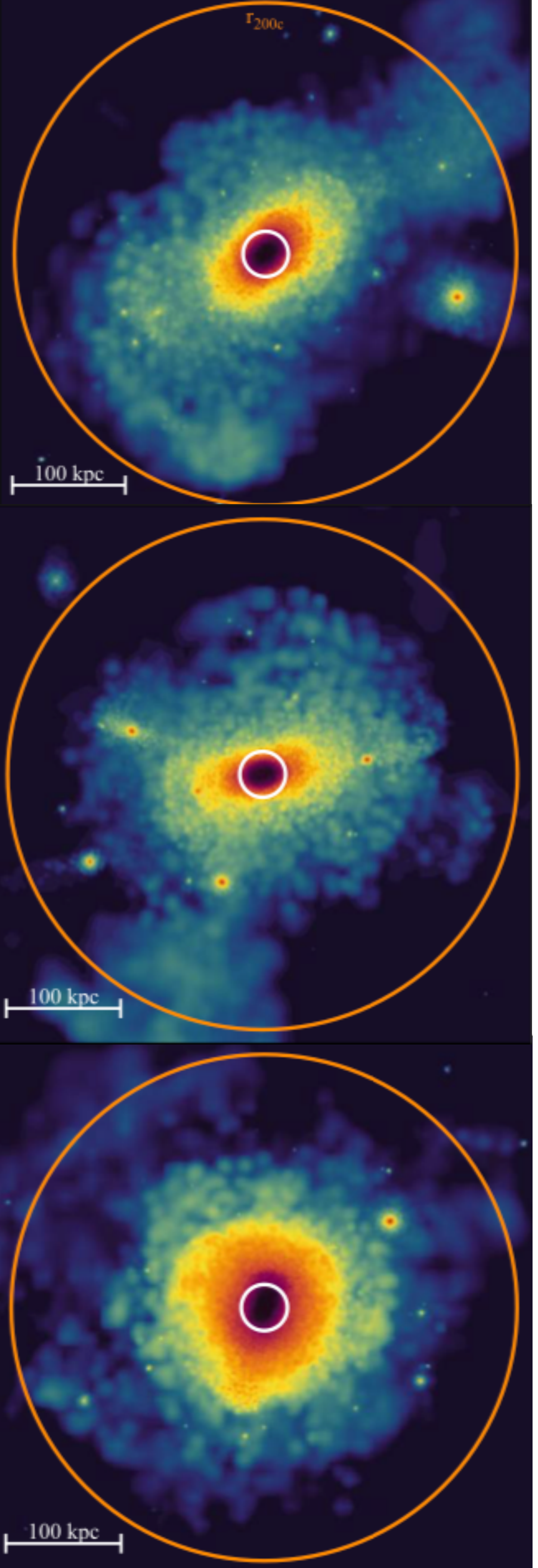

The observability of stellar halos and stellar streams in external galaxies

Tjitske Starkenburg
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In collaboration with:
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STELLAR HALOS AND SATELLITE DEBRIS PROVIDE A WEALTH OF INFORMATION

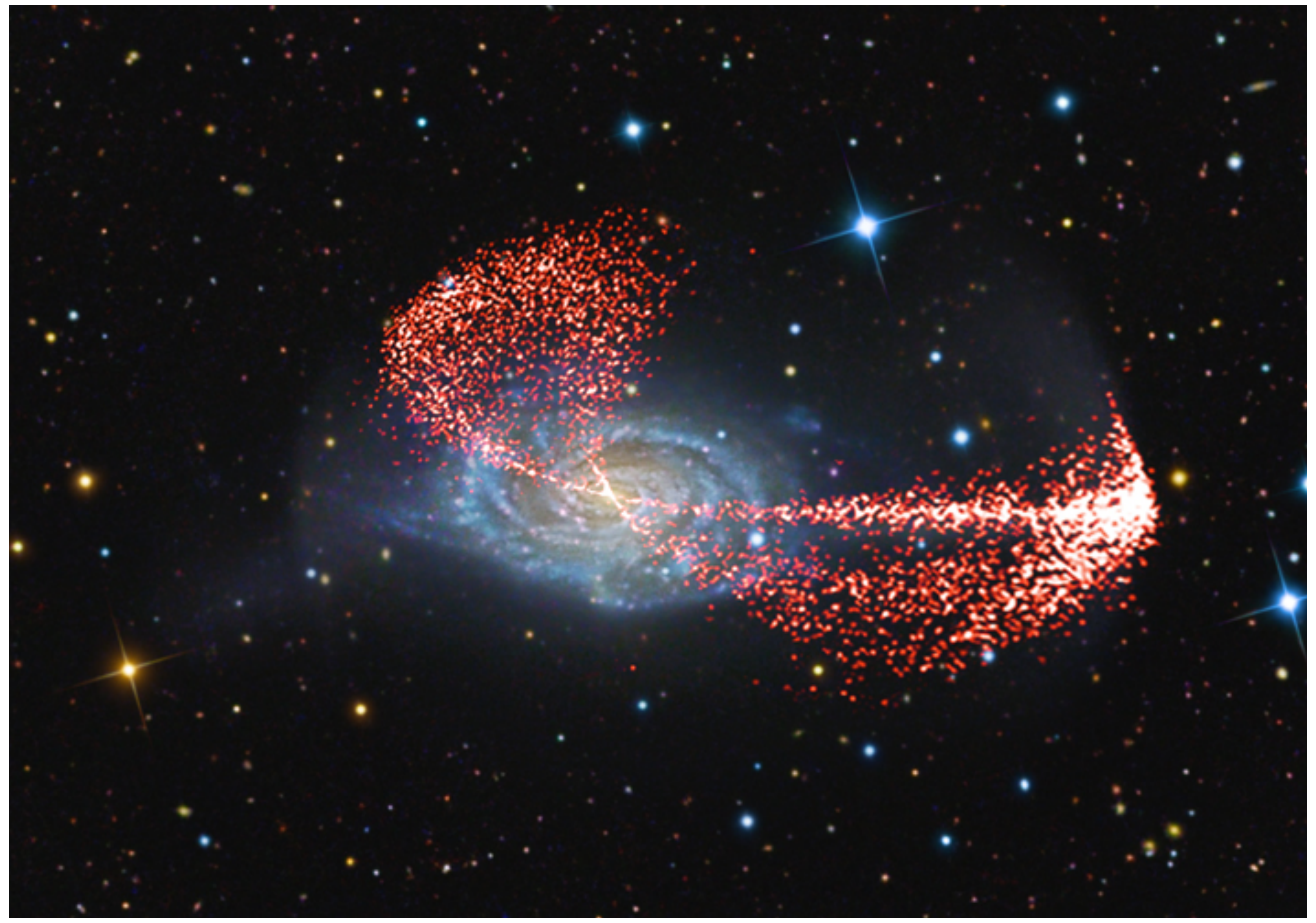
- Stellar halos predominantly form through the merger history of galaxies, so they can provide clues to a *galaxy's past evolution* (e.g. Helmi & White 1999; Cole+2000; Johnston+2001; Bullock+2001; Bullock & Johnston 2005; Bell+2008; Lowing+2015; Amorisco 2017; Monachesi+2019; Merritt+2020; Cook+2016; Helmi+2018; Donlon+2020; Renaud+2021)

- As remnants of lower mass systems, stellar halos and surviving satellites provide insights on *low-mass galaxy formation* (e.g. Bullock & Johnston 2005; Deason+2021; Cunningham+2021)

- Extended and/or cold streams trace the host potential providing key constraints on *dark matter halo masses and shapes* (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)

- *Interactions with smaller substructure* (small dark matter halos) may be observed in ***globular cluster*** stellar streams (e.g. Ibata+2002; Yoon+2011; Carlberg & Grillmair 2013; Erkal & Belokurov2015a,b; Erkal+2016; Amorisco+2016; Bonaca+2019; de Boer+2020; Koppelman & Helmi 2021; Banik+2021)

