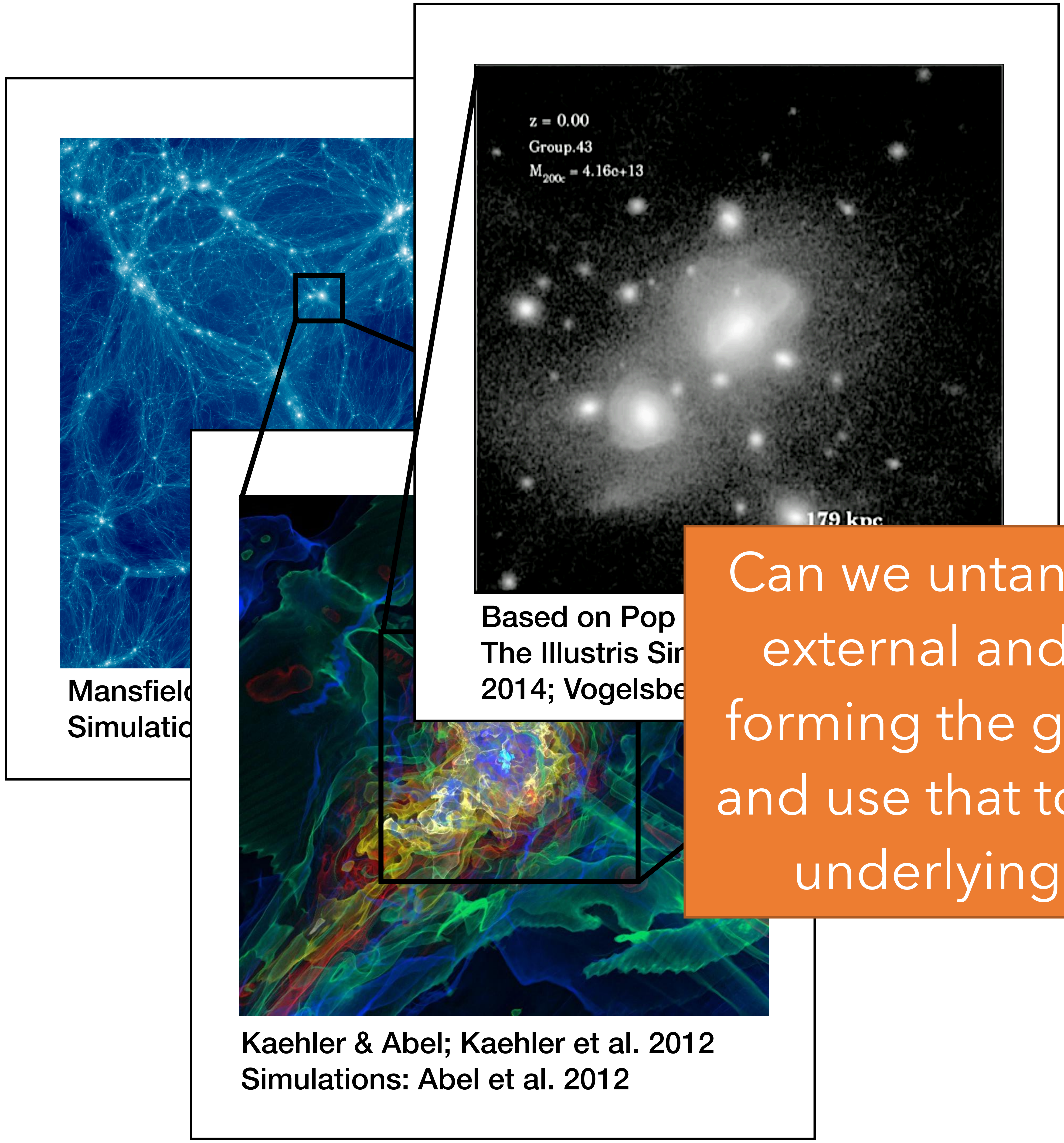
Figure from Martin+2022 (incl. TS): Synthetic Rubin images

Galaxy formation histories and the tidal debris in their stellar halos

Tjitske Starkenburg
CIERA, Northwestern University

In collaboration with:
Martin Rey (Oxford), Sarah Pearson (NYU),
Kathryn Johnston (Columbia), Rachel Somerville (Rutgers/CCA),
Christian Aganze (UCSD), Sachi Weerasooriya (TCU)

GALAXY EVOLUTION: EXTERNAL AND INTERNAL PHYSICAL PROCESSES



Mansfield
Simulatio

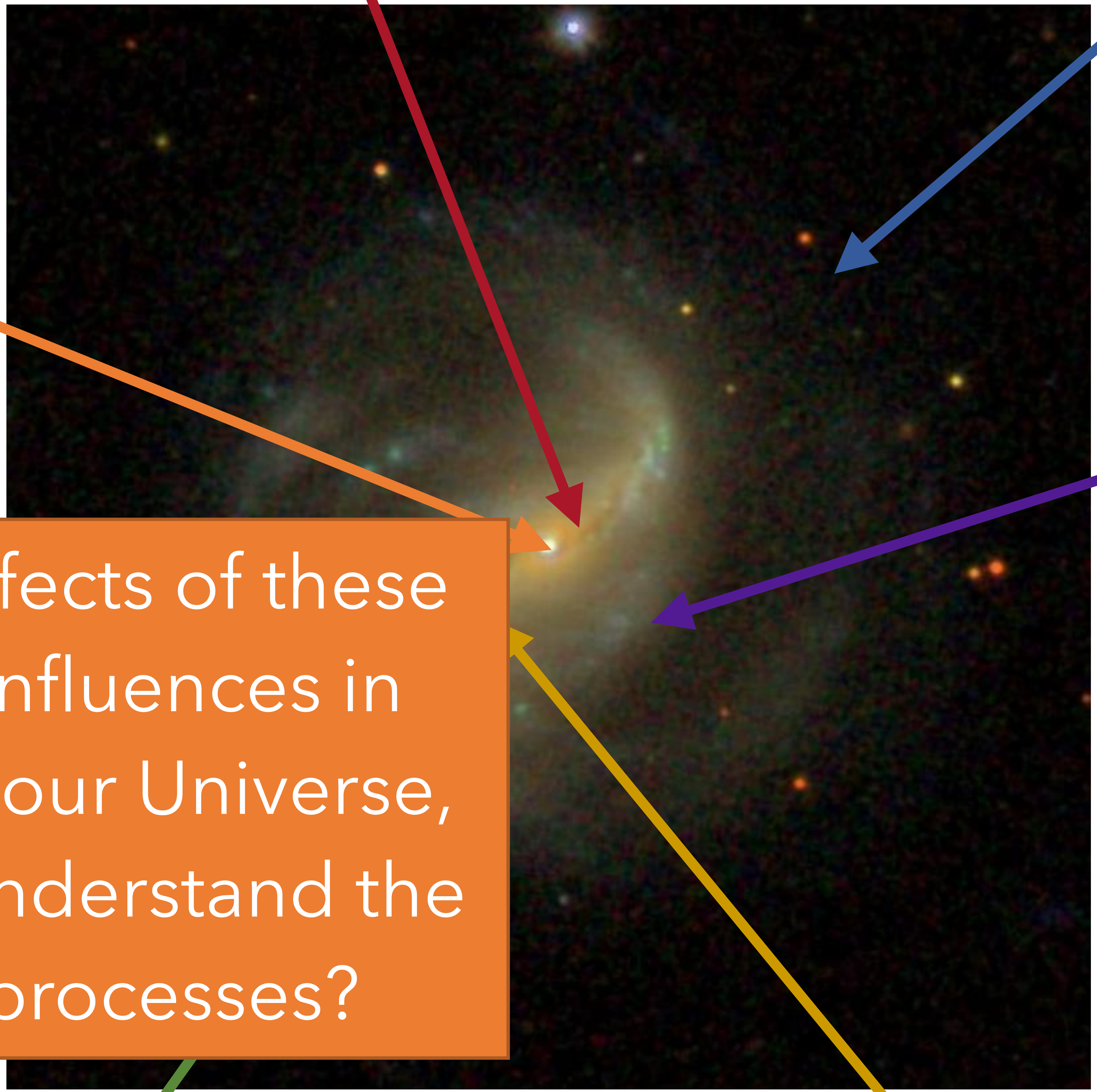
Based on Pop
The Illustris Sir
2014; Vogelsbe

Kaehler & Abel; Kaehler et al. 2012
Simulations: Abel et al. 2012

A quenching of star formation, locally or globally

Gas accretion, cooling and heating, inflows and outflows

Super-massive black hole formation.



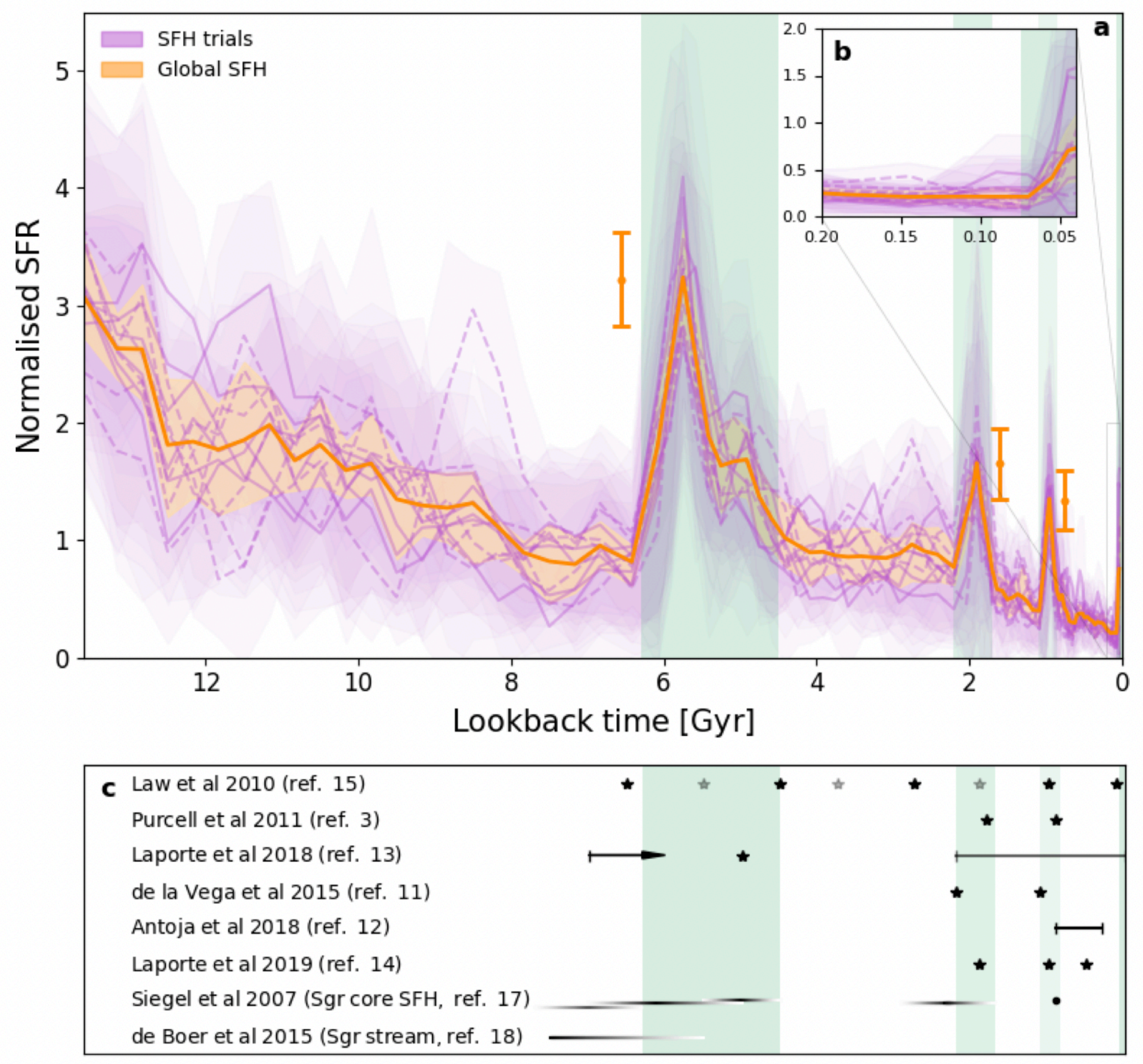
Small-scale physical and chemical processes involving gas, dust and radiation.

Can we untangle the effects of these external and internal influences in forming the galaxies in our Universe, and use that to better understand the underlying physical processes?

