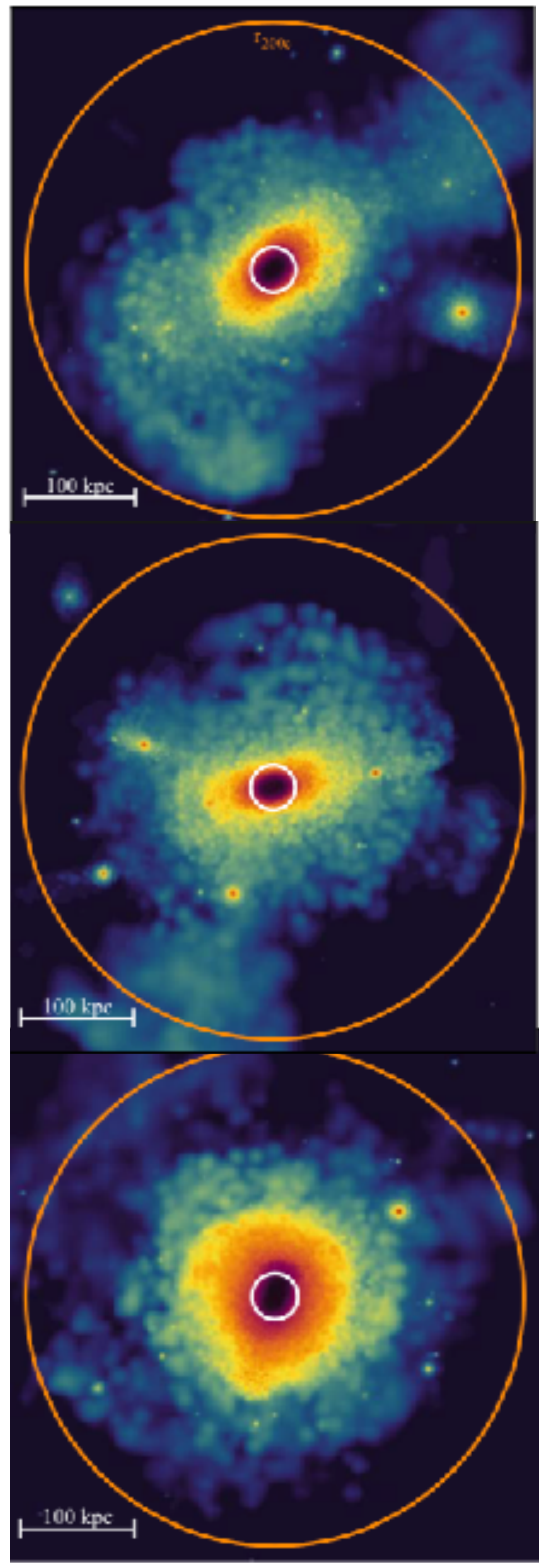
Dynamical modeling in isolation: flexible in galaxy/potential models and satellites streams. High resolution



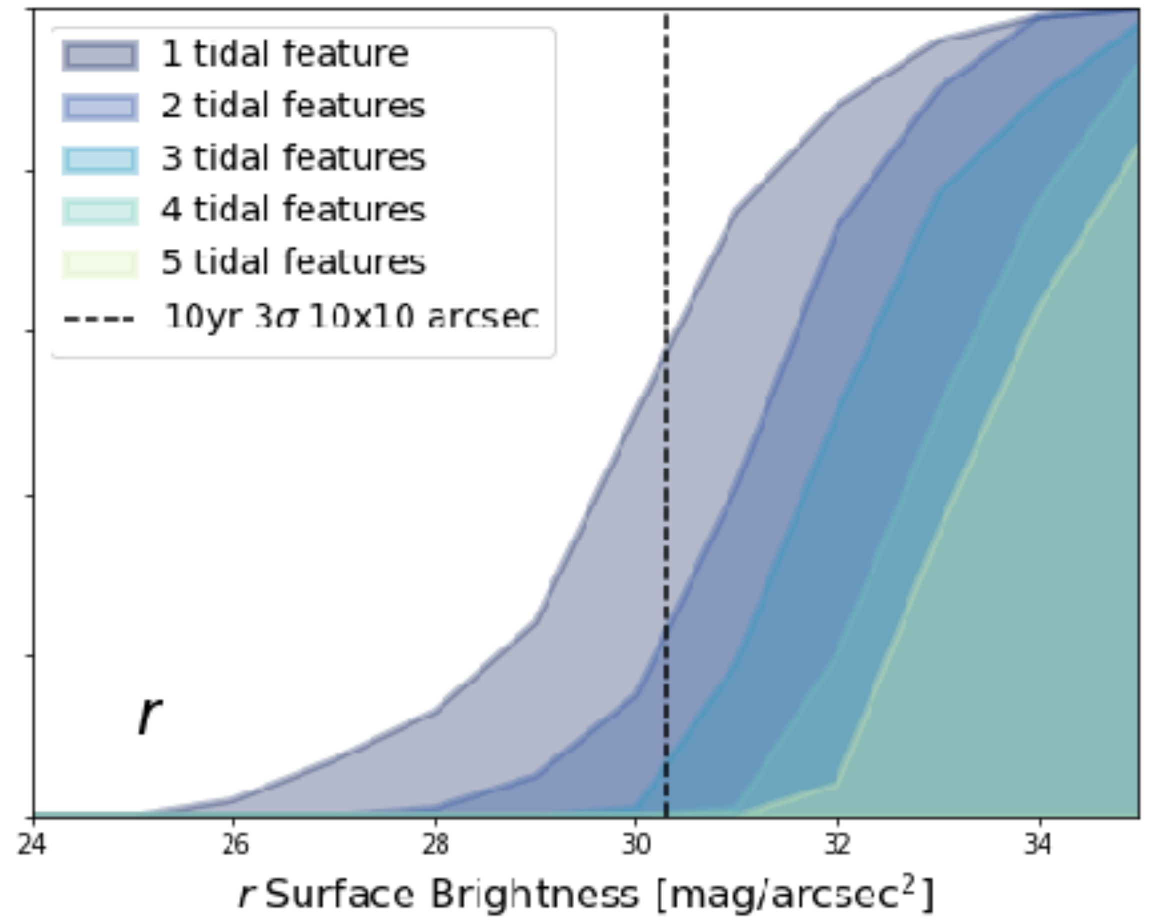
Martin+2022 (incl. TS)



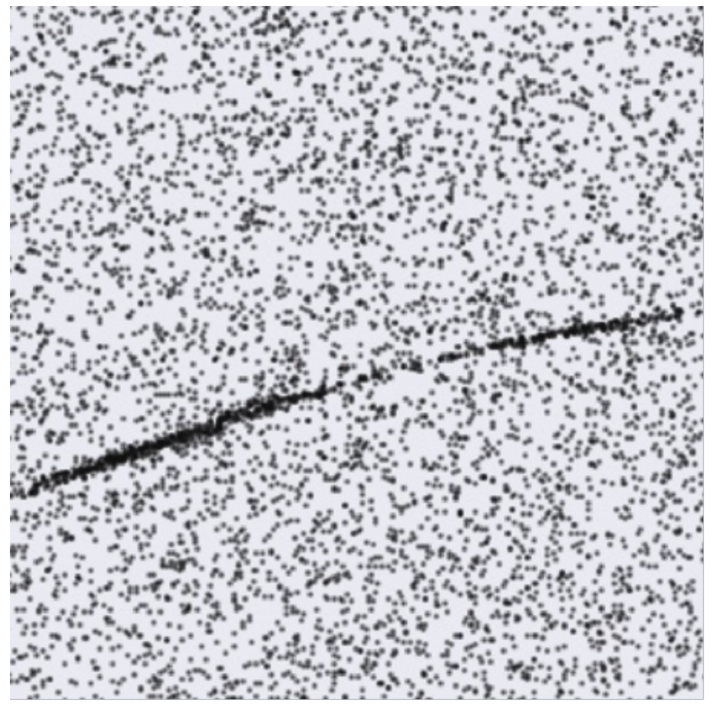
Sanderson et al. 2020, FIRE simulations (Hopkins 2014, 2018)



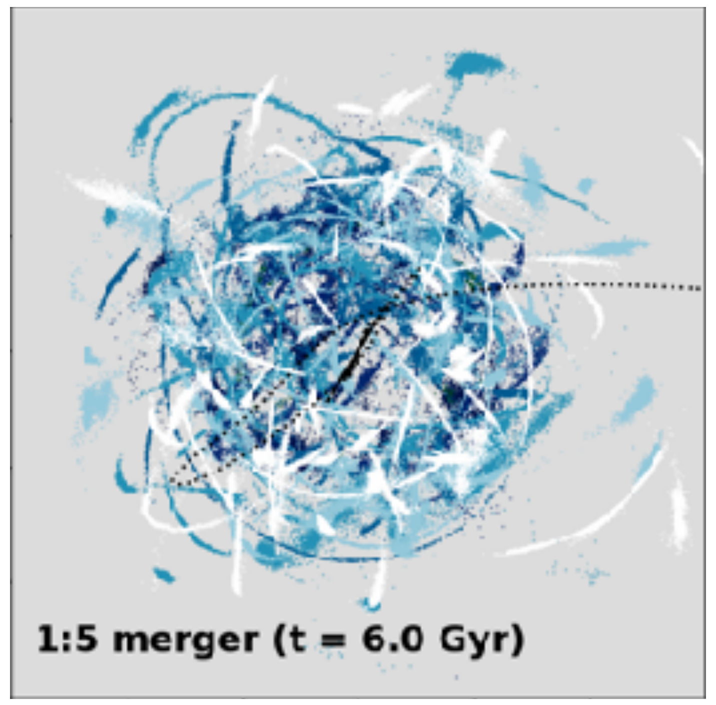
Rey & Starkenburg 2022



Starkenburg, et al. in prep.