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



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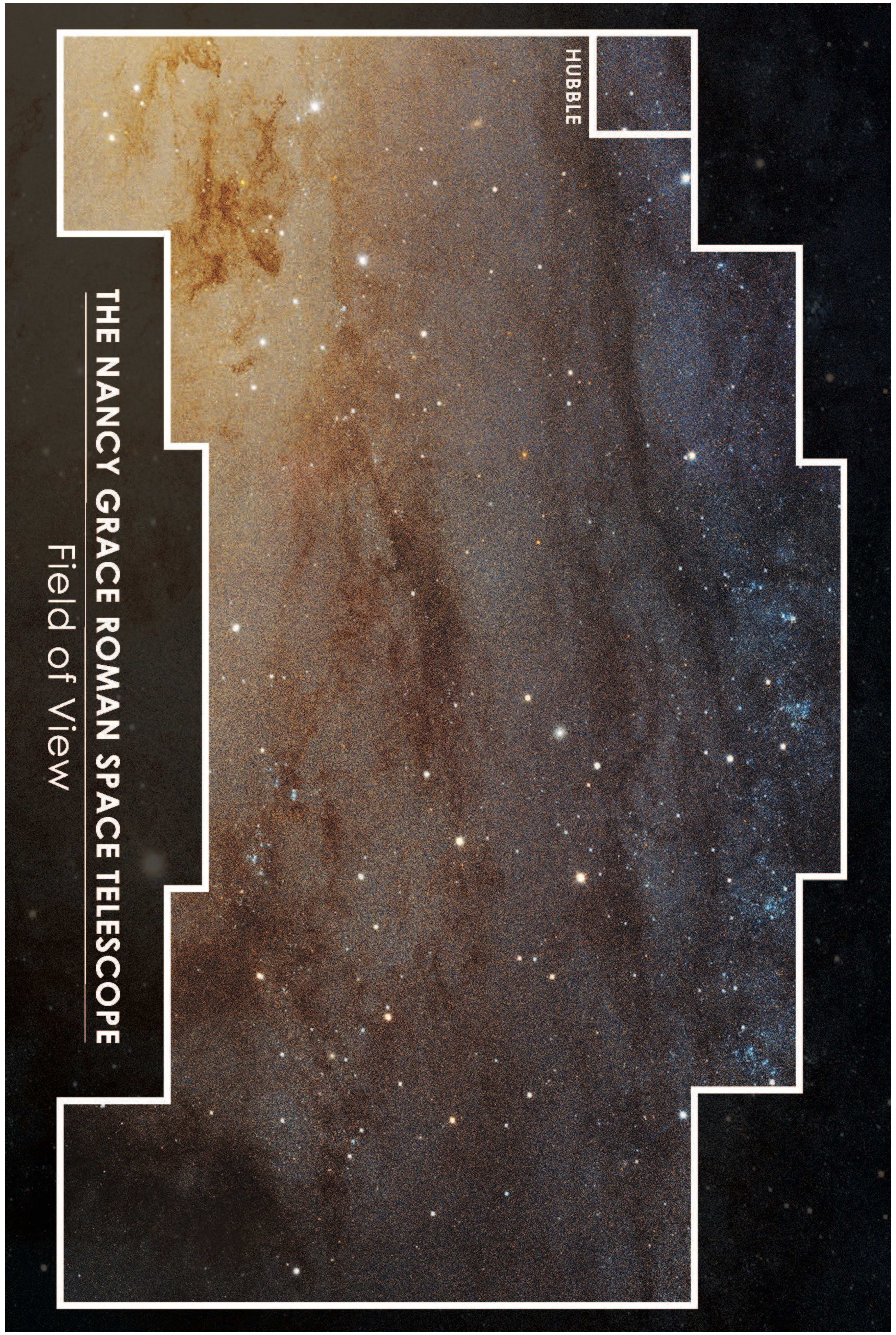
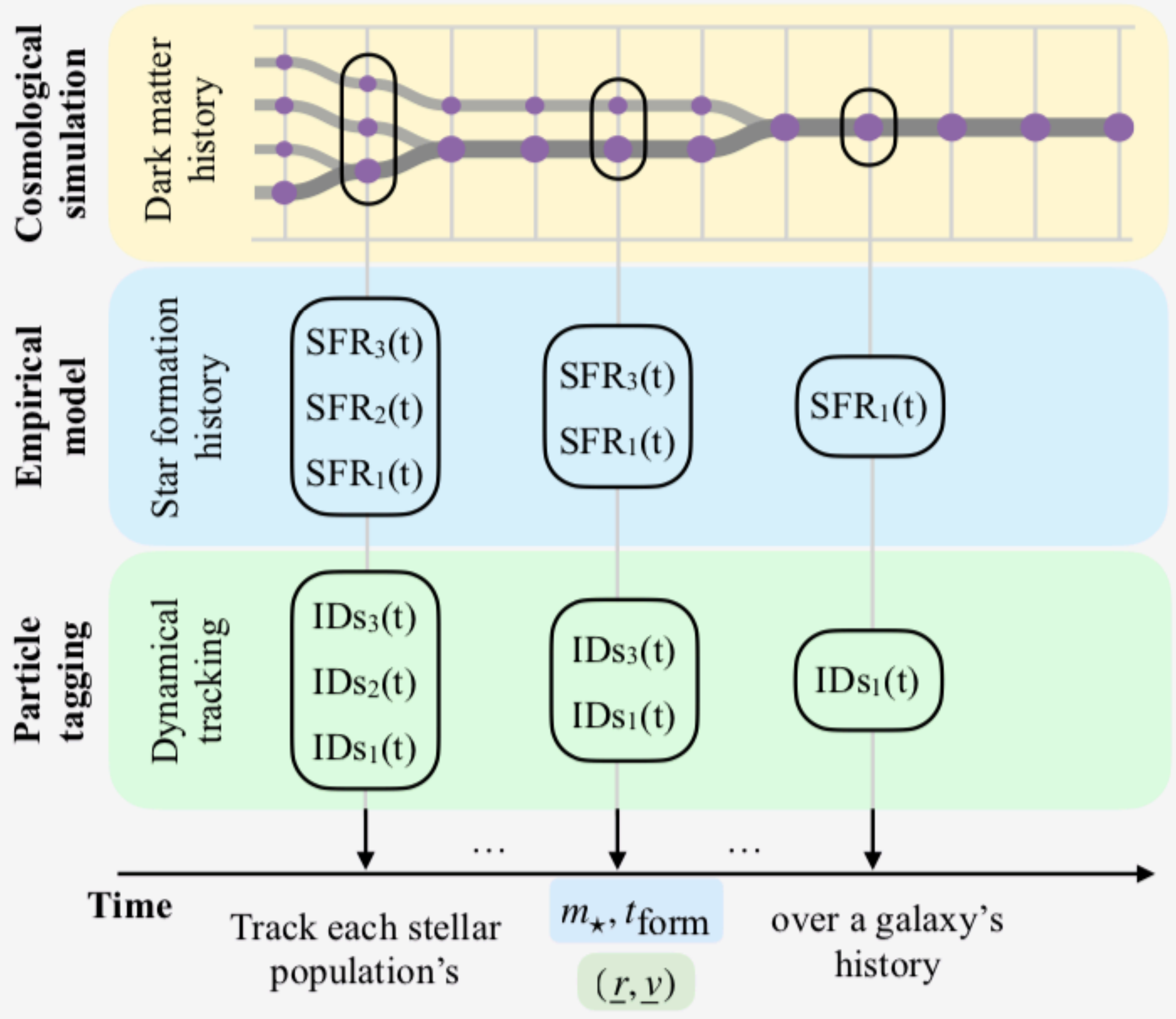


HOW COSMOLOGICAL MERGER HISTORIES SHAPE THE DIVERSITY OF STELLAR HALOS

- Dark matter-only zoom simulations of Milky Way-mass halos
- Star formation histories from empirical galaxy formation model
- Repeated particle tagging along a galaxy's evolution
- Genetic modifications of merger histories to create small specific variations

➡ **Cleanly separate effects from merger histories and star formation histories**



Rey & Starkenburg 2022

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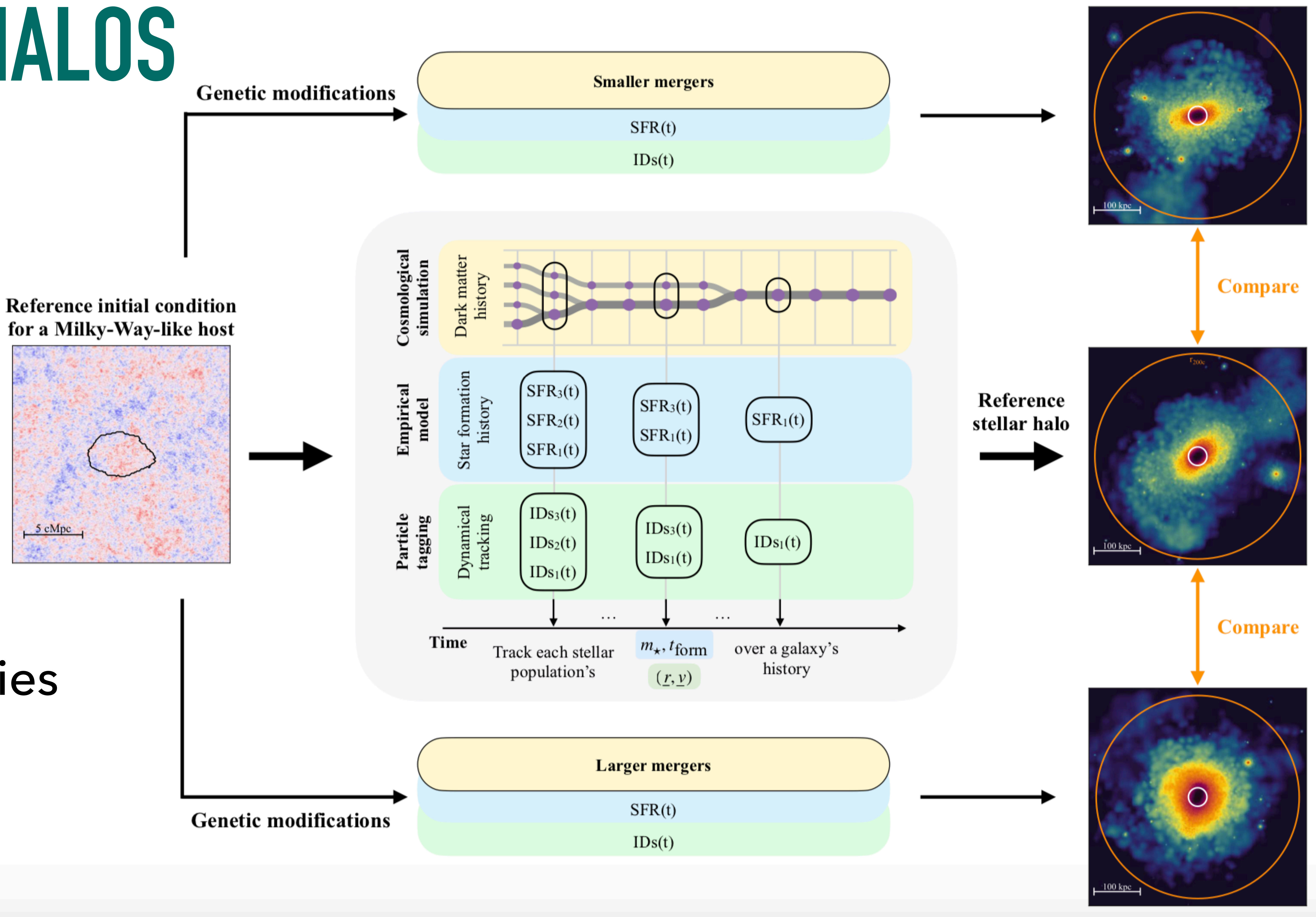