Star formation, stellar evolution, and feedback, e.g. stellar winds and supernovae

“Secondary” internal dynamical processes involving disks, bars, and bulges

GALAXY EVOLUTION: EXTERNAL AND INTERNAL PHYSICAL PROCESSES



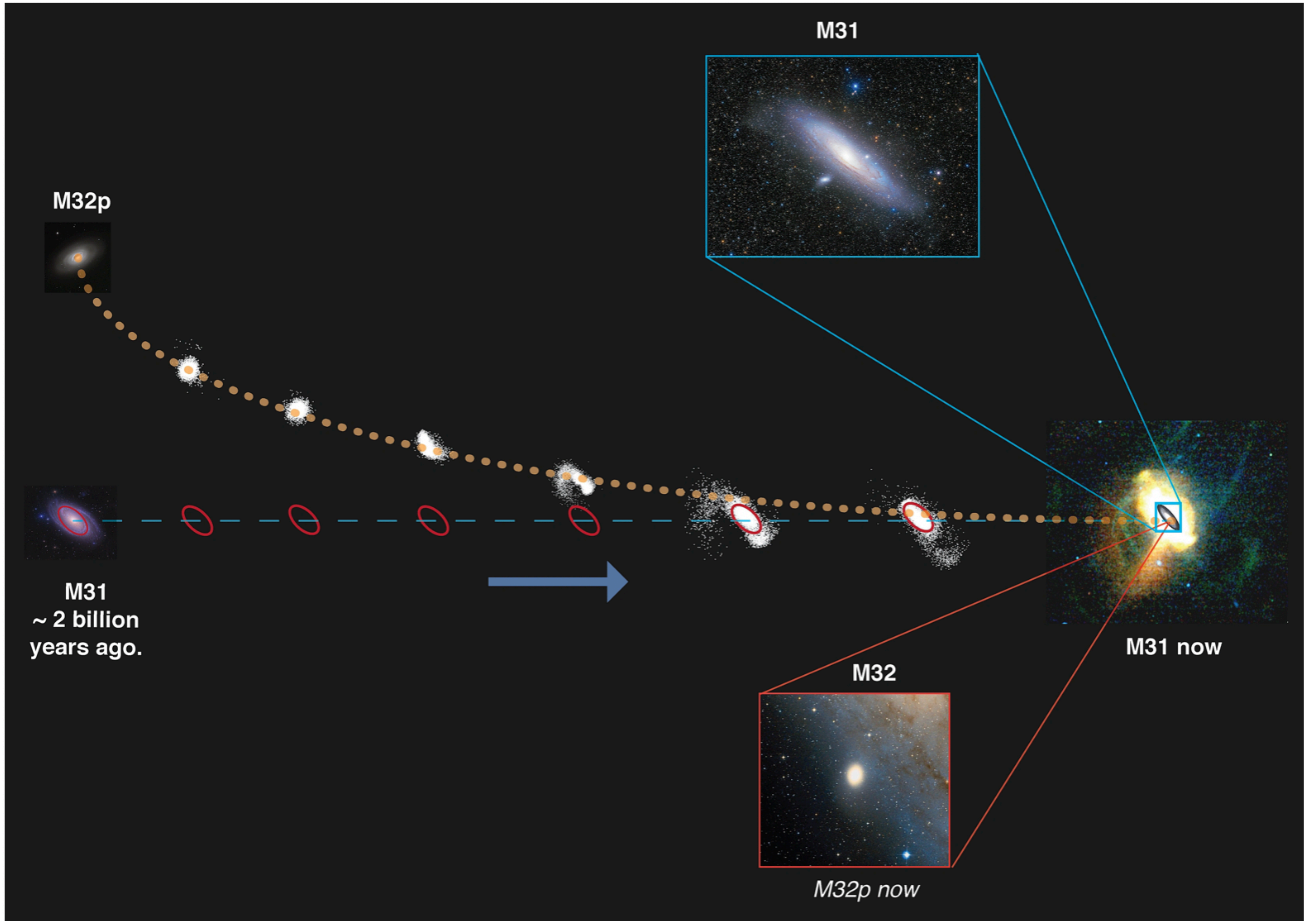
Milky Way

Ruiz-Lara et al. 2020:

star formation enhancements in the MW disk coinciding with Sagittarius pericenter passages

Possible connections to MW internal dynamics (e.g. phase-space spiral; Antoja+2018, Darragh-Ford+2023 and many more) and chemistry (e.g. Spitoni+2023)

GALAXY EVOLUTION: EXTERNAL AND INTERNAL PHYSICAL PROCESSES



M31

D'Souza & Bell (2018): likely experienced a significant merger ~2 Gyr ago

- M31's massive, relatively metal-rich stellar halo
- The giant stellar stream
- Its rotating inner stellar halo
- Compact, metal-rich satellite M32
- M31's global burst of star formation ~2 Gyr ago

Kinematics from DESI seems to agree (Dey+2023)

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 …)

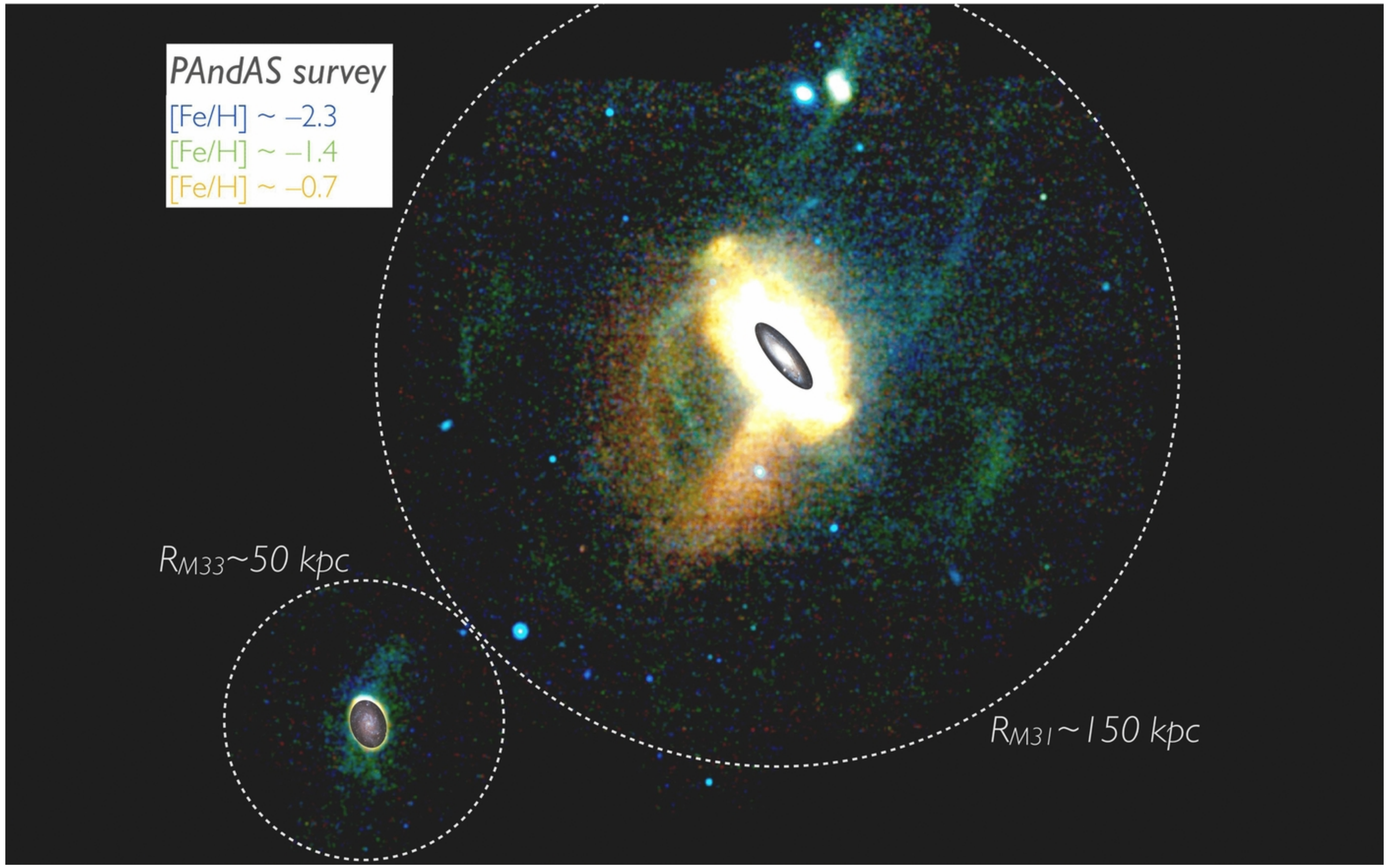


Figure from Martin+2013

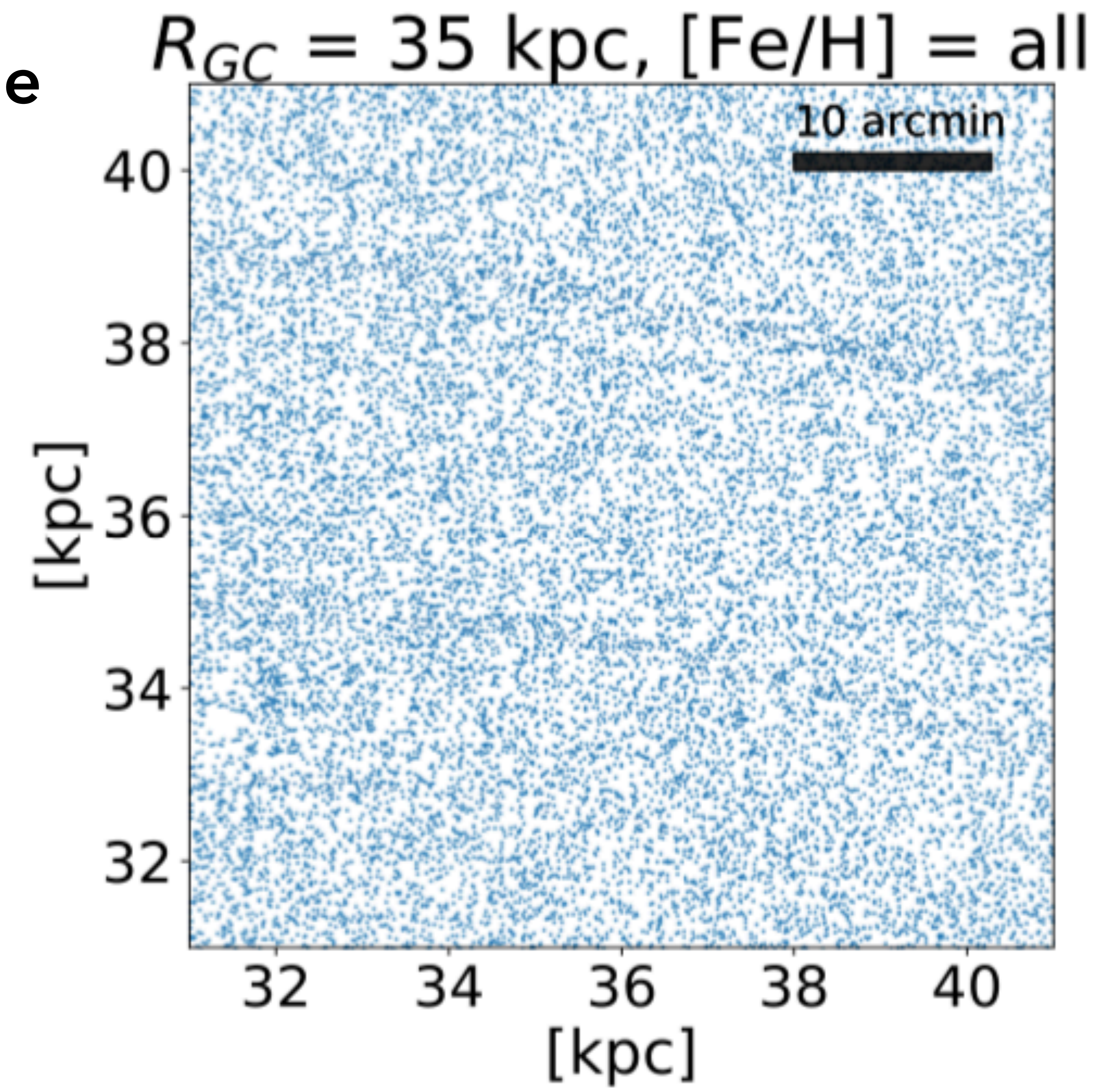
- Now: SAGA (Geha+2017, Mao+2021), Elves (Carlsten+2022), Stellar Streams Legacy Survey (Martinez-Delgado+2021), LIGHTS (Trujillo+2021), MADCASH (Carlin+2016,2021), LBT-SONG (Davis+2020, Garling+2021), Dwarfs gobbling dwarfs (Martinez-Delgado+2021)
- Coming: **A low-surface brightness discovery space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

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.