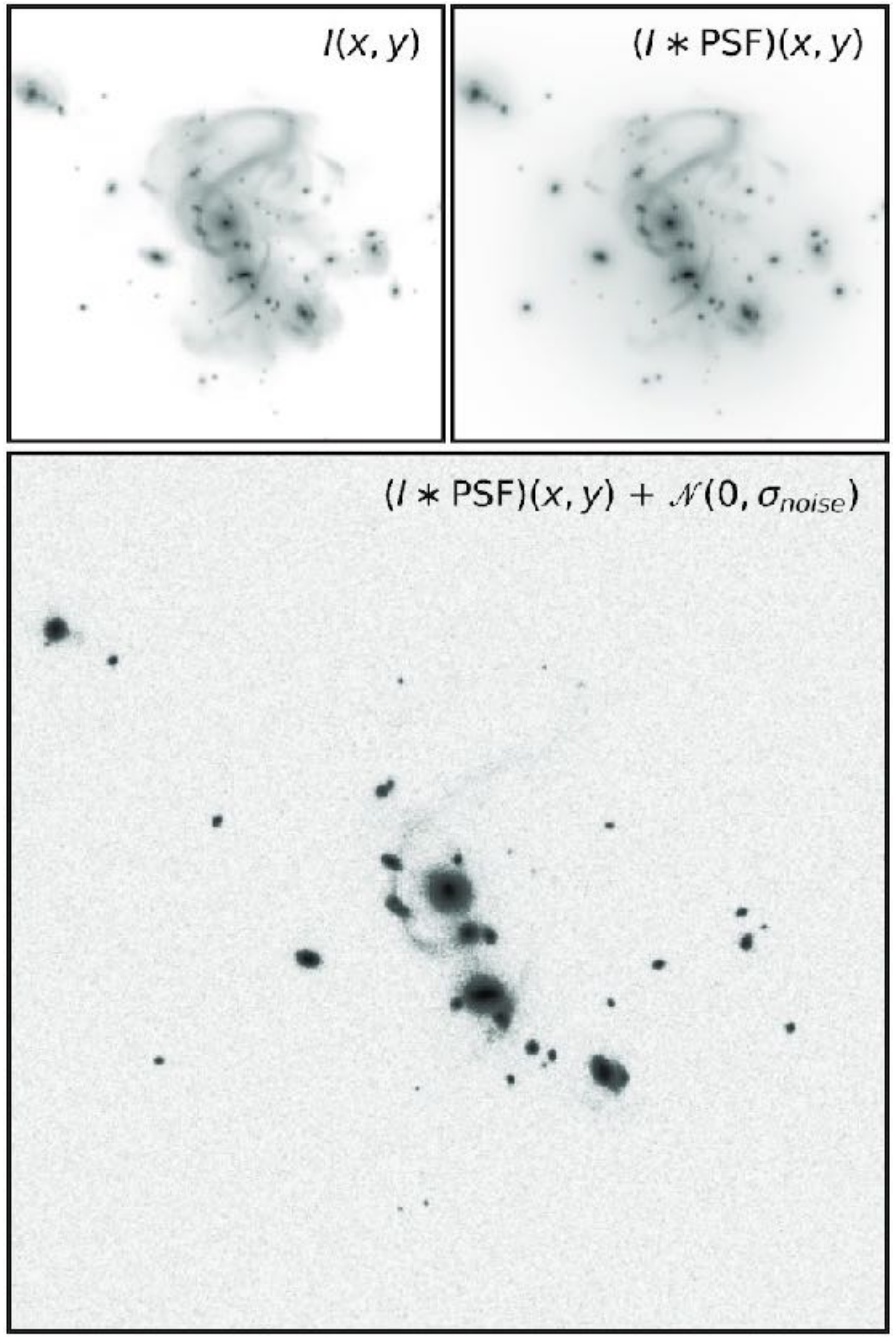


Aganze+ (incl TS) 2023

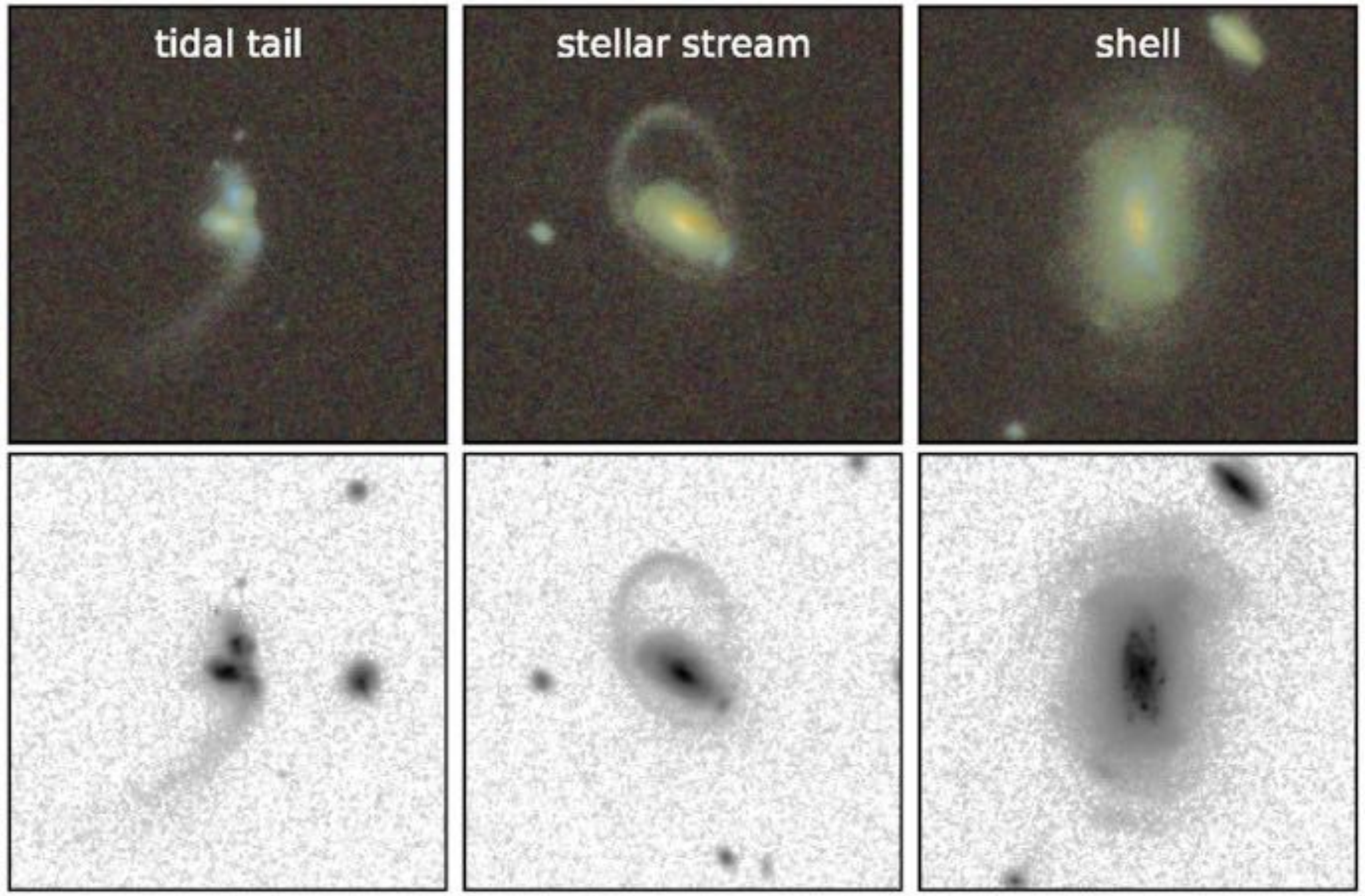


Weerasooriya, Starkenburg, et al. in prep.

LOW-SURFACE BRIGHTNESS GALAXY OUTSKIRTS IN RUBIN



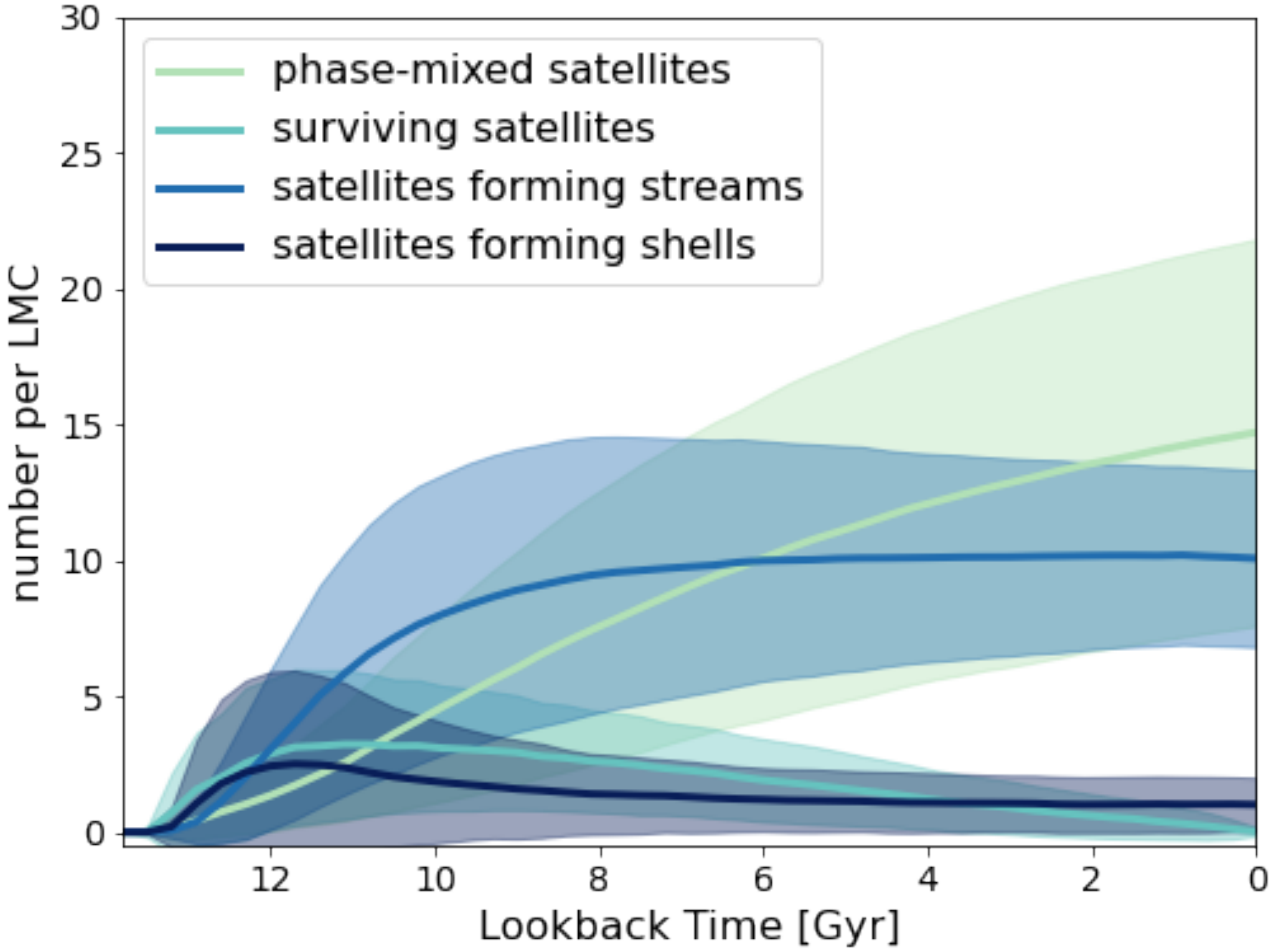
Figures from Martin+2022 (incl. TS):
Synthetic Rubin images