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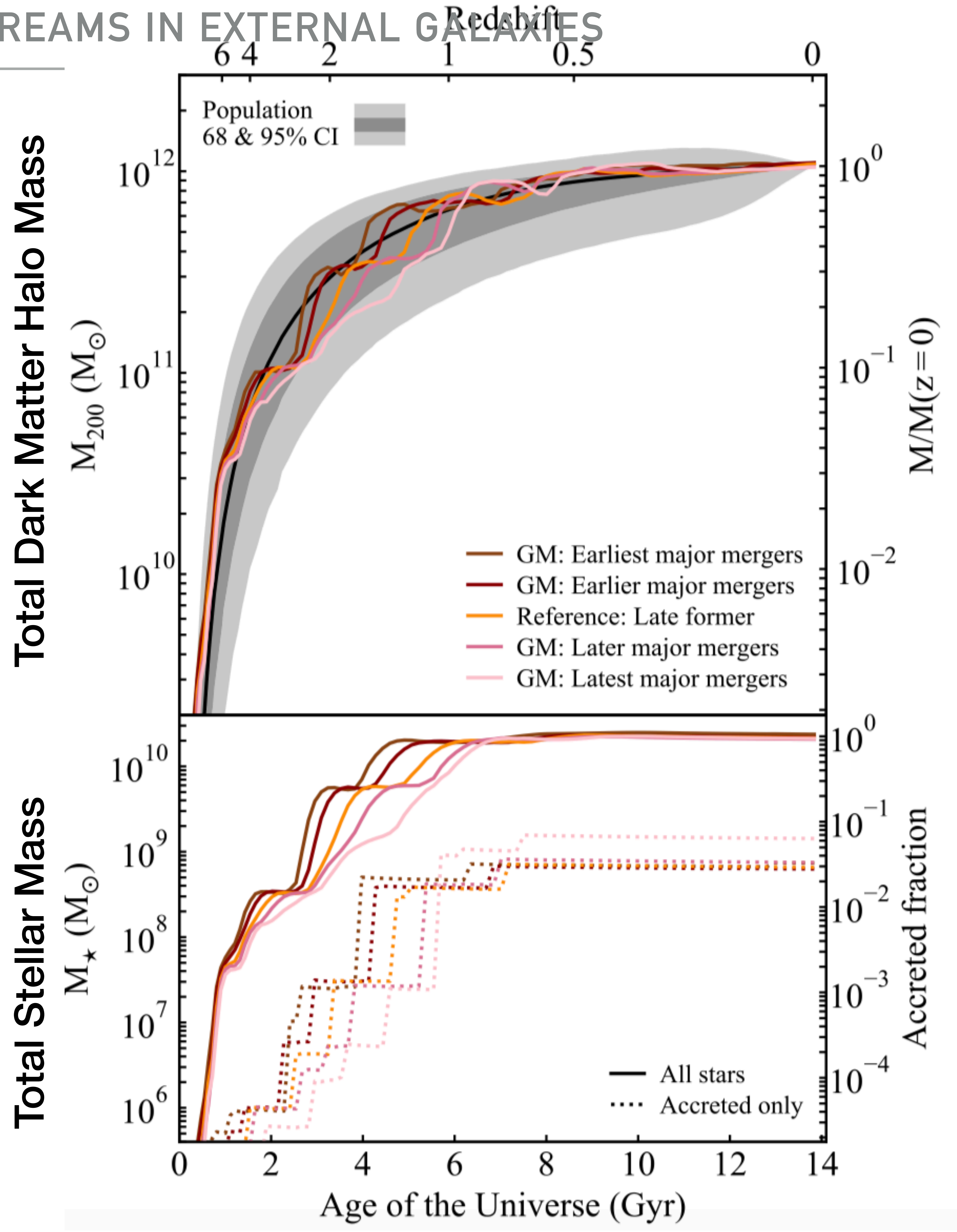

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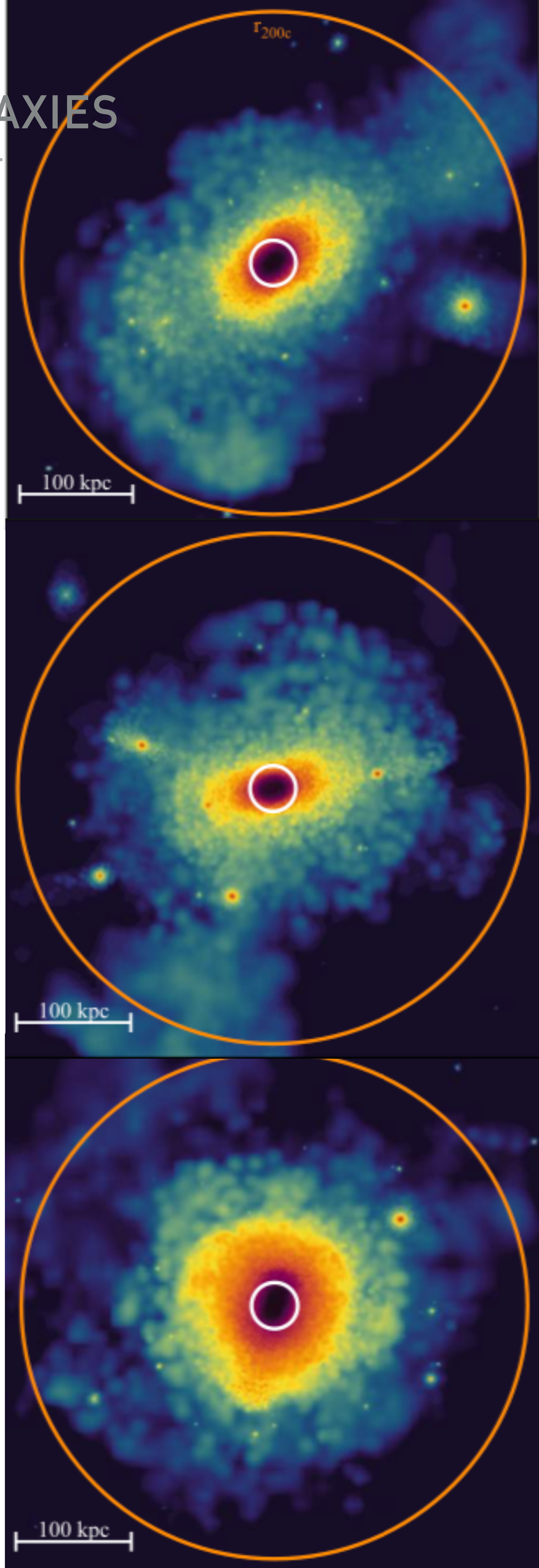
Variant with major mergers at earlier times

Original halo

Variant with major mergers at later times



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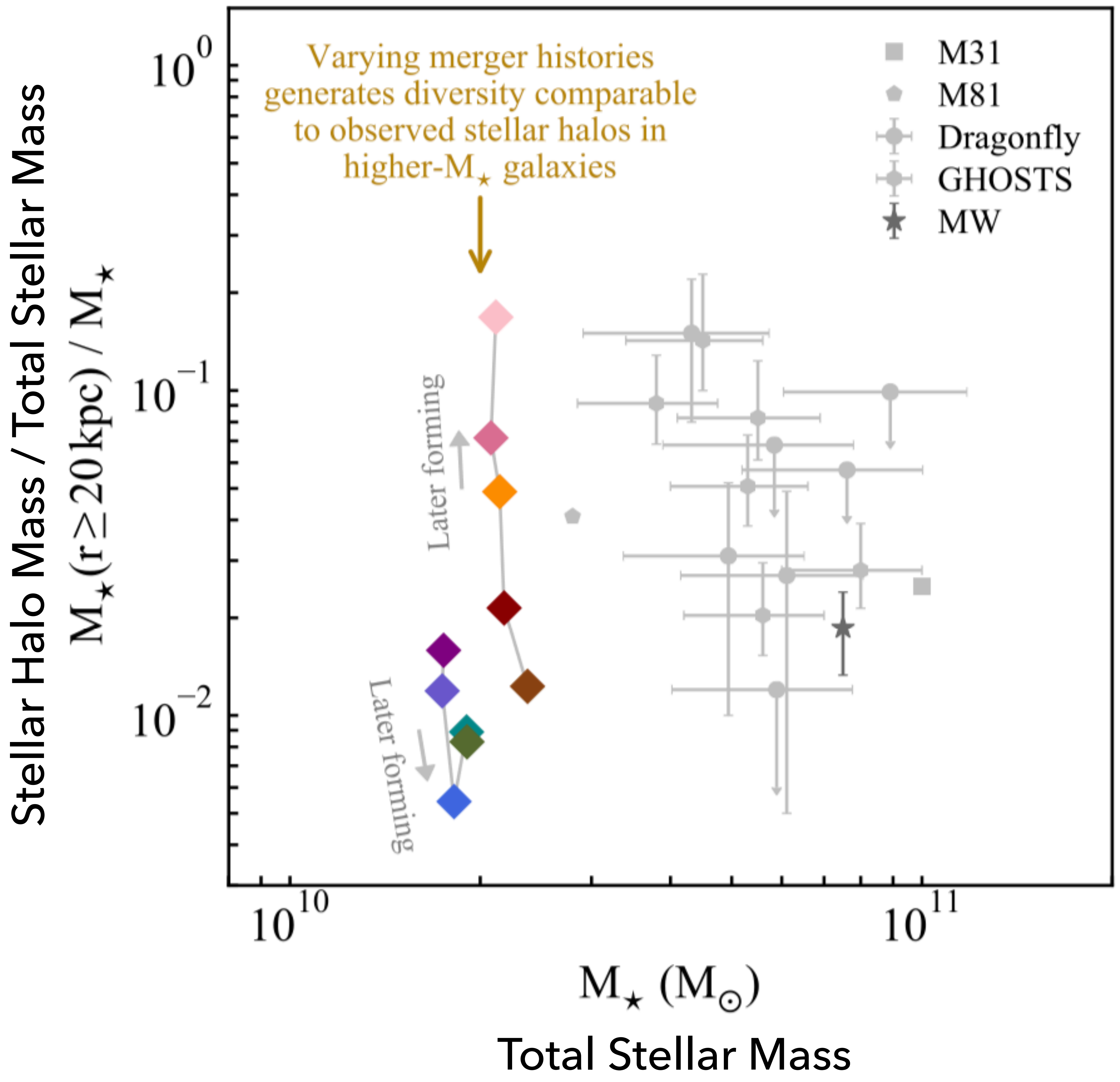
HOW COSMOLOGICAL MERGER HISTORIES SHAPE THE DIVERSITY OF STELLAR HALOS