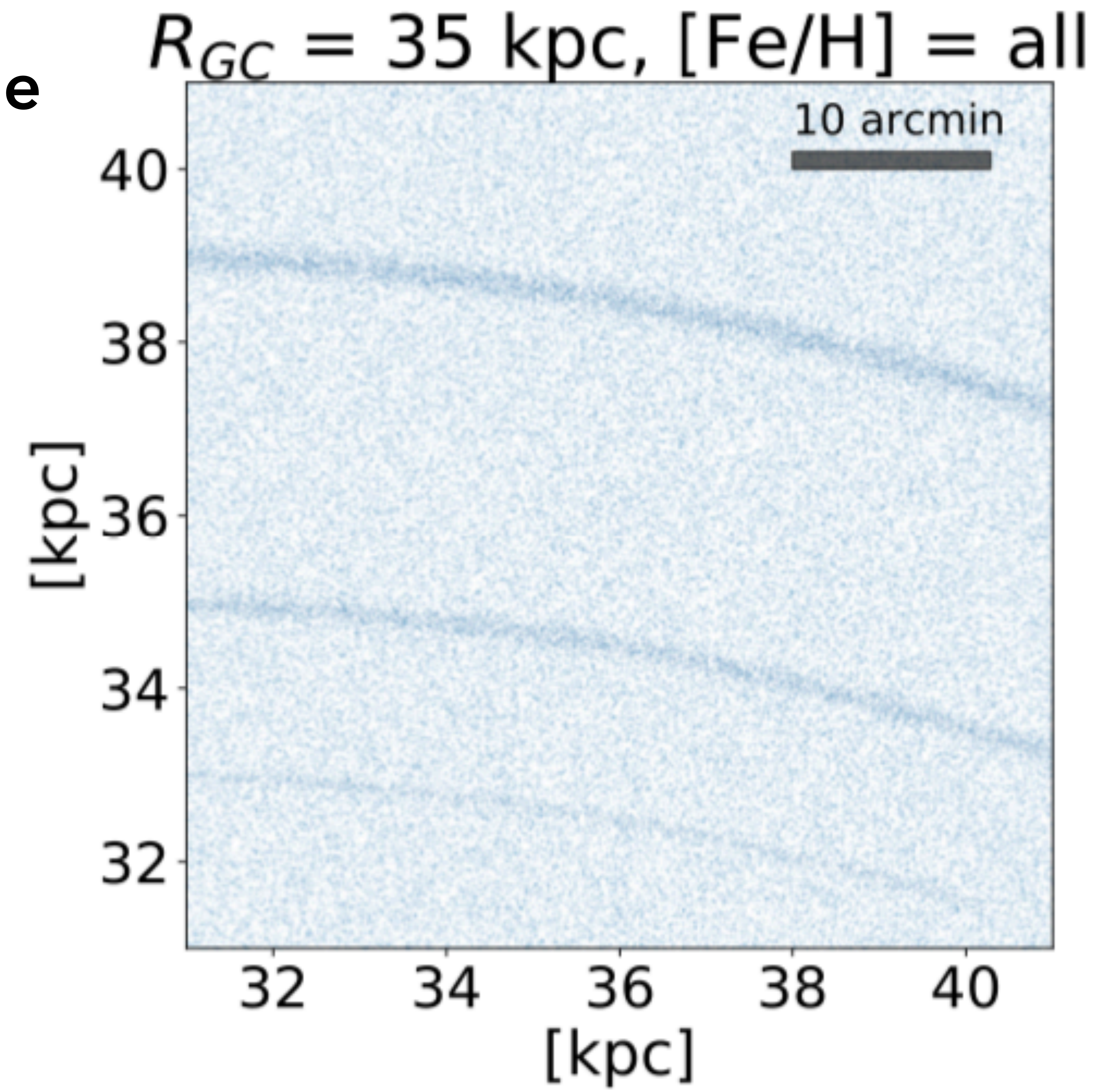
THIN STREAMS IN EXTERNAL GALAXIES WITH ROMAN

- **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

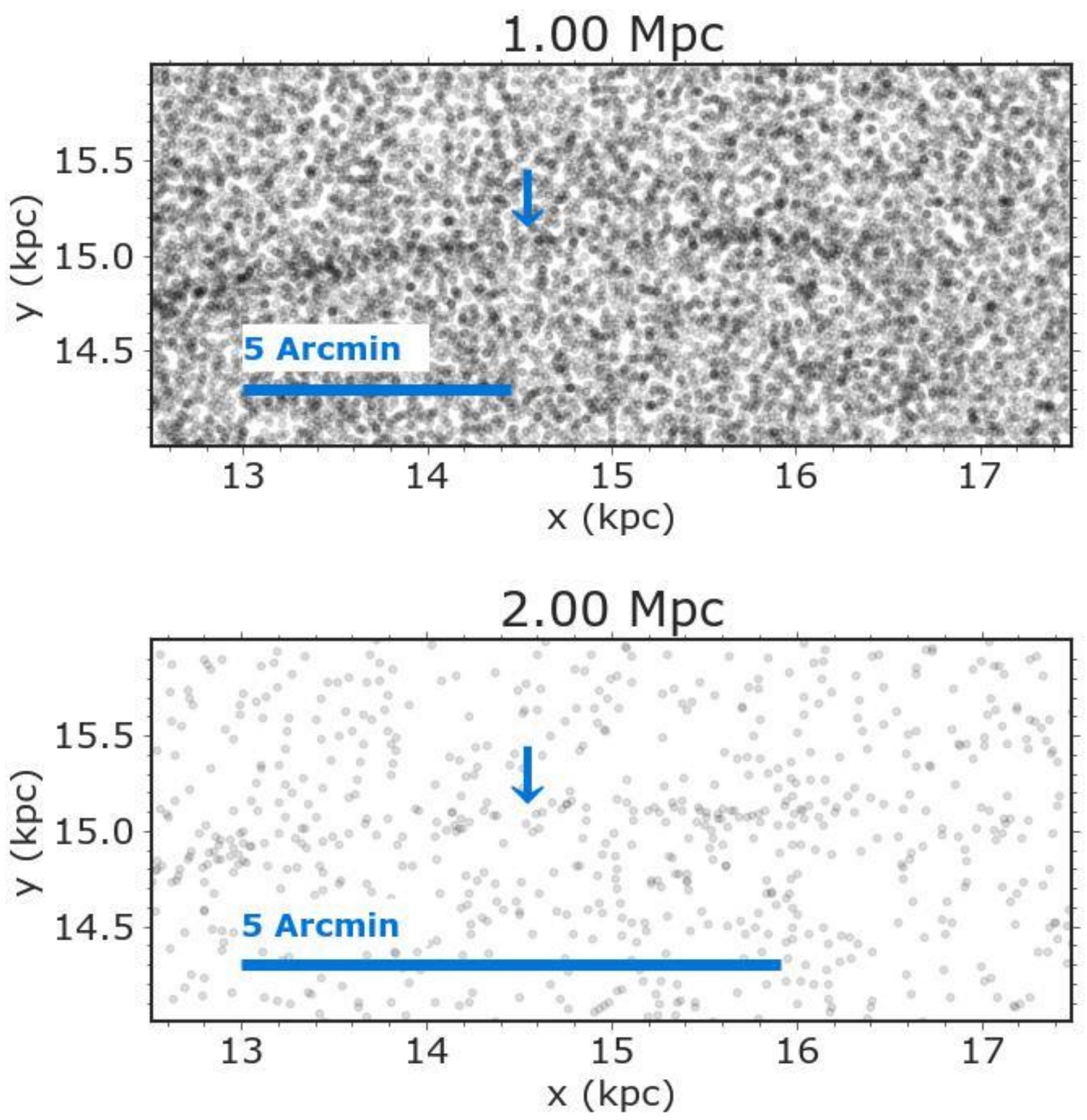
- This is true out to 3.5 Mpc, a volume that contains ~200, mostly lower-mass galaxies



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

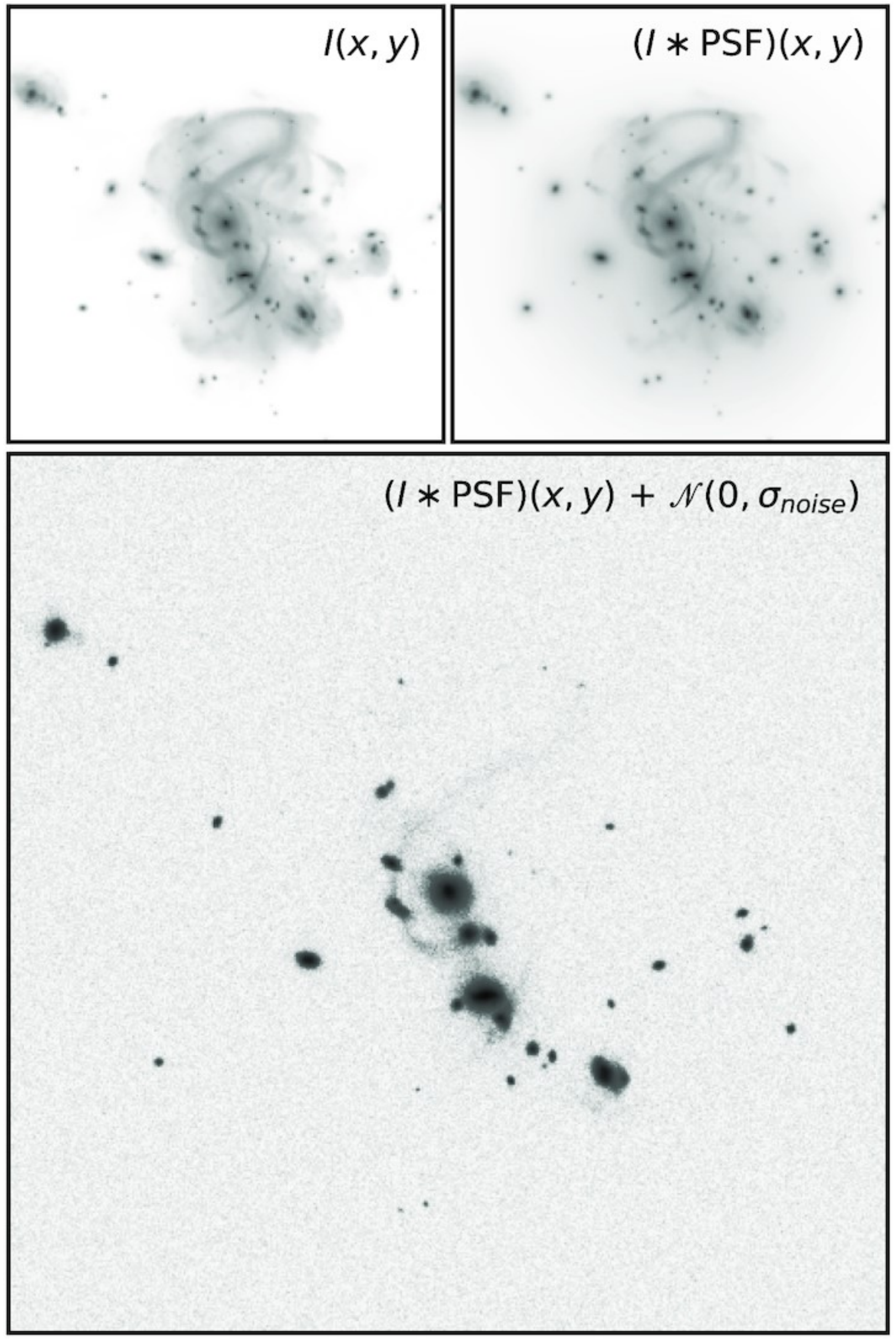
THIN STREAMS IN EXTERNAL GALAXIES WITH ROMAN