- Euclid, Rubin and Roman will hugely increase the samples of observed tidal features around galaxies
- Prepatory work to automatically classify tidal features (Hendel+2019; Walsmley+2019; Sola+2022; Euclid Collaboration 2022; Dominguez-Sanchez+2023)
- ***Interpretation*** *is still challenging*

PREDICTING TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

Starkenburg, Pearson et al. in prep.



- Generate accretion histories for *statistical samples* ***of*** isolated halos using the SC-SAM
- Sample infalling orbits, integrate in an evolving (growing) halo
- predict *evolving* substructure
- Use our (arbitrarily) large sample size to provide robust predictions and test the effects of galaxy formation models, assumptions and input parameters

▸ **Nearby galaxies will have tidal features (streams)**

See also Adriana's talk on Wed!

PREDICTING TIDAL DEBRIS AROUND LMC–SIZED GALAXIES

Starkenburg, Pearson et al. in prep.

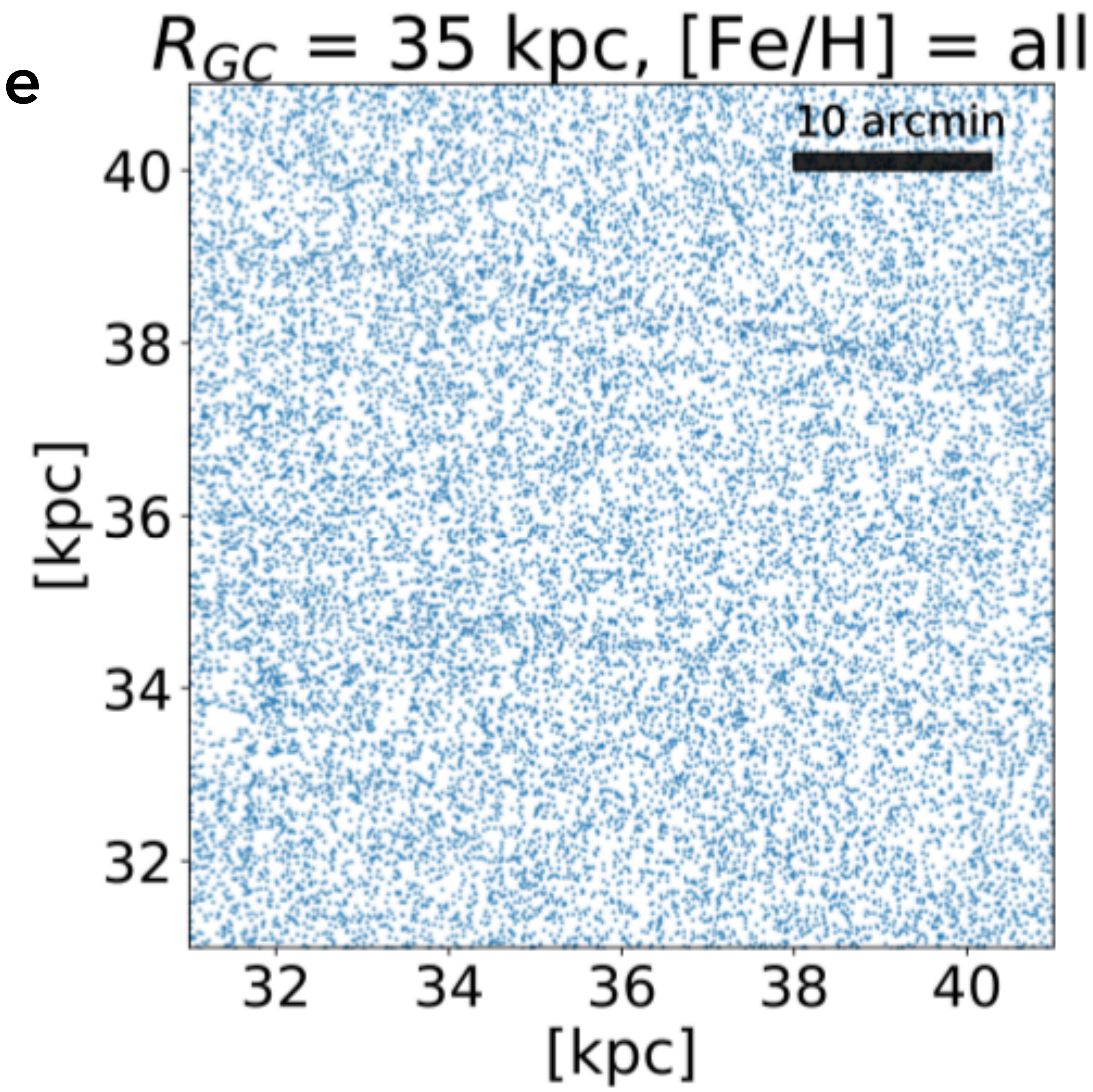
- Generate accretion histories for *many* isolated halos
- Use our (arbitrarily) large sample size to provide robust predictions and test the effects of models, assumptions and input parameters
  - **Nearby galaxies will have visible tidal features with Euclid, Roman, and Rubin**
  - These are challenging to detect (sky subtraction & masks, galactic cirrus, …) -> work in progress in collaborations

THIN STREAMS IN EXTERNAL GALAXIES WITH ROMAN

- **A low-surface brightness discovery space for Euclid, the Vera Rubin Observatory, and the Nancy Grace Roman Space Telescope**

- Inserting globular cluster streams in PAndaS M31 fields (McConnachie et al. 2018)

- Most massive streams would have been possible to see in PAndaS data



Pearson, **Starkenburg**+2019:
Mock streams in M31 with Roman.

THIN STREAMS IN EXTERNAL GALAXIES WITH ROMAN

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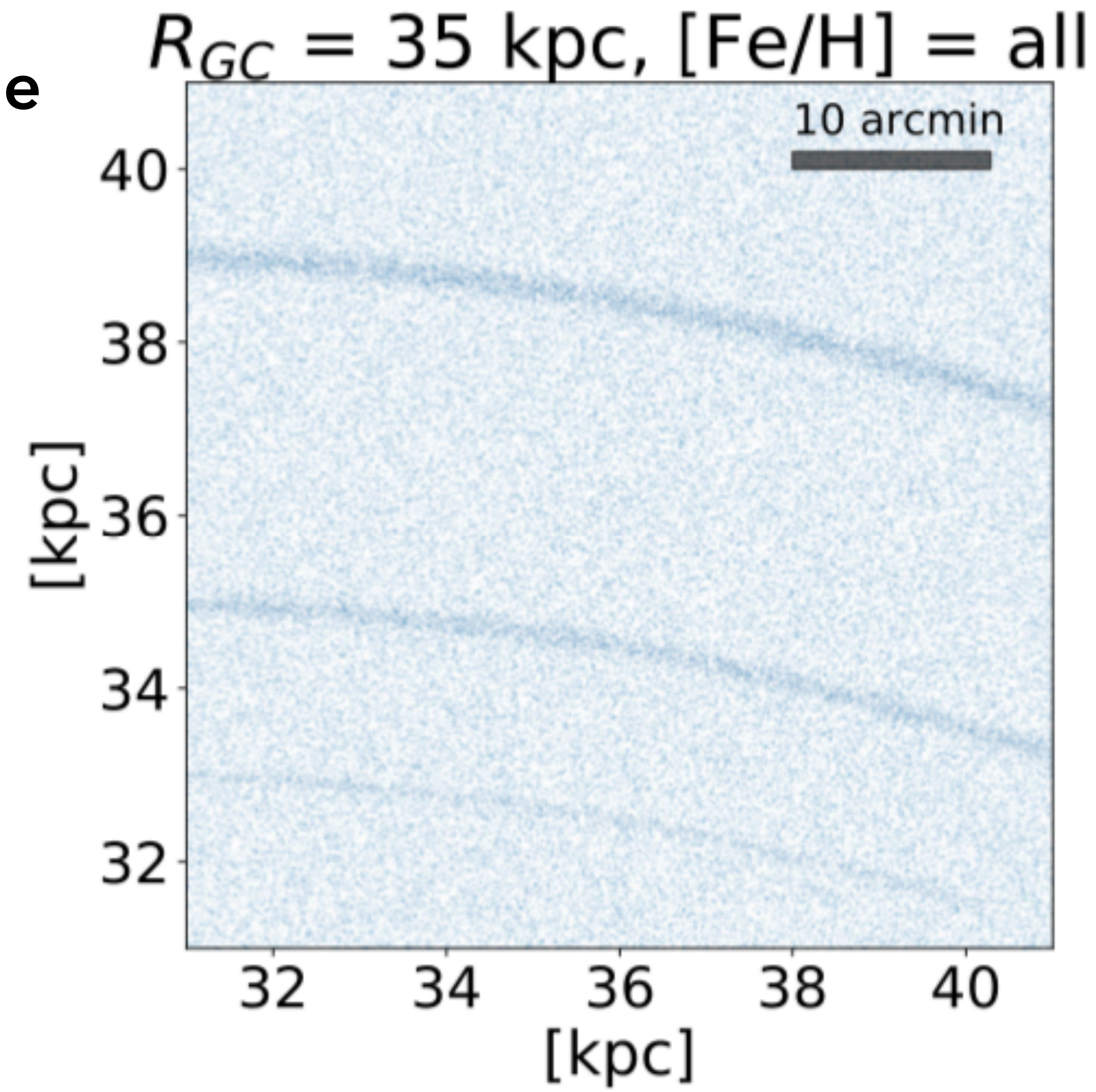
  - The Roman Telescope will resolve most streams
  - This is true out to 3.5 Mpc, a volume that contains ~200, mostly lower-mass galaxies