- Observing stellar halos is extremely challenging but there are now results for nearby MW-like disk galaxies (Monachesi et al. 2016; Merritt et al. 2016; Courteau et al. 2011; Season et al. 2019; Smercina et al. 2020)
- Observationally there is a huge diversity in stellar halo masses at fixed total stellar mass (~1.5dex)
- Just small variations in two sets of merger histories span almost all of the observed range, mostly caused by late violent mergers than bring in-situ stars out in the halo
- While later forming halos (t_{50}-based) generally are more massive this is not always true, and the whole merger history matters
- There is a dependence of the diversity (spread) on the low-mass end slope of the SMHM relation



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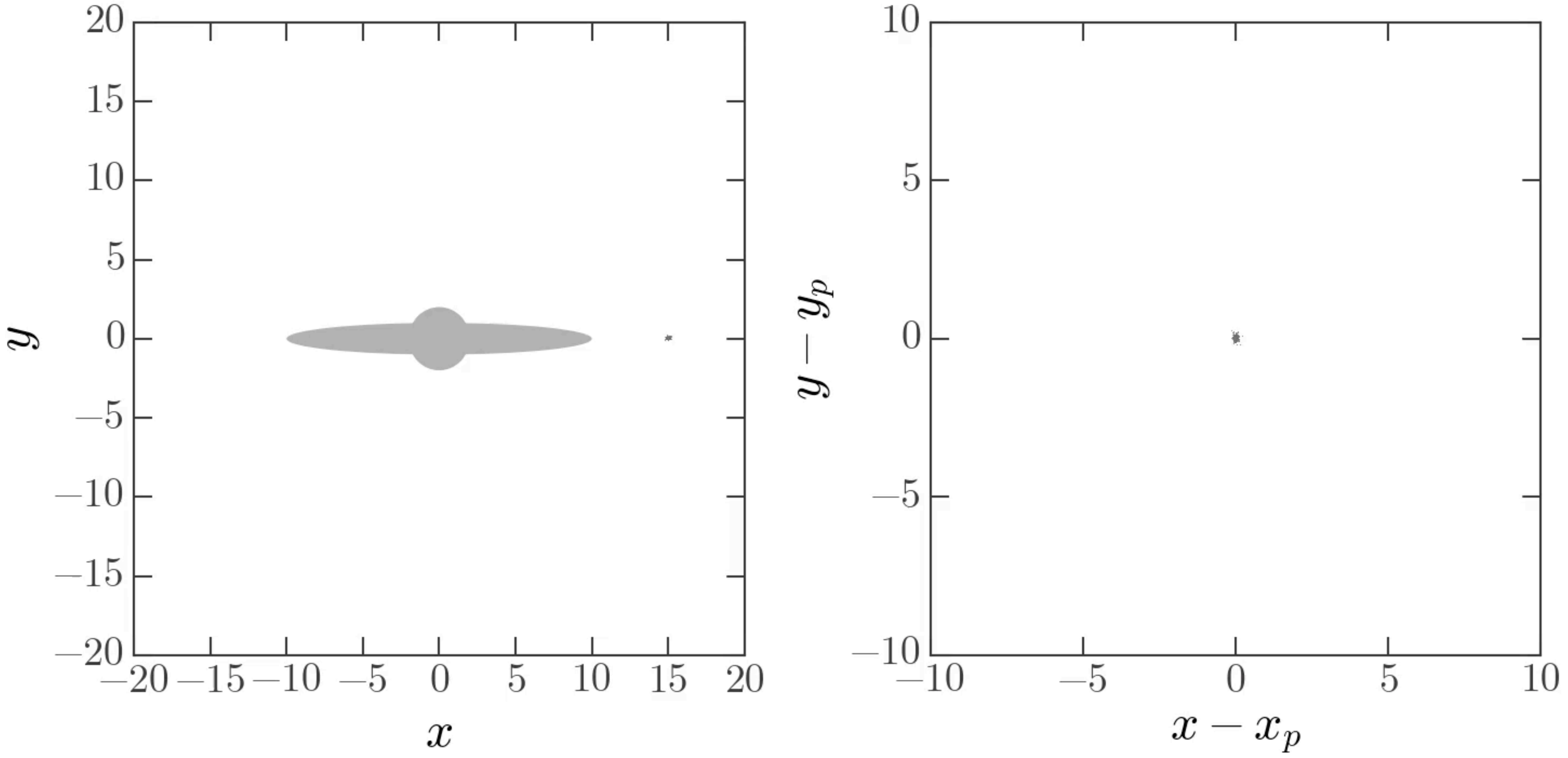
STELLAR HALO SUBSTRUCTURE: TIDAL DEBRIS

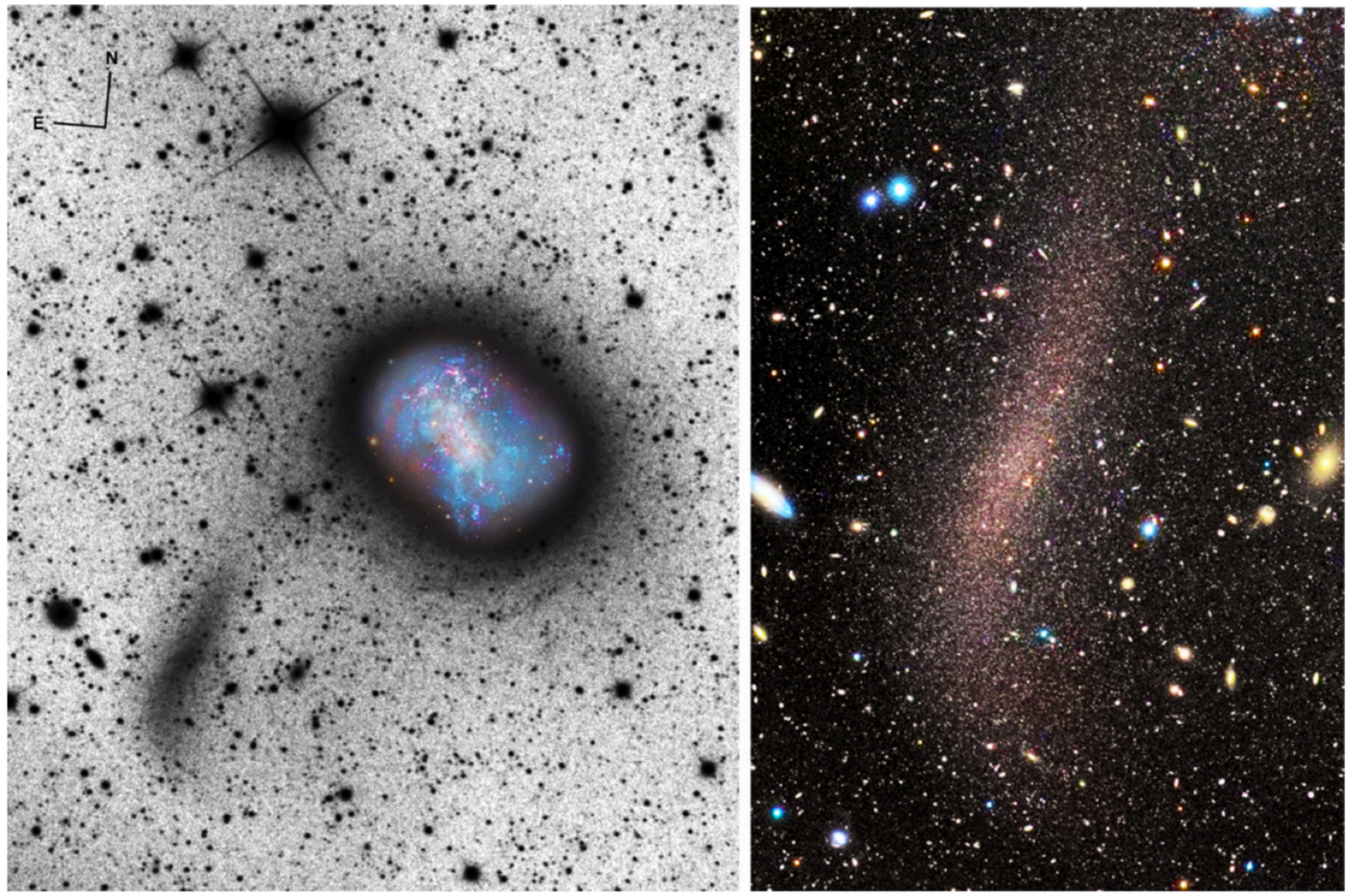
- Accreted dwarf galaxies or globular clusters, get slowly stripped apart in the (larger) galaxy's gravitational tidal field
- The stripped material forms a stellar stream, but depending on the orbit can form shell-like structures as well