- **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

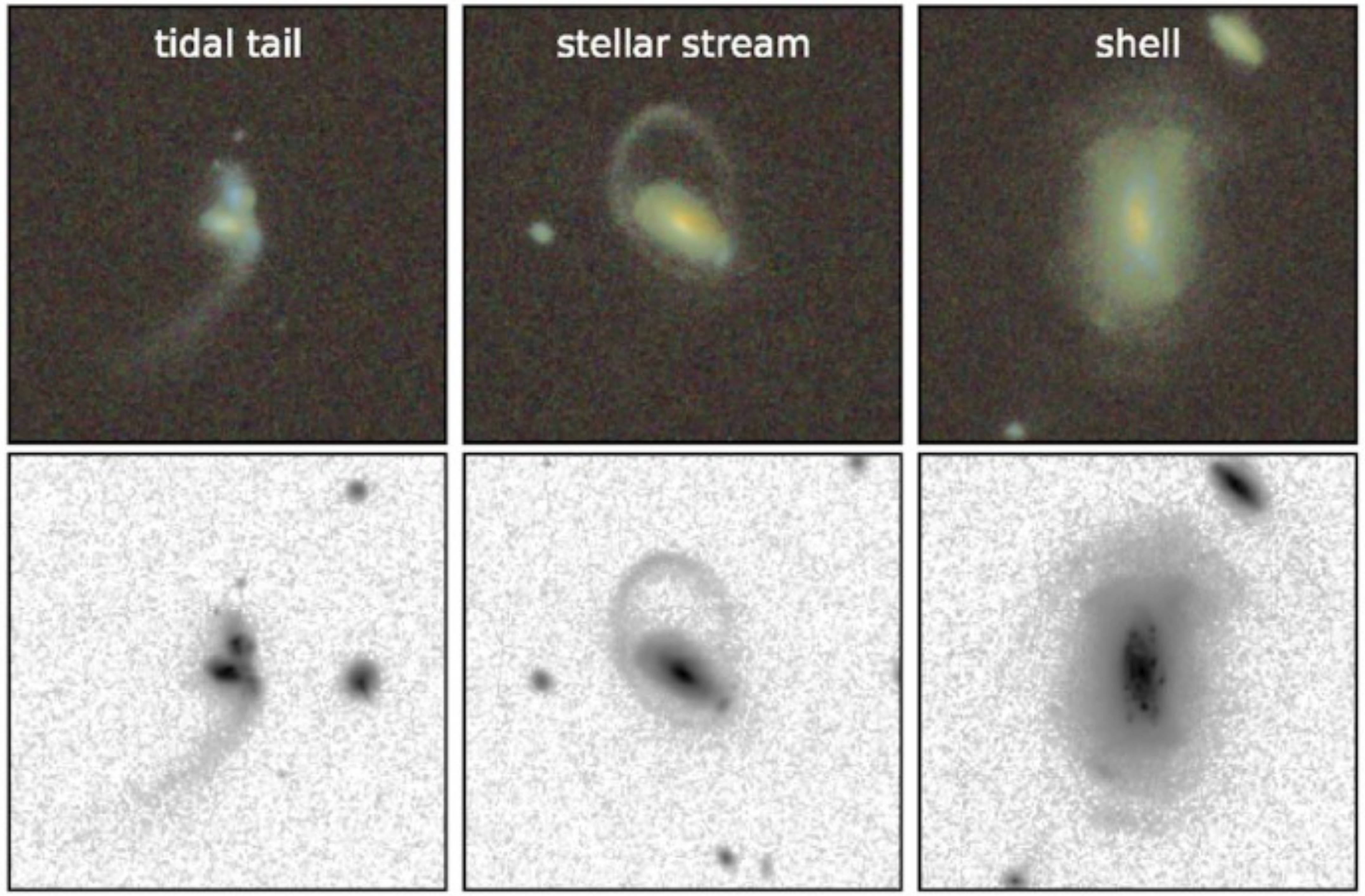


Aganze, Pearson, TS+ in prep.
Mock streams and gaps with Roman

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*

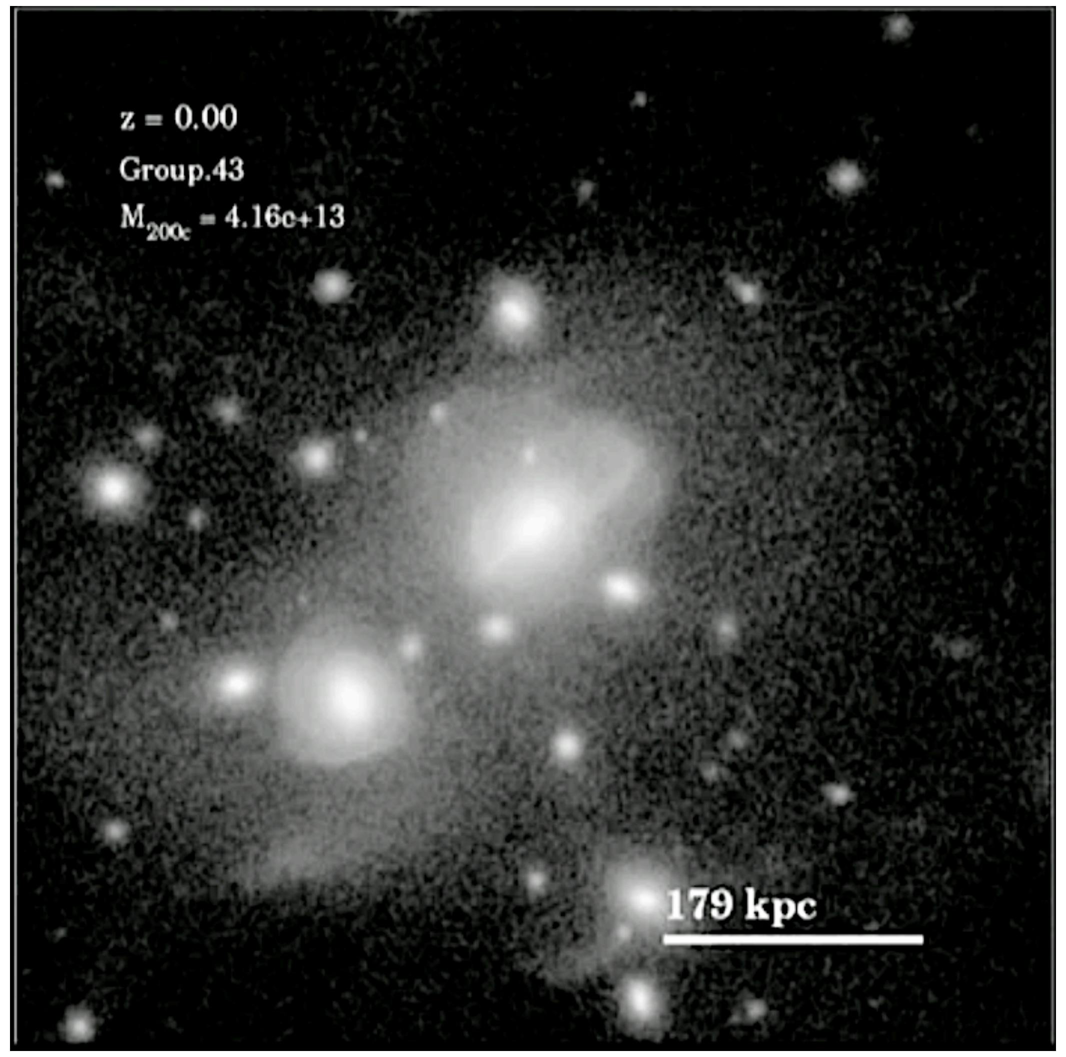
CHALLENGES OF THEORETICAL PREDICTIONS

Cosmological,
large # of galaxies,
low resolution

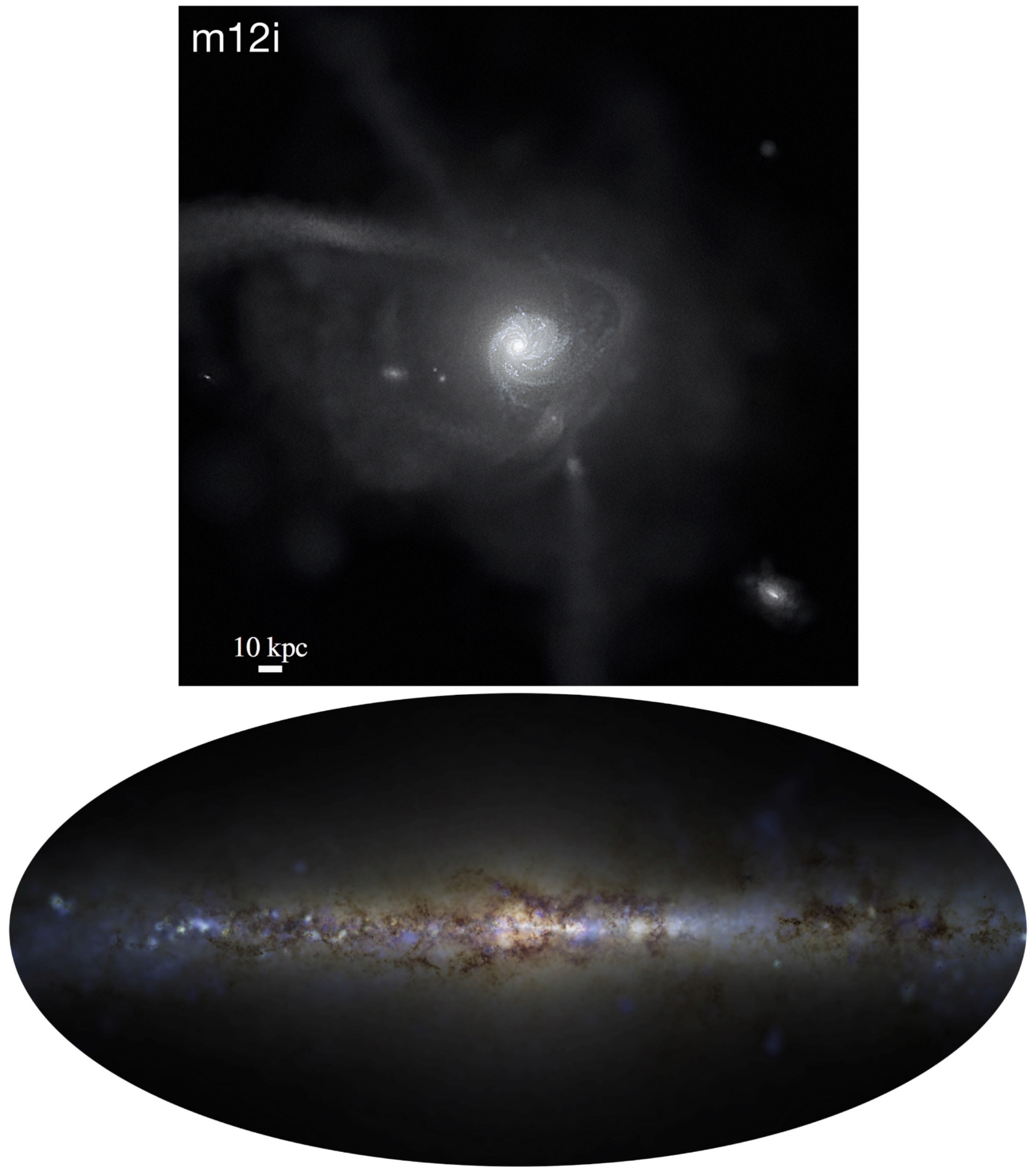
Cosmological,
Few galaxies,
Higher resolution

?

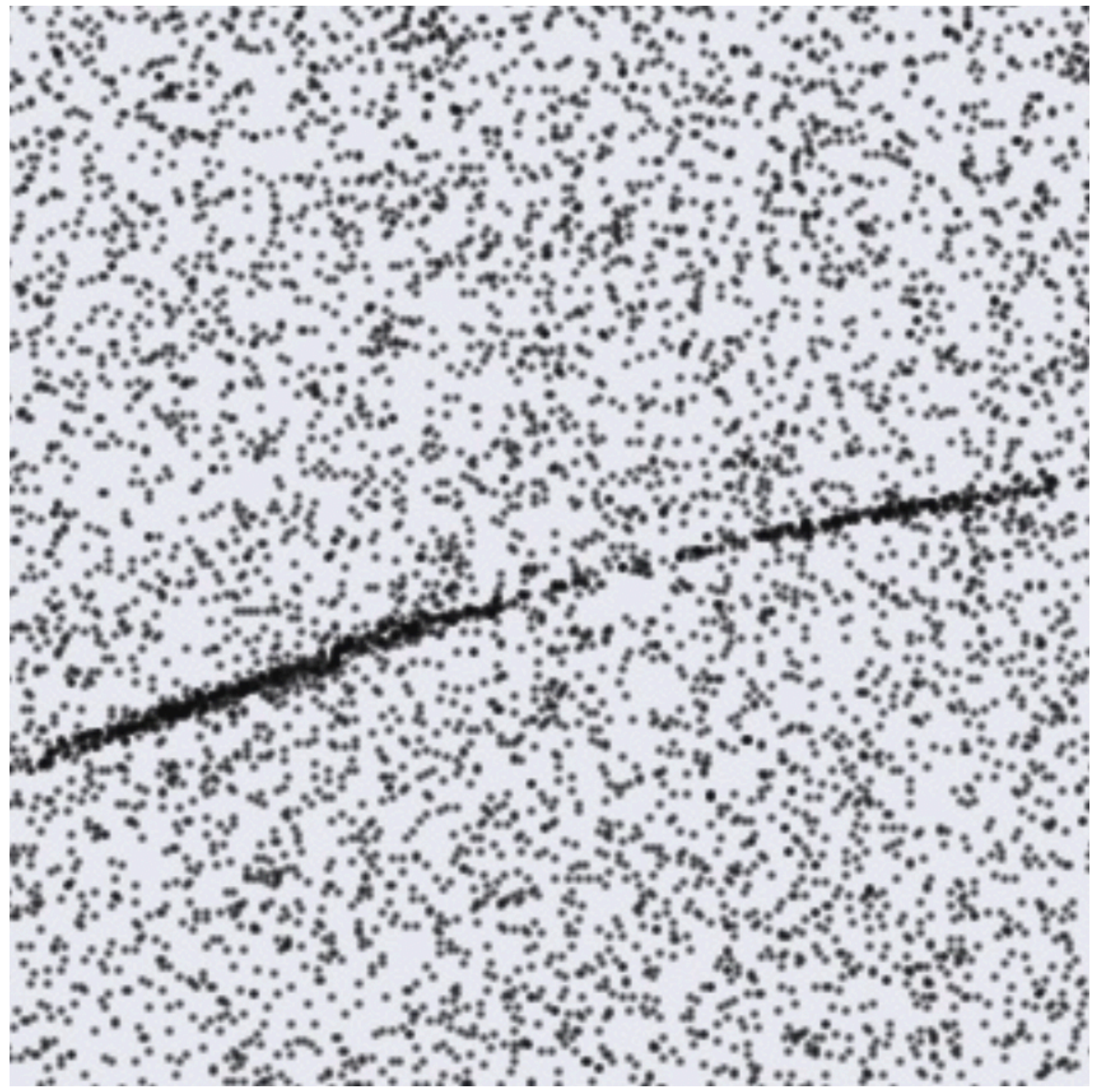
Dynamical modeling in isolation,
Flexible in galaxy/potential models
and satellites streams,
High resolution



Based on Pop et al. 2018
The Illustris Simulations: Genel et al. 2014; Vogelsberger et al. 2014a,b