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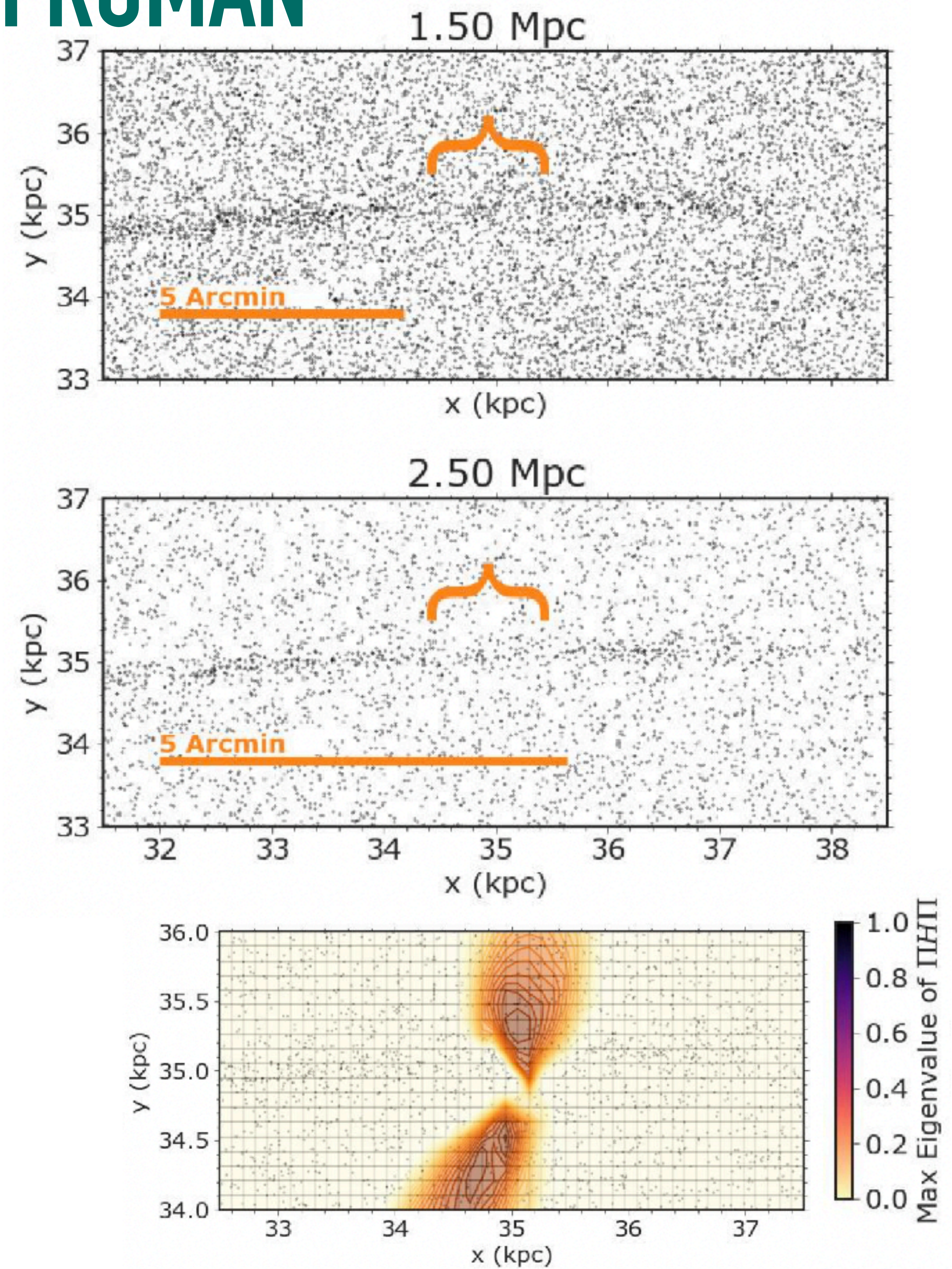
THIN STREAMS IN EXTERNAL GALAXIES WITH ROMAN

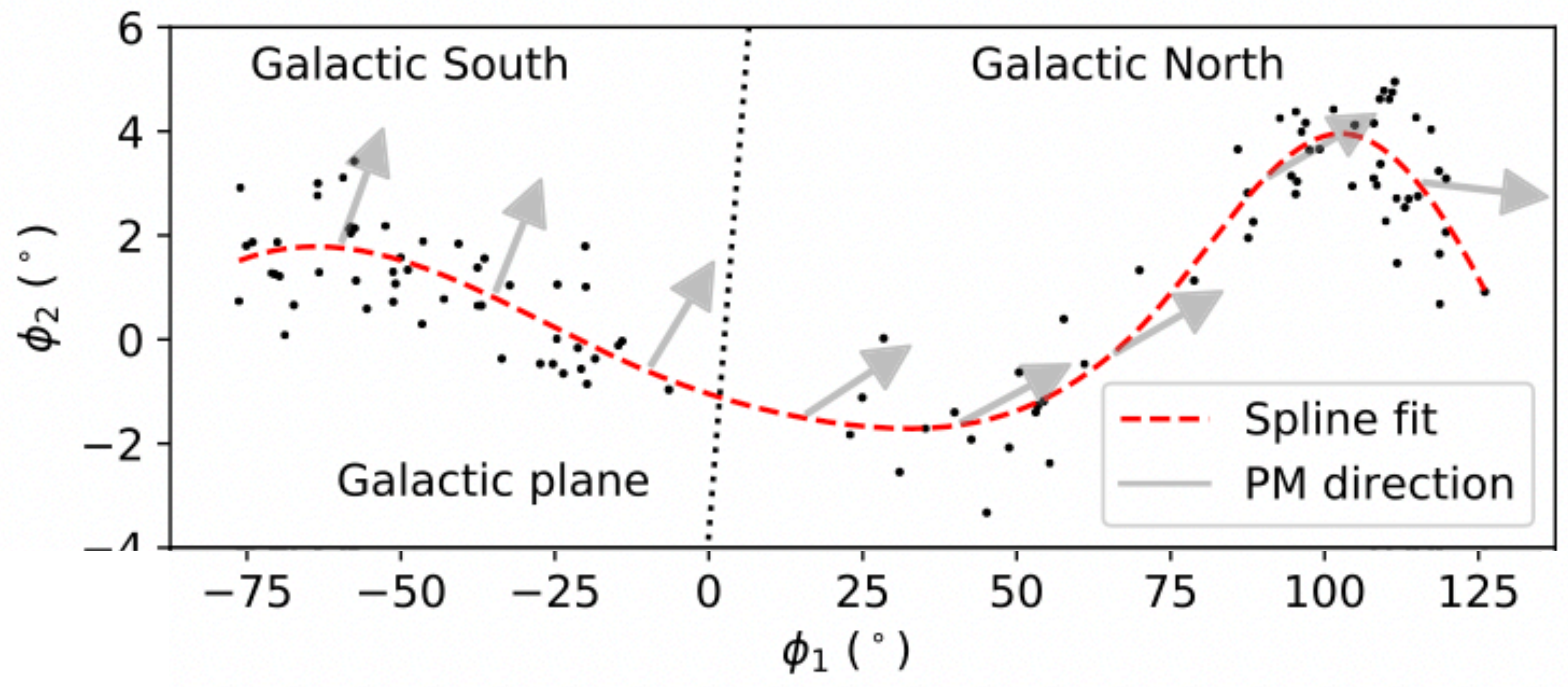
- **A low-surface brightness discovery space for Euclid, the Vera Rubin Observatory, and the Nancy Grace Roman Space Telescope**

- Inserting globular cluster streams in PAndaS M31 fields (McConnachie et al. 2018)
- The Roman Telescope will resolve most streams
- This is true out to 3.5 Mpc, a volume that contains ~200, mostly lower-mass galaxies
- Likely to be able to detect gaps in stellar streams out to ~2 Mpc