Movie by Adrian Price-Whelan

TIDAL DEBRIS AROUND EXTRAGALACTIC DWARF GALAXIES

- Dwarf galaxies are the most ubiquitous galaxies in the universe
- Larger samples are needed to really improve constraints on hierarchical galaxy evolution
- Out of the influence sphere of the Milky Way/Local Group (unlike LMC/SMC)
- Observational examples and ongoing surveys exist (e.g. SAGA *Geha+2017, Mao+2021*, MADCASH *Carlin+2016,2021*, LBT-SONG *Davis+2020, Garling+2021*), and future surveys will open up this discovery space further (Rubin, Roman, Euclid)

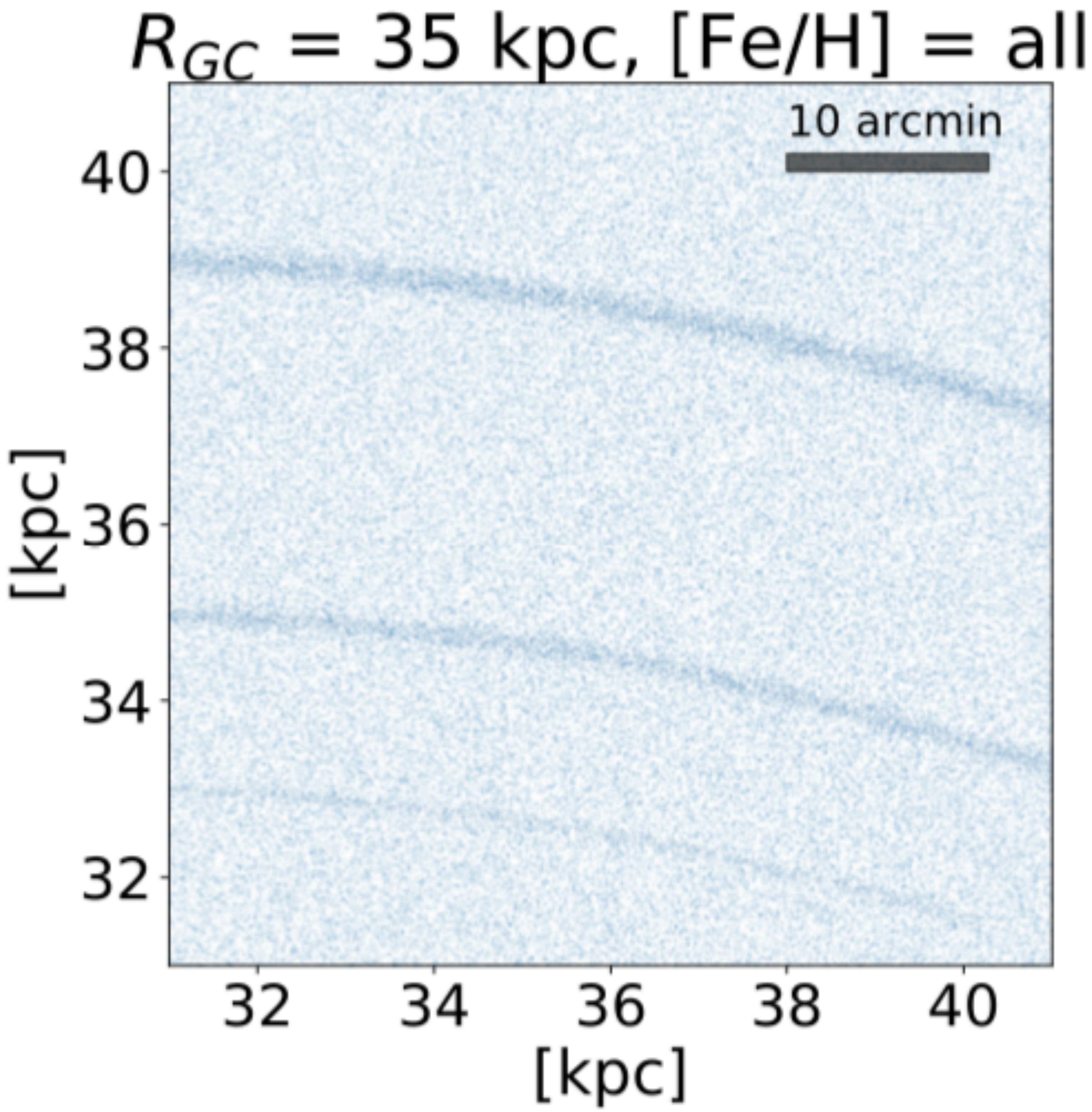


NGC4449; Martinez-Delgado et al. 2010
See also: NGC 2403 and DDO 44;
Carlin et al. 2019; Martinez-Delgado et al. 2021

➡ ***(Statistical) predictions are needed***

EXAMPLE: COLD STREAMS IN EXTERNAL GALAXIES

- Inserting Pal-5-like, and 5x and 10x more massive globular cluster streams in M31 fields
- More massive streams may be found in the PANDAS data
- The Roman Telescope will be able to observe and resolve Pal-5-like streams
- This is true out to 3.5 Mpc, a volume that contains ~200 galaxies, mostly dwarfs
- For perfect star/galaxy separation: 7.8 Mpc and 667



See Sarah's talk (and Pearson+2022) for more!

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

TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

Starkenburg, Pearson et al. in prep.

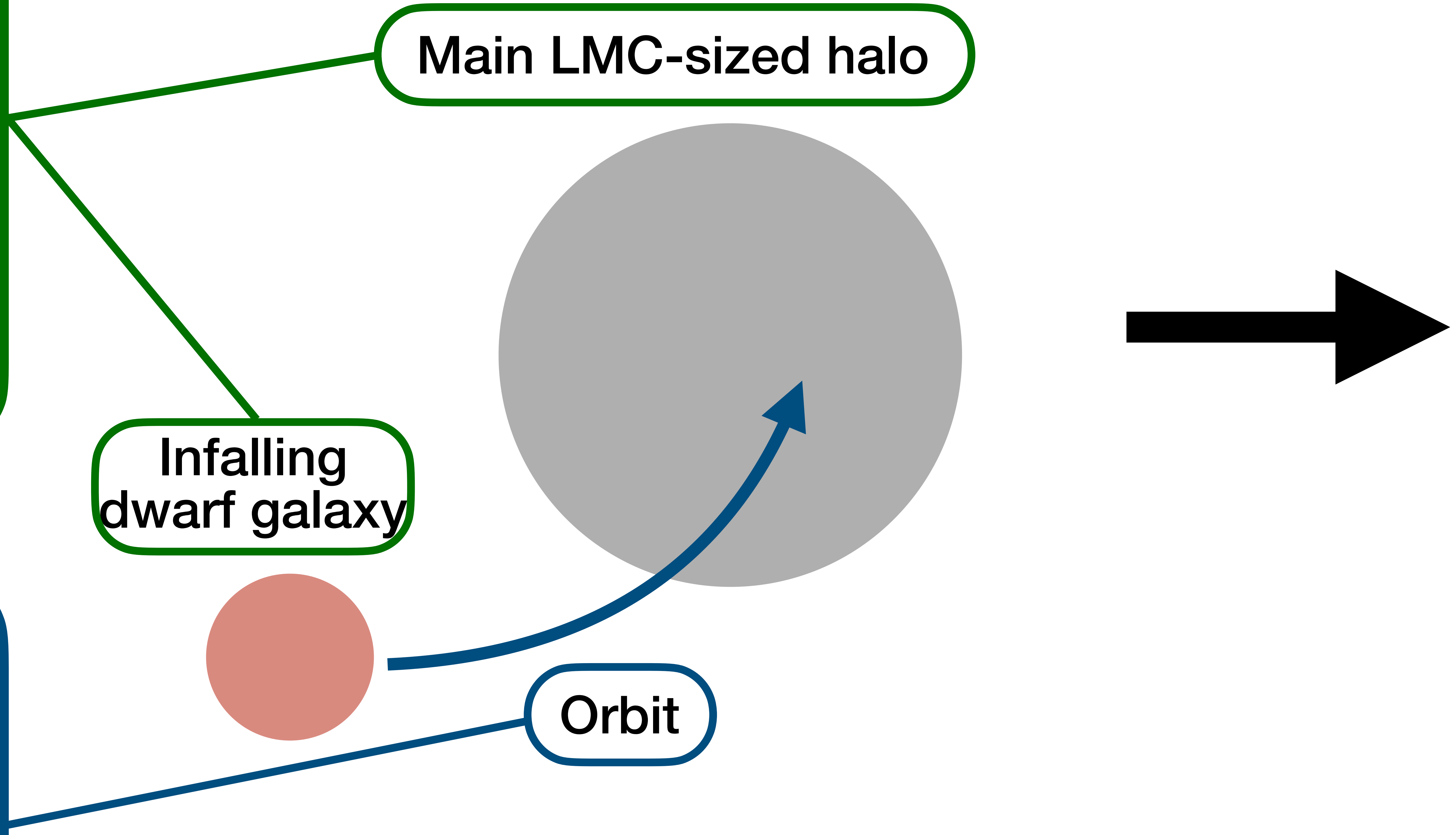
Input from the Santa Cruz Semi-Analytic Model *(Somerville+2008,2012)***:**

- Infall time for all accreted dwarf galaxies
- Evolution of the main halo
- Properties of accreted dwarf galaxies at infall

+

Input from orbit distributions in cosmological N-body simulations *(Wetzel+2011)***:**