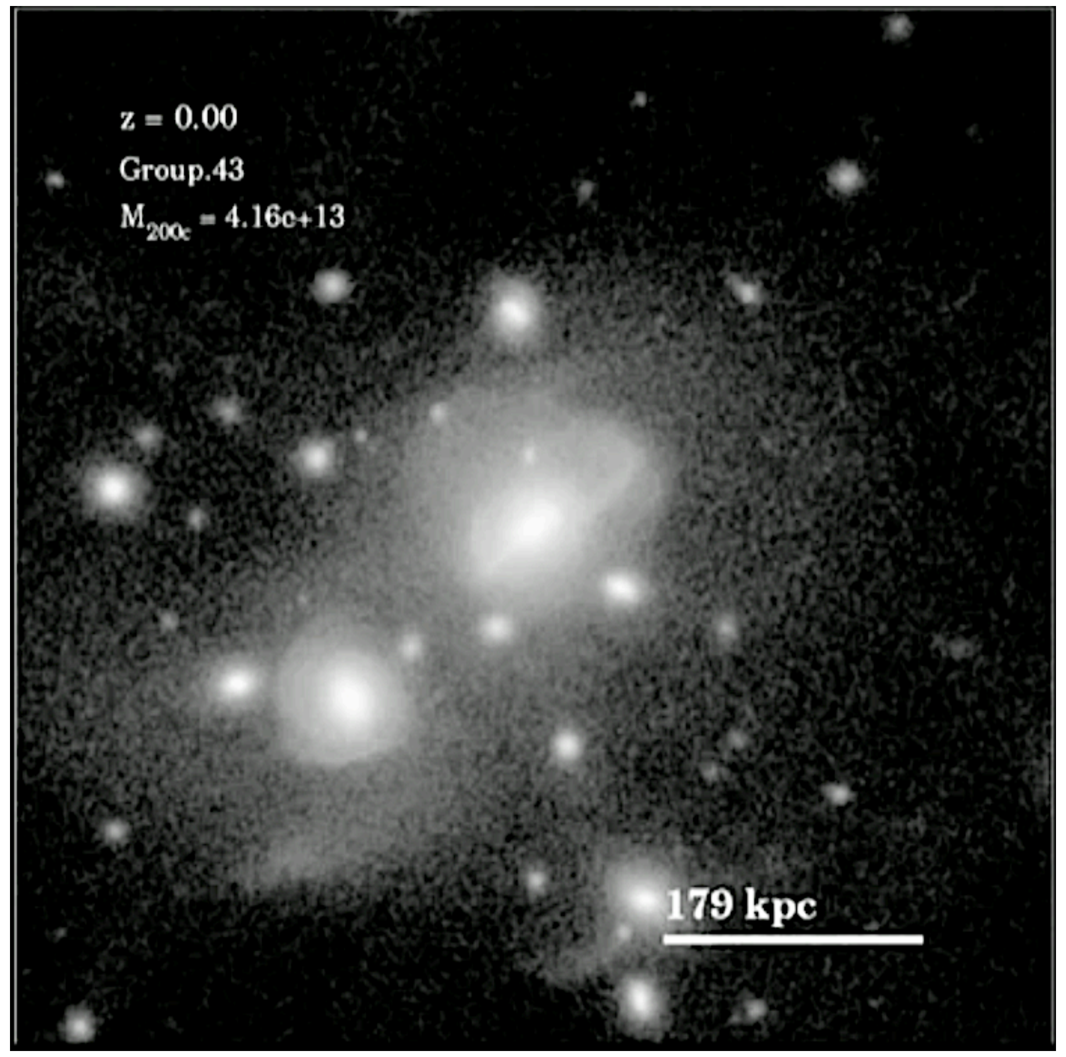
Sanderson et al. 2020
FIRE simulations (Hopkins 2014,2018)



Aganze+ (incl TS) in prep.

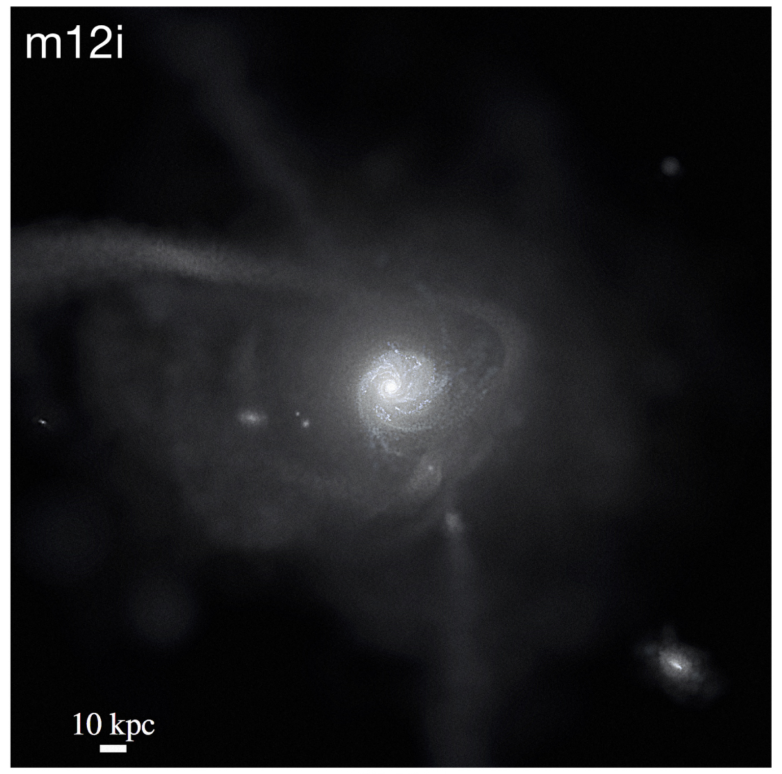
CHALLENGES OF THEORETICAL PREDICTIONS

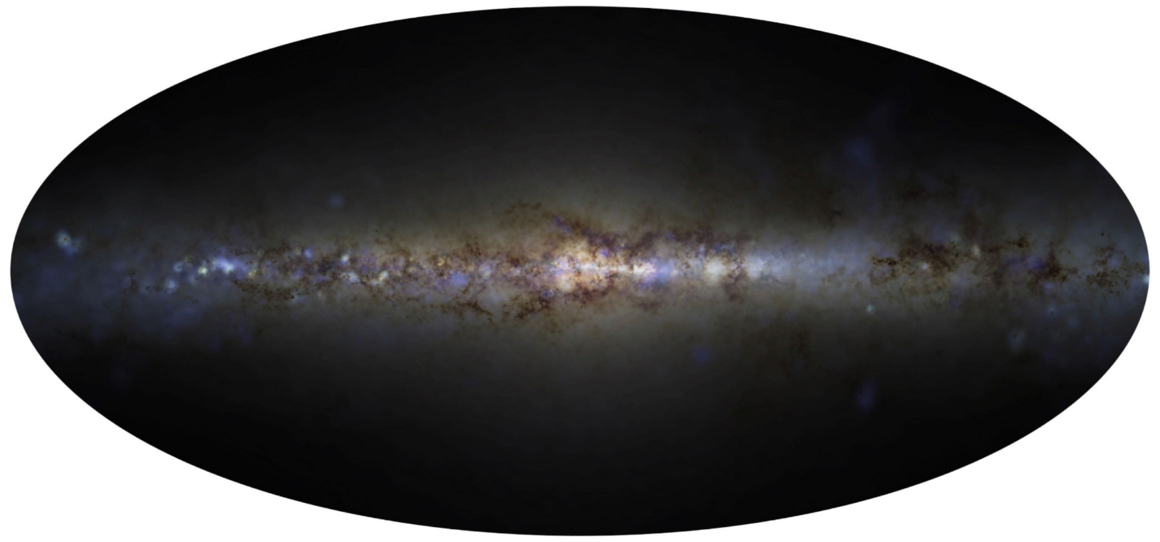
Cosmological,
large # of galaxies,
low resolution



Based on Pop et al. 2018
The Illustris Simulations: Genel et al. 2014; Vogelsberger et al. 2014a,b

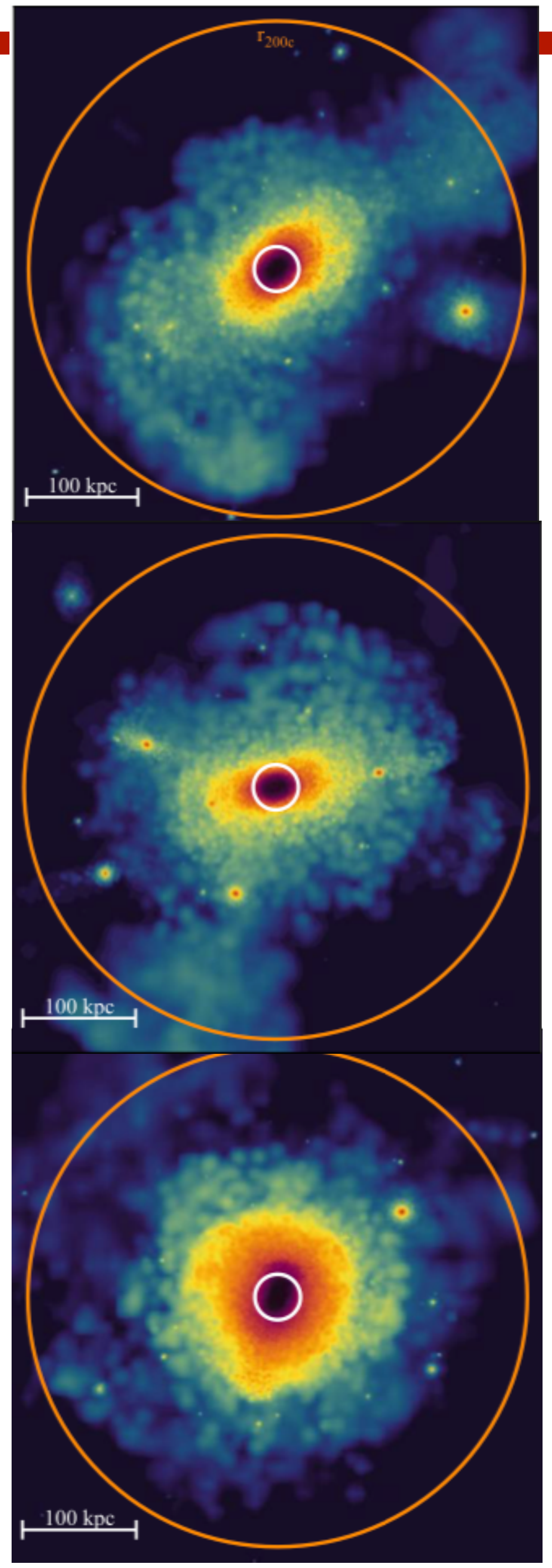
Cosmological,
Few galaxies,
Higher resolution





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

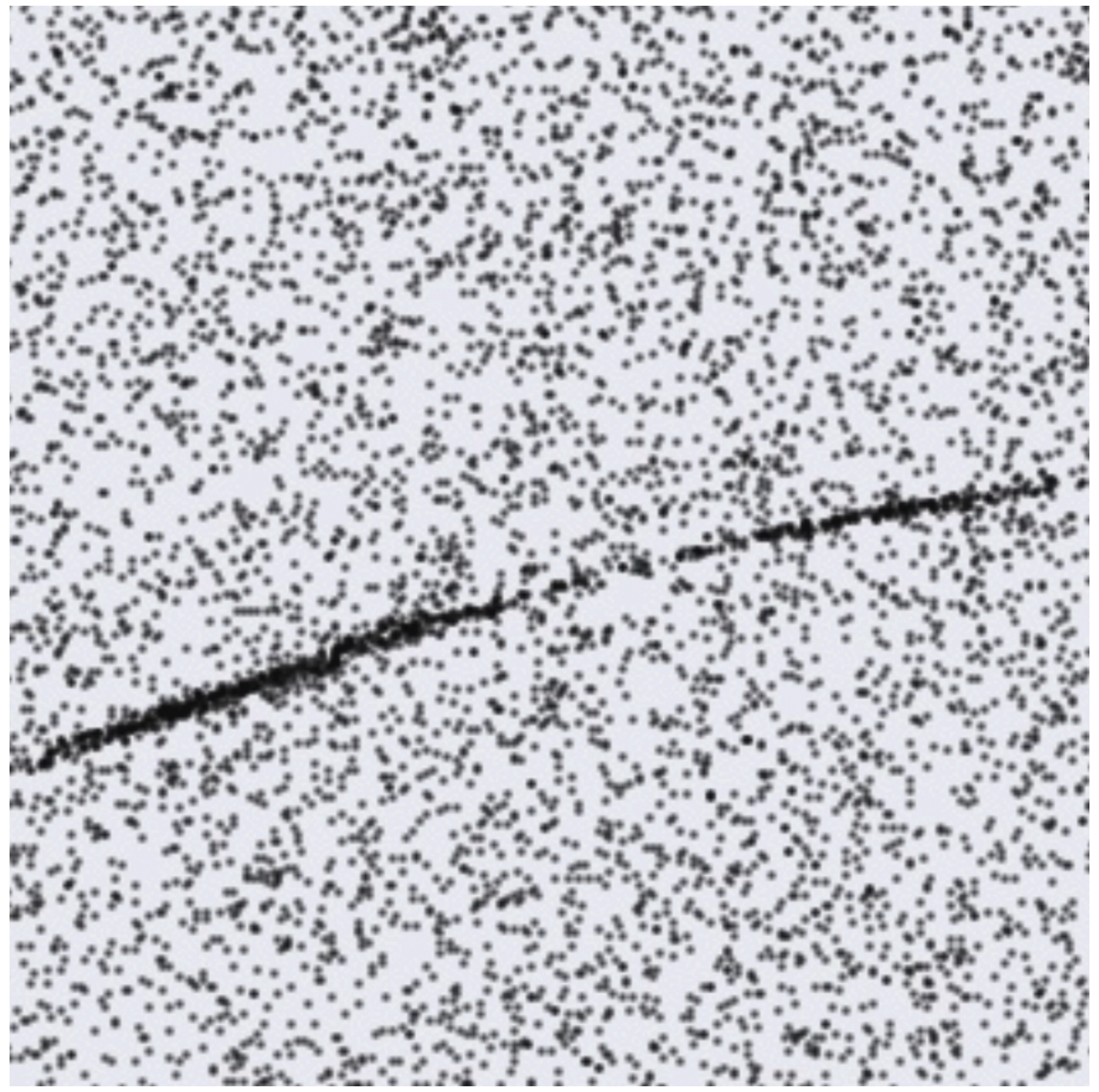
Cosmological, more galaxies,
higher DM resolution,
flexible empirical models



Rey & Starkenburg 2022

?