Aganze, Pearson, **Starkenburg** et al 2023

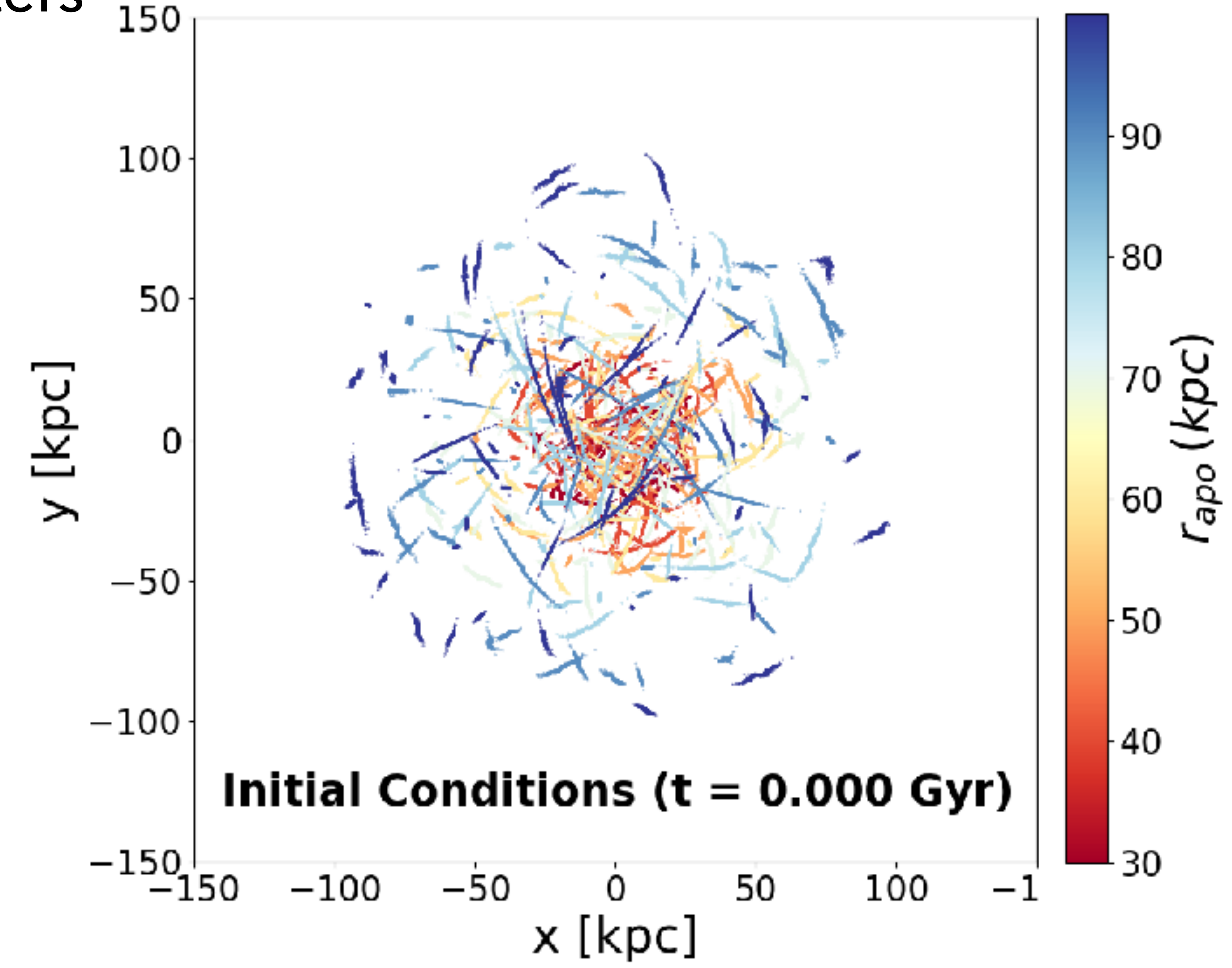
MILKY WAY STREAMS INFLUENCED BY THE LMC



Orphan stream; Erkal+2019; see also Shipp+2019

–> How do streams evolve during mergers?

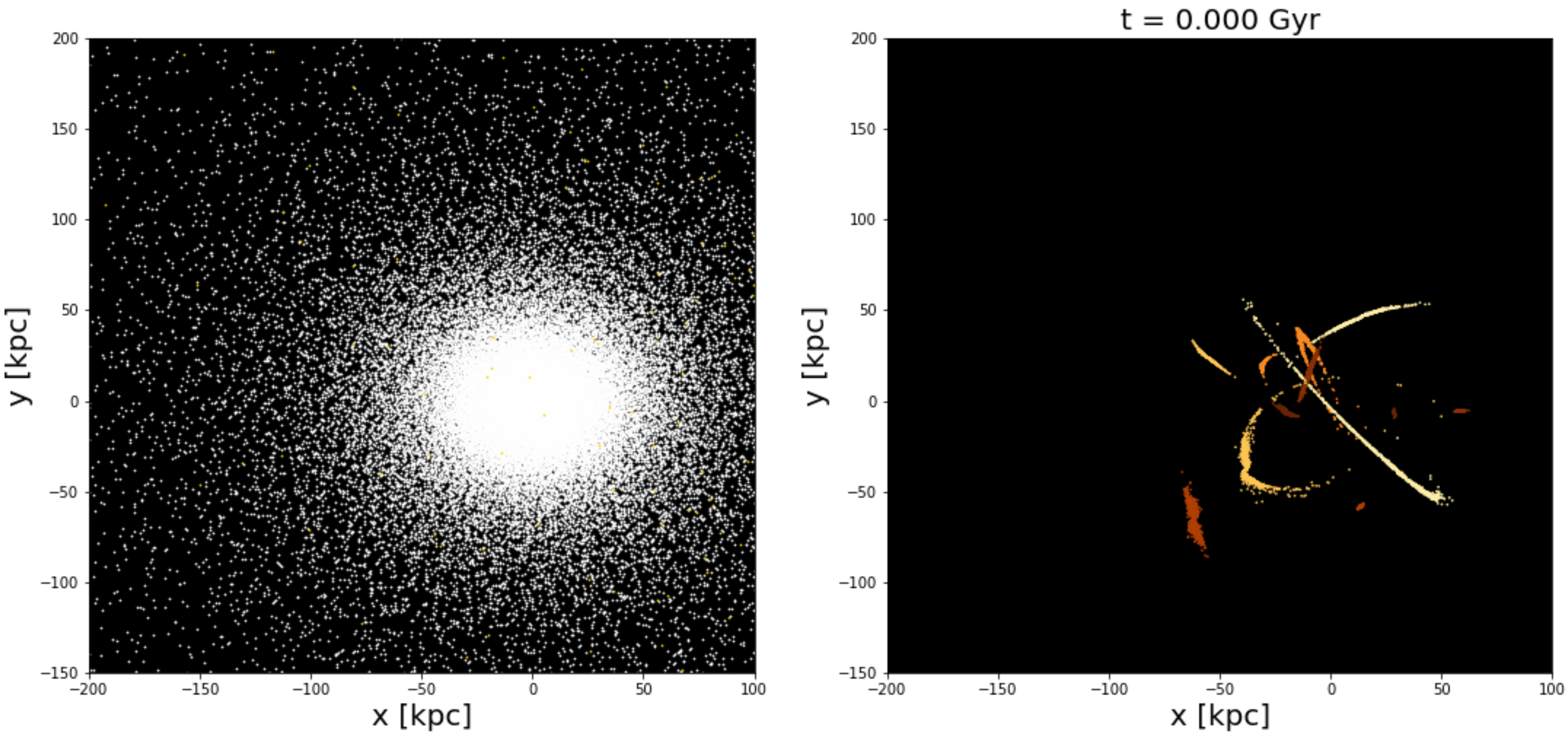
- Using a statistical sample of streams (1024)
- With ranges in orbital properties
- Well-resolved and systematically changing merger parameters



To explain the shape and in particular kinematics of a number of streams the infall and mass of the LMC needs to be taken into account, and also the response of the Milky Way dark matter halo to that infall.

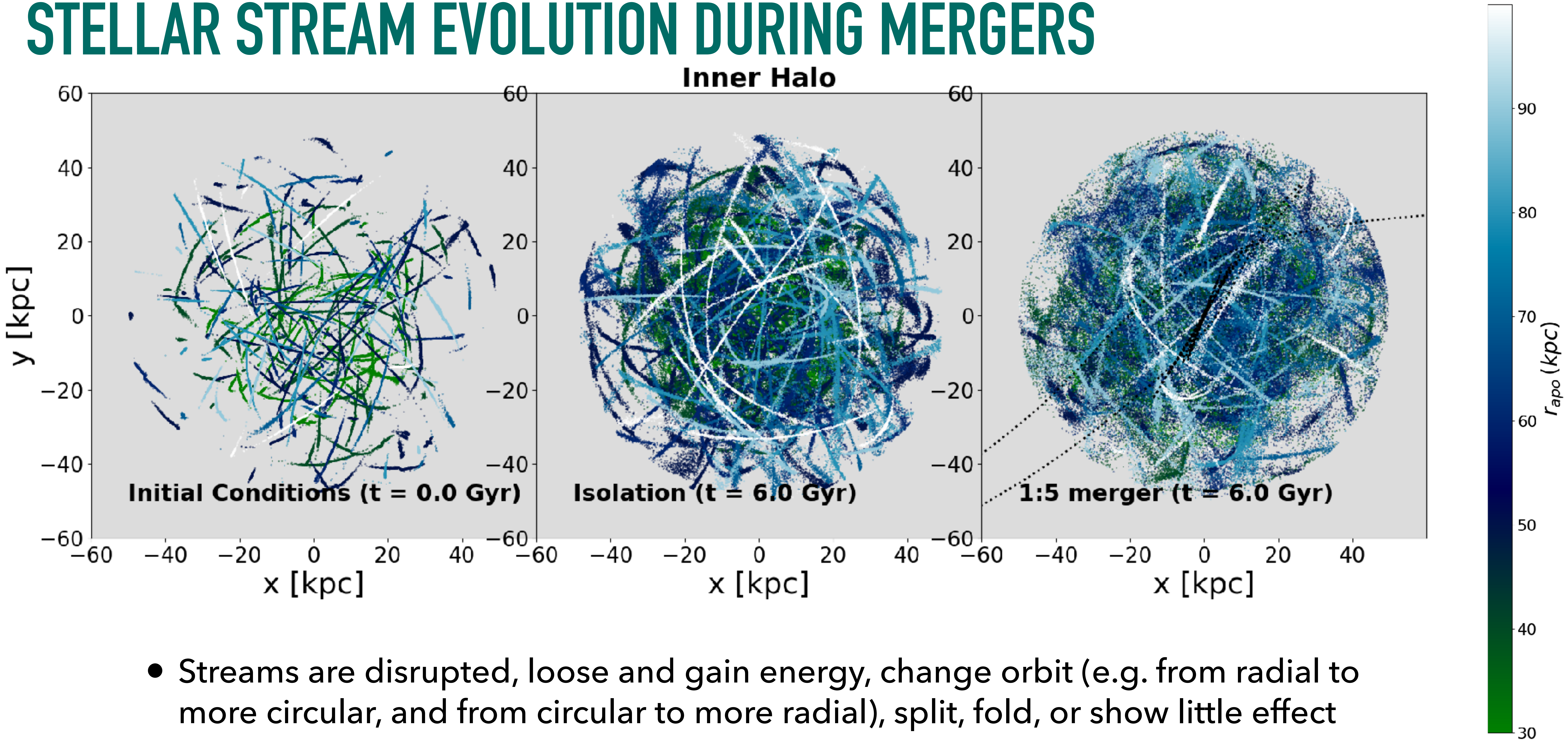
(e.g. Vera-Ciro & Helmi 2013, Gomez+2015; Erkal+2019; Shipp+2019; Garavito-Camargo+2019; Vasiliev+2020, Cunningham+2020; Petersen & Penarrubia 2020; Garavito-Camargo+2021; PanithanPaisal+2022; Lilleengen+2023)

STELLAR STREAM EVOLUTION DURING MERGERS



Weerasooriya, **Starkenburg** et al. in prep.