- Sample pericenter radii and orbital circularity of satellites at infall



TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

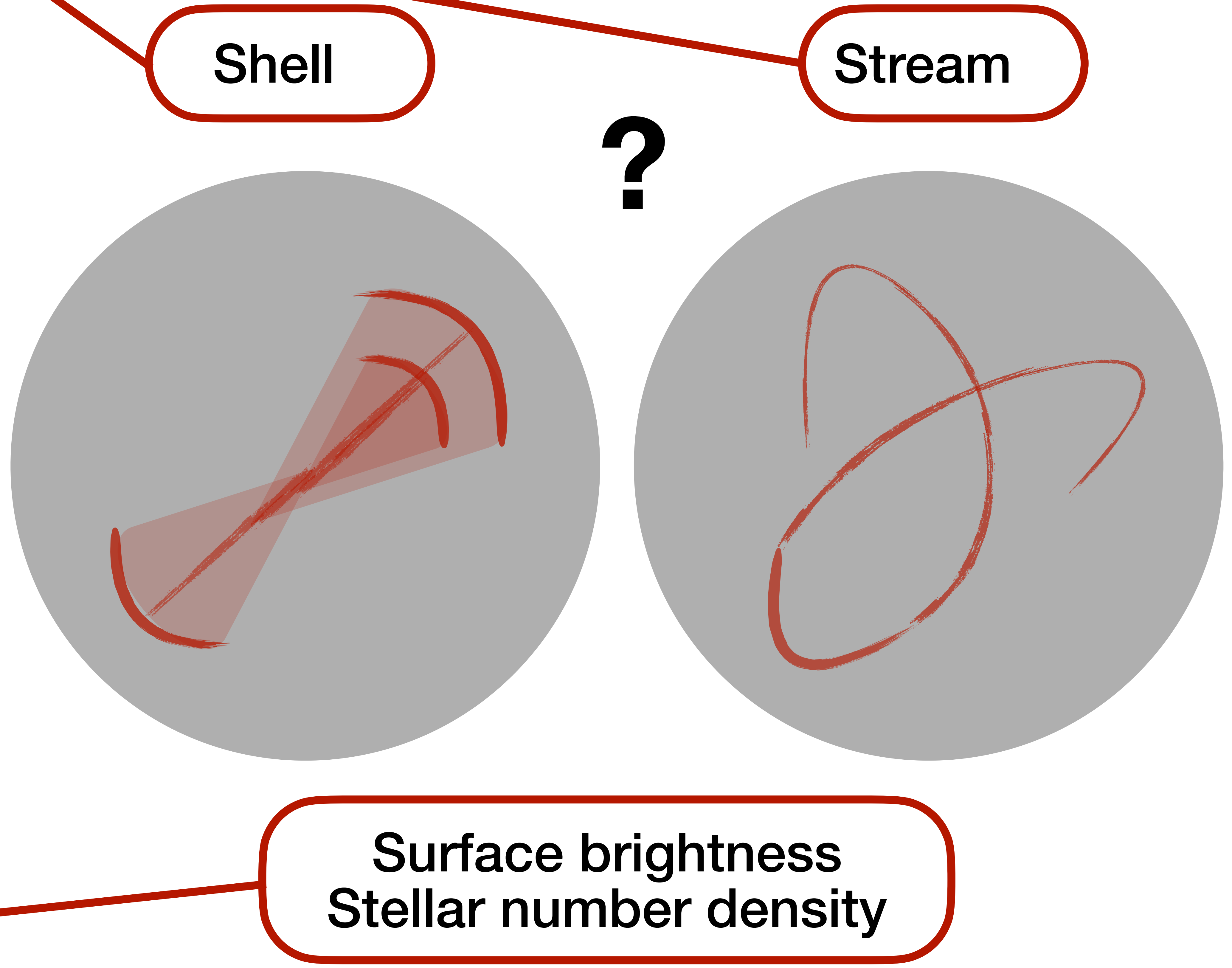
Starkenburg, Pearson et al. in prep.

Predict debris Morphology and Observability:

- Estimate dark matter halo stripping timescale
- Estimate lifetime of the tidal debris until phase-mixed

- **Predict debris morphology for each subsequent orbit**
- **Predict surface brightness and stellar density**

(Johnston 2001; Hendel & Johnston 2015; Sanderson & Helmi 2013)



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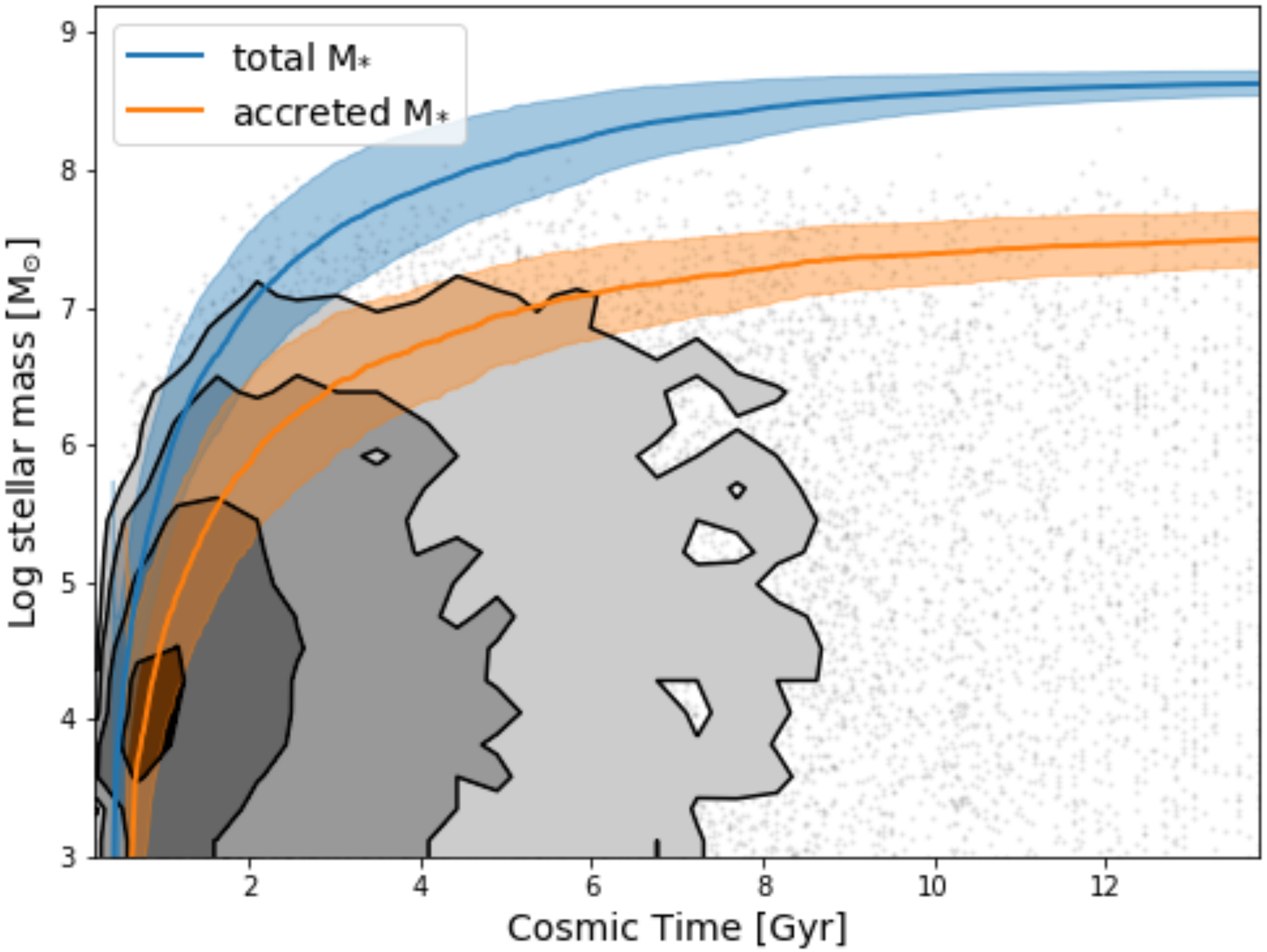