Dynamical modeling in isolation,
Flexible in galaxy/potential models
and satellites streams,
High resolution



Aganze+ (incl TS) in prep.

PREDICTING TIDAL DEBRIS EVOLUTION WITH SEMI-ANALYTIC MODELING

Starkenburg, Pearson et al. in prep.

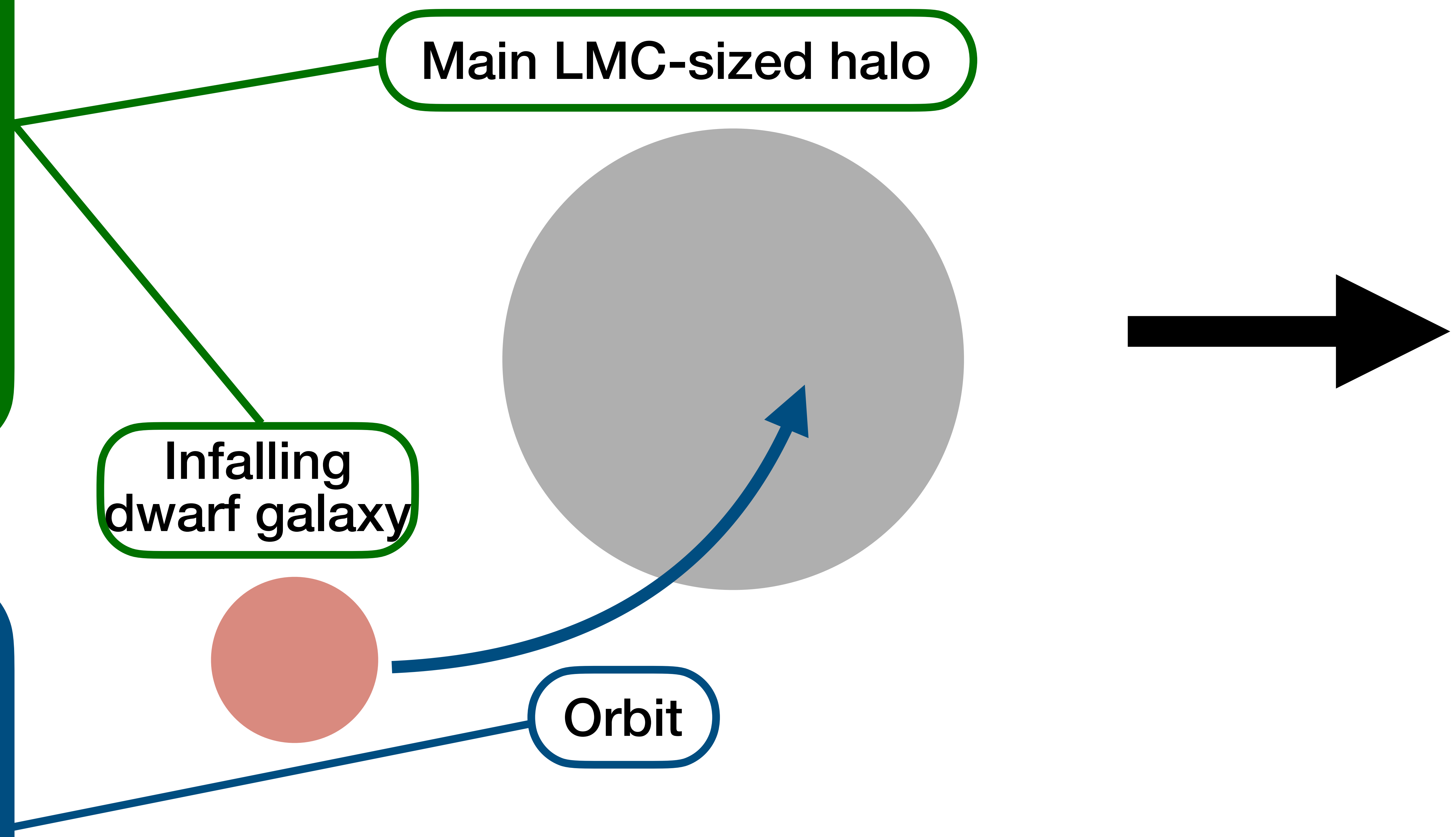
Input from the Santa Cruz Semi-Analytic Model *(Somerville+2008,2012)*:

- 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

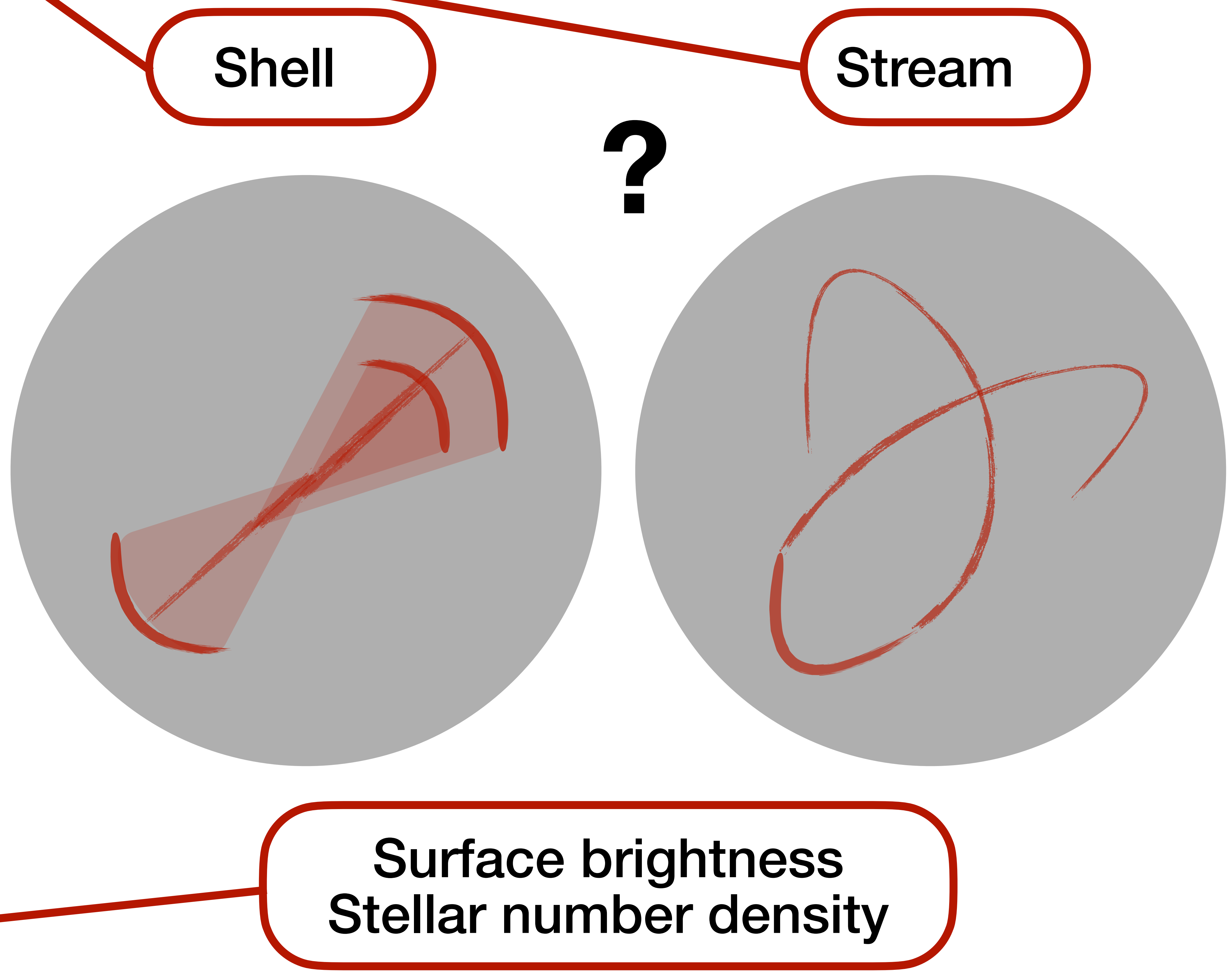


PREDICTING TIDAL DEBRIS EVOLUTION WITH SEMI-ANALYTIC MODELING

Starkenburg, Pearson et al. in prep.

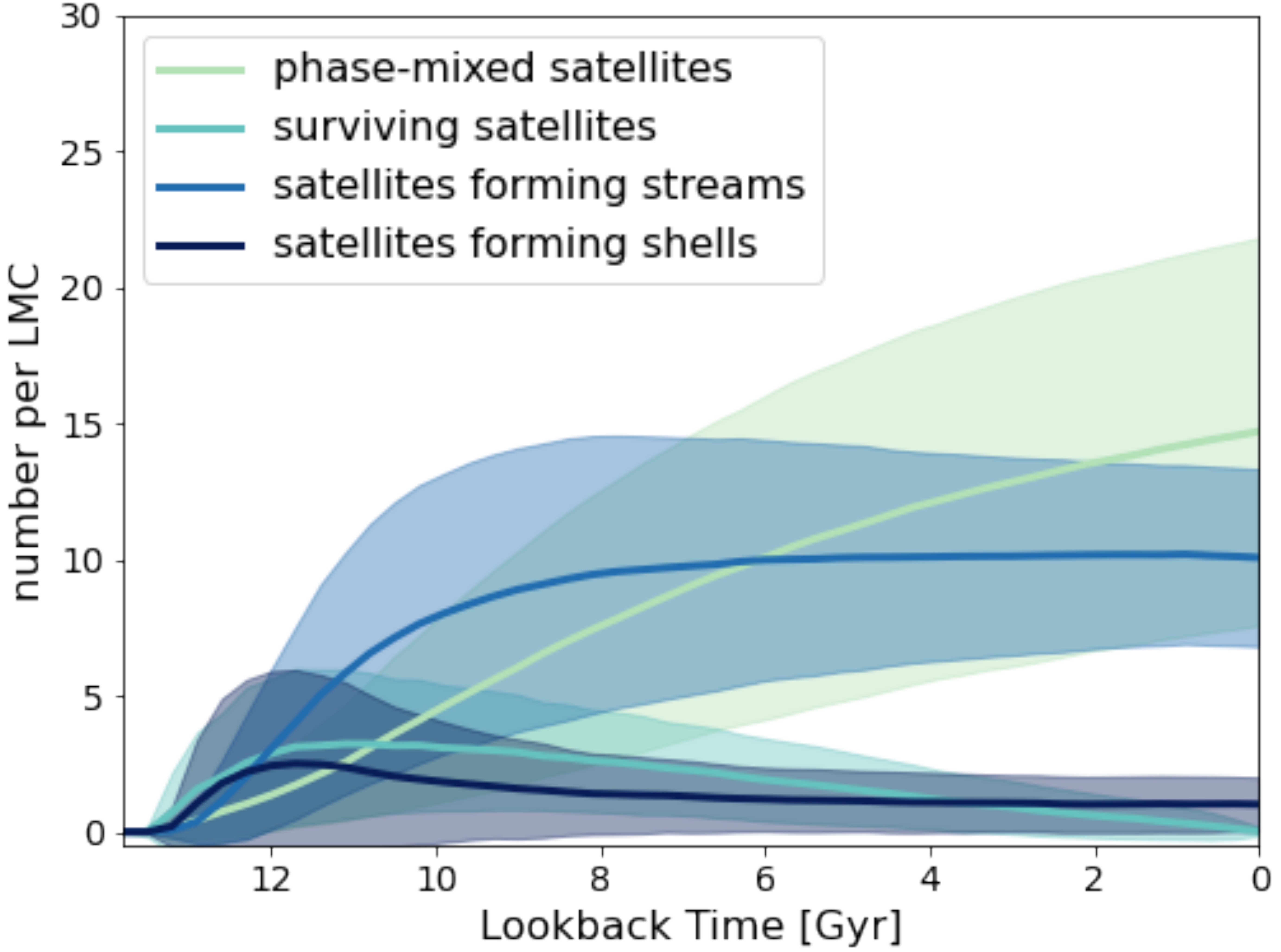
Predict debris Morphology and Observability:

- Estimate dark matter halo stripping timescale using mass loss semi-analytic model SatGen *(Jiang+2021; Green+2022)*
- Estimate lifetime of the tidal debris until phase-mixed
- **Predict debris morphology for each subsequent orbit** *(Johnston 2001; Hendel & Johnston 2015)*
- **Predict surface brightness and stellar density**



PREDICTING TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

Starkenburg, Pearson et al. in prep.