STELLAR STREAM EVOLUTION DURING MERGERS



- Streams are disrupted, loose and gain energy, change orbit (e.g. from radial to more circular, and from circular to more radial), split, fold, or show little effect

Weerasooriya, **Starkenburg** et al. in prep.

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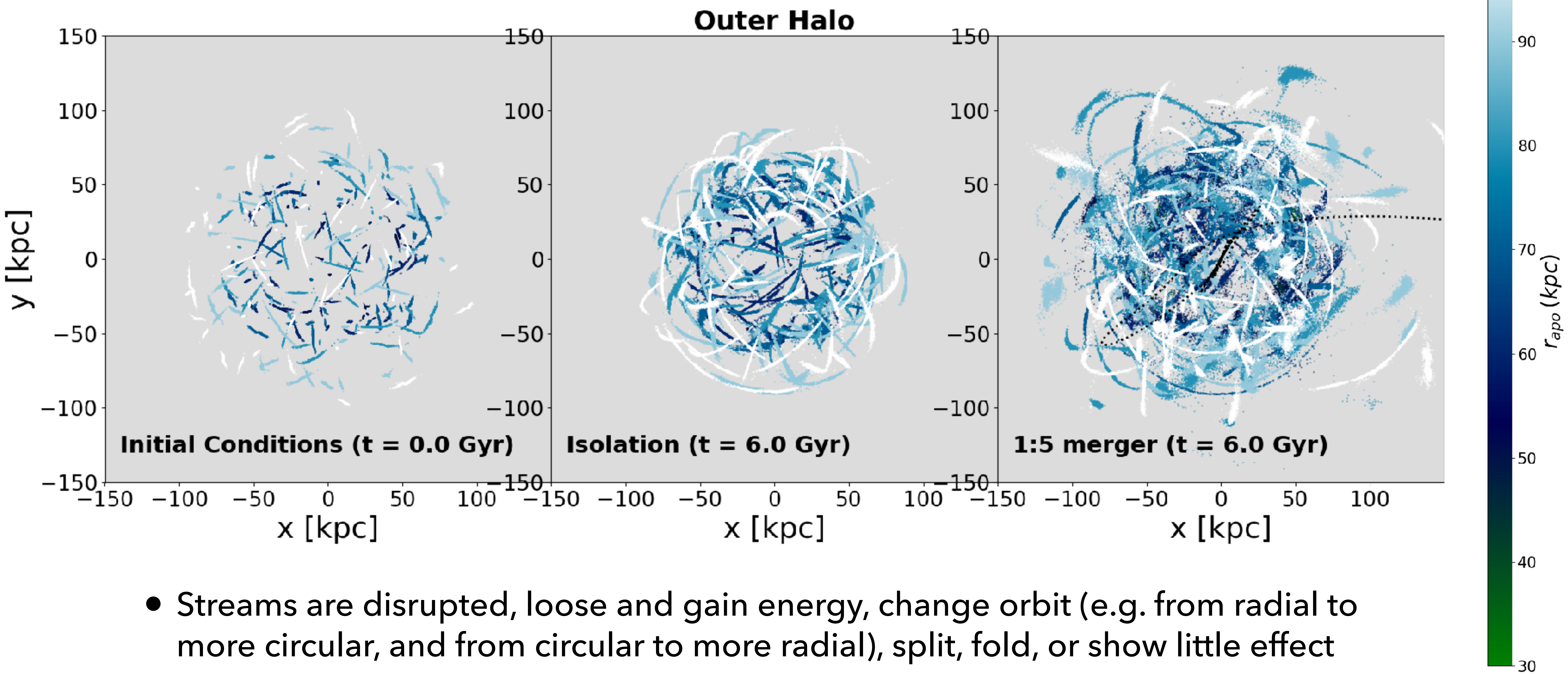

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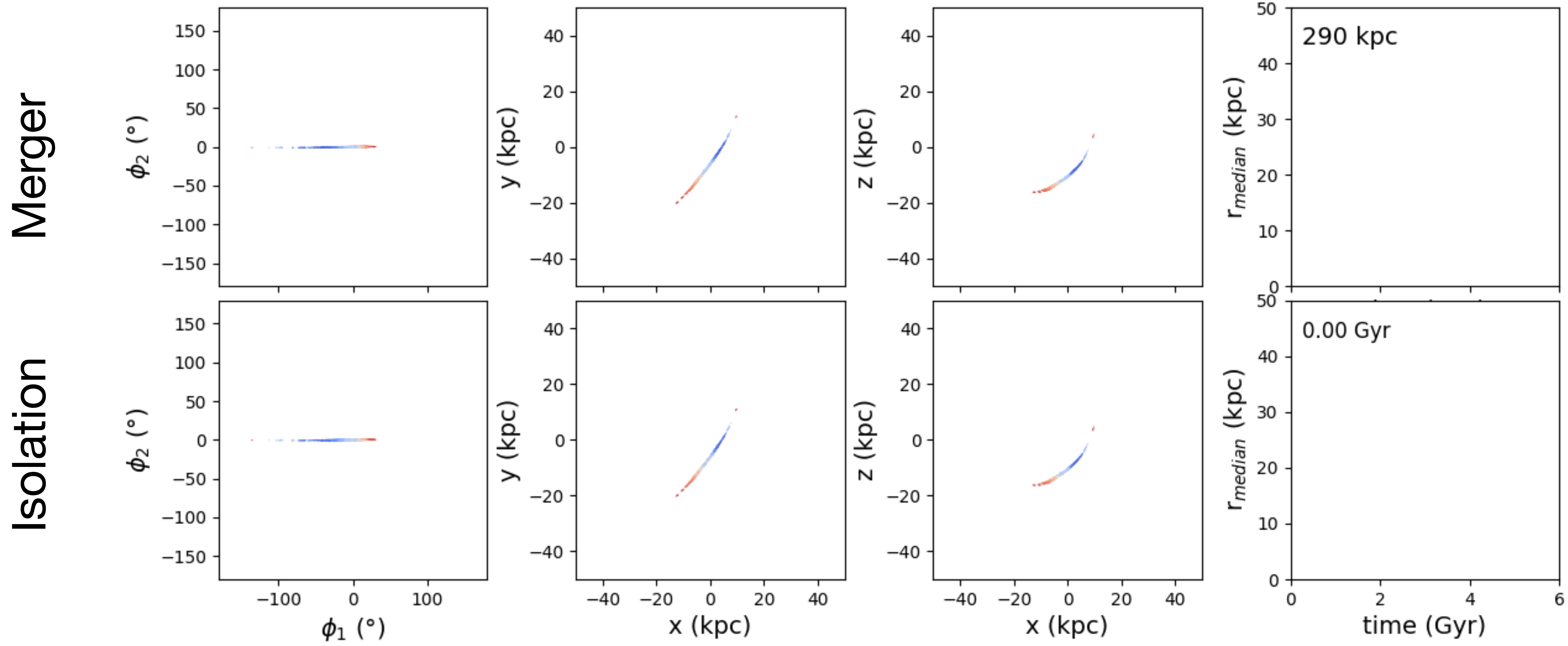

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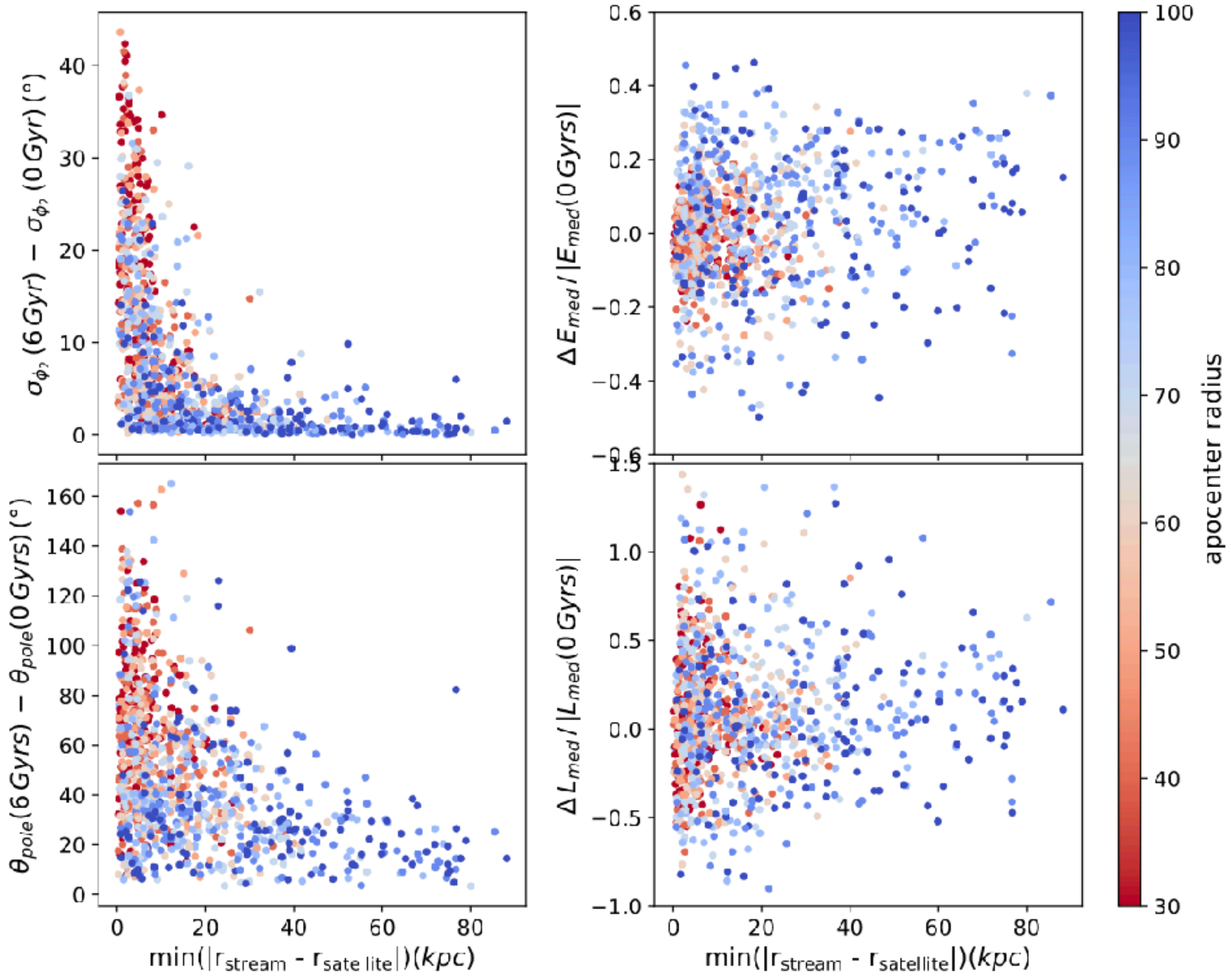