- Generate accretion histories for *many* isolated LMC-sized halos

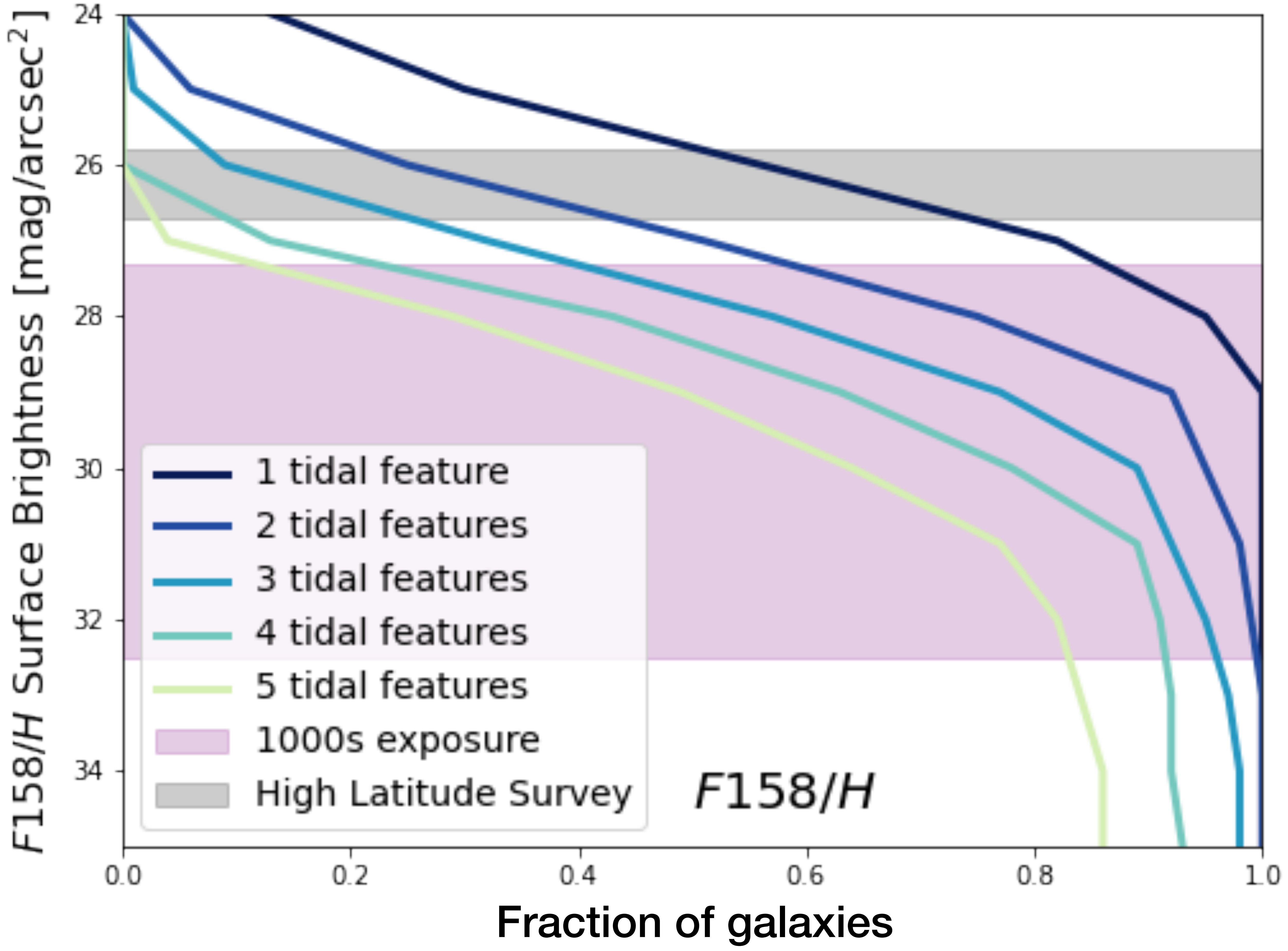
- Use our (arbitrarily) large sample size to provide robust predictions and test the effects of assumptions and input parameters

  - 9% accreted mass fractions, but skewed to lower fractions

  - 4% when excluding major mergers (DM mass ratio > 0.3)

TIDAL DEBRIS AROUND NEARBY GALAXIES

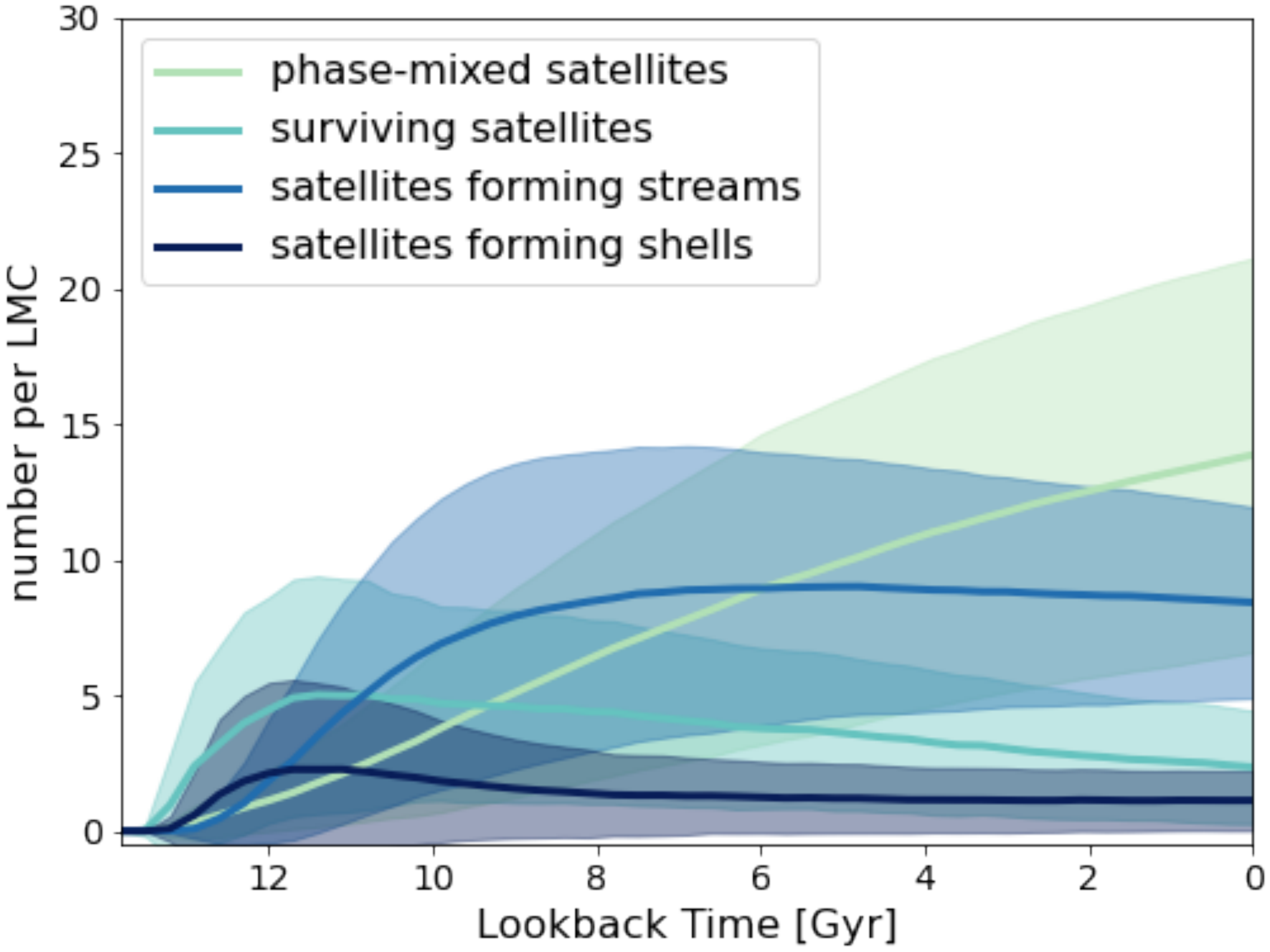
Starkenburg, Pearson et al. in prep.

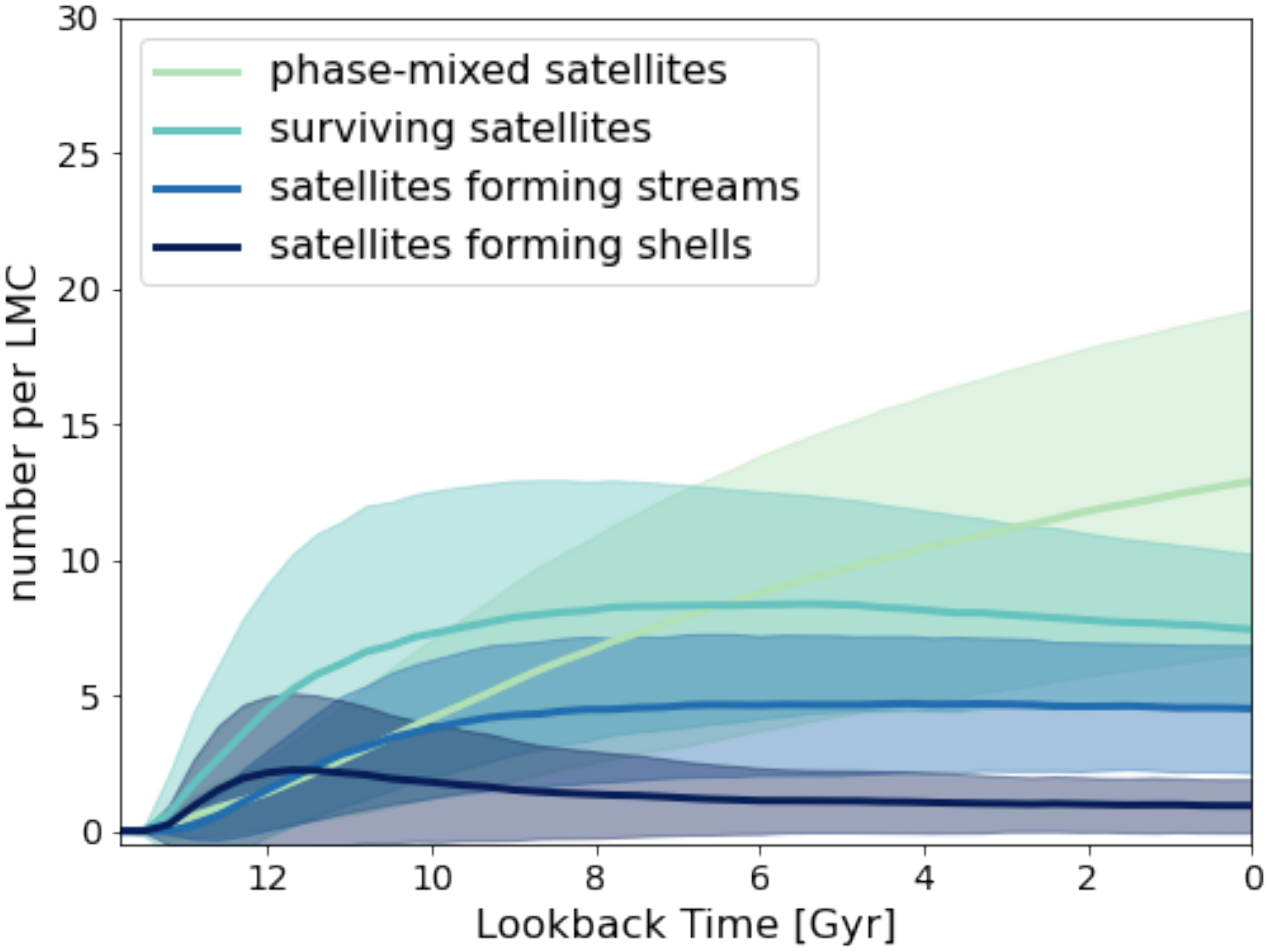


- Generate accretion histories for *many* isolated halos
- Use our (arbitrarily) large sample size to provide robust predictions and test the effects of models, assumptions and input parameters
  - Nearby galaxies will have visible tidal features (streams) for Roman observations depending on observing depth and band (for Rubin too)
  - Number of observable structures depends on modeling parameters, and will thus provide novel constraints for models