- Generate accretion histories for *many* isolated halos

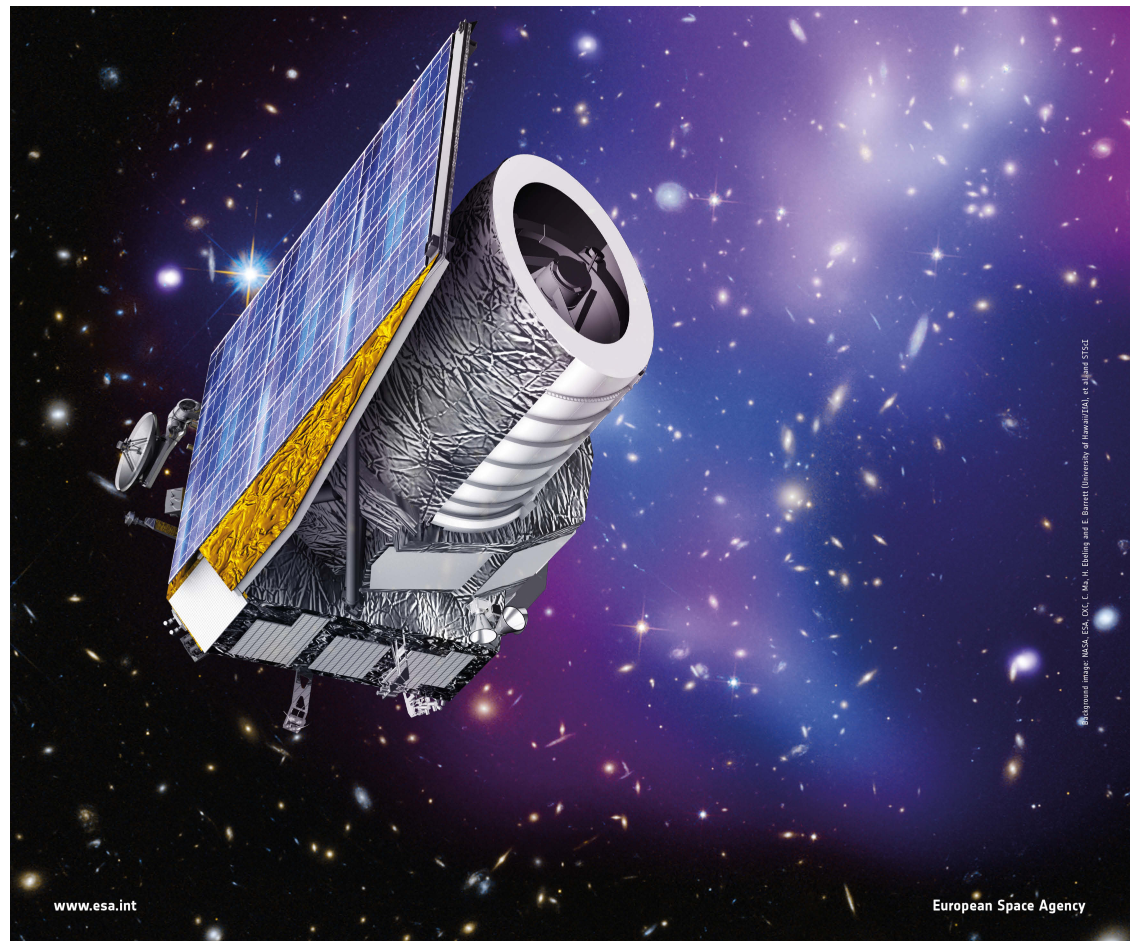
- Use our (arbitrarily) large sample size to provide robust predictions and test the effects of models, assumptions and input parameters

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

PREDICTING TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

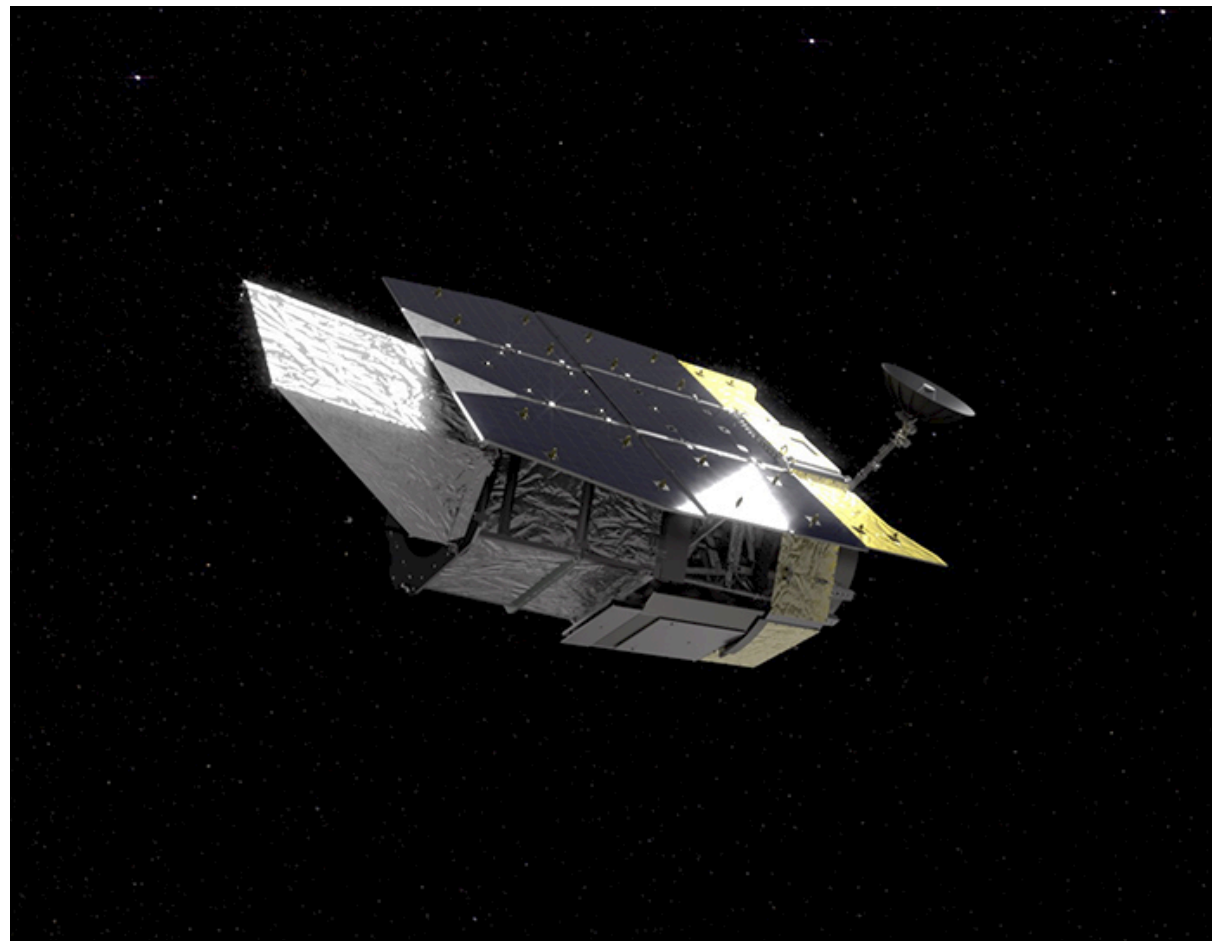
Starkenburg, Pearson et al. in prep.

Euclid



Rubin / LSST

Roman



- 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 tidal features (streams)**

PREDICTING TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

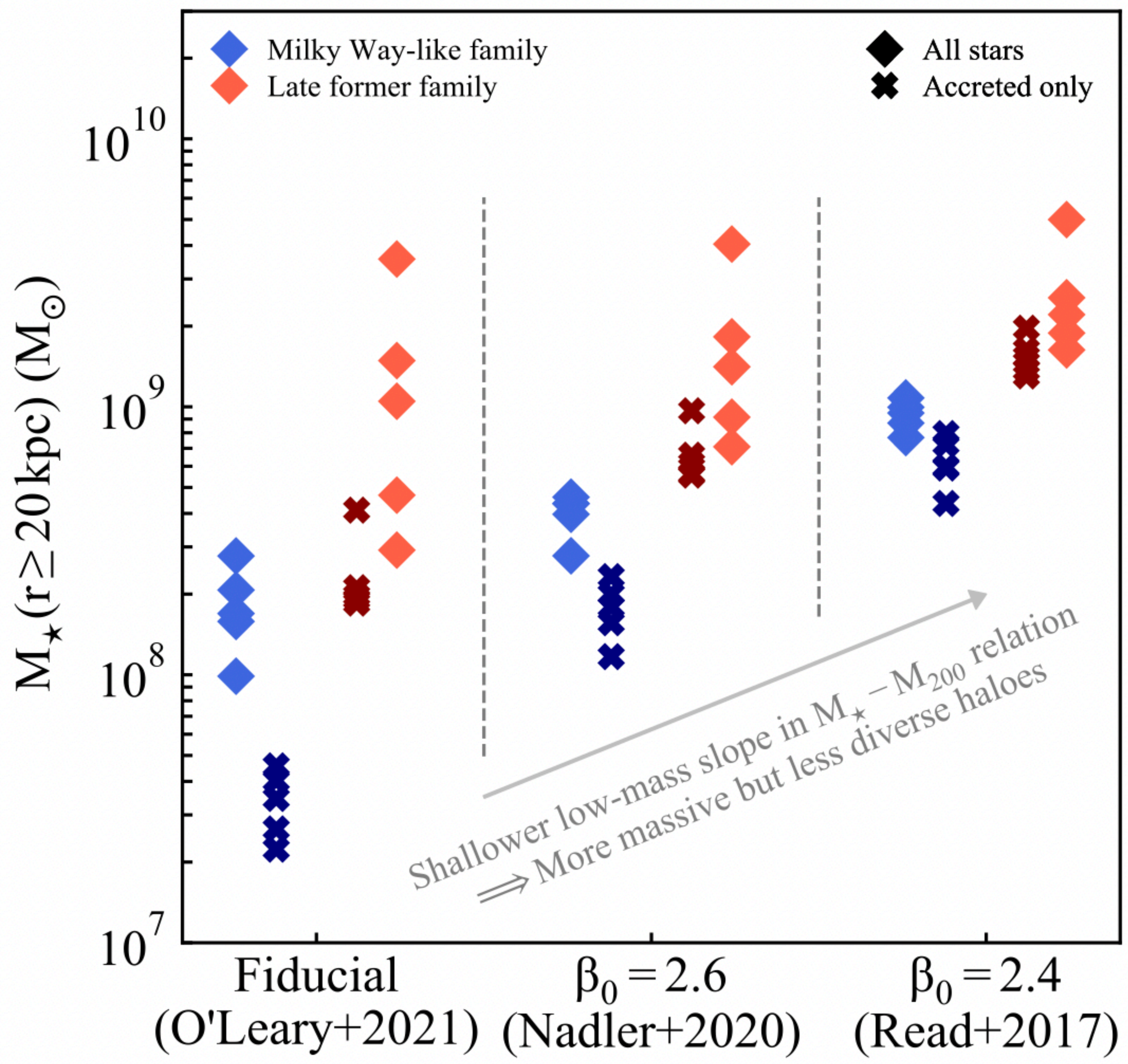
Starkenburg, Pearson et al. in prep.

- 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

STELLAR HALOS AND TIDAL DEBRIS ARE TRACERS OF GALAXY FORMATION AT THE LOW-MASS END

Rey & Starkenburg 2022:

- The diversity (spread) if stellar halo masses varies with changes in the low-mass end slope of the Stellar mass-Halo mass relation



PREDICTING TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

Starkenburg, Pearson et al. in prep.

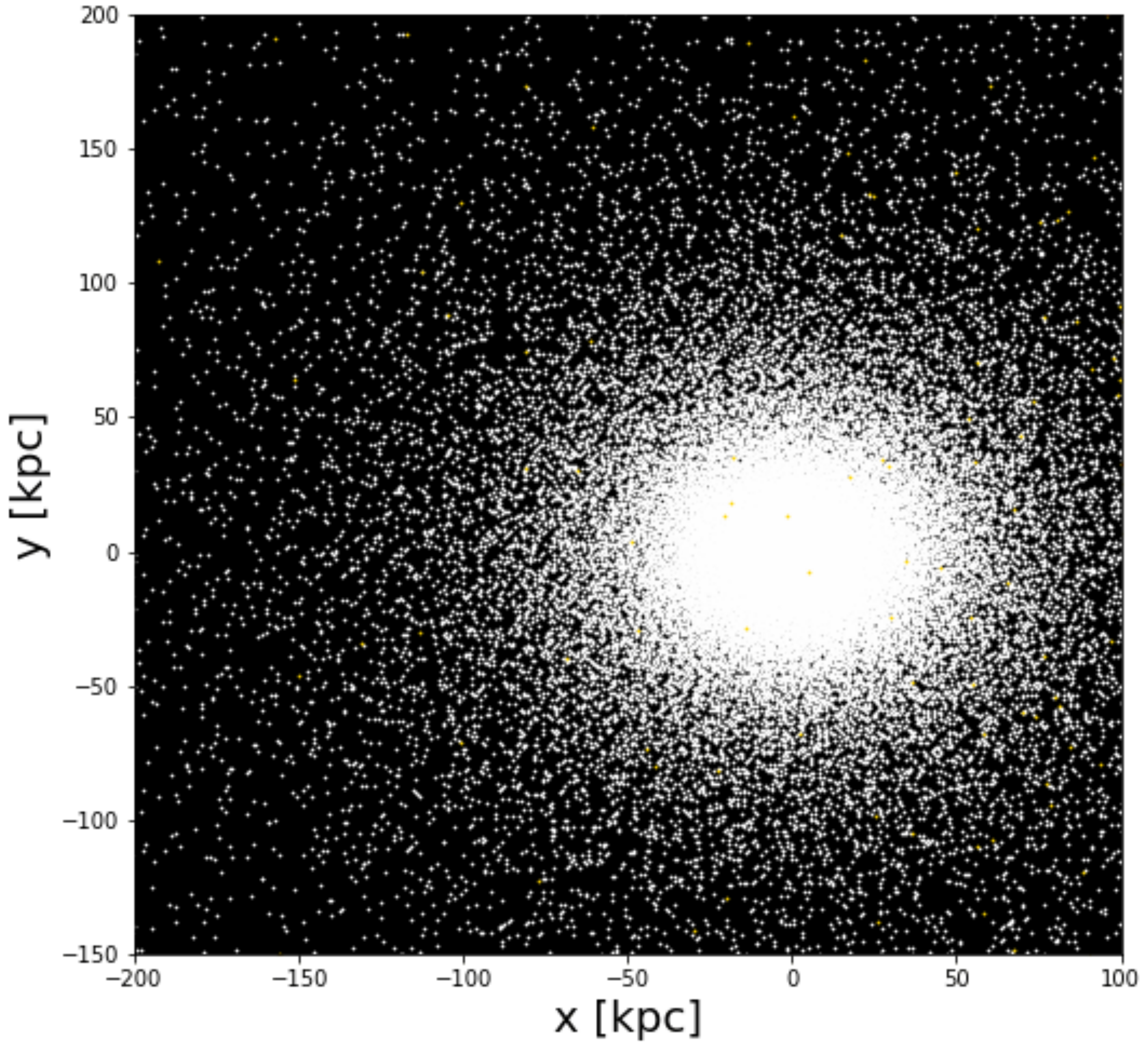
- Generate accretion histories for *many* isolated halos
- Use our (arbitrarily) large sample size to provide robust predictions and test the effects of models, assumptions and input parameters
  - **Nearby galaxies will have visible tidal features with Euclid, Roman, and Rubin**
  - These are challenging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