- Energy correlates somewhat with significant changes, but
- *key* is whether a part of the stream encounters the satellite (within ~20 kpc)
- Circularity affects how changes in energy and angular momentum are correlated

Weerasooriya, **Starkenburg** et al. in prep.

TAKE-AWAYS

- Stellar halos provide a wealth of information: about their host halo and about many lower mass structures such as dwarf galaxies and globular clusters
- Many galaxies (including dwarfs!) in Rubin, Roman, and Euclid surveys will have observable satellites and tidal features, providing amazing data and *statistics*
- Globular cluster stellar streams will be observable in the nearby universe with the Nancy Grace Roman Space Telescope, and even gaps in those streams
- Thin stellar streams can experience major changes in their morphology, kinematics and orbit as a result of their hist merging
- More theoretical work is needed to help interpret these upcoming datasets

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Cosmological,
Few galaxies,
High resolution to resolve dwarfs, satellites and streams

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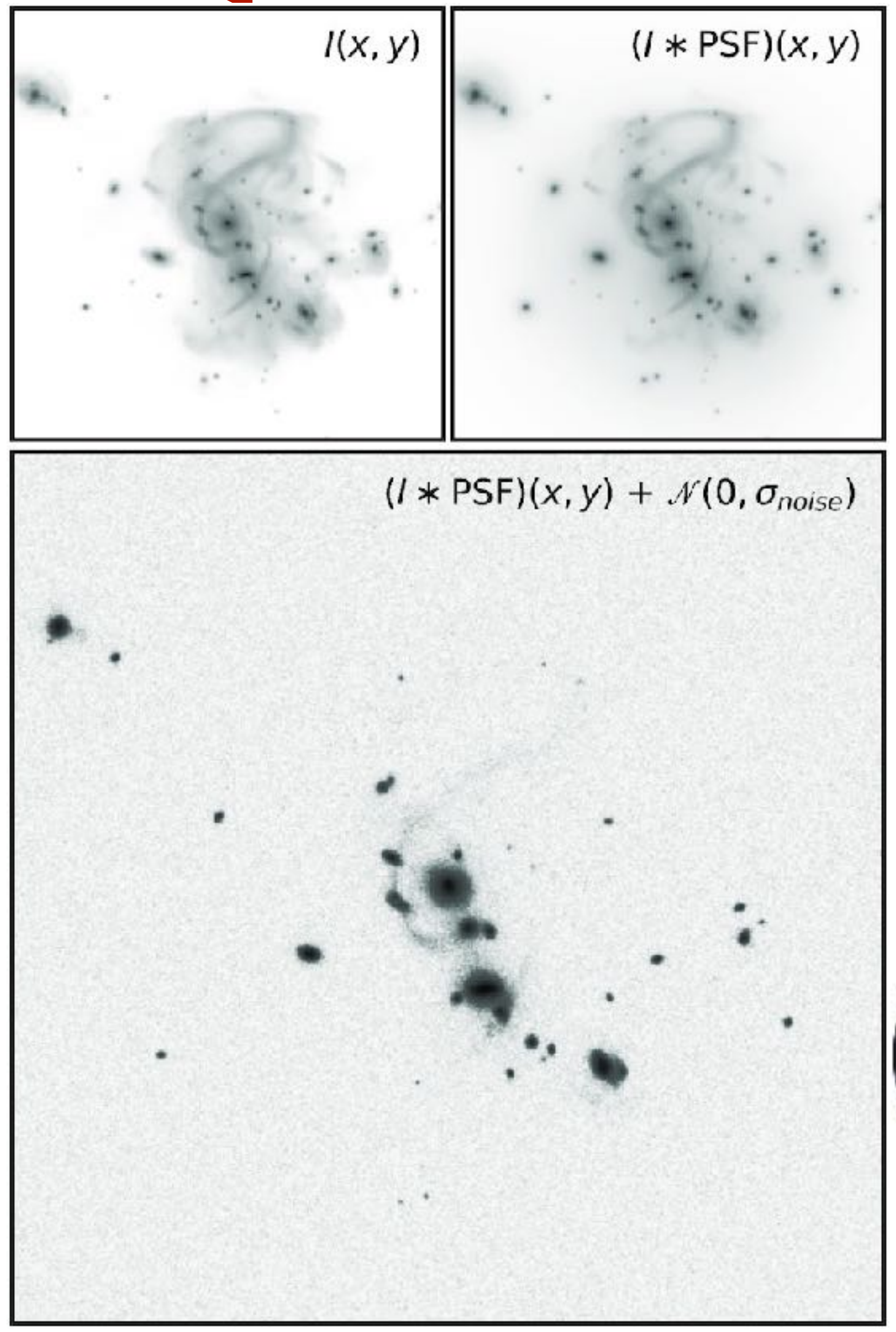
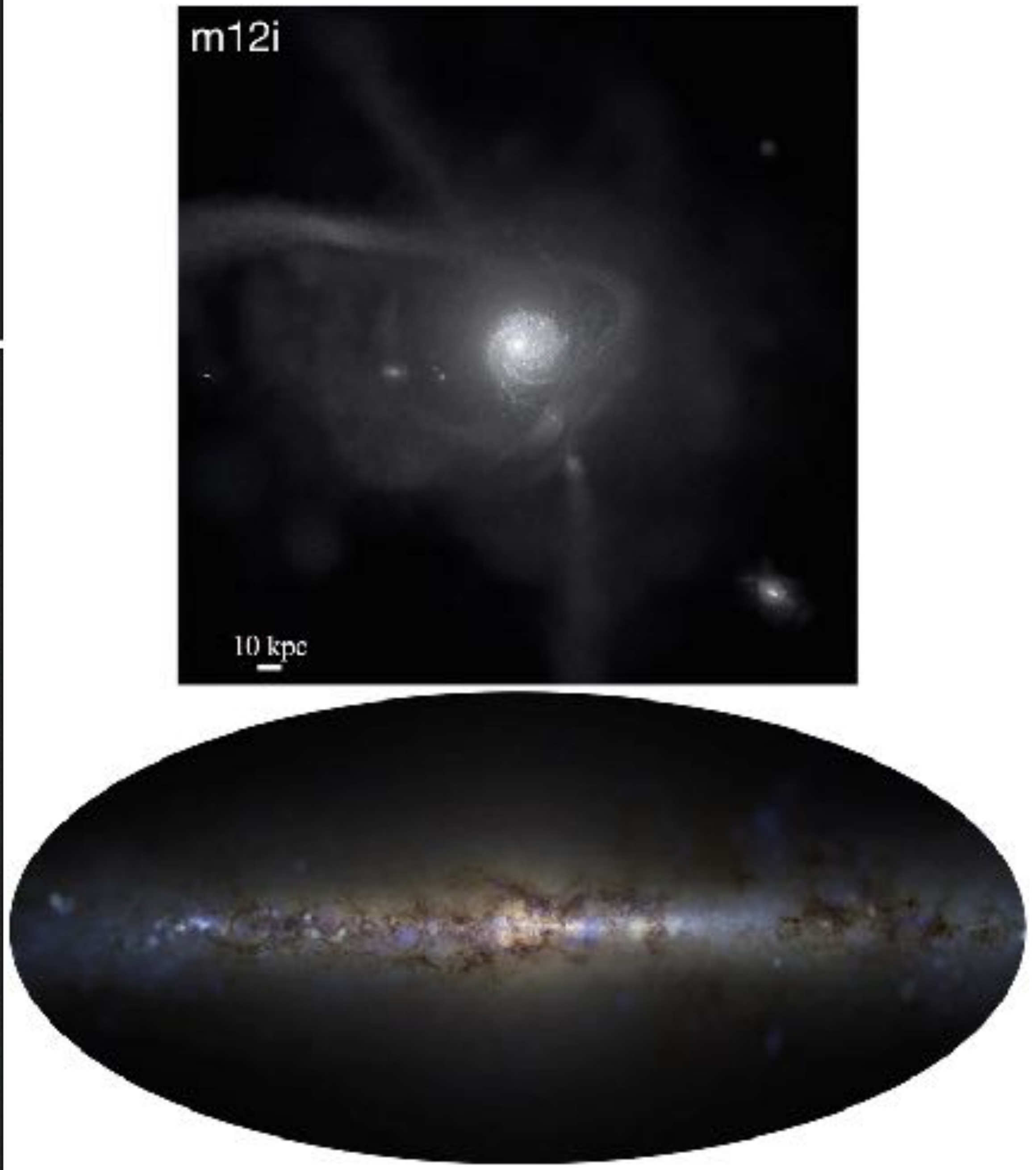
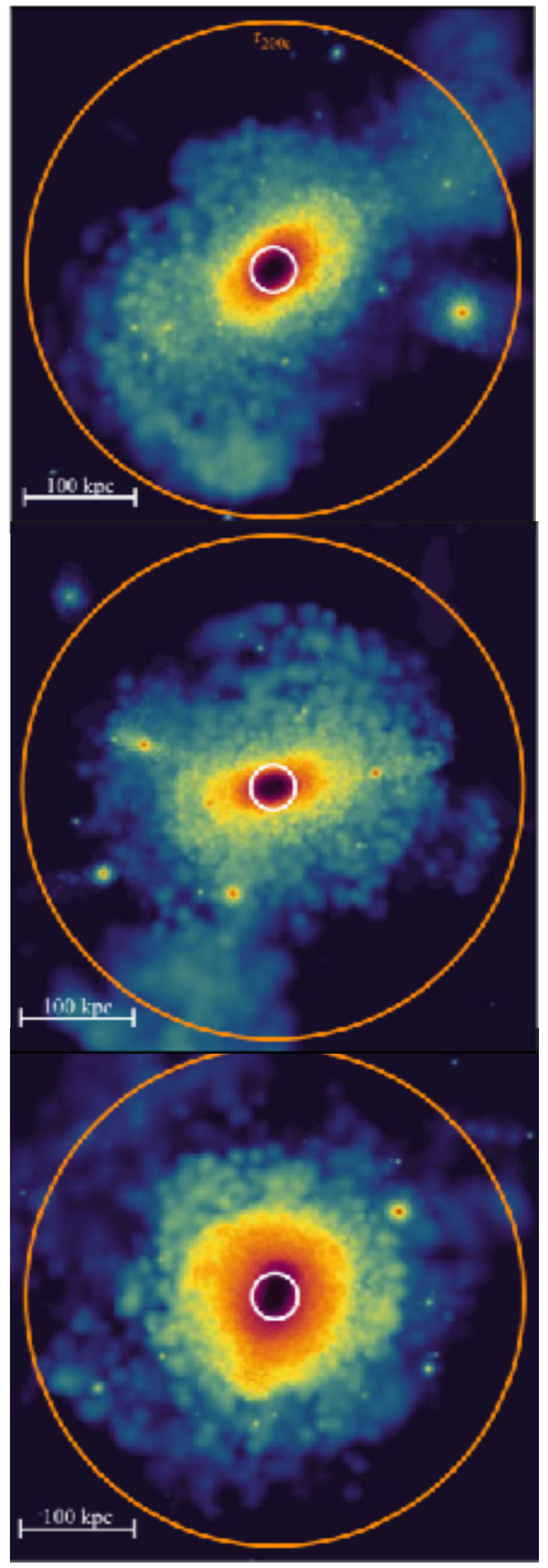