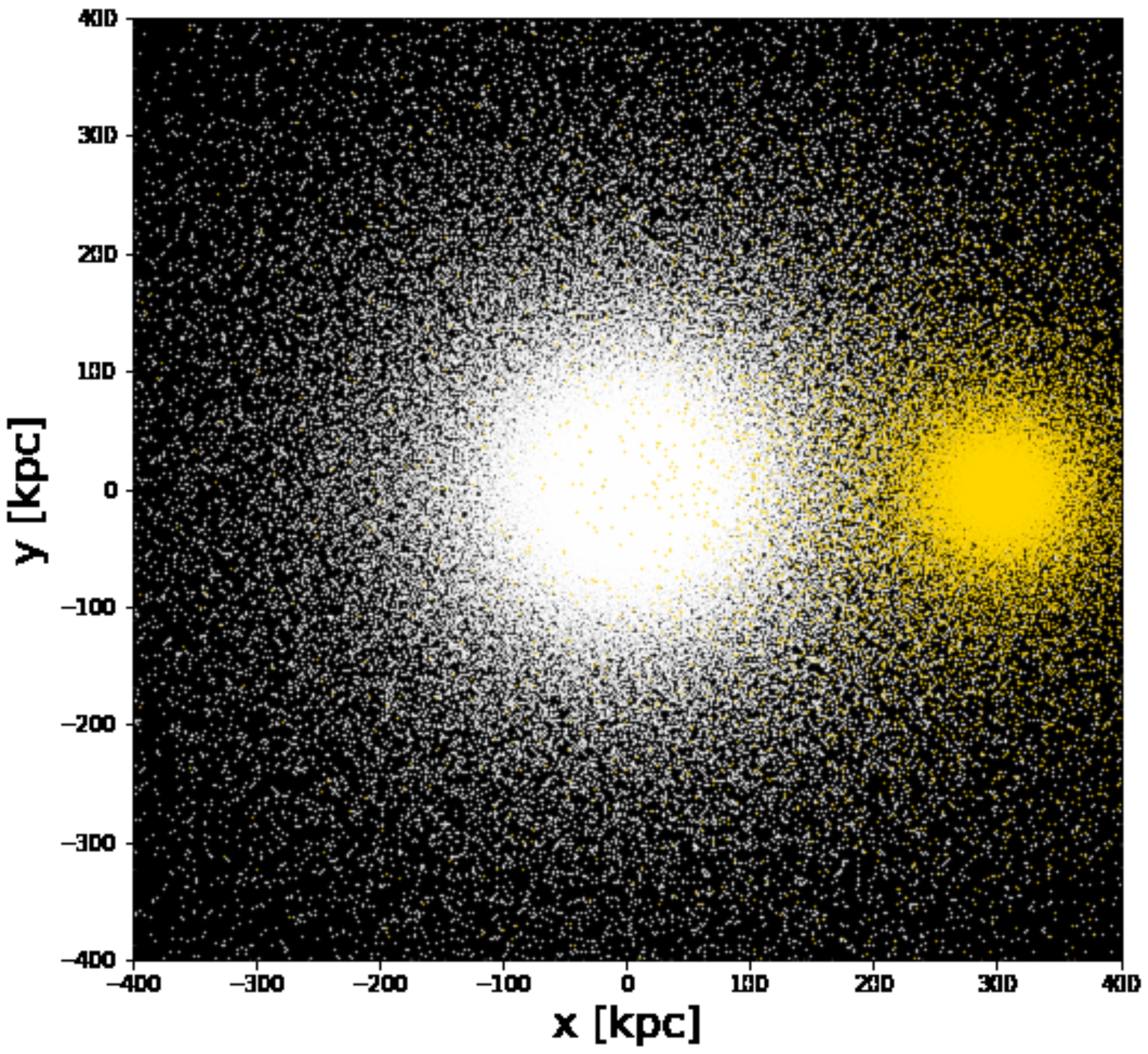
TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

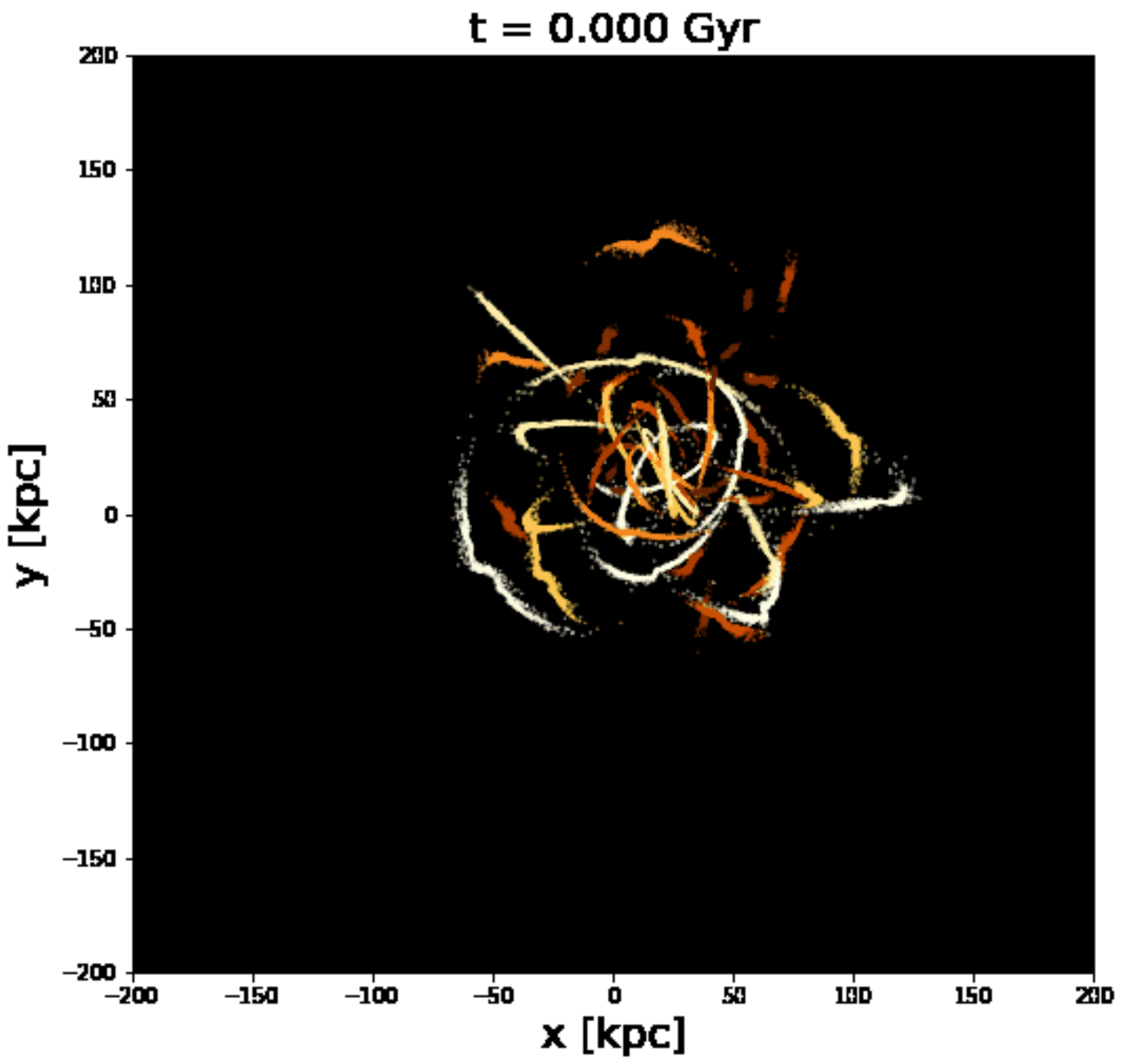
Starkenburg, Pearson et al. in prep.





GLOBULAR STELLAR STREAM EVOLUTION DURING MERGERS





Work by Sachithra (Sachi) Weerasooriya, grad student at TCU

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

CONCLUSIONS

- Stellar halo masses and density profiles are affected by the *full* details of their merger histories as well as low-mass galaxy formation, and can provide constraints on these
  (Rey & Starkenburg 2022)

- Many nearby galaxies (including dwarfs!) will have observable stellar streams and satellites in their halo, and statistics on these can provide novel constraints on galaxy formation models
  (Starkenburg, Pearson et al. in prep.)

- With upcoming facilities (Roman, Rubin) we will start to resolve stellar streams in nearby galaxies
  (Pearson, Starkenburg et al. 2019)

- Including globular clusters and disrupted clusters/stellar streams in both these approaches will provide additional constraints on both the galaxy and cluster sides

- Existing structure in stellar halos (globular cluster stellar streams!) are significantly affected by subsequent mergers
  (Weerasooriya, Starkenburg et al. in prep.)