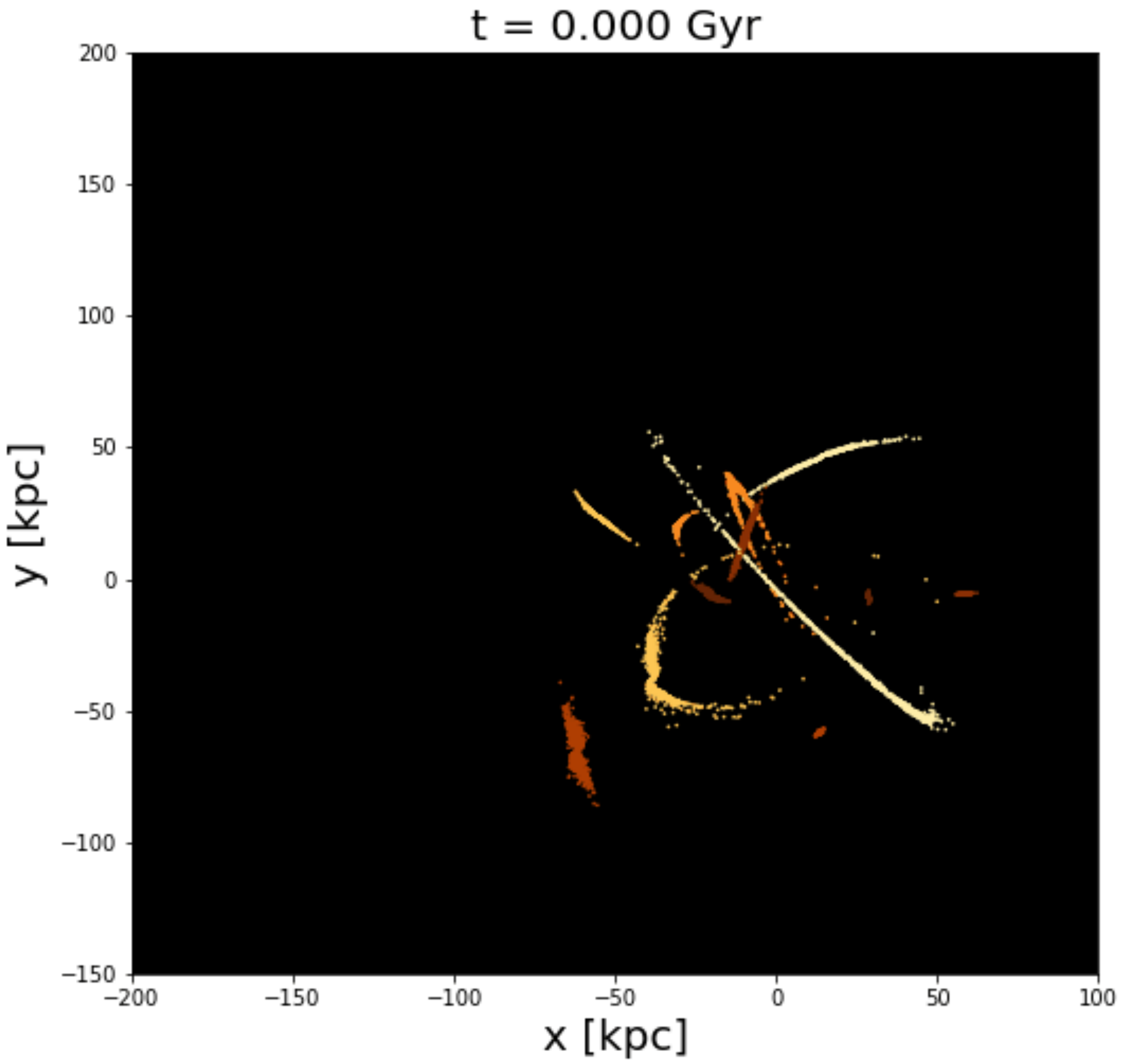
PREDICTING TIDAL DEBRIS AROUND LMC-SIZED GALAXIES

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**
  - **Statistics will provide constraints on galaxy formation! Here: very steep low-mass stellar mass-halo mass relation**

STELLAR STREAM EVOLUTION DURING MERGERS





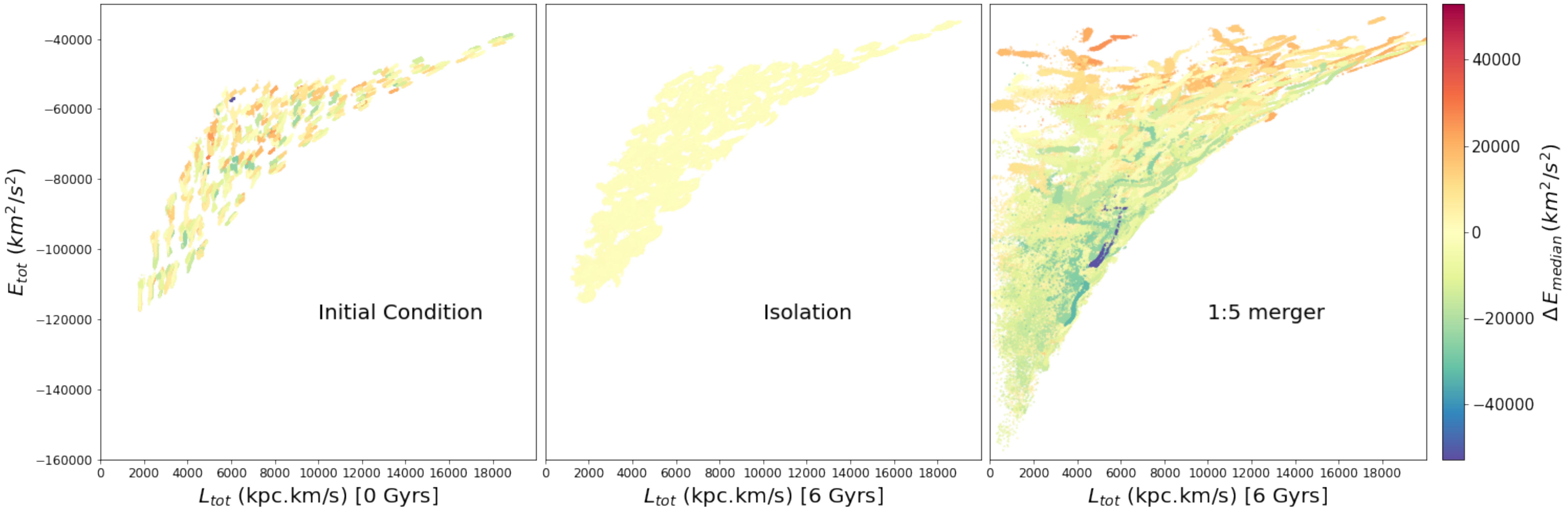
Sachithra (Sachi) Weerasooriya, grad student at TCU
-> Carnegie

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

STELLAR STREAM EVOLUTION DURING MERGERS

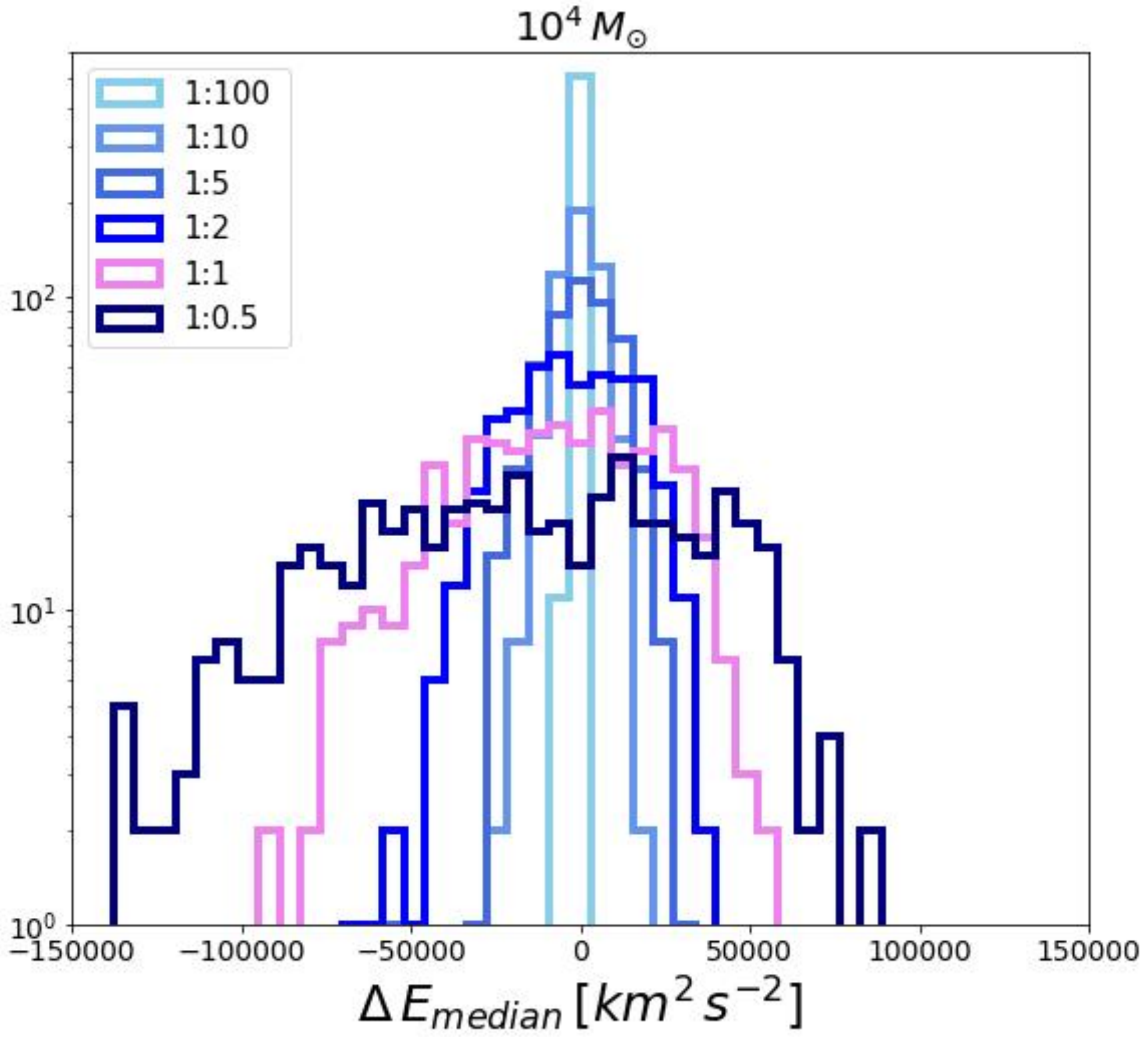
Sachithra (Sachi) Weerasooriya, grad student at TCU -> Carnegie

Energy



Change in energy

Angular momentum



Change in energy

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

TAKE-AWAYS

- **Stellar halos trace a galaxies' full merger histories, correlated with the galaxy's own "internal" evolution, and are sensitive to lower-mass galaxy formation**

- **Many galaxies (including dwarfs!) in Rubin, Roman, and Euclid surveys will have observable satellites and tidal features, providing us amazing data and statistics**

- **Building large and flexible theoretical datasets is crucial to interpret the observations. Combining simulation techniques will help in providing all of the statistics, the resolution, the cosmological context, and the physical models that we need**

- **Data-driven techniques will be crucial to bridge from observed substructure and galaxy properties to galaxy formation histories and physics** (I have toy projects and ideas; love to chat more!)

If you're interested in writing a proposal for a KITP program, feel free to bug me about the process!