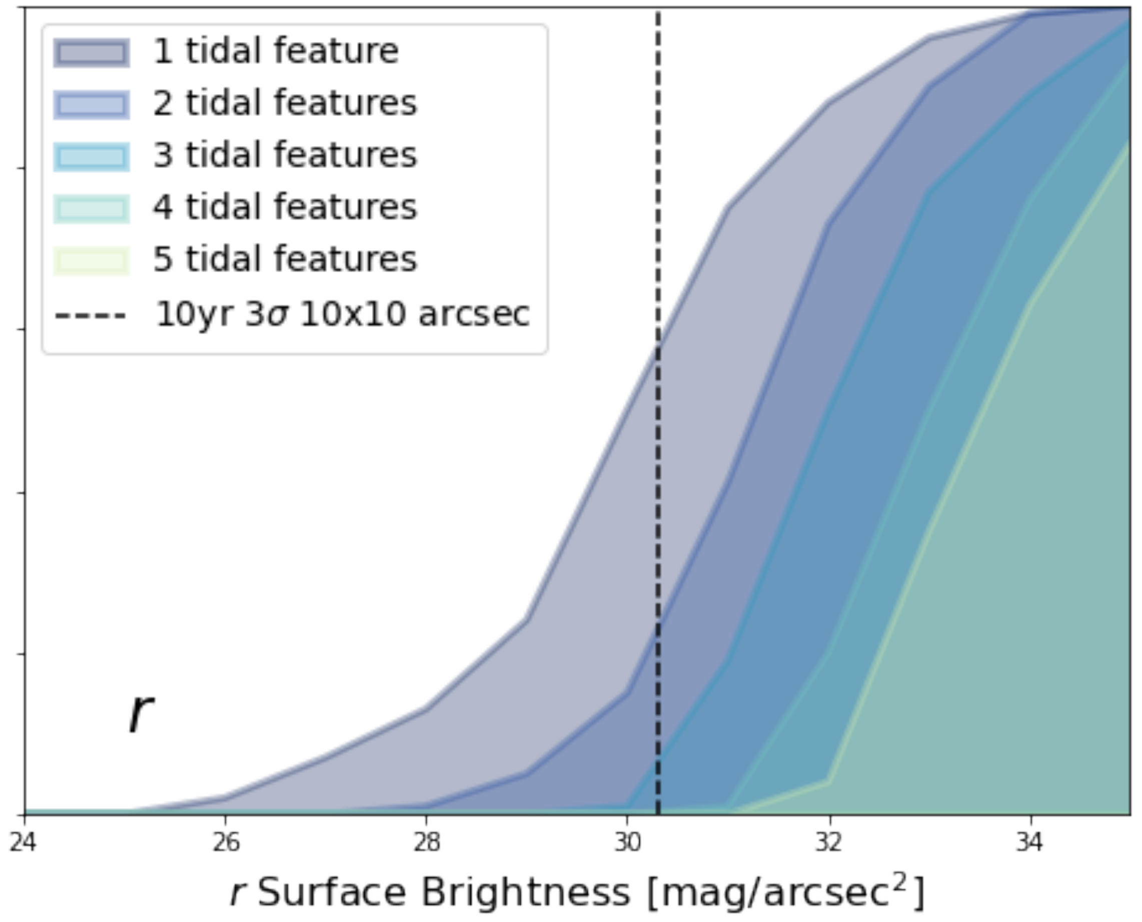
Martin+2022 (incl. TS)



Sanderson et al. 2020, FIRE simulations (Hopkins 2014, 2018)



Rey & Starkenburg 2022



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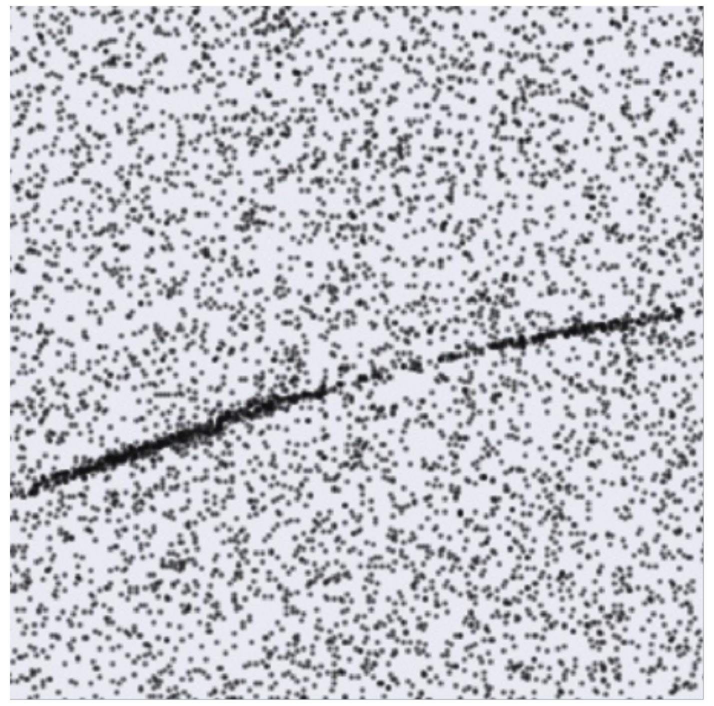
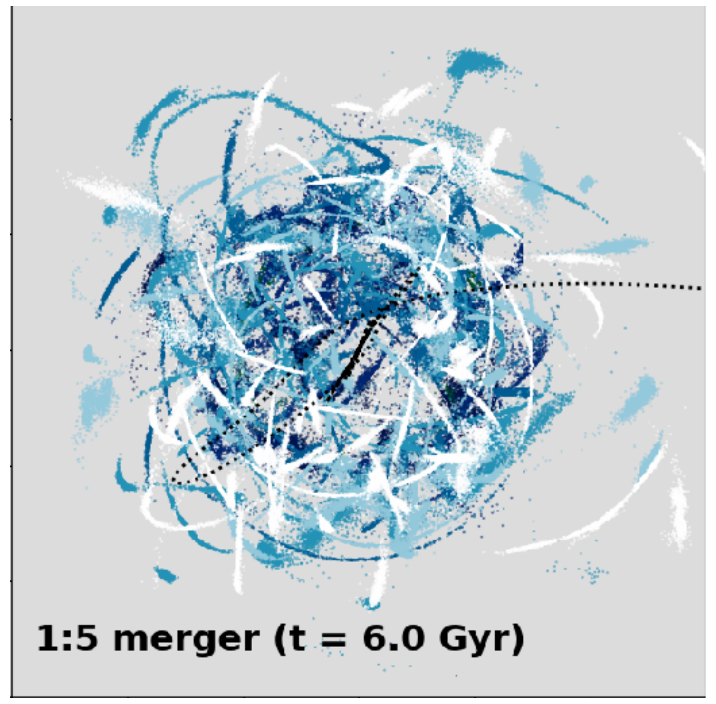


Aganze+ (incl TS) 2023